ASME B5.54-2005
(Revision of ASME B5.54-1992)

Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers

AN AMERICAN NATIONAL STANDARD



The American Society of Mechanical Engineers

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FOREWORD

The primary purpose of this Standard is to provide procedures for the performance evaluation of computer numerically controlled (CNC) machining centers. The secondary purpose is to facilitate performance comparisons between machines and to provide for machine evaluation after refit. Definitions, environmental requirements, and test methods are specified. This Standard defines the test methods capable of yielding adequate results for most machines, but is not intended to supplant more complete tests that may be required for particular special applications.

This first revision of this Standard provides consistency with the recently published standard for turning centers (ASME B5.57-1998) with respect to some definitions, data analysis, and reported parameters. To achieve consistency, uncertainty analysis was used to analyze data and report parameters for many of the procedures, deemed appropriate, within this Standard. Availability of improved measurement technology and increasing demand for greater accuracy require more robust procedures for assessing performance of machining centers, as provided within this revision of the B5.54 standard. This Standard does not address issues of machine safety.

This revision was approved by the American National Standards Institute on July 7, 2003 and January 12, 2005.

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The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

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METHODS FOR PERFORMANCE EVALUATION OF COMPUTER NUMERICALLY CONTROLLED MACHINING CENTERS

Chapter 1
Scope

1.1 GENERAL

This Standard establishes methodology for specifying and testing the performance of CNC machining centers. In addition to clarifying the performance evaluation, this Standard facilitates performance comparisons between machines by unifying terminology, general machine classification, and the treatment of environmental effects. It provides a series of tests that should be used to perform acceptance testing (runoff) of new and reconditioned machines and could be used to verify continued capability of production machines, already in operation, through periodic testing. The set of acceptance tests and the specification limits for machine conformance shall be the subject of contractual agreement between the Supplier and the User. This Standard is rather comprehensive; therefore, for smaller and less expensive machines the conformance to specifications could be based on a recommended subset of tests to evaluate machine performance.

1.2 PERFORMANCE FORMS

Any performance forms described, as complying with this Standard, shall include at least those items specified in Forms 1.1 through 1.6. Other forms shall be included, depending on the acceptance tests agreed between the Supplier and the User. The form for machining test parts is included in Chapter 8 as Form 8.1.

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Form 1.1 General Form

Machine Classification (Para. 4.2): A code number classifying the machining center configuration, axis designation, and directions of positive travel shall be specified as described in para. 4.2.

Code number _____

In addition, a schematic of the machine with axis directions should be provided.

Linear Axes

	Full Travel		Control Resolution		Minimum Programming Increment	
Axis Name	mm	in.	mm	in.	mm	in.
X						
Y						
Z						

	Maximum Programmable Feed Rate		Rapid Traverse Speed		Acceleration/Deceleration	
Axis Name	mm/min	in./min	mm/min	in./min	mm/s^2	$in./sec^2$
X						
Y						
Z						

Rotary Machining Axes

Axis Name	Full Travel, deg	Control Resolution, deg	Minimum Programming Increment, deg	Maximum Programmable Feed Rate, deg/min	Rapid Traverse Speed, deg/min	Acceleration/ Deceleration, deg/sec^2	Time to Rotate, sec	
							90 deg	180 deg
A								
B								
C								

Rotary Positioning Axes

Axis Name	Full Travel, deg	Minimum Index Increment, deg	Time to Index, sec	
			90 deg	180 deg
A				
B				
C				

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Form 1.1 General Form (Cont'd)

Principal Spindle Parameters (for Each Spindle)

Spindle Range	Rotation Speed		Spindle Power Continuous Duty	
	Min., rpm	Max., rpm	kW	hp
1				
2				

Minimum programmable speed: _____ rpm

Supplier shall furnish torque/power curves for each spindle range. Intermittent duty cycle details for each spindle range shall be supplied if applicable.

Tool holder type: _____

Machine Tool Probes (for Each Probe)

Probe type: ☐ Part probe ☐ Tool setting probe
☐ Contact ☐ Noncontact
☐ Switching ☐ Proportional ☐ Nulling
☐ 1D ☐ 2D ☐ 3D

Operating parameters: Probe approach rate _____ mm/s _____ in./sec
Probe approach distance _____ mm _____ in.
Settling time (proportional probes only) _____ sec

Software: ☐ Allows only 1D Measurements
☐ Allows only 2D measurements
☐ Allows 3D measurements

List of Compensation Tables in the Controller: Supplier shall provide a technical description of the machine compensation system (where applicable), as well as a statement describing User access to compensation system parameters.

Compensation Description	Accessible by User (Y/N)	Information Attached (Y/N)

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Form 1.2 Chapter 5 Environmental Specifications Guidelines

Thermal Information (Para. 5.2)

Temperature	°C	°F
Mean ambient temperature		
Minimum safe operating temperature		
Maximum safe operating temperature		
Daily (24 hr) temperature cycling amplitude, plus or minus		

Superimposed cycle(s)
Amplitude: ± _____ °C ± _____ °F
Frequency: _____ cycles/hr

Maximum temperature gradients
Vertical: _____ °C/m _____ °F/ft
Horizontal: _____ °C/m _____ °F/ft

Maximum mean air speed surrounding the machine: _____ m/s _____ ft/sec

Additional guidelines on machine component placement and special flow parameters, such as mean flow rate, are to be specified if appropriate.

Nominal Coefficient of Thermal Expansion of Linear Machine Feedback Device Axis

Axis	Nominal Coefficient of Thermal Expansion	
	10^{-6}/°C	10^{-6}/°F
X		
Y		
Z		

Seismic Vibration Allowances (Para. 5.3)

☐ Option 1 (response function data):
(detailed permissible vector vibration spectra shall be attached as a part of this specification)
☐ Option 2 (broadband data):

Frequency Range		Peak-to-Peak Amplitude	
Minimum, Hz	Maximum, Hz	mm	in.

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Form 1.2 Chapter 5 Environmental Specifications Guidelines (Cont'd)

Electrical (Equivalent Specification Required for Each Electrical Supply; Para. 5.4)

Steady state requirements:
Voltage _____ V Frequency _____ Hz Amperage _____ A

Allowable short duration RMS voltage variations (instantaneous):
Voltage sag (8.3 msec to 500 msec) _____ percent of nominal
Voltage swell (8.3 msec to 500 msec) _____ percent of nominal

Allowable long duration RMS variations:
Overvoltages (>1 min) _____ percent of nominal
Undervoltages (>1 min) _____ percent of nominal

Allowable transient voltage (0.5 to 800 μsec) _____ percent of nominal

Utility Air (if Applicable; Para. 5.5)

Pressure _____ MPa _____ psi
Flow rate _____ dm^3/s _____ scfm
Dew point _____ °C _____ °F

Particulate removal requirements:
Maximum particulate size _____ μm _____ μin. _____ % removal

Other Services (if Applicable; Para. 5.6)

Foundation/installation specifications (must be included by Supplier)
Construction drawings: ☐ Yes ☐ No

Suppliers shall provide a technical description of the coolant system
Coolant through spindle: ☐ Yes ☐ No

GENERAL NOTE: The parameters listed here are based on assumptions regarding normal air-conditioned rooms. Another set, if provided as part of the machine specification and agreed on between Supplier and User, shall be acceptable for the purposes of this Standard. In some cases, other fluids (rather than air) are used to provide thermal stability. In those cases, separate guidelines should also be provided.

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Form 1.3 Chapter 6 Environmental Tests

Environmental Temperature Variation Error (Para. 6.2)

Date: _____ Time: _____ Operator: _____

Axis	Location for ETVE Test (Machine Coordinates)	
	mm or deg	in. or deg
X		
Y		
Z		
A		
B		
C		

Reported Result	Range Drift	
	mm or s	in. or sec
$ETVE_X$		
$ETVE_Y$		
$ETVE_Z$		
$ETVE_{XX}$		
$ETVE_{YY}$		

Relative Vibration Test (Para. 6.3)

If the nominal location for this test is different from that of environmental temperature variation test, the nominal location shall be recorded on this sheet.

Date: _____ Time: _____ Operator: _____

Direction	Relative Vibration	
	mm	in.
X		
Y		
Z		

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Form 1.4 Chapter 7 Machine Performance

Machine Compliance and Hysteresis (Para. 7.2)

Date: _____ Time: _____ Operator: _____

Location for Tests (Machine Coordinates)

	Location of Test (Machine Coordinates)								
	X		*Y*		*Z*		*A*,	*B*,	*C*,
Compliance	mm	in.	mm	in.	mm	in.	deg	deg	deg
X									
Y									
Z									
A									
B									
C									

Machine Compliance and Hysteresis Measured Between Machine Spindle and Workpiece

Direction of Measured Compliance	Rotary Axis	Distance From Table, *R*	Clamped or Servo Held	Axis That Generates the Force [Note (1)]	Compliance		Hysteresis	
					mm/N	in./lb	mm	in.
X	N/A		N/A					
Y	N/A		N/A					
Z	N/A		N/A					
☐ *X* or ☐ *Y*	*A*							
☐ *X* or ☐ *Z*	*B*							
☐ *Y* or ☐ *Z*	*C*							

NOTE:
(1) Enter "N/A" if the force is applied using an external actuator such as a differential screw or hydraulic jack.

Positioning Accuracy and Repeatability (Para. 7.3): Linear Axes

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No

	Maximum Unidirectional Systematic Deviation of Positioning, $E\uparrow$ or $E\downarrow$		Bidirectional Systematic Deviation of Positioning, *E*		Bidirectional Accuracy of Positioning, *A*		Periodic Error, *P*	
Axis	mm	in.	mm	in.	mm	in.	mm	in.
X								
Y								
Z								

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Form 1.4 Chapter 7 Machine Performance (Cont'd)

Axis	Maximum Unidirectional Repeatability, $R\uparrow$ or $R\downarrow$		Bidirectional Repeatability, R		Reversal Deviation, B	
	mm	in.	mm	in.	mm	in.
X						
Y						
Z						

Min. ambient temperature _____ °C _____ °F Max. ambient temperature _____ °C _____ °F
Ambient air pressure _____ mm Hg _____ in. Hg Relative humidity _____ %
Feed rate of testing _____ mm/min _____ in./min Machine temperature _____ °C _____ °F

Positioning Accuracy and Repeatability (Para. 7.3): Rotary Axes

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No

Axis	Maximum Unidirectional Systematic Deviation of Positioning, $E\uparrow$ or $E\downarrow$, sec	Bidirectional Systematic Deviation of Positioning, E, sec	Bidirectional Accuracy of Positioning, A, sec	Periodic Error, P, sec
A				
B				
C				

Axis	Maximum Unidirectional Repeatability, $R\uparrow$ or $R\downarrow$, sec	Bidirectional Repeatability, R, sec	Reversal Deviation, B, sec
A			
B			
C			

Min. ambient temperature _____ °C _____ °F Max. ambient temperature _____ °C _____ °F
Rotary feed rate _____ deg/min

Geometric Accuracy Tests (Para. 7.4)

Geometric Errors of Linear Axes (Para. 7.4.2)

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No

Axis	*X* Straightness		*Y* Straightness		*Z* Straightness		Roll, E, sec	Pitch, E, sec	Yaw, E, sec
	mm	in.	mm	in.	mm	in.			
X	N/A	N/A							
Y			N/A	N/A					
Z					N/A	N/A			

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Form 1.4 Chapter 7 Machine Performance (Cont'd)

Geometric Errors of Rotary Axes (Para. 7.4.3)

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No

Axis	Error Motion in *X*		Error Motion in *Y*		Error Motion in *Z*		Tilt Around *X*, sec	Tilt Around *Y*, sec	Tilt Around *Z*, sec
	mm	in.	mm	in.	mm	in.			
A							N/A		
B								N/A	
C									N/A

Squareness Errors (Para. 7.4.4.1)

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No

Squareness Error	Error Magnitude, sec
XY squareness	
XZ squareness	
YZ squareness	
AZ squareness	

Parallelism (Para. 7.4.4.2)

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No

Parallelism Error	Error Magnitude, sec
ZW parallelism in *XZ* plane	
ZW parallelism in *YZ* plane	

Spindle Axis of Rotation (For Each Spindle; Para. 7.5)

Date: _____ Time: _____ Operator: _____ Spindle: _____ Compensated: ☐ Yes ☐ No

Structural Motion, Spindle OFF (Para. 7.5.2)

Direction	Machine Drives OFF		Machine Drives ON	
	mm	in.	mm	in.
Along *X* or *Y* direction				
Along *Z* direction				

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Form 1.4 Chapter 7 Machine Performance (Cont'd)

Spindle Tests, Rotating Sensitive Direction (Para. 7.5.3)

Date: _____ Time: _____ Operator: _____ Spindle: _____

Percentage of Maximum Speed	Spindle Speed, rpm	Average Radial Error Motion		Asynchronous Radial Error Motion		Total Axial Error Motion		Average Tilt Error Motion, sec	Asynchronous Tilt Error Motion, sec
		mm	in.	mm	in.	mm	in.		
10%									
50%									
100%									

Machine Thermal Tests (Para. 7.6)

Spindle Warm-Up and Transient Shut-Off Test (for Each Spindle; Para. 7.6.2)

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No
Spindle: _____ Duration of test: _____ Spindle speed: _____ Coolant: ☐ On ☐ Off

Displacement and Tilt of the Axis of Rotation

Error Motion	Drift During Warm-Up		Drift During Transient Shut-Off	
	mm or s	in. or sec	mm or s	in. or sec
Displacement in *X*, D_X				
Displacement in *Y*, D_Y				
Displacement in *Z*, D_Z				
Tilt around *X*, D_{XY}				
Tilt around *Y*, D_{YZ}				

Thermal Distortion Caused by Moving Linear Axes (for Each Axis; Para. 7.6.3)

Date: _____ Time: _____ Operator: _____ Duration of Test: _____ Compensated: ☐ Yes ☐ No

Axis	Range of the Drift at Position 1 in Axis Direction				Range of the Drift at Position 2 in Axis Direction			
	Forward Direction ↑		Reverse Direction ↓		Forward Direction ↑		Reverse Direction ↓	
	mm	in.	mm	in.	mm	in.	mm	in.
X								
Y								
Z								

Composite Thermal Error (Para. 7.6.4)

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No
Duration of test: _____ Distance between indicator 1 and indicator 2: _____ mm _____ in.

Location	Drift After 30 min		Drift After _____ min	
	mm	in.	mm	in.
X Indicator 1				
X Indicator 2				
Y Indicator 1				
Y Indicator 2				
Z Indicator 1				
Z Indicator 2				

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Form 1.4 Chapter 7 Machine Performance (Cont'd)

Diagonal Displacement Test (Para. 7.7)

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No

Body or Face Diagonal	Length of Diagonal		Bidirectional Systematic Deviation, *E*		Reversal Deviation, *B*	
	mm	in.	mm	in.	mm	in.
#1						
#2						
#3						
#4						

Subsystems Repeatability (Para. 7.8)

Tool Change Repeatability (Para. 7.8.2)

Date: _____ Time: _____ Operator: _____
Length from gage line for short tool: _____ mm _____ in. Length from gage line for long tool: _____ mm _____ in.

Error Direction	Tool Change Repeatability			
	Short Tool		Long Tool	
	mm	in.	mm	in.
X				
Y				
Z				

Pallet Change Repeatability (Para. 7.8.3)

Date: _____ Time: _____ Operator: _____

X Position		*Y* Position		*Z* Position		*A* Angle, sec	*B* Angle, sec	*C* Angle, sec
mm	in.	mm	in.	mm	in.			

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Form 1.4 Chapter 7 Machine Performance (Cont'd)

Tool Setting Repeatability (Para. 7.8.4)

Date: _____ Time: _____ Operator: _____
Can measure tool diameter? ☐ Yes ☐ No
Measured while rotating spindle? ☐ Yes ☐ No
Tool setting repeatability length measurement: _____ mm _____ in.
Tool setting repeatability diameter measurement: _____ mm _____ in.

Machine Performance as a Measuring Tool (Para. 7.9)

	Feature Location Repeatability					
	1D		2D		3D	
Axis	mm	in.	mm	in.	mm	in.
X						
Y						
Z						

2D feature measurement accuracy: _____ mm _____ in. 2D probe lobing range: _____ mm _____ in.
3D feature measurement accuracy: _____ mm _____ in. 3D probe lobing range: _____ mm _____ in.

Linear measurement accuracy in *X*: _____ mm _____ in. *Y*: _____ mm _____ in. *Z*: _____ mm _____ in.

Volumetric measuring performance: _____ mm _____ in.

Workpiece Location

	Workpiece Location Working Tolerance	
Axis	mm	in.
X		
Y		
Z		

CNC Performance Tests (Para. 7.10)

Date: _____ Time: _____ Operator: _____

Minimum Block Execution Time (Para. 7.10.2)

Maximum steady feed rate (V_{max}): _____ mm/min _____ in./min Minimum block execution time (MBET): _____ sec

Varying Segment Feed Rate (Para. 7.10.3)

Varying segment feed rate (VSFR) _____ mm/min _____ in./min

Least Increment Test (Para. 7.10.4)

	Least Increment Step		Reversal Error	
Axis	mm	in.	mm	in.
X				
Y				
Z				

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Form 1.4 Chapter 7 Machine Performance (Cont'd)

Linear and Rotary Axes Feed Rate and Acceleration Tests (Para. 7.10.5)

Axis	Direction, ↑ or ↓	Nominal Feed Rate			Mean Actual Feed Rate		Range of Variation, % Nominal	Time to Reach 63.2% of Nominal Feed Rate, sec	Acceleration		Deceleration	
		% max.	mm/min or rpm	in./min	mm/min or rpm	in./min			mm/s^2 or rev/s^2	$in./sec^2$	mm/s^2 or rev/s^2	$in./sec^2$
X	↑	10										
X	↓	10										
X	↑	100										
X	↓	100										
Y	↑	10										
Y	↓	10										
Y	↑	100										
Y	↓	100										
Z	↑	10										
Z	↓	10										
Z	↑	100										
Z	↓	100										
A	↑	10										
A	↓	10										
A	↑	100										
A	↓	100										
B	↑	10										
B	↓	10										
B	↑	100										
B	↓	100										
C	↑	10										
C	↓	10										
C	↑	100										
C	↓	100										

Average acceleration: _____ mm/s^2 _____ $in./sec^2$ _____ rev/sec^2

Average deceleration: _____ mm/s^2 _____ $in./sec^2$ _____ rev/sec^2

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Form 1.4 Chapter 7 Machine Performance (Cont'd)

Contouring Performance Using Circular Test (Para. 7.11)

Date: _____ Time: _____ Operator: _____ Compensated: ☐ Yes ☐ No

	Nominal Radius		Feed Rate			Circular Deviation, $G\uparrow$ (cw)		Circular Deviation, $G\downarrow$ (ccw)		Radial Deviation, $F_{min}\uparrow$ (cw)		Radial Deviation, $F_{min}\downarrow$ (ccw)		Radial Deviation, $F_{max}\uparrow$ (cw)		Radial Deviation, $F_{max}\downarrow$ (ccw)	
Plane	mm	in.	% max.	mm/ min	in./ min	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm	in.
XY			10														
XY			80														
YZ			10														
YZ			80														
XZ			10														
XZ			80														

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Form 1.5 Chapter 9 Cutting Performance Tests

Date: _____ Time: _____ Operator: _____

Spindle Idle Run Losses (Para. 9.4)

Maximum spindle speed: _____ rpm

Percentage of Maximum Speed	Lost Power, kW
20	
40	
60	
80	
100	

Chatter Limits Test (Para. 9.5)

NOTE: A table of values is required for each cutting performance chatter test. A minimum of three tests are to be performed: a face milling and an end milling test in 4340 steel (300–350 Brinell hardness number) and an end milling test in 7075-T6 aluminum. In one case, where the Supplier gives limited information on the machine dynamics, each of these tests is to be conducted at two spindle speeds, which yields six tests.

Date: _____ Time: _____ Operator: _____
Machine range (para. 9.3): _____ Test material (para. 9.5.1): _____ Cutting tool (para. 9.5.5): _____
Spindle speed (para. 9.5.4): _____ rpm Feed rate (para. 9.5.6): _____ mm/min

Direction	Radial Immersion, i, mm	Milling Direction	Limit Axial Depth of Cut, b_{lim}, mm	Limit Cross-Sectional Area of Cut, $a \times b_{lim}$, mm^2
X	0.25	Up		
X	0.50	Up		
X	1.00	N/A		
X	0.50	Down		
X	0.25	Down		
Y	0.25	Up		
Y	0.50	Up		
Y	1.00	N/A		
Y	0.50	Down		
Y	0.25	Down		

Full Torque Test (Para. 9.5.8)

Date: _____ Time: _____ Operator: _____

Test material: 4340 steel (300–350 Brinell hardness number)
Machine range (para. 9.3): _____ Cutting tool (para. 9.5.5): _____
Spindle speed (para. 9.5.4): _____ rpm Feed rate (para. 9.5.8): _____ mm/min

Direction: ☐ *x* ☐ *y* ☐ Up ☐ Down

Radial depth of cut a: _____ mm Axial depth of cut b: _____ mm Expected torque, T_{ev}: _____ N·mm
Measured power, P_{meas}: _____ W Measured torque, T_{meas}: _____ N·mm

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Form 1.5 Chapter 9 Cutting Performance Tests (Cont'd)

End Milling Deflection Test (Para. 9.5.9)

Date: _____ Time: _____ Operator: _____

Test material: 7075-T6 aluminum
Machine range (para. 9.3): _____ Cutting tool (para. 9.5.5): _____
Spindle speed (para. 9.5.9): _____ rpm Feed rate (para. 9.5.9): _____ mm/min

Direction	Milling Direction	Radial Depth of Cut, *a*		Maximum Error, e_{max}, mm	Error Range, Δe, mm
		mm	in.		
X	Up	0.05	0.002		
X	Up	0.50	0.020		
X	Up	1.50	0.060		
X	Down	0.05	0.002		
X	Down	0.50	0.020		
X	Down	1.50	0.060		
Y	Up	0.05	0.002		
Y	Up	0.50	0.020		
Y	Up	1.50	0.060		
Y	Down	0.05	0.002		
Y	Down	0.50	0.020		
Y	Down	1.50	0.060		

Face Milling Deflection Test (Para. 9.5.10)

Date: _____ Time: _____ Operator: _____

Test material: 4340 steel (300–350 Brinell hardness)
Machine range (para. 9.3): _____ Cutting tool (para. 9.5.5): _____
Spindle speed (para. 9.5.9): _____ rpm Feed rate (para. 9.5.9): _____ mm/min

Direction	Case	1 mm (0.04 in.) Axial Depth		2 mm (0.08 in.) Axial Depth	
		Maximum Error, e_{max}, mm	Error Range, Δe, mm	Maximum Error, e_{max}, mm	Error Range, Δe, mm
X	Slot				
X	$^1/_2$ up				
X	$^1/_2$ down				
Y	Slot				
Y	$^1/_2$ up				
Y	$^1/_2$ down				

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Form 1.6 Multifunction Cycle Test

Date: _____ Time: _____ Operator: _____

Duration of test: _____ min Number of failures: _____ Maximum time required for correction: _____ min

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Chapter 2
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The following is a list of publications referenced in this Standard.

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EIA-267-C-1990, Axis and Motion Nomenclature for Numerically Controlled Machines

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ISO 3205:1976, Preferred Test Temperatures

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NAS 979, Uniform Cutting Tests

Publisher: Aerospace Industries Association (AIA), 1000 Wilson Boulevard, Arlington, VA 22209

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Chapter 3
Nomenclature

A = bidirectional accuracy of positioning of an axis[1]
$A\uparrow$ = unidirectional accuracy of positioning of an axis, forward direction
$A\downarrow$ = unidirectional accuracy of positioning of an axis, reverse direction
A_{ae} = bidirectional total angular error
$A_{ae}\uparrow$ = unidirectional total angular error, forward direction
$A_{ae}\downarrow$ = unidirectional total angular error, reverse direction
a = radial depth of cut
a^+ = upper limit of a uniform distribution
a^- = lower limit of a uniform distribution
B = maximum of the absolute reversal values at all target positions along an axis[1]
$\overline{B}$ = mean reversal value of an axis
B_{ae} = reversal deviation of angular error
B_i = reversal value at target position, i, along or around an axis
b = axial depth of cut
b_{cr} = estimated chatter limit depth of cut for slot milling
b_{lim} = axial depth of cut for which chatter occurs
C = a programmable spindle axis[1]
CD = corrected diameter
CLR = corrected laser reading
CMR = corrected machine reading
$CPMA$ = circular profile measurement accuracy
CX_n = mean X circle center at position $n = 1, 2$, two-sphere axis alignment
CY_n = mean Y circle center at position $n = 1, 2$, two-sphere axis alignment
c = chip load
DIA = diameter of a circle or part
D_c = diameter of a test cylinder
D_g = distance between two gages
D_i = gage reading during spindle warm-up test ($i = 1$ to 5)
D_X = spindle thermal drift, X direction
D_{XZ} = spindle angular thermal drift of axis average line, XZ plane
D_Y = spindle thermal drift, Y direction
D_{YZ} = spindle angular thermal drift of axis average line, YZ plane
D_Z = spindle thermal drift, Z direction
$1D$ = one-dimensional
$2D$ = two-dimensional
$3D$ = three-dimensional
d = tool diameter
E = bidirectional systematic deviation of position of an axis
$E\uparrow$ = unidirectional systematic deviation of position of an axis, forward direction
$E\downarrow$ = unidirectional systematic deviation of position of an axis, reverse direction
$ETVE$ = environmental temperature variation error
$ETVE_A$ = thermal drift of tilt about a nominal axis direction
$ETVE_X$ = thermal drift in X direction
$ETVE_{XX}$ = thermal drift of tilt about the X direction
$ETVE_Y$ = thermal drift in Y direction
$ETVE_{YY}$ = thermal drift of tilt about the Y direction
$ETVE_Z$ = thermal drift in Z direction
$E(X)$ = bidirectional systematic deviation of positioning, X-axis
$E(Z)$ = bidirectional systematic deviation of positioning, Z-axis
E_{ae} = bidirectional systematic angular error
$E_{ae}\uparrow$ = unidirectional systematic angular error, forward direction
$E_{ae}\downarrow$ = unidirectional systematic angular error, reverse direction
$e(x_n\uparrow)$ = range of thermal drift, target position n, X direction, forward, thermal distortion test
$e(x_n\downarrow)$ = range of thermal drift, target position n, X direction, reverse, thermal distortion test
$e(z_n\uparrow)$ = range of thermal drift, target position n, Z direction, forward, thermal distortion test
$e(z_n\downarrow)$ = range of thermal drift, target position n, Z direction, reverse, thermal distortion test
F = linear axis feed rate
F = out-of-squareness angle between a straightedge and a spindle axis
FLR_X = feature location repeatability
FMA_X = feature measurement accuracy
$FM(X)$ = feature measurement accuracy, X direction
$FM(Z)$ = feature measurement accuracy, Z direction
$F_{\max}\uparrow$ = radial deviation, maximum, clockwise direction, circular test

[1] Capital letters such as A, B, C, X, Y, Z, and W are also used to designate linear and rotary machine tool axes. (See ISO 841:2001 for axis nomenclature.)

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$F_{max}\downarrow$ = radial deviation, maximum, counterclockwise direction, circular test
$F_{min}\uparrow$ = radial deviation, minimum, clockwise direction, circular test
$F_{min}\downarrow$ = radial deviation, minimum, counterclockwise direction, circular test
f_n = natural frequency of the dominant mode
$G\uparrow$ = circular deviation, clockwise, circular test
$G\downarrow$ = circular deviation, counterclockwise, circular test
H = circular hysteresis, circular test
H_c = dynamic compliance at the natural frequency of the dominant mode
$INCR$ = segment length used to test block execution time
$Im(G)$ = imaginary part of the transfer function G
i = index of target position
j = index for number of measurements
k = coverage factor
L = dimension of the workpiece at 20°C
LDR = laser display reading
$LMA(X)$ = linear measurement accuracy, X direction
$LMA(Z)$ = linear measurement accuracy, Z direction
LSC = least-squares circle center of a polar profile
$LUTM$ = length uncertainty due to temperature measurement
L_c = length of a test cylinder
L_{cte} = distance between the displacement indicators in the composite thermal error test
L_d = distance between two measurement points used to calculate angle
L_s = dimension of the reference and/or working standard at 20°C
L_T = dimension of an object at temperature $T \neq 20$°C
L_X = traverse length of the X-axis
L_Z = traverse length of the Z-axis
$L_{1,2}$ = distance between indicator 1 or 2 and the spindle face, spindle thermal stability test
M = range of the mean bidirectional positional deviations of an axis
$MBET$ = minimum block execution time
MCC = minimum circumscribed circle center of a polar profile
MD = measured diameter
MDR = machine display reading
MIC = minimum inscribed circle center of a polar profile
$MR(R)$ = measurement repeatability of a radius
MRS = minimum radial separation center of a polar profile
$MR(X)$ = measurement repeatability, X direction
$MR(Z)$ = measurement repeatability, Z direction
$Max[q]$ = maximum value of a quantity, q
$Min[q]$ = minimum value of a quantity, q
m = number of target points on an axis
N = newton, unit of force
NDE = nominal differential expansion
NE = nominal thermal expansion of the object to be measured or calibrated
NE_s = nominal thermal expansion of the standard
n = number of measurements of the same quantity
n_{max} = maximum spindle speed for chatter limits and spindle torque test
n_{min} = minimum spindle speed for chatter test
n_{rpm} = spindle speed
n_s = stable spindle speed for chatter test
n_T = maximum spindle speed for acceptable tool life
P = periodic error of a linear or rotary axis
P_i = target position in the positioning tests, ith position
P_{idle} = electrical power consumed by a rotating spindle cutting air
P_{ij} = measured position at the jth approach to the target position, P_i
P_{meas} = electrical power consumed by a rotating spindle cutting metal
P_s = air pressure
P_w = electrical power
q = a quantity to be measured (i.e., a measurand)
$\bar{q}$ = mean of a set of measurements of a quantity, q
q_j = the jth measurement of a quantity, q
R = bidirectional repeatability of a measurement or axis
$R\uparrow$ = unidirectional repeatability for an axis, forward direction (maximum value)
$R\downarrow$ = unidirectional repeatability for an axis, reverse direction (maximum value)
RH = relative humidity
R_A = radius of an artifact
R_{ae} = bidirectional repeatability of angular error
$R_{ae}\uparrow$ = unidirectional repeatability of angular error, forward direction
$R_{ae}\downarrow$ = unidirectional repeatability of angular error, reverse direction
R_i = bidirectional repeatability of positioning at position i
$R_i\uparrow$ = unidirectional repeatability of positioning in the forward direction at position i
$R_i\downarrow$ = unidirectional repeatability of positioning in the reverse direction at position i
R_{pcx} = pallet change repeatability along the X-axis
R_{pcxy} = pallet surface tilt motion repeatability in the XY plane

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R_{sphere} = radius of a sphere
R_{xts} = the tool-change repeatability for the short tool length in the X direction
rpm = revolutions per minute
$r(\theta)$ = radial error motion of a spindle
$SMTC$ = significant mean temperature change
$SOTR$ = safe operating temperature range
SZ = specification zone for a quantity specified in this Standard
s_i = estimator of the standard uncertainty of a quantity measured at the ith position
$s_i\uparrow$ = estimator of the standard uncertainty in the forward direction at position i
$s_i\downarrow$ = estimator of the standard uncertainty in the reverse direction at position i
T = temperature of workpiece
TEI = thermal error index
T_a = mean air temperature
T_{ex} = expected spindle torque calculated based on part material properties, cutting conditions, and the number of teeth on the cutter
T_{meas} = spindle torque calculated from measured spindle power
T_q = torque
T_R = rated spindle torque
T_s = temperature of reference and/or working standard
t = time
$UNDE$ = uncertainty of nominal differential expansion
UNE = uncertainty of nominal thermal expansion
UNE_s = uncertainty of nominal thermal expansion of a standard
$U_T(A)$ = angular expanded thermal uncertainty
$U_T(L)$ = expanded thermal uncertainty
upr = undulations per revolution
$u(T)$ = uncertainty of temperature of the object being measured or calibrated
$u(T_s)$ = uncertainty of temperature of the reference and/or working standard
$u(\alpha)$ = uncertainty of the coefficient of thermal expansion of the object being measured or calibrated
$u(\alpha_s)$ = uncertainty of the coefficient of thermal expansion of reference standard and/or working standard
$u_{cT}(A)$ = combined angular standard thermal uncertainty
$u_{cT}(L)$ = combined standard thermal uncertainty
u_{ETVE} = standard uncertainty due to the environmental temperature variation
u_{pcx2} = standard uncertainty for the pallet linear positioning error along the X-axis that includes the combined effect of machine's linear axis repeatability, probe system repeatability, and the pallet change repeatability
$u_{pc\beta xy}$ = standard uncertainty for the pallet tilt motion error in the XY plane that includes the combined effect of machine's linear axis repeatability, probe system repeatability, and the pallet change repeatability
u_{px2} = standard uncertainty for the pallet linear positioning error along the X-axis that includes the combined effect of machine's linear axis repeatability and probe system repeatability
$u_{p\beta xy}$ = standard uncertainty for the pallet tilt motion error in the XY plane that includes the combined effect of machine's linear axis repeatability and probe system repeatability
u_q = standard uncertainty of a quantity, q
u_{sub} = standard uncertainty of a measurement, denoted by the subscript "sub"
u_{tcx} = standard uncertainty for combined effect of machine linear axis repeatability, test instrument repeatability, and tool change repeatability
u_{tx} = standard uncertainty for combined effect of machine linear axis repeatability and test instrument repeatability
VMA = volumetric measurement accuracy
$VSFR$ = varying segment feed rate
V_{max} = maximum steady feed rate observed, minimum block execution time test
W = out-of-squareness angle[1]
$\bar{x}_i$ = mean bidirectional deviation of axis positioning at position i
$\bar{x}_i\uparrow$ = mean deviation of axis positioning in the forward direction at the ith position
$\bar{x}_i\downarrow$ = mean deviation of axis positioning in the reverse direction at the ith position
x_{ij} = positional deviation for the jth measurement at the ith position
$x_{ij}\uparrow$ = jth positional deviation at the ith position along an axis, forward direction
$x_{ij}\downarrow$ = jth positional deviation at the ith position along an axis, reverse direction
$\bar{x}_{p2}$ = average of the ten readings for measurement point 2 in the X direction
x_{p2j} = jth reading in the X direction for measurement point 2
$\bar{x}_{tcx}$ = average of the ten readings in the X direction
x_{tcxj} = jth reading in the X direction
$\bar{x}_{tx}$ = average of the ten readings in the X direction
x_{txj} = jth reading in the X direction

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α = coefficient of thermal expansion of the object being measured or calibrated
α_s = coefficient of thermal expansion of the reference and/or working standard
$\beta(\theta)$ = tilt degree of freedom for a rotary axis in the sensitive direction
$\overline{\beta}_{pxy}$ = average tilt motion of the pallet in the XY plane
β_{pxyj} = jth reading of the tilt motion of the pallet in the XY plane
$\gamma(\theta)$ = tilt degree of freedom for a rotary axis in the nonsensitive direction
$\Delta X(\theta)$ = output of the X-axis gage in spindle testing
$\Delta Y(\theta)$ = output of the Y-axis gage in spindle testing
θ = angular position of a rotary axis (spindle axes included) or the angle between two lines
κ = thermal conductivity of a material
μm = micrometer (one millionth of a meter), unit of length
μrad = microradian (one millionth of a radian), unit of angle
τ = time constant of a physical quantity

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Chapter 4
Definitions

4.1 GLOSSARY

Abbe error: measurement error resulting from angular motion of a movable component and an Abbe offset.

Abbe offset: instantaneous value of the perpendicular distance between the line where the displacement is measured and the line where the displacement is to be determined.

Abbe principle: displacement-measuring system should be in line with the functional point whose displacement is to be measured. If this is not possible, either the slideways that transfer the displacement must be free of angular motion or angular-motion data must be used to calculate the consequences of the offset.

accessory spindle: a spindle supplied with a machine, not the main spindle, which was not manufactured by the Supplier of the base machine and is, by the machine Supplier, considered an "add-on."

accuracy: quantitative measure of the degree of conformance to recognized national or international physical standards and methods of measurement.[1]

accuracy (of measurement): closeness of the agreement between the result of a measurement and a true value of the measurand.

NOTES:
(1) The term *accuracy* is a qualitative concept.[1]
(2) The term *precision* should not be used for *accuracy.*

actual path: path produced by the machine tool when programmed to move along a nominal path.

actual position, P_{ij} ($i = 1$ to m; $j = 1$ to n): measured position reached by the moving component on the jth approach to the ith target position.

ambient temperature: temperature of the ambient air (or other working fluid, such as oil on an oil-showered machine) surrounding a machine. See also *mean ambient temperature.*

angular drift of axis average line: change in angle of a spindle's axis average line caused by thermal effects due to spindle rotation.

artifact: generic term used to describe a stable, physical object used as a master in machine testing. Particularly used to describe a ball, a set of balls, or a mandrel, in many tests in this Standard.

aspect ratio: ratio of the travel of the longest linear axis to the shortest linear axis. A large aspect ratio machine is defined as having an aspect ratio greater than 3.

autocollimator: optical instrument that allows measurement of the angle between its optical axis and a mirror whose calibration is independent of the distance between the instrument and the mirror.

auxiliary spindle: see *accessory spindle.*

average: average value of a series of measurements. Used synonymously with *mean.*

axial depth of cut: depth of cut in the spindle axis direction when milling.

axial error motion: error motion collinear with the Z reference axis of an axis of rotation. See Fig. 4.1, illustration (d).

axis acceleration/deceleration: rate at which the machine drive systems control the transition between different programmed axis feed rates.

axis average line: average axis of rotation of a rotating spindle. The axis average line is obtained by least-squares fitting a line through the centers of several average error motion polar plots at different distances from the spindle face.

axis direction, linear axes: direction of any line parallel to the motion direction of a linearly moving component. Due to straightness errors, squareness, parallelism, and angular errors, the direction of a linear axis can best be defined by a least-squares fit of a straight line to the appropriate straightness data.

axis direction, rotary axes: direction of rotation of a rotary axis. Such rotation shall be either clockwise or counterclockwise around a positive axis of rotation. For example, the direction of axis rotation shown in Fig. 4.1, illustration (g) is counterclockwise.

axis of rotation: line about which rotation occurs.

axis travel: maximum travel, linear or rotary, over which the movable component of a machine can move under numerical control.

backlash: a relative movement between interacting mechanical parts, resulting from looseness.

[1] ISO defines *accuracy* (of measurement) as the "closeness of the agreement between the result of a measurement and the true value of the measurand," with the conditions that "*accuracy* is a qualitative concept" and "the term *precision* should not be used for *accuracy.*" This ASME Committee does not concur that "*accuracy* is a qualitative concept."

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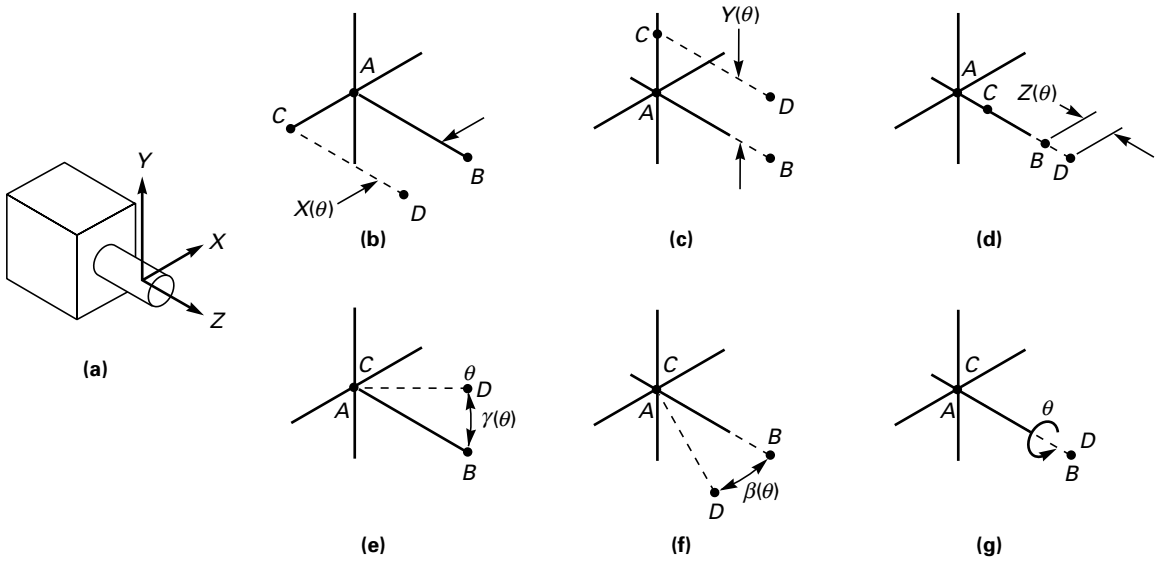


Fig. 4.1 Schematic Diagrams of the Six Basic Degrees of Freedom of an Axis of Rotation

ball bar (magnetic, telescoping): a gage with two high-precision ball and magnetic socket pairs held at the end of a telescoping rod, with an integral displacement sensor to measure the change of distance between the balls/sockets.

bearing error motion: error motion of a rotary axis due to imperfect bearings.

bidirectional: refers to a parameter derived from a series of measurements in which the approach to a target position is made in either direction along or around an axis.

bidirectional accuracy of positioning of an axis, A: range derived from the combination of the bidirectional systematic deviations and the estimator of the standard uncertainty of bidirectional positioning, obtained using a coverage factor of 2.

$$A = \text{max. } [\bar{x}_i\uparrow + 2s_i\uparrow; \bar{x}_i\downarrow + 2s_i\downarrow] - \text{min. } [\bar{x}_i\uparrow - 2s_i\uparrow; \bar{x}_i\downarrow - 2s_i\downarrow] \quad (4\text{-}1)$$

bidirectional repeatability for an axis, R: maximum value of the bidirectional repeatability of positioning at any position for an axis; that is, $R = \text{max. } [R_i]$.

bidirectional repeatability of angular error, R_{ae}: maximum value of the bidirectional repeatability of angular error at any position for an axis.

bidirectional repeatability of positioning at a position, R_i: maximum range representing the expanded uncertainty of bidirectional positional deviations, including the reversal deviation, obtained using a coverage factor of two or four times the standard uncertainty in either direction at the position, whichever is larger; that is,

$$R_i = \text{max. } [2s_i\uparrow + 2s_i\downarrow + |B_i|; R_i\uparrow; R_i\downarrow] \quad (4\text{-}2)$$

where

B_i = reversal deviation at position i
$R_i\uparrow = 4s_i\uparrow$
$R_i\downarrow = 4s_i\downarrow$
$s_i\uparrow$, $s_i\downarrow$ = estimators of the standard uncertainty at that position

bidirectional systematic angular error, E_{ae}: difference between the maximum and minimum of the mean unidirectional angular motions for both directions of approach at any position along the linear axis being measured. Computed the same as bidirectional systematic deviation of positioning of an axis, *E*.

bidirectional systematic deviation of positioning of an axis, E: difference between the maximum and minimum of the mean unidirectional positional deviations for both approach directions (i.e., $E\uparrow$ and $E\downarrow$ at any position along or around the axis).

$$E = \text{max. } [\bar{x}_i\uparrow; \bar{x}_i\downarrow] - \text{min. } [\bar{x}_i\uparrow; \bar{x}_i\downarrow] \quad (4\text{-}3)$$

bidirectional total angular error, A_{ae}: range derived from the combination of the bidirectional systematic angular error and the estimator of the standard uncertainty of bidirectional angular error, obtained using a coverage factor of 2. Computed the same as the bidirectional accuracy of an axis, *A*.

block look-ahead limit: maximum number of part program blocks ahead of the block being executed that a CNC controller uses to plan motion.

body diagonal: space diagonal of a rectangular prism within the working volume of the machine tool as shown in Fig. 4.2.

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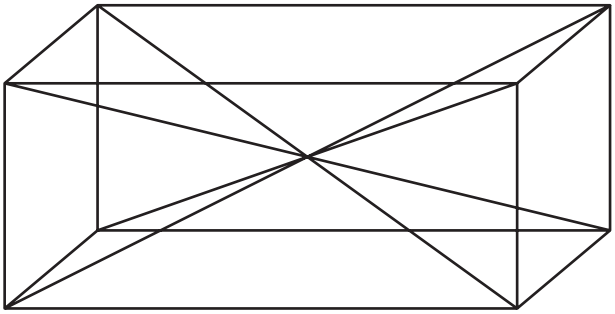


Fig. 4.2 Four Body Diagonals of a Rectangular Prism

broadband vibration amplitude: the amplitude of vibration allowed over a specified frequency band, usually specified as the maximum vibration from a low frequency (e.g., 1 Hz) to an upper frequency of several thousand hertz.

Bryan principle: the straightness-measuring system should be in line with the functional point whose straightness is to be measured. If this is not possible, either the slideways that transfer the straightness must be free of angular motion or angular-motion data must be used to calculate the consequences of the offset.

canned cycle: see *fixed cycle.*

cap test: a check for electrical noise and drift of a transducer, most commonly applied to displacement transducers, sensors, or indicators (see Appendix I). In this Standard the check is normally performed by placing a stable "cap" on a displacement indicator and monitoring its output over time. See also *transducer drift check.*

capacitance ("cap") gage: a displacement measuring device of relatively short range and high resolution that functions by measuring the electrical capacitance between the probe tip and the surface being displaced.

catenary: curve formed by a flexible string, wire, band, or cable suspended between two spatially separated points of equal height in a gravitational field. The form of the curve is determined primarily by the tension in the suspended element and its mass per unit length. In the context of this Standard, a catenary correction refers to the difference between this curve and a straight line between the two suspension points, measured in a vertical direction.

chatter: self-excited relative vibrations between the tool and the workpiece during the cutting process that may damage the cutting tool, the machine, or the part in roughing cuts and degrade the surface finish in finishing cuts.

chip load: relative motion of the feed axis of the tool with respect to the workpiece, per tooth pass, usually measured in millimeters per tooth.

circular deviation: minimum radial separation of two concentric circles enveloping the actual path (minimum zone circles) in the circular test and that may be evaluated as maximum radial range around the least-squares circle. It is equivalent to the total error motion value (see also *error motion value*). Values are denoted $G\uparrow$ for clockwise rotations and $G\downarrow$ for counterclockwise rotations.

coefficient of thermal expansion: the true coefficient of expansion, α, at a temperature, T, of a body is the rate of change of length of the body, L, with respect to temperature at the given temperature divided by the measured length at the given temperature, L_T.

$$\alpha = \frac{1}{L_T}\left(\frac{dL}{dT}\right)_T \tag{4-4}$$

cold machine: a machine at a stable operating temperature where during the last 2-hr period, (1) the hydraulic systems and servos have been on, (2) the spindle has not been rotated above 10% of the maximum rotations per minute, and (3) the axes' motions have been restricted to only those necessary to set up measurement equipment. A secondary definition is that the machine has been allowed to stabilize thermally for a Supplier-specified or User-specified soak-out time.

combined angular standard thermal uncertainty: for the purposes of this Standard, the combined angular standard thermal uncertainty for angle measurement is given by

$$u_{cT}(A) = \sqrt{\frac{ETVE_A^2}{12}} \tag{4-5}$$

combined standard thermal uncertainty: for the purposes of this Standard, the combined standard thermal uncertainty for a length measurement made at a temperature other than 20°C in a changing environment is given by

$$u_{cT}(L) = \sqrt{\begin{array}{l} u_{ETVE}^2 + L_s^2\,(T_s - 20)^2 u^2(\alpha_s) \\ + L^2(T - 20)^2 u^2(\alpha) + L_s^2 \alpha_s^2 u^2(T_s) + L^2 \alpha^2 u^2(T) \end{array}} \tag{4-6}$$

command: operative order to initiate a movement or a function.

command mode: mode of operation of the command or data entry device and display device in which entries are interpreted as functions to be executed.

comparator: any device used to perform the comparison of the part and the master is called a comparator. For the purposes of this Standard, the comparator can be a simple short-range indicating device, such as a gage block comparator, or a complex comparator, such as a coordinate measuring machine.

compensation: the practice of using prerecorded error tables and in-process sensing of variables such as temperature for correcting the position of a CNC machine using the CNC controller.

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compliance: displacement per unit static force between two objects, specified with respect to the structural loop, the location and direction of the applied forces, and the location and direction of the displacement of interest. The following terms can be applied when the structural loop contains an axis of rotation or a linear axis:

(a) radial compliance: applicable when the force and displacement directions are at 90 deg to the reference axis.

(b) axial compliance: applicable when the force and the displacement are collinear with the reference axis.

(c) tilt compliance: applicable for a pure moment and a tilt displacement in a plane containing the reference axis.

(d) face compliance: applicable when the force and displacement are parallel to the reference axis and at a specified radial location.

(e) linear compliance: applicable when the force and displacement are applied to a machine axis designed for linear motion. Linear compliance can be in the direction of the slide axis or perpendicular to that direction.

(f) angular compliance: applicable when a pure moment is applied to a rotary axis in the direction of the designed angular displacement.

computer numerical control (CNC): numerical control system in which the data handling sequence, control functions, and response to data input are determined primarily by a control program executed by a computer.

contouring control system: system of control in which two or more machine axes move in a coordinated fashion so that the desired angular path or contour is generated.

contouring mode: mode of operation of a CNC system that operates in one of the defined modes of interpolation (e.g., linear, circular, parabolic).

control program: ordered set of instructions in a computer language and a format that provide a computer-based control system with the capability of properly executing system functions and commands of the machine program.

cosine error: measurement error in the motion direction caused by angular misalignment between a linear displacement measuring system and the displacement being measured.

coverage factor: numerical factor used as a multiplier of the standard uncertainty to obtain an expanded uncertainty, normally denoted k.

critical depth of cut: axial depth of cut in milling where chatter will begin to occur if the spindle speed is such that a minimum in the lobing diagram is encountered.

critical speed: a spindle speed which is such that at that speed and tool combination a minimum in the lobing diagram would be encountered.

cutter diameter (radius) compensation: a displacement compensation normal to the cutter path to adjust for the difference between the actual and programmed cutter radius or diameter.

cutter diameter (radius) offset: a displacement normal to the cutter path to adjust for the difference between the actual and programmed cutter radius or diameter.

cycle time: period of time from starting one set of machine operations to starting another (in a pattern of continuous repetition).

deviation: in general, the difference between an actual value and the desired value, or commanded value, of a quantity. In this Standard, this word will be used synonymously with error and will refer to the difference between an actual value and the desired value, unless otherwise specified. See also *error*.

deviation of position; positional deviation, x_{ij}: actual position reached by the moving component minus the target position,

$$x_{ij} = P_{ij} - P_i \tag{4-7}$$

diagonal displacement: displacement of the "tool" of a machine tool along a diagonal in its work zone. The diagonal may be either a face diagonal; that is, in a plane defined by two machine axes, or, in the general case, along a body diagonal defined by the displacement of three machine axes.

differential expansion: difference between the expansion of the part and the expansion of the master from 20°C to their time-mean temperatures at the time of the measurement.

displacement indicator: any one of a family of devices that measures displacement between a datum and a moving element. Such instruments could be, for example, capacitance gages, linear variable differential transformers (LVDTs), dial gages, laser interferometers, or eddy current probes.

drift test: experiment conducted to determine the actual drift inherent in a system under normal operating conditions. The test usually consists of simultaneous recordings of drift and environmental temperatures. The recommended procedure for the conduct of a drift test is given in para. 6.2 for the measurement of environmental temperature variation error (ETVE).

drifts of axis average line: positional drifts of a spindle's axis average line caused by spindle thermal effects. For the purposes of this Standard, these drifts are defined as close to the chuck, part-holding device, or tool-holding device as is practical (see para. 7.6.2).

environmental temperature variation error, ETVE: an estimate of the maximum possible position uncertainty induced solely by deviation of the environment from average conditions. For the purposes of this Standard, it is assumed that the errors due to temperature variation are uniformly distributed with a total range equal to the

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measured ETVE. Since the ETVE is a total range, it must be converted to a standard uncertainty as is discussed in para. 6.2.3.3.1.

error: difference between the actual response of a machine to a command issued according to the accepted protocol of that machine's operation and the response to that command anticipated by that protocol. See also *deviation*.

error motion: change in position relative to the reference coordinate axes of the surface of a perfect tool or workpiece with its centerline coincident with the axis of rotation. Error motions are specified as to location and direction as shown in Fig. 4.1, illustration (a), and do not include motions due to thermal drift.

error motion measurements: a measurement record of error motion that should include all pertinent information regarding the machine, instrumentation, and test conditions.

error motion polar plot: polar plot of error motion made in synchronization with the rotation of the spindle. The following terms apply to the error motion polar plot and its components:

(a) total error motion polar plot: the complete error motion polar plot as recorded.

(b) average error motion polar plot: the mean contour of the total error motion polar plot averaged over a number of revolutions that can be divided into:

(1) fundamental error motion polar plot: the best-fit reference circle fitted to the average error motion polar plot.

(2) residual error motion polar plot: deviation of the average error motion polar plot from the fundamental error motion polar plot.

(c) asynchronous error motion polar plot: deviation of the total error motion polar plot from the average error motion polar plot.

(d) inner error motion polar plot: contour of the inner boundary of the total error motion polar plot.

(e) outer error motion polar plot: contour of the outer boundary of the total error motion polar plot.

error motion value: a magnitude assessment of error motion.

(a) asynchronous error motion value: maximum scaled width of the error motion polar plot, measured along a radial line through the polar chart center.

(b) average error motion: average (mean) error motion in the spindle performance test. At least 20 revolutions are required by this Standard.

(c) average error motion value: scaled difference in radii of two concentric circles from a least-squares motion center just sufficient to contain the average error motion polar plot.

estimator of the unidirectional standard uncertainty of positioning at a position, $s_i\uparrow$ or $s_i\downarrow$: estimator of the standard uncertainty of the positional deviations obtained by a series of n unidirectional approaches at a position P_i,

$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_{ij}\uparrow - \bar{x}_i\uparrow)^2} \tag{4-8}$$

$$s_i\downarrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_{ij}\downarrow - \bar{x}_i\downarrow)^2} \tag{4-9}$$

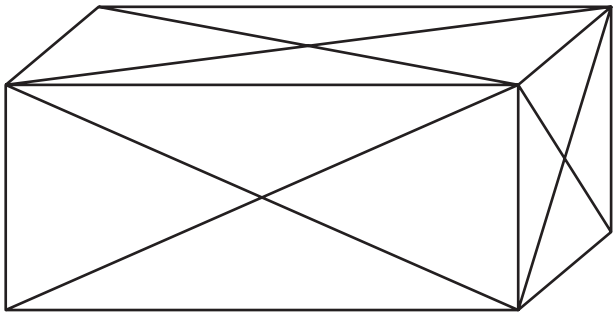


Fig. 4.3 Face Diagonals of a Rectangular Prism

expanded thermal uncertainty: in the case where the effective number of degrees of freedom for each of the uncertainties in the combined standard thermal uncertainties (see para. 4.1) is known, the expanded uncertainty should be computed following the example given in the ISO Guide, para. H.1.6 (ISO, 1993). In the absence of such information, it is the recommendation of this Standard that a coverage factor of $k = 2$ be used to yield an expanded uncertainty of length measurement at approximately the 95% confidence level, due to temperature, $U_T(L)$, given by:

$$\pm U_T(L) = \pm k u_{cT}(L) = \pm 2 u_{cT}(L) \tag{4-10}$$

expanded uncertainty: quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values.

face diagonal: diagonal in a plane of a rectangular prism within the working volume of the machine tool as shown in Fig. 4.3.

face error motion: error motion parallel to the Z reference axis at a specified radial location.

feed function: command defining a feed rate.

feed hold: action of the controller to temporarily suspend all axis motion and machine program execution, in response to some condition or command that is not part of the machine program.

feed rate: rate of motion of the feed axis of the tool relative to the workpiece, measured in millimeters per minute (mm/min) or millimeters per revolution (mm/rev).

fixed cycle: a preset series of operations that directs the machine axis movement and/or causes spindle operation to perform a complex function (e.g., boring, drilling,

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tapping, probing, facing, and a combination thereof).

fixed zero: a reference position of the origin of the coordinate system not readily movable.

NOTE: This is typically a characteristic of a machine having absolute feedback elements.

floating zero: a characteristic of a numerical control system permitting the zero point on an axis to be established readily at any point; the control retains no information on the location of any previously established zeroes.

functional point: point on the machine tool where a cutting tool would contact a part for the purposes of material removal.

fundamental error motion: in spindle testing, a sinusoidal error motion that is at the spindle rotation frequency.

gage: a mechanical artifact, often of high precision, used either for checking a part or for checking the accuracy of a machine, or a measuring device with a proportional range and some form of displacement indicator. When referring to a measuring device, the term *gage* is synonymous with a *displacement indicator* or *sensor,* as used in this Standard.

grid encoder: a type of two-axis positioning readout sensor which, through the use of a two-dimensional grid or grating and an electronic read head, allows the position of the read head with respect to the grid to be accurately measured in two dimensions.

high-speed spindle: for the purposes of this Standard, a high-speed spindle is any spindle that can operate at continuous duty at over 10,000 rpm.

hysteresis: a component of bidirectional repeatability caused by mechanisms such as drive train clearance, guideway clearance, mechanical deformations, friction, and loose joints. For the purposes of this Standard, two types of hysteresis are defined:

(a) setup hysteresis: hysteresis of the various elements in a test setup, normally due to loose mechanical connections.

(b) machine hysteresis: hysteresis of the machine structure when subjected to specific loads.

identification of axes: the identity of an axis moved to produce an actual path during machine testing.

incremental dimension: dimension expressed with respect to the preceding point in a sequence of points.

incremental feed: manual or automatic input of a preset motion command for a machine axis.

indicator: device used to measure displacements between a surface and a reference point. For the purposes of this Standard, an indicator could be a dial gage, an LVDT, or a capacitance gage. The term *displacement transducer* will be considered synonymous with the term *indicator.*

initial position: a fixed point along an axis referenced with respect to a machine datum.

NOTE: This is typically used for start-up.

initialization: sequence of operations establishing the starting point of a machine.

intermittent duty: with respect to motors, a measure of the time that the motor is operated as a fraction of 100% operation, continuous duty.

laser interferometer: fringe-counting interferometer for displacement measurement that uses a laser as a light source.

laser scales: machine scales that are based on laser interferometric principles.

lathe: any one of a class of machine tools where the part to be machined is rotated in a spindle to provide the surface speed necessary for material cutting.

length uncertainty due to temperature measurement: the use of this Standard requires that the measured length of a body be corrected to 20°C. This requires a measurement of the temperature of the body and an estimate of its thermal expansion coefficient. The uncertainty that the temperature measurement induces in the calculated length is called the length uncertainty due to temperature measurement (LUTM). In the case where there is a mechanical part and a mechanical master, it is given by

$$LUTM = \sqrt{\alpha^2 L^2 u(T)^2 + \alpha_s^2 L_s^2 u(T_s)^2} \qquad (4\text{-}11)$$

where $u(T)$ and $u(T_s)$ are the standard uncertainties in temperature measurement of the part and the standard. In the case where the standard is a laser interferometer, α_s should be taken as $0.93 \times 10^{-6}/°C$.

level: the condition of perpendicularity between a surface and the local gravitational field vector, or an instrument used to measure such perpendicularity.

load cell: transducer that is used to measure force. Normally a load cell has the capability to convert a force into a proportional electrical signal.

lobing diagram (or stability lobing diagram): diagram that relates the effects of spindle speed and axial depth of cut on stability in machining. These diagrams are constructed from computations for all the values of radial immersion, workpiece material, tool/tool holder combinations, and structural modes of interest.

LVDT (linear variable differential transformer): electromagnetic device used for displacement measurement. Normally an LVDT has the capability to convert a displacement into a proportional electrical signal.

machine coordinate system: coordinate system that corresponds to the axes of the machine on which a part is to be manufactured. The coordinate system usually includes one or more linear axes designated *X*, *Y*, or *Z* (see EIA 267). (The machine may also include rotary axes usually designated *A*, *B*, and *C*.)

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machine datum: built-in zero position of the machine elements used to establish the origin of the machine coordinate system.

machine home: condition in a machine coordinate system where all machine elements are at home position (i.e., at the machine datum).

machine program: an ordered set of instructions in automatic control language and format sufficiently complete to affect the direct operation of an automatic control system.

machine tool duty rating (MTDR): power level that a machine tool's spindle motor can operate above its continuous power rating for a short period of time (intermittent duty). This rating is supplied by the machine tool Supplier.

machine zero: origin of the coordinates in the machine system.

machining center: computer numerically controlled machine tool with at least one main spindle equipped for holding rotating tools. The purpose of this spindle(s) shall be to generate sufficient surface speed between tool and part to allow effective material removal by cutting. Such a machine shall also have automatic tool-changing capabilities and be capable of automatically performing multiple operations, including milling, drilling, tapping, and boring.

master: standard against which the desired dimension of the part is compared. The standard may be in the form of the wavelength of light, length of a gage block, line standard, lead screw, etc.

maximum steady feed rate, V_{max}: maximum steady feed rate measured (less than 5% fluctuation) for a given part program segment length during the minimum block execution time test.

mean: the mean (arithmetic average) of a physical quantity in this Standard is defined as the average value of that quantity and denoted with a bar over the symbol. Both terms, *average* and *mean*, are used in this Standard synonymously.

mean ambient temperature: mean temperature of the ambient environment surrounding a machine as computed from at least two readings taken at the center of the machine's work zone during the interval required for the test.

mean bidirectional positional deviation at a position, $\bar{x}_i$: arithmetic mean of the mean unidirectional positional deviations $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$, obtained from the two directions of approach at a position P_i,

$$\bar{x}_i = \frac{\bar{x}_i\uparrow + \bar{x}_i\downarrow}{2} \tag{4-12}$$

mean gage temperature: mean temperature of a gage used for machine testing as computed from at least two readings taken on the gage during the interval required for a test.

mean reversal value of an axis, $\overline{B}$: arithmetic mean of the reversal values, B_i, at m target positions along or around the axis,

$$\overline{B} = \frac{1}{m}\sum_{i=1}^{m} B_i \tag{4-13}$$

mean scale temperature: mean temperature of a machine scale as computed from at least two temperature readings taken on that scale during the interval spanning the time required for a test.

mean temperature: average temperature computed from a stated number of temperature measurements at equally spaced time intervals at a specified location.

mean unidirectional positional deviation at a position, $\bar{x}_i\uparrow$ or $\bar{x}_i\downarrow$: arithmetic mean of the positional deviations obtained by a series of n unidirectional approaches to a position P_i,

$$\bar{x}_i\uparrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\uparrow \tag{4-14}$$

and

$$\bar{x}_i\downarrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\downarrow \tag{4-15}$$

measurement line: line in the work zone of a machine along which measurements are taken.

measurement point: point in the work zone of a machine at which measurements are taken.

measurement travel: part of the axis travel that is used for data capture. It is selected so that the first and last target positions may be approached bidirectionally (see para. 7.3.1).

minimum block execution time, MBET: minimum time required by a CNC controller to execute one program block.

movable component: major structural component that is movable relative to the machine base during measurement.

nominal coefficient of thermal expansion: estimate of the coefficient of thermal expansion of a body. For the purposes of this Standard and in reference to the nominal coefficient of expansion of machine scales, it shall mean the effective coefficient of the scale and its mounting to the machine as measured in line with the scale for typical machines of the given design. Since the true coefficient for a given machine is not known, an uncertainty must be applied when making nominal differential expansion corrections (see para. 6.2.3.3.2). Following ISO practice, this Standard does not differentiate between the

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expected value of a quantity and its actual value. Therefore, the nominal coefficient of expansion in this Standard will be denoted α.

nominal differential expansion (NDE)[2]*:* difference between the nominal expansion of the object to be calibrated and the standard:

$$NDE = NE - NE_s \quad (4\text{-}16)$$

When measuring at temperatures other than 20°C, corrections for the NDE must always be made. The NDE is a systematic error and cannot be considered to be an uncertainty.

nominal expansion (NE): estimate of the expansion of an object from 20°C to its time-mean temperature. It shall be determined from the following relationship:

$$NE = \alpha L(T - 20) \quad (4\text{-}17)$$

nominal path: numerically controlled and programmed path defined by the machine's appropriate programming protocol. For the purposes of the circular tests, this path would be defined by its diameter or radius, the position of its center, and its orientation in the work zone of the machine. Nominal paths for the circular tests may be either full circles or partial arcs.

nonsensitive direction: any direction perpendicular to any sensitive direction. See also *sensitive direction*.

numerical control system: special purpose computer that processes primarily numeric data to control the movements and functions of a machine to which it is connected.

optical polygon: optical element composed of a number of plane surface mirrors arranged to form a regular polygon.

outlier: a measured value that is greater than +2 times the repeatability or less than −2 times the repeatability from the average of all data values for the same quantity in the sample, where the repeatability of the machine is as defined in para. 7.3.4 of this Standard.

parametric: for the purposes of this Standard, parametric is defined as referring to the measurement of any of the geometrical errors of a machine. These include, for example, positioning errors, angular errors, straightness errors, error motions of spindle, and alignment errors such as parallelism and squareness.

part coordinate: the Cartesian (*X, Y, Z*) coordinate system in which the part is defined and in which the tool coordinates are specified.

part or workpiece: in every dimensional or geometric measurement process, there is usually some physical object for which a dimension is to be determined. This object is called the part or workpiece.

part programming, computer-aided: preparation of a part program to obtain a machine program using a computer and appropriate processor and post-processor.

performance test: any of a number of test procedures that are used to measure machine performance.

periodic error: error in the positioning of a machine axis that is periodic over an interval that normally coincides with the natural periodicity of the machine scales or their equivalent. For example, in a lead screw driven machine with rotary encoders, the periodicity is usually synchronous with the pitch of the lead or ball screw.

pitch: angular motion of a carriage, designed for linear motion, about an axis perpendicular to the motion direction and perpendicular to the yaw axis.

play: condition of low or zero stiffness over a limited range of displacement due to clearance between members of the structural loop.

polar chart (PC) center: center of the polar chart.

polar profile center: center derived from the polar profile. In this Standard, the least-squares circle center, LSC, is used. The list of possible centers follows:

(a) minimum radial separation (MRS) center: center that minimizes the radial difference required to contain the error motion polar plot between two concentric circles (see Fig. 4.4).

(b) least-squares circle (LSC) center: center of a circle that minimizes the sum of the squares of a sufficient number of equally spaced radial deviations measured from it to the error motion plot.

(c) maximum inscribed circle (MIC) center: center of the largest circle that can be inscribed within the error motion plot.

(d) minimum circumscribed circle (MCC) center: center of the smallest circle that will just contain the error motion polar plot.

positional deviation: see *deviation of position.*

positioning control system: numerical control in which

(a) each numerically controlled motion operates in accordance with instructions that specify only the next required position

(b) the movement in the different axes of motion are not necessarily coordinated with each other and may be executed simultaneously or consecutively

(c) velocities are not specified by the input

positioning mode: mode of operation of NC or CNC system that performs in accordance with the definition of a positioning control system.

probe: in this Standard, a device that establishes the location of the movable components of a machine tool relative to a measurement point. Three types of probes are discussed in this Standard. They are

[2] It is a requirement of this Standard that nominal differential expansion corrections always be made. See para. 7.3.2.1 for details.

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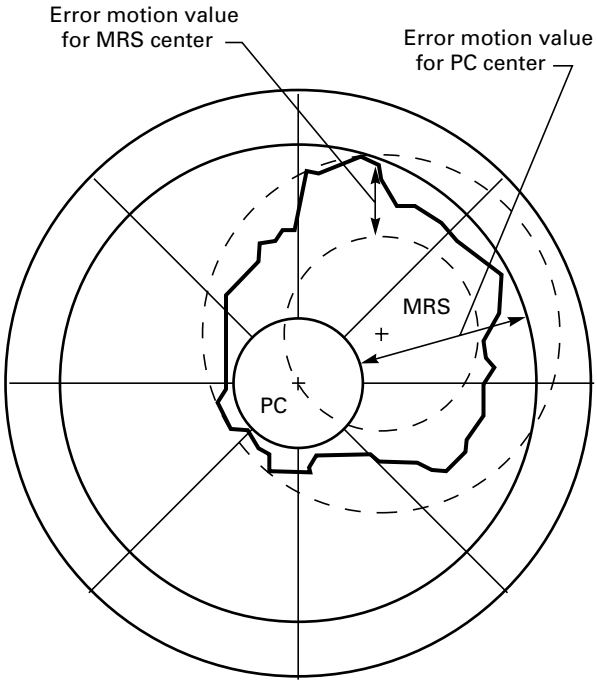


Fig. 4.4 Error Motion Polar Plot Showing Polar Chart (PC) Center, a Minimum Radial Separation (MRS) Center, and Error Motion Values About These Centers

(a) switching probe: probe that gives a binary signal as a result of contact with or in proximity to a workpiece.

(b) proportional probe: probe that gives a signal proportional to a displacement of the probe from its free position.

(c) nulling probe: probe that, in reference to a workpiece, gives a signal that causes the machine to be driven to a position that will null the probe reading.

probe approach distance: distance of approach to the part at which the machine traverse speed is reduced to the probe approach rate for measurement.

probe approach rate: nominal speed of approach of the probe toward the part during the acquisition of data.

probe cycle: fixed cycle using a probe.

probe lobing: systematic error in the measuring accuracy of probing systems such that a measured value depends on the displacement direction of the probe tip.

process damping: condition in milling where the wavelengths of undulations created by chatter on the cut surface decrease, the slope of these waves increases, and the damping component of the cutting force strongly increases, thus attenuating the regeneration of waviness.

pure radial motion: concept of radial motion in the absence of tilt motion.

quadrant photodiode: photodetector, used for measuring displacements in 2D, composed of four separate photodetectors arranged in a form that resembles the quadrants of a circle.

radial depth of cut: depth of cut perpendicular to the spindle axis direction when milling.

radial deviation: deviation in radial direction between the actual path and the nominal circular path, where the center of the nominal path is obtained from either one of the following:

(a) from the centering of the measuring instruments on the machine tool

(b) from the least-squares centering analysis for a full circle only.

radial error motion: error motion of a rotary axis normal to the Z reference axis and at a specified angular orientation.

radial immersion: ratio of the actual width of the cut to the cutter diameter in milling.

radian: natural unit of angle. For small angles, the radian is often represented by "rise over run." Radians can be converted to decimal degrees by multiplying by 57.29 or to arc seconds by multiplying by 206,265. The microradian (μrad) is a millionth of a radian.

range: difference between the maximum and minimum values of a set of measurements of nominally the same quantity.

reference coordinate axes: mutually perpendicular X-, Y-, and Z-axes fixed with respect to an object.

relative vibration: for the purposes of this Standard, relative vibration refers to nonzero frequency relative motion between the position of a nominal tool and a nominal workpiece.

repeatability: for the purposes of this Standard, repeatability is defined as a measure of the ability of a machine to sequentially position a tool with respect to a workpiece under similar conditions. Repeatability is defined on a per-axis basis (see para. 7.3).

resolution: least increment of a measuring device. On a digital instrument, the least significant bit.

retroreflector: optical element with the property that an input light beam is reflected to return along the same angle as it was incident.

reversal deviation of angular error, B_{ae}: maximum of the absolute reversal values at all target positions along a linear axis when measuring angular error. Computed similarly to the reversal value of an axis.

reversal value (error) at a position, B_i: value of the difference between the mean unidirectional deviations obtained from the two directions of approach,

$$B_i = \bar{x}_i\uparrow - \bar{x}_i\downarrow \tag{4-18}$$

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reversal value of an axis, B: maximum of the absolute reversal values, $|B_i|$, at all target positions along or around the axis

$$B = \max. \left[|B_i|\right] \quad (4\text{-}19)$$

roll: angular motion of a carriage, designed for linear motion, about the linear motion axis.

rotary axis: any motion axis of a machine whose function is to provide a rotary motion either for the purposes of positioning or for moving a part or a tool to provide sufficient surface speed for cutting (i.e., a spindle). In this Standard, three types of rotary axes are defined. They are

(a) rotary machining axis: rotary axis where the axis can be used to provide continuous-path contour cutting in a rotary direction.

(b) rotary positioning axis: rotary axis that allows the rotation of a part into a new position for the purposes of cutting only; that is, this axis is not used to provide continuous, contour cutting, but only to reposition different faces of the part for the purpose of metal removal.

(c) spindle: see *spindle*.

runout: total range of displacements measured by an instrument sensing against a moving surface or moved with respect to a fixed surface.

safe operating temperature range: temperature range in which a machine tool may be expected to operate without physical damage to the machine or its support systems (i.e., computers, controllers, etc.).

scale: part of a transducer system that provides the linear or rotary position of a machine axis. For the purposes of this Standard, the transducer system could be a line scale, inductive scale, shaft encoder, or any type of linear or rotary positional measuring device. Where temperature is mentioned in this Standard with respect to a scale, it refers to the temperature of the material that comprises the portion of the scale that establishes the unit of length. That is, in a line scale it refers to the matrix on which the lines have been deposited; for a lead or ball screw it refers to the temperature of the material composing the screw itself, etc.

segment length (chordal length): distance between two points in a part program.

seismic vibration: for the purposes of this Standard, seismic vibration is defined as vibration of the support surface on which the machine tool is mounted that is induced as the result of external forces in the surrounding area.

sensitive direction: direction where relative motion between the tool and the workpiece causes one-for-one form errors to be cut into the workpiece. Two types of sensitive directions are recognized:

(a) fixed sensitive direction: the workpiece is rotated by the spindle and the point of machining or gaging is fixed.

(b) rotating sensitive direction: the workpiece is fixed and the point of machining or gaging rotates with the spindle.

NOTE: A lathe has a fixed sensitive direction; a jig borer and a machining center have a rotating sensitive direction. With a fixed sensitive direction, the reference coordinate axis is fixed; with a rotating sensitive direction, the reference coordinate system rotates with spindle.

sensor: generic term used for an indicator that senses a particular physical quantity. In this Standard the term *sensor* is normally used to mean a displacement indicator. See *displacement indicator.*

sensor nest: group of more than one sensor assembled together in a stable fixture to allow displacement measurements in more than one direction.

sequence number: number identifying blocks or group of blocks in a machine program.

settling time: time required between contact of a proportional probe with the workpiece and the time at which valid data may be taken.

significant mean temperature change: change in the mean ambient temperature surrounding a machine that, in the Supplier's judgment, will cause sufficient degradation in machine performance such that performance evaluation (Chapter 7) should be repeated.

soak out: one of the characteristics of an object is that it has a thermal "memory." When a change in environment is experienced, such as occurs when an object is transported from one room to another, there will be some period of time before the object completely "forgets" about its previous environment and exhibits a response dependent only on its current environment. The time elapsed following a change in environment until the object is influenced only by the new environment is called *soak out time.* After soak out, the object is said to be in equilibrium with the new environment. In cases where an environment is time variant, the response of the object is also a variable in time.

socket: spherical cup that allows for accurate repositioning of one end of a telescoping ball bar.

specific power or specific force: the power or force required for the removal of a unit volume of a particular material per unit time in cutting.

specification zone: value specified in a machine specification for the result of a particular test, as defined in this Standard, shall be called the specification zone for that test and denoted *SZ.*

spindle: device which provides an axis of rotation for the purpose of rapidly rotating a part or a tool to provide sufficient surface speed for cutting operations.

spindle speed: rate of rotation of a machine spindle, usually expressed in revolutions per minute.

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spindle speed function: command defining the spindle speed.

squareness: a plane surface is "square" to an axis of rotation if coincident polar profile centers are obtained for an axial and face motion polar plot at different radii. Also, for linear axes, the angular deviation from 90 deg, measured between the best-fit lines drawn through two sets of straightness data derived from two orthogonal axes in a specified work zone.

staging: the moving of a gage from a first position to a second position such that a series of measurements started in the first position may be continued in the second position.

standard uncertainty due to the environmental temperature variation error: the environmental temperature variation error (ETVE) is measured as the range of the total drift of the instrument/master/part system as described in Chapter 6. To convert this to a standard uncertainty according to ISO guidelines, it is assumed that this environmental error is uniformly distributed within this range for a given measurement. The resulting standard uncertainty, $u_{ETVE,}$ is then given by

$$u_{ETVE} = \sqrt{\frac{ETVE^2}{12}} \tag{4-20}$$

standard uncertainty (of a quantity, q), u_q or u(q): given a set of n measurements of a quantity, q, the standard uncertainty in q is given as

$$u_q = u(q) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(q_j - \overline{q})^2} \tag{4-21}$$

where the q_j denote the individual measurements and $\overline{q}$ is the mean of the set of measurements. This quantity is also sometimes called the estimator of the standard deviation and commonly symbolized by s_q.

static error motion measurement: special case of error motion measurement in which the error motion is sampled with the spindle at rest at a series of discrete rotational positions.

steering mirror: mirror used to steer the laser beam to the appropriate angle in the diagonal displacement measurement test.

step gage: gage comprising a rigid bar with calibrated steps used for determining accuracy of distance measurements in a direction of linear motion.

stiffness: the reciprocal of compliance. Usually defined statically as a ratio of the applied force to the displacement of a machine element. For the purposes of this Standard, stiffness is defined with respect to the structural loop.

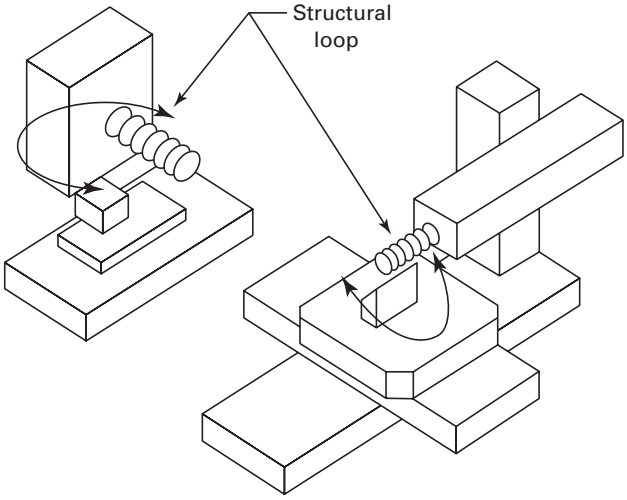


Fig. 4.5 Example of a Structural Loop Showing a Part, Spindle, Machine Frame, and Tool

straightness error: slide straightness error is the deviation from straight line movement that a displacement indicator positioned perpendicular to a slide direction exhibits when it is either stationary and reading against a perfect straightedge supported on the moving slide, or moved by the slide along a perfect straightedge that is stationary.

NOTE: In some documents the moving indicator against the stationary straightedge is called lateral deviation.

structural loop: assembly of mechanical components that maintain relative position between specified objects. A typical pair of specified objects is the cutting tool and the workpiece; the structural loop would include the spindle shaft, the bearings and housing, the slideways and frame, possibly the foundation, and the tool and work-holding fixtures (see Fig. 4.5).

Supplier: party who contracts, or indicates readiness to contract, to supply a machine tool to a User (also called a vendor in some ISO documents).

synchronous error motion: another term for average error motion, used in axis of rotation testing.

systematic error: mean that will result from an infinite number of measurements of the same measurand carried out under repeatability conditions, minus the true value of the measurand.

NOTE: Systematic error is equal to error minus random error; like true value, systematic error and its causes cannot be completely known; for a measurement instrument, systematic error is often called bias.

target position, P_i (i = 1 to m): position to which the moving component is programmed to move. The subscript "i" identifies the particular position among other selected target positions along or around the axis.

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temperature of a body:

(a) temperature at a point: when discussing a body that does not have a single uniform temperature, it is necessary to refer in some manner to the distribution of temperature throughout the body. Temperature at a point in a body is assumed to be the temperature of a very small volume of the body centered at that point. The material of which the body is composed is assumed to form a continuum.

(b) temperature of a body: when the differences between the temperatures at all points in a body are negligible, the body is said to be at a uniform temperature. This temperature is then the temperature of the body.

(c) instantaneous average temperature of a body: when the body is not at a uniform temperature at all points, but it is desirable to identify the thermal state of the body by a single temperature, the temperature that represents the total heat stored in the body may be used. When the body is homogeneous, this is called the average temperature of the body. (This temperature is the average, over the volume of the body, of all point temperatures.)

(d) time-mean temperature of a body: the average of the average temperature of a body, over a fixed period of time, is called the time-mean temperature of the body. The fixed period is selected as appropriate to the measurement problem.

thermal error index (TEI): in some cases, particularly in factories, dimensional measurements are made at temperatures other than 20°C, corrections are not made for the nominal differential expansion between standard and part, and the environment is constantly changing. In this case, there is a systematic error that is coupled with the thermal uncertainty index to give an overall estimate of the error made in manufacturing or measurement. Since the nominal differential expansion correction is a systematic error, it is not subject to statistical analysis. This Standard defines, in this particular case, a thermal error index that estimates the maximum possible percentage error that would be made in these conditions as the sum of the absolute value of the uncorrected differential expansion and the expanded thermal uncertainty, divided by the specification zone. That is,

$$TEI = \frac{|NDE| + U_T(L)}{SZ} 100\% \qquad (4\text{-}22)$$

Here SZ is the desired specification zone (see para. 4.1) on the measurement.

thermal expansion: the difference between the length (or volume) of a body at one temperature and its length (or volume) at another temperature is called the linear (or volumetric) thermal expansion of the body.

thermally induced drift: drift caused by variations in the thermal environment or internal heat sources of the machine.

tilt error motion: error motion in the angular direction relative to a linear axis. [See Fig. 4.1, illustrations (e) and (f).]

tolerance: for the purposes of this Standard, the tolerance is a range on either side of a desired dimension of a manufactured part or a gage. In some cases, tolerances are expressed as plus (+) or minus (−) a single value. That value is called the tolerance.

tool change under program control: process on a machining center or work center where the cutting tool is exchanged, usually with its tool holder, for another tool under control of the part program (i.e., without human intervention).

tool (fixture) offset: a relative displacement that is applied to an axis of a machine for a specified portion or the whole of a program and causes a displacement in that axis only in the direction determined by the sign of the offset value (may not apply for some 5-axis machines).

NOTE: For example, the tool offset is typically applied in pairs of independent values for *X, Y,* and *Z* for the tool tip location on turning machines, individually or in combination on milling machines.

tool function: command identifying a tool or a tool offset.

tool (length) offset: incremental displacement in the axial direction of the tool.

NOTE: This is typically used on milling and drilling machines.

tool-setting probe: see *tool-setting system*.

tool-setting system: instrument supplied with a machining center that allows for the measurement of tool offsets or tool diameter as part of a computer-controlled cycle. Also sometimes called a tool-setter, a tool-gage, or a tool-setting probe(s).

tow-along carriage: machine carriage that is positioned with the mechanical assistance of another machine carriage; thus the term tow-along.

transducer: any device that converts a measurand of one physical quantity into another physical parameter. For example, a strain gage that converts strain to an electrical signal would be considered a transducer. For the purposes of this Standard, most transducers discussed are displacement transducers. The term displacement transducer will be used synonymously with the term *displacement indicator.*

transducer drift check: experiment conducted to determine the drift in a displacement transducer and its associated amplifiers and recorders when it is subjected to a thermal environment similar to that being evaluated by the drift test itself. The transducer drift is the sum of the "pure" amplifier drift and the effects of the environment on the transducer, amplifier, etc. The transducer drift check is performed by blocking the transducer and observing the output over a period of time at least as long as the duration of the drift test to be performed. Blocking a

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transducer involves making a transducer effectively indicate on its own frame, base, or cartridge. In the case of a cartridge-type gage head, this is accomplished by mounting a small cap over the end of the cartridge so the plunger registers against the inside of the cap. Finger-type gage heads can be blocked with similar devices. Care must be exercised to see that the blocking is done in such a manner that the influence of temperature on the blocking device is negligible.

transfer function: for the purposes of this Standard, the transfer function is the ratio of the relative vibration between tool and workpiece to the input variable force acting between tool and workpiece as a function of frequency. The transfer function has both amplitude and phase (or a real and imaginary part).

type test: machine performance test that is likely to yield nearly the same results for all machines of the same model or type, as long as the machine has been assembled to specification.

uncertainty of nominal coefficient of expansion: the uncertainty in the nominal thermal expansion coefficient of a body shall be denoted $u(\alpha)$ for the object being calibrated or measured and $u(\alpha_s)$ for the standard. This value, like that of α itself, must be an estimate. (See para. 6.2.3.3.2 for further explanation.)

uncertainty of nominal differential expansion (UNDE): the square root of the sum of the squares of the uncertainties of nominal expansion of the object to be calibrated or measured and the standard,

$$UNDE = \sqrt{(UNE)^2 + (UNE_s)^2} \tag{4-23}$$

uncertainty of nominal expansion (UNE): the uncertainty in the value chosen for the nominal expansion. It is determined as

$$UNE = L(T - 20)u(\alpha) \tag{4-24}$$

uncertainty of temperature measurement: when the temperature of a body or the ambient environment is measured, there is an uncertainty associated with this measurement. This uncertainty comes from the calibration of the thermometer, thermometer mounting procedures, and instrumental variations. (See para. 6.2.3.3.3 for further explanation.)

undulations per revolution (upr): term commonly used when referring to spindle error testing. It refers to the highest order (frequency) sine wave detected in a spindle error analysis (highest harmonic of the spindle speed). The bandwidth of a sensor used for spindle error detection should be several times higher than the product of the upr and the revolutions per second of the spindle being tested (see ASME B89.3.4M for a more detailed explanation).

unidirectional: refers to a series of measurements in which the approach to a target position is always made in the same direction along or around the axis. The symbol $\uparrow$ signifies a parameter derived from a measurement made after an approach in the forward or clockwise direction, and $\downarrow$ signifies one in the reverse or counterclockwise direction (e.g., $x_{ij}\uparrow$ or $x_{ij}\downarrow$).

unidirectional accuracy of positioning of an axis, $A\uparrow$ or $A\downarrow$: range derived from the combination of the unidirectional systematic deviations and the estimator of the standard uncertainty of unidirectional positioning using a coverage factor of two.

$$A\uparrow = \text{max. } [\bar{x}_i\uparrow + 2s_i\uparrow] - \text{min. } [\bar{x}_i\uparrow - 2s_i\uparrow] \tag{4-25}$$

and

$$A\downarrow = \text{max. } [\bar{x}_i\downarrow + 2s_i\downarrow] - \text{min. } [\bar{x}_i\downarrow - 2s_i\downarrow] \tag{4-26}$$

unidirectional repeatabilities of angular error, $R_{ae}\uparrow$ and $R_{ae}\downarrow$: maximum value of repeatability of angular error at any position along a linear axis. Computed similarly to unidirectional repeatability of positioning.

unidirectional repeatability of positioning at a position, $R_i\uparrow$ or $R_i\downarrow$: range derived from the expanded uncertainty of unidirectional positional deviations at a position, using a coverage factor of 2,

$$R_i\uparrow = 4s_i\uparrow \tag{4-27}$$

and

$$R_i\downarrow = 4s_i\downarrow \tag{4-28}$$

unidirectional repeatability of positioning, $R\uparrow$ or $R\downarrow$, of an axis: maximum value of the unidirectional repeatabilities of positioning at any position along or around an axis,

$$R\uparrow = \text{max. } [R_i\uparrow] \tag{4-29}$$

and

$$R\downarrow = \text{max. } [R_i\downarrow] \tag{4-30}$$

unidirectional systematic angular error, $E_{ae}\uparrow$ and $E_{ae}\downarrow$: difference between the algebraic maximum and minimum of the mean unidirectional angular errors for both approach directions, at any position along a linear axis, computed similarly to unidirectional systematic deviation of positioning of an axis.

unidirectional systematic deviation of positioning of an axis, $E\uparrow$ or $E\downarrow$: difference between the algebraic maximum and minimum of the mean unidirectional positional deviations for both approach directions (i.e., $\bar{x}_i\uparrow$ or $\bar{x}_i\downarrow$ at any position along or around the axis).

$$E\uparrow = \text{max. } [\bar{x}_i\uparrow] - \text{min. } [\bar{x}_i\uparrow] \tag{4-31}$$

and

$$E\downarrow = \text{max. } [\bar{x}_i\downarrow] - \text{min. } [\bar{x}_i\downarrow] \tag{4-32}$$

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unidirectional total(s) angular error, $A_{ae}\uparrow$ and $A_{ae}\downarrow$: range derived from the combination of the unidirectional systematic angular error and the estimator of the standard uncertainty of unidirectional angular error, using a coverage factor of 2. Computed similarly to unidirectional accuracy of positioning of an axis.

User: party who contracts to accept a machine tool from a Supplier.

vibration amplitude: the size (amplitude) of a given frequency component of a vibration spectrum. Common practice is to express the vibration amplitude in either displacement or acceleration units. In some cases, broadband vibration amplitude is also used (see *broadband vibration amplitude*).

volumetric performance: ability of a machine tool to perform the intended multiaxis functions anywhere within the volume defined by the maximum travel of the machine linear axes.

wobble plate: mechanical device that allows the tilting (wobbling) of a test fixture by adjustment screws.

work zone: working (machining) volume of a machine as specified by the Supplier. More than one work zone may be specified for a given machine, and specification zones may be specified separately for each work zone.

workpiece: object to be turned, machined, or measured.

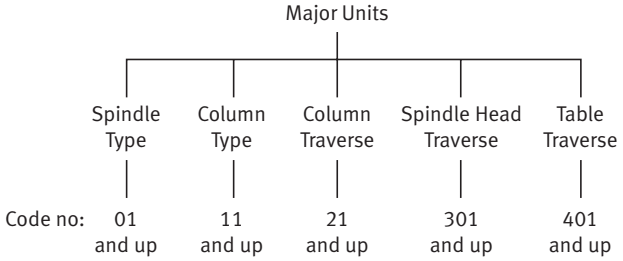
yaw: angular motion of a carriage, designed for linear motion, about a specified axis perpendicular to the motion direction. In the case of a carriage with horizontal motion, the specified axis shall be vertical unless explicitly specified. For a carriage that does not have horizontal motion, the axis must be explicitly specified.

4.2 MACHINE CLASSIFICATIONS

The following classifications of different types of machining centers are provided for ease of machine specification. This Standard does not seek to standardize pallet configurations or pallet change mechanisms; thus a specification should include details regarding such devices in equivalent detail. A position is provided in the machine performance form (Form 1.1), which should be used to designate the machine classification as described below.

If a machine is to be supplied that does not conform to one of the described machines, a drawing similar in content to those shown in this classification paragraph with axis designation and directions of positive travel should be provided as part of the machine specification. Axis and motion nomenclature should be consistent with EIA 267, ISO 841, ASME B89.3.4M, and NAS 938.

For the purposes of classifying machining center configurations, the machine structure is divided into five major units. The units are further subdivided into types and each assigned a code number. The order in which these major units shall be specified is:



Specific code numbers corresponding to the various spindle, column, and table configurations are given in Table 4.1 and Figs. 4.6 through 4.11. A machining center configuration can therefore be identified by reference to the assigned code numbers in the specified sequence.

For example, a machining center classification of 01-11-23-302-402.4 would describe a 4-axis horizontal spindle machining center having a single column travelling in the *X*-axis direction with spindle head moving in the vertical *Y*-axis direction on column and a rotary machining table mounted on an *X*-axis table base.

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Table 4.1 Key to Unit Code

Spindle Type (See Fig. 4.6)	
(Spindle Attitude)	Code Number
Horizontal	01
Vertical	02
Tilt	03

Multispindle Heads

Multispindle heads can be specified by adding a suffix to the spindle type code number corresponding to the number of spindles required.
Example: Code number 02.3 would specify a three spindle vertical head.
If no suffix is attached to the code number, a single spindle head is assumed.
For identification purposes, the spindles shall be numbered 1, 2, 3, etc., starting from the left when facing the spindle heads.

NOTE: When a machine tool has additional linear axis moving parallel to the primary axis, the axis designation of the secondary axis, as indicated by its specified code number, will change in compliance with ISO 841 (1994).

Column Type (See Fig. 4.7)	
	Code Number
Single	11
Fixed bridge	12
Moving bridge	13

Column Traverse (See Fig. 4.8)	
Direction(s) of Travel (Depending on Spindle Attitude)	Code Number
None	21
X	22
Z or *Y*	23
X over *Z* or *X* over *Y*	24
Z over *X* or *Y* over *X*	25
X	26

A spindle head can be converted into a tilting head spindle or gimbal head by adding a suffix to an appropriate spindle head code number.
For example:
301.1 or 303.2.

Spindle Head Traverse (See Fig. 4.9)	
Direction(s) of Travel (Depending on Spindle Attitude)	Code Number
Y	301
Y or *Z*	302
Z	303
Z over *Y*	304
Z over *X*	305
None	306
Y over *X*	307
Z over *Y* over *X*	308
Z	309
Z over *Y*	310
Tilt head	XXX.1
Gimbal head	XXX.2

Rotary table(s) with centerline of rotation(s) at 90 deg or parallel to *X*-axis travel can be specified by adding a suffix(s) to an appropriate table code number.
For example:
402.3 or 408.2.4.

Table Traverse (See Fig. 4.10)			
Direction(s) of Travel (Depending on Spindle Attitude)			Code Number
None	Trunnion table	Pos.	XXX.1
		Mach.	XXX.2
X	Rotary table (centerline at 90 deg to table traverse)	Pos.	XXX.3
		Mach.	XXX.4
Y or *Z*	Rotary table (centerline parallel to table traverse)	Pos.	XXX.5
		Mach.	XXX.6
Z or *Y*			403
X over *Y* or *X* over *Z*			404
X over *Z* or *X* over *Y*			405
Z over *Z* or *X* over *Z*			406
Z over *X* or *Y* over *X*			407
Z over *X* or *Y* over *X*			408
X over *Z* over *Y* or *X* over *Y* over *Z*			409

Pos. = rotary positioning
Mach. = rotary machining

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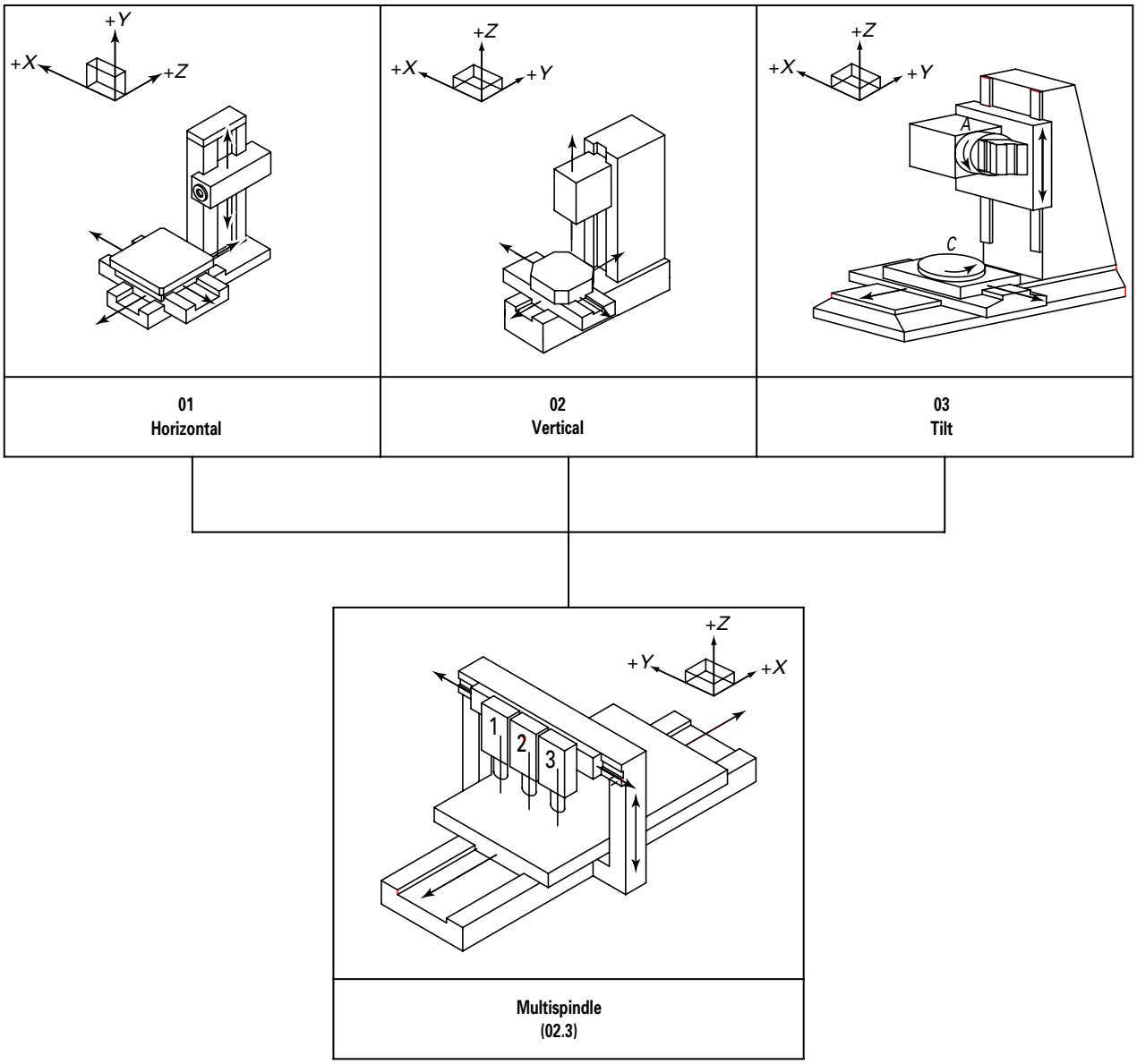


Fig. 4.6 Code Numbers for Spindle Types

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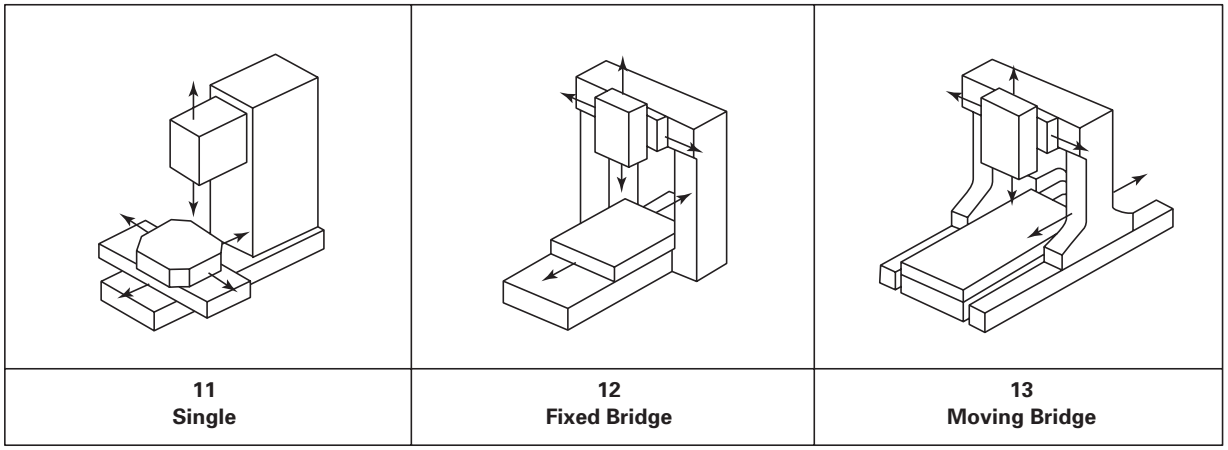


Fig. 4.7 Code Numbers for Column Types

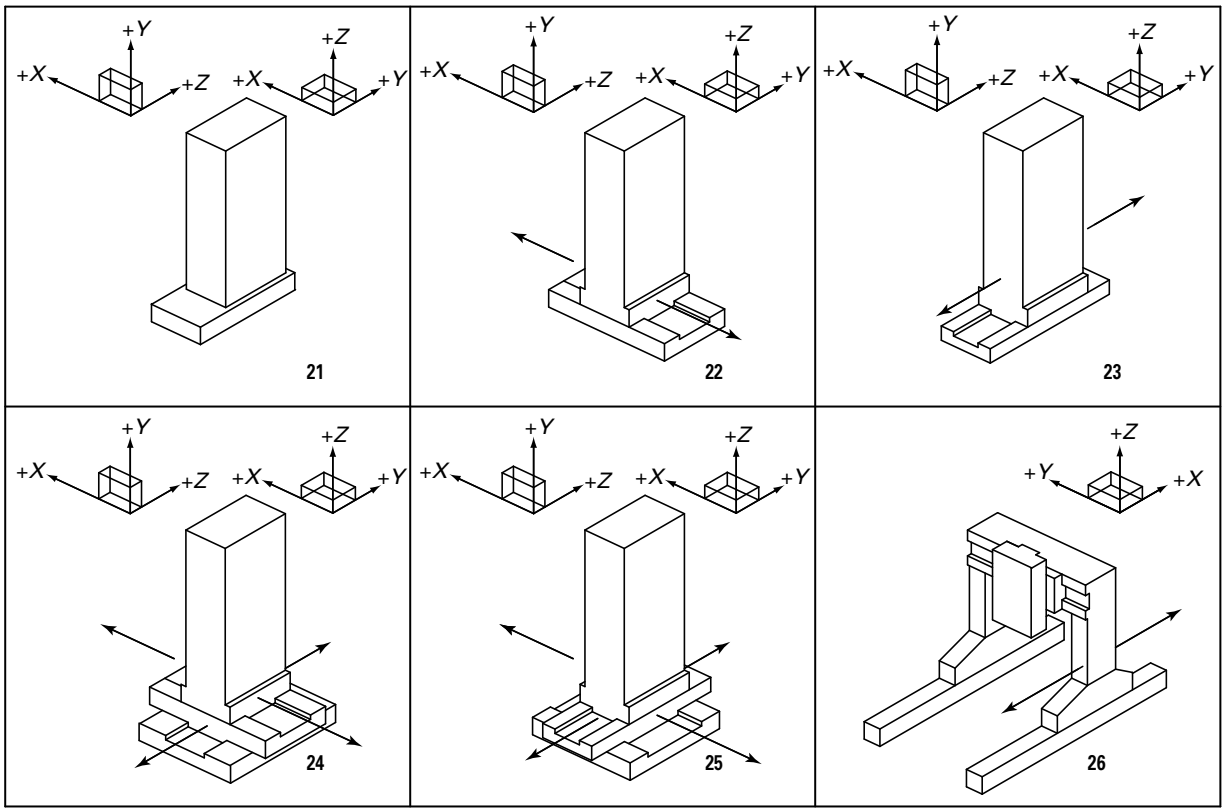


Fig. 4.8 Code Numbers for Column Traverse

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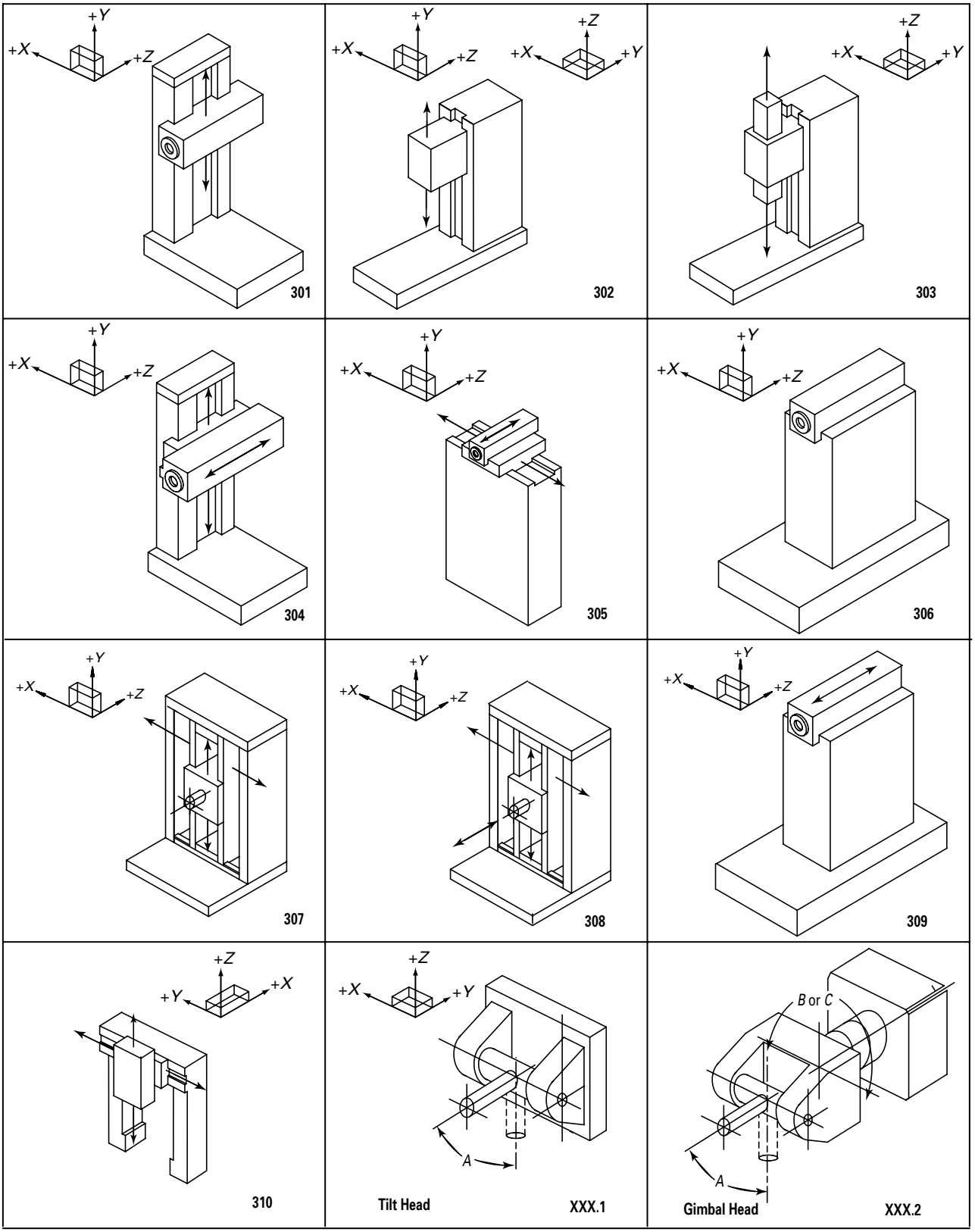


Fig. 4.9 Code Numbers for Spindle Head Traverse

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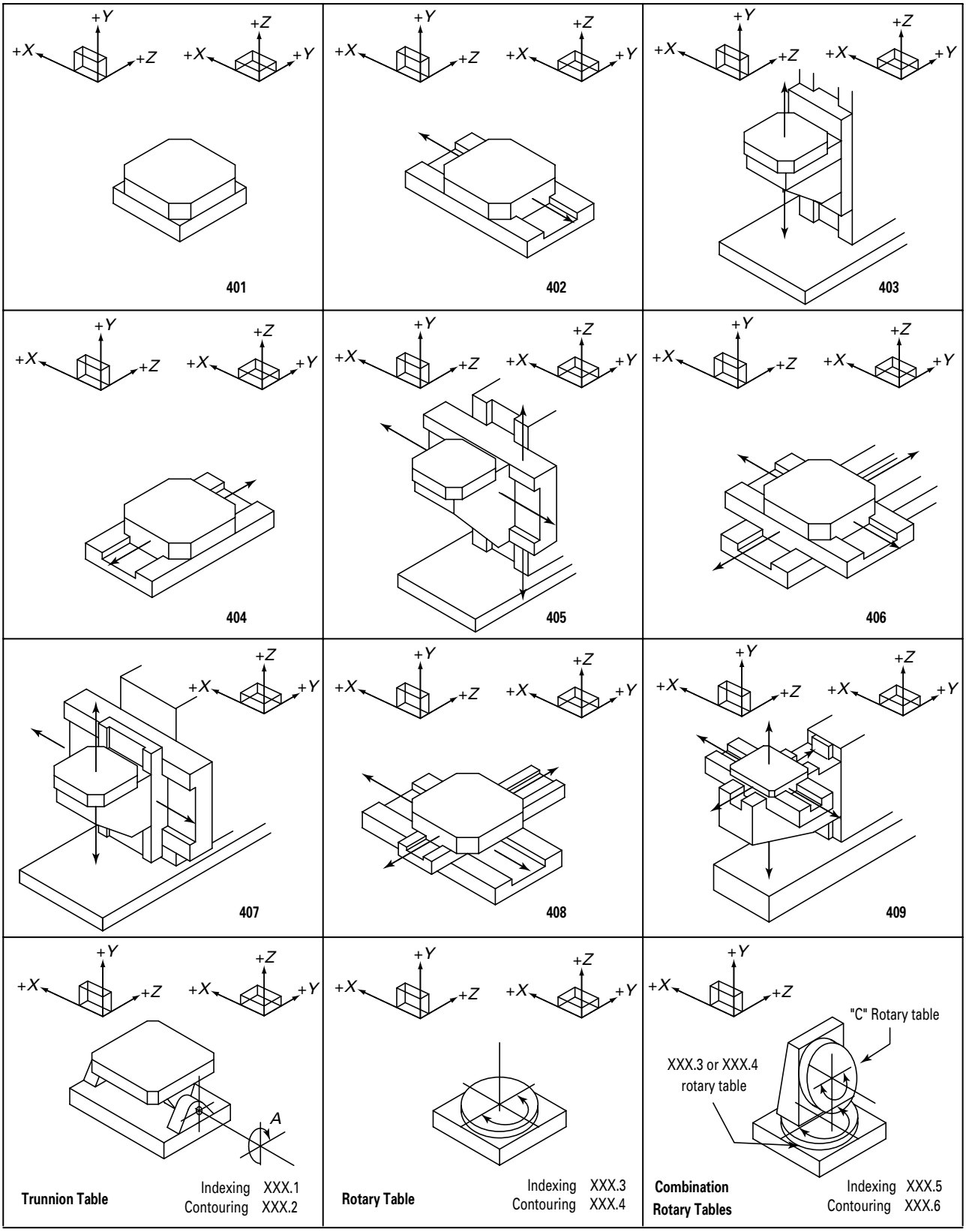


Fig. 4.10 Code Numbers for Table Traverse

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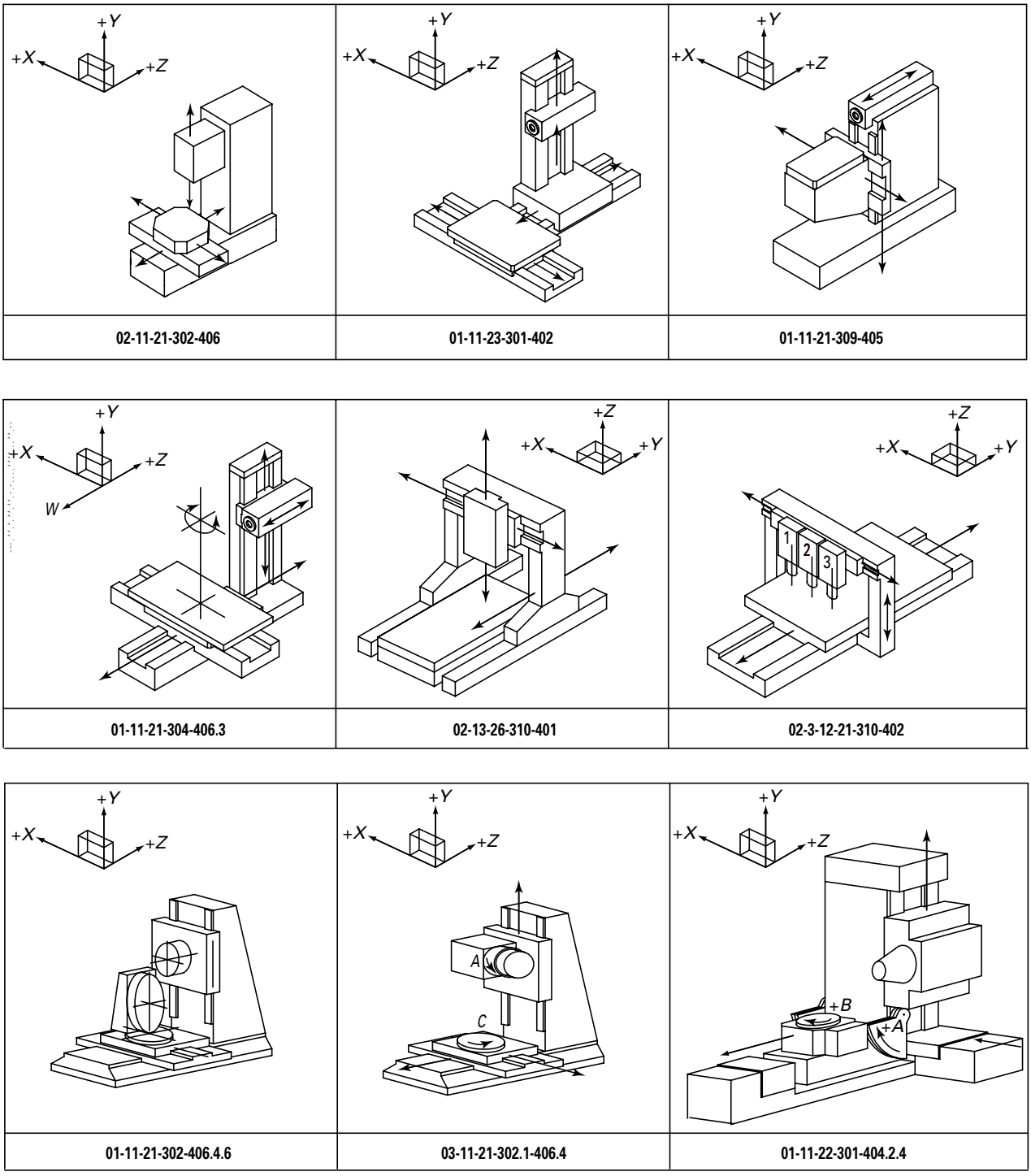


Fig. 4.11 Examples of Machining Centers Classified by Code Numbers

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Chapter 5
Environmental Specifications

5.1 GENERAL

It shall be the responsibility of the User to provide an acceptable environment for performance testing of the machine tool at the installation site. Environmental parameters recommended in this Standard are given in para. 1.2. The environment shall be considered acceptable if the requirements of this Chapter and Chapter 6 are met. The User shall be responsible for conducting all environmental tests at the installation site. The Supplier shall have a right to witness all tests. The Supplier shall, on request, supply test equipment as specified in Chapter 11, and support for equipment and tests, at a price to be negotiated between Supplier and User.

5.2 TEMPERATURE

5.2.1 General

Temperature has a significant influence on the accuracy of machine tools and measuring instruments, and its effects are often misunderstood. The provisions of ASME B89.6.2 form a part of this Standard, but interpretation is needed for application to machine tools. ASME B89.6.2 defines two alternative conditions under which a test environment is thermally acceptable. The first, that all pertinent components of the measuring system are at exactly 20°C (68°F), is generally unobtainable. This Standard is primarily concerned with the second: that the expanded thermal uncertainty (see para. 6.2.3.2) be a reasonable percentage of the specification zone. Acceptability of a thermal environment is specified in terms of its effects on the machine.

5.2.2 Thermal Environment Guidelines

The Supplier shall offer guidelines regarding what thermal environment should be acceptable for the machine. Such general guidelines could contain, for example, a specification on mean room temperature, maximum amplitude and frequency range of deviations from this mean temperature, environmental thermal gradients, air flow rate, and air speed surrounding the machine, as listed in para. 1.2. The User shall be informed that the conformance to such guidelines does not guarantee an acceptable machine thermal environment, but does constitute due care on the User's part and thus shifts responsibility for performance degradation due to environmental sensitivity from User to Supplier. If the User chooses not to conform to the guidelines supplied, the tests of environmental sensitivity (see Chapter 6) may lead to an increase in the acceptable specification zone for a given performance test. In this second case, the degradation in performance shall be solely the responsibility of the User.

5.2.2.1 Time Variations. Particular attention should be given to time variations of temperature, although this Standard does not offer specific guidelines in this area. Machine tools are composed of numerous elements, each with different thermal behavior. For example, the ram of a machine may have a short thermal time constant, and the bed of the machine may have a very long thermal time constant. Therefore, when the machine is in an environment with time variations of the temperature, the resulting response in terms of spindle motion with respect to the table can be quite complex. Furthermore, when a part is being machined there are other time constants like that of the part and the part fixture, which also serve to complicate this problem. Efforts should be made to keep the time variations of temperature either much faster than the fastest time constant in the system or to reduce them to acceptable levels.

5.2.2.2 Thermal Radiant Energy. The machine shall not be exposed to direct sunlight or other powerful radiant energy sources. Other direct radiant energy sources (e.g., fluorescent lighting, radiant heaters, high-intensity lamps, etc.) shall be as far from the machine as possible, to reduce their effects on the machine's thermal behavior. Where this distance requirement is impractical, indirect lighting designed for diffuse reflection and increased path length shall be used. Users and Suppliers should be aware that lights in the machine enclosure might sometimes have unwanted thermal influence.

5.3 SEISMIC VIBRATION

5.3.1 General

The support surface (floor, foundation, isolation pad, etc.) upon which the machine will be mounted can have motion induced as a result of external forces in the surrounding area (due to other machines, lift trucks, compressors, etc.). This motion can be continuous vibration, interrupted shock, or both. Such motion, if transmitted to the machine, has a degrading effect on the overall accuracy and repeatability of a machine tool by causing

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relative motions among the tool, the machine axes position measuring transducers, and the workpiece. Improperly installed or designed isolators can also cause excessive motions. In addition, certain excessive motion amplitudes can cause damage to the machine. Several major American corporations have developed extensive standards for vibration analysis on machine tools. These standards have primarily diagnostic purposes. This Standard in no way supersedes these other standards.

5.3.2 Responsibilities

The User shall be responsible for site selection, environmental shock and vibration analysis, and additional special isolators required to ensure compliance with the maximum permissible vibration levels specified by the Supplier. All questions of compliance shall be determined at the interface between the support system provided by the User and the machine system provided by the Supplier. Functional tests for measuring the relative vibration are described in para. 6.3.

5.3.3 Seismic Vibrational Parameters

The Supplier shall provide, as part of the machine specification, a statement of the acceptable vibration spectra at the User–Supplier interface. (This interface may be very different, depending upon details of the contractual arrangement between Supplier and User. For example, if the machine is supplied with isolators, the interface will be between the foundation and those isolators. However, if the User provides an isolation system from another source, the interface shall be at the connection between those isolators and the machine. In any event, it is a requirement of this Standard that the appropriate interface be defined as part of the machine specification.) This statement can contain a complete description of the allowable vibration displacement amplitude as a function of frequency for each vector component of the vibration spectrum, or can be simply a limit on the total vibrational displacement amplitude over a specified frequency range. In lieu of vibration displacements, accelerations or velocities will also be acceptable. The sample performance form in para 1.2 allows for the displacement options. Users desiring to specify a machine in terms of accelerations or velocities shall create forms and test procedures in equivalent detail. The statement of acceptable vibration spectra applies with the machine in place. It is recognized that in some atypical cases it is physically possible that the vibration spectrum of the foundation or floor may be significantly altered by the installation of the machine, particularly for large or very heavy machines. In such cases, the party (User or Supplier) contracted to supply the vibration isolation system shall be responsible for achieving an acceptable vibration environment for the machine.

5.4 ELECTRICAL

5.4.1 General

The electrical power supplied to a machine can have an effect on the machine's ability to perform accurate and repeatable machining operations. This is especially true with today's modern machines, which typically incorporate electronic and electrical components that can be sensitive to voltage variations. For this reason, it is necessary to characterize the machine in the range of the electrical environment in which it will operate. It is also necessary to know the operating range in which the machine was designed to operate.

5.4.2 Responsibilities

It shall be the responsibility of the User to provide electrical power meeting typical requirements as specified by current standards. The Supplier shall be responsible for providing a specification for which the equipment will operate properly.

5.4.3 Electrical Parameters

The Supplier shall provide, as part of the machine specification, a statement of the steady state requirements including voltage(s), frequency, and amperage for the machine, allowable short and long term RMS voltage variations, and allowable transient voltages expressed in percent of nominal voltage.[1] These parameters are listed in para. 1.2.

5.5 UTILITY AIR

5.5.1 General

Air supplies to machines can affect their accuracy and useful working life. Temperature variations in the utility air can generate thermal gradients in the machine, and particulates, oils, and water can degrade bearing performance, increase friction, and accelerate wear.

5.5.2 Responsibilities

For all machines requiring utility air, it shall be the responsibility of the User to supply utility air meeting requirements specified by the Supplier.

5.5.3 Specifications

For utility air, the Supplier shall provide specification for all air parameters required for the proper operation and maintenance of the machine to be supplied. For air bearing machines these should include mean temperature, permissible temperature variation, pressure, and pressure variations. Further, on some machines, the acceptable dew point and the particulate content shall

[1] Percentage of nominal voltage is the percentage of the remaining voltage. For example, a reduction in voltage of 15% would be expressed as 85% of nominal voltage.

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be specified. These parameters are listed in the environmental specification form in para. 1.2. Air quality parameters, such as particulate, oil, and water content, are the sole responsibility of the User, although the Supplier shall offer guidelines.

5.6 OTHER

5.6.1 General

Just as air supplies can affect the accuracy and useful working life of a machine, so can hydraulic supplies, coolant supplies, foundations, and the like. For example, temperature variations caused by pumping can generate large thermal gradients in the machine and, of course, particulates, oil, and water can degrade machine performance and accelerate wear. Large machine tools also often rely on a User-supplied foundation for their stiffness, and improperly installed foundations can significantly increase a machine's compliance.

Both the Supplier and the User recognize the importance of foundations when the machine design utilizes the foundation as an integral part of the structure. It should be anticipated that test data collected at the Supplier or User facility will likely be affected if static stiffness tests or horsepower cuts are attempted and the foundation at the Supplier or User facility does not comply with the foundation specification, which was generated as part of the machine design. In new installations it is particularly important to pay attention to the inherent instability and cure time of hydraulic concrete, as this material can lead to unstable machine structures if improperly installed. For further discussions related to foundations, see Appendix F.

5.6.2 Responsibilities

For all machines requiring hydraulics or other services, it shall be the responsibility of the Supplier to provide for proper filtering and temperature control, such that these services do not degrade machine performance. If, for some reason, hydraulics, coolants, or other services are to be supplied by the User, then the User shall be responsible for meeting all requirements as specified by the Supplier. In the case of foundations, the responsibility for foundation design and installation shall be negotiated as part of the original contract, but foundation specifications, including construction drawings (where applicable), shall be supplied by the Supplier.

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Chapter 6
Environmental Tests

6.1 GENERAL

The environmental tests are intended to verify that the environment is suitable for the performance tests to follow. The Supplier may choose to defer these tests. This might be reasonable when test specification zones are large, when the environment provided by the User is known to be adequate, or when the machine tool system is designed to be environmentally robust. If the machine performs within the test specification zones, the deferred tests and computations of this Chapter may be eliminated. If the performance fails, the environmental tests may be performed as part of the diagnostic process.

6.2 ENVIRONMENTAL TEMPERATURE VARIATION ERROR (ETVE)

6.2.1 General

The ETVE test estimates the expected positioning error due to changes in machine ambient temperature. It does not address changes in the above-mentioned errors due to the effects of internal heat sources of the machine tool. Therefore, these effects should be minimized by a machine stabilization procedure described in para. 6.2.2.

6.2.2 Test Procedure

6.2.2.1 Equipment. Also see para. 6.2.4.

(a) test artifact
(b) five displacement indicators
(c) gage holding fixture
(d) data recording system/software (as required)
(e) air temperature sensor
(f) metal surface temperature sensor

6.2.2.2 Machine Warm-Up

(a) The machine shall be stabilized to "cold machine" condition. All systems that normally operate while the machine is idle (including systems to control effects of environmental temperature) shall be operating.

(b) To detect the effects of spatial temperature gradients across the machine work volume, the location of the machine axes during warm-up shall be as far as possible from the position selected by the machine Supplier for the ETVE test.

6.2.2.3 Test Location

(a) The location for the ETVE test may be specified by the machine Supplier. The description shall include the location of the test artifact with respect to the spindle and the position of each axis.

(b) The default location of the test artifact shall be on the spindle centerline, 150 mm from the spindle face.

(c) The default position of the linear axes shall be approximately at the center of the axis travel.

6.2.2.4 Measurement Procedure. See Fig. 6.1.

(a) Place the test artifact in the machine spindle.

(b) Fix the gage holder and indicators to the workpiece table aligned to the axes.

(c) Place the air temperature sensor near the center of the machine work volume.

(d) Place the surface temperature sensor on the spindle nose.

(e) Adjust the machine axes and indicators so that all indicators are near the centers of their ranges.

(f) Check for setup hysteresis in each direction as discussed in para. 7.1.4.2.

(g) Ensure that electronic test equipment, computers, etc., do not touch the machine. These shall be located as far as possible from the machine tool for the duration of the test.

(h) Place the machine in the "feed-hold" condition and zero indicators electronically (if applicable).

(i) Ensure the setup has thermally stabilized from the effects of handling before recording data.

(j) Record data from the five displacement indicators and two temperature sensors at intervals of 60 sec or less. The test period should be at least 4 hr. However, the minimum recommended test time is 24 hr.

(k) Normal activities surrounding the machine shall continue during the test.

6.2.3 Data Analysis

6.2.3.1 Computation of ETVE

(a) The thermal drift in the X direction, $ETVE_X$, shall be taken as the maximum range of readings from either displacement indicator in this direction for any 4-hr period over the duration of the test.

(b) The thermal drift in the Y direction, $ETVE_Y$, shall be taken as the maximum range of readings from either displacement indicator in this direction for any 4-hr period over the duration of the test.

(c) The thermal drift in the Z direction, $ETVE_Z$, shall be taken as the maximum range of displacement readings recorded with the single displacement indicator in

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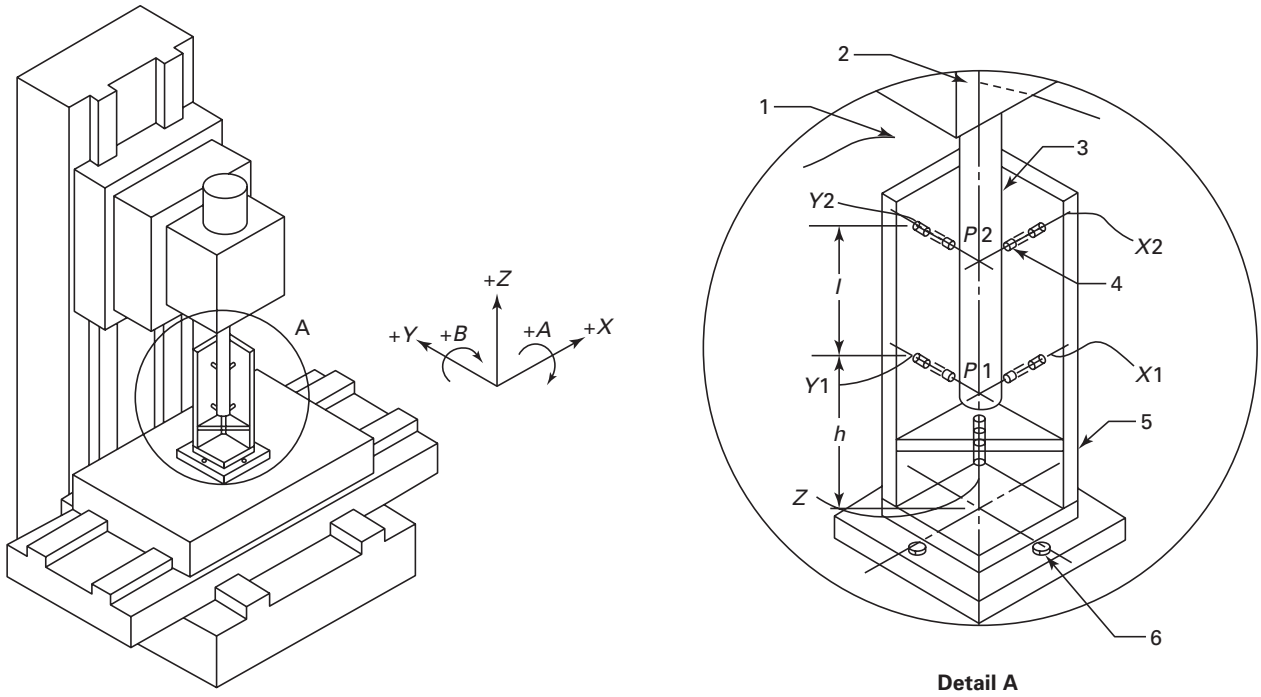


Fig. 6.1 Typical Setup for Environmental Temperature Variation Error (ETVE) Measurement on a Vertical Machining Center

this direction for any 4-hr period over the duration of the test.

(d) Tilt about the *X* direction (relative to the starting position) shall be calculated and recorded for each measurement interval. It is obtained by taking the difference between the two *Y* direction indicators and dividing by the distance between them.

(e) The thermal drift of tilt about the *X* direction, $ETVE_{XX}$, shall be taken as the maximum range of recorded tilts for any 4-hr period over the duration of the test.

(f) Tilt about the *Y* direction (relative to the starting position) shall be calculated and recorded for each measurement interval. It is obtained by taking the difference between the two *X* direction indicators and dividing by the distance between them.

(g) The thermal drift of tilt about the *Y* direction, $ETVE_{YY}$, shall be taken as the maximum range of recorded tilts for any 4-hr period over the duration of the test.

(h) Values of thermal drift for each direction and angular thermal drift about the *X* direction and *Y* direction may be taken directly from a graph of the results such as that shown in Fig. 6.2.

6.2.3.2 Thermal Computations. For all tests that measure machine accuracy, corrections shall be applied for the nominal differential expansion of machine scales, mechanical masters (standards), and, if applicable, changes in the wavelength of the laser interferometer. These computations are described in the paragraphs on the specific tests.

The User shall also compute the expanded thermal uncertainty and the angular expanded thermal uncertainty. These shall be used to verify that the environmental temperature is suitable for the appropriate performance tests or to modify the appropriate test specification zones.

The expanded thermal uncertainty $U_T(L)$ shall be calculated for each performance test from the following equation:

$$\pm U_T(L) = k u_{cT}(L) = \pm 2 u_{cT}(L) \qquad (6\text{-}1)$$

where

k = coverage factor (which, for this computation, will be assumed to be 2)

$u_{cT}(L)$ = combined standard thermal uncertainty (para. 6.2.3.3)

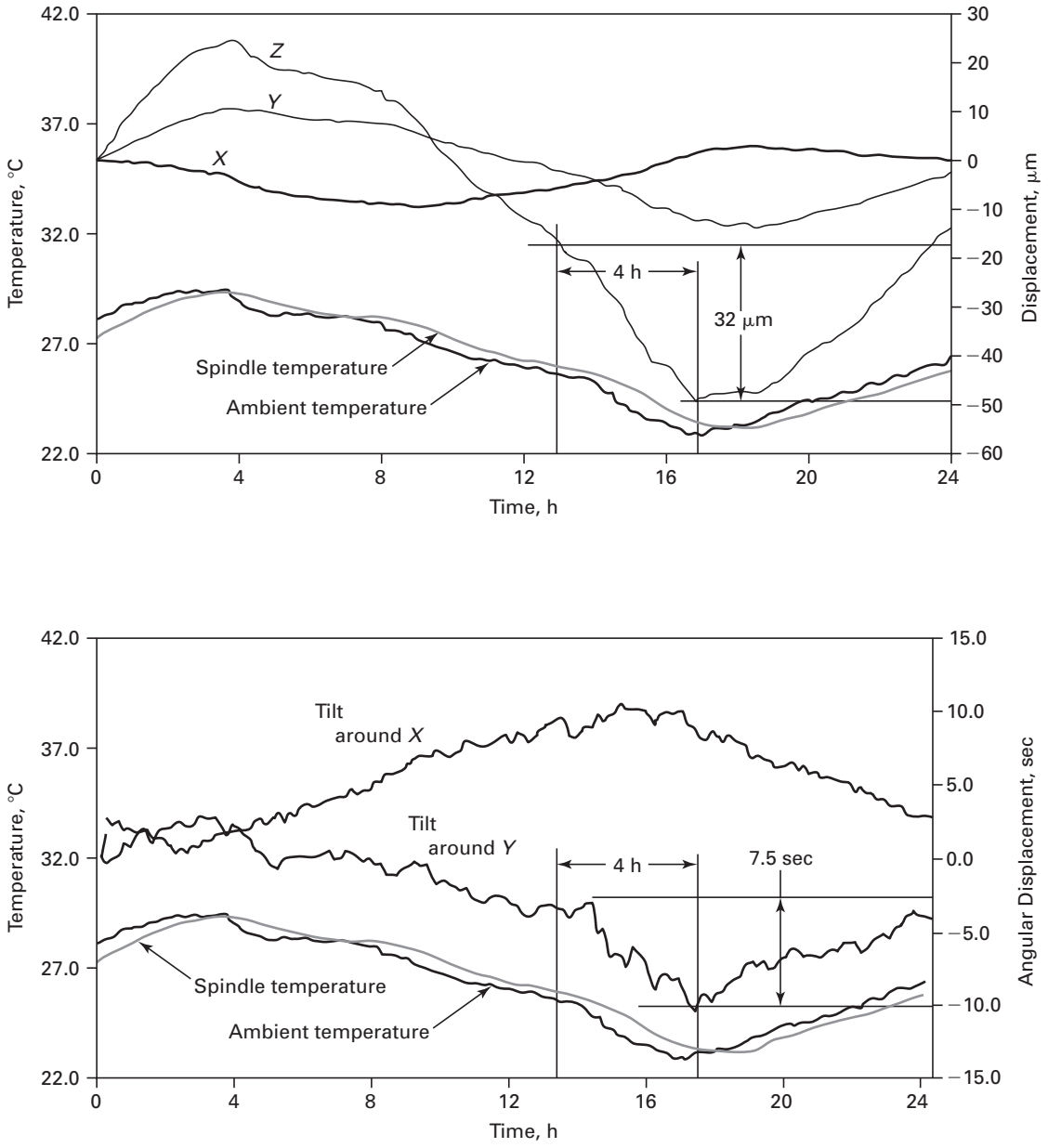
Values in the equation are absolute values and should be taken as positive.

The angular expanded thermal uncertainty shall be calculated for each performance test from the following equation:

$$\pm U_T(A) = k u_{cT}(A) = \pm 2 u_{cT}(A) \qquad (6\text{-}2)$$

where

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GENERAL NOTE: Values for thermal drift in the *Z* direction, $ETVE_Z$, and thermal drift of tilt about the *Y* direction, $ETVE_{YY}$, are shown graphically. In practice, values for the other directions are found similarly.

Fig. 6.2 Temperature, Displacement, and Tilt Motion Results From a Typical ETVE Test

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$u_{cT}(A)$ = combined angular standard thermal uncertainty, which is given by

$$u_{cT}(A) = \sqrt{\frac{ETVE_A^2}{12}} \quad (6\text{-}3)$$

When k is 2,

$$\pm U_T(A) = \pm 0.577\ ETVE_A \quad (6\text{-}4)$$

where $ETVE_A$ for the particular test is found as follows:

(a) The maximum range of indicated values for any 4-hr period over the duration of the test is determined from the recorded data in the relevant direction. That is, $ETVE_{XX}$ or $ETVE_{YY}$ as defined above.

(b) The ratio of the time for the particular test (in hours) divided by 4 is calculated. (For example, a test time of 1 hr results in a ratio of 0.25.)

(c) The $ETVE_A$ value to be used in calculation of $u_{cT}(A)$ for the particular test is the value determined in para. 6.2.3.2(a) times the ratio calculated in para. 6.2.3.2(b).

6.2.3.3 Combined Standard Thermal Uncertainty, $u_{cT}(L)$. The combined standard thermal uncertainty is defined in the glossary for the general case of a length measurement. The general form is given by

$$u_{cT}(L) = \sqrt{\begin{array}{l} u_{ETVE}^2 + L_s^2(T_s - 20)^2u^2(\alpha_s) + L^2(T - 20)^2u^2(\alpha) \\ + L_s^2\alpha_s^2u^2(T_s) + L^2\alpha^2u^2(T) \end{array}} \quad (6\text{-}5)$$

where

L = length being measured (usually in machine tool applications, this is nominally the same as the length of the standard)
L_s = length of the standard (calibrated gage or laser displacement)
T = temperature of machine scales, °C
T_s = temperature of standard, °C
u_{ETVE} = standard uncertainty due to the environmental temperature variation error
$u(T)$ = uncertainty in the measurement of the temperature of the machine scale
$u(T_s)$ = uncertainty in the measurement of the temperature of the standard (air temperature in the case of the laser)
$u(\alpha)$ = uncertainty of the nominal coefficient of expansion of the machine scale
$u(\alpha_s)$ = uncertainty of the nominal coefficient of expansion of the master [$u(\alpha_s) = 0$ for laser interferometers]
α = thermal expansion coefficient of the machine scale
α_s = thermal expansion coefficient of the standard ($\alpha_s = 0.93 \times 10^{-6}$/°C for lasers)

6.2.3.3.1 Standard Uncertainty Due to the Environmental Temperature Variation Error. The standard uncertainty due to the environmental temperature variation error is calculated for each test based on the axis direction of the test result and the duration of the test. It is given by

$$u_{ETVE} = \sqrt{\frac{ETVE^2}{12}} \quad (6\text{-}6)$$

where $ETVE$ for the particular test is found as follows:

(a) The maximum range of indicated values for any 4-hr period over the duration of the test is determined from the recorded data in the relevant direction. That is, $ETVE_X$, $ETVE_Y$, and $ETVE_Z$ as defined above.

(b) The ratio of the time for the particular test (in hours) divided by 4 is calculated. (For example, a test time of 6 hr results in a ratio of 1.5.)

(c) The $ETVE$ value to be used in calculation of u_{ETVE} for the particular test is the value determined in para. 6.2.3.3.1(a) times the ratio calculated in para. 6.2.3.3.1(b).

6.2.3.3.2 Standard Uncertainty Due to Uncertainty in the Nominal Thermal Expansion Coefficient. The uncertainty in the nominal thermal expansion coefficient of a body shall be denoted $u(\alpha)$ for the part and $u(\alpha_s)$ for the standard. This value, like that of α itself, must be an estimate. Various methods can be used to make this estimate. Examples follow:

(a) Option (a). The estimate may be based on the distribution found among results of actual experiments conducted on a number of like objects.

(b) Option (b). The estimate may be based on the distribution found among published data.

(c) Option (c). In the absence of other information, for the purposes of this Standard, it is recommended that the uncertainty in the nominal coefficient of expansion be represented by a rectangular distribution with bounds of $\pm 0.1\alpha$. The standard uncertainty is then

$$u(\alpha) = 0.1\frac{1}{\sqrt{3}}\alpha \quad (6\text{-}7)$$

for the machine scale and

$$u(\alpha_s) = 0.1\frac{1}{\sqrt{3}}\alpha_s \quad (6\text{-}8)$$

for the standard.

Of the three possibilities given above, Option (a) is the recommended procedure.

When a laser is used as the standard, a thermal expansion coefficient and an uncertainty in thermal expansion coefficient are required. The coefficient used to correct laser readings for changes in air temperature (0.93×10^{-6}/°C) shall be used for the thermal expansion coefficient. Because this number is well known, the uncertainty in thermal expansion coefficient can be assumed 0 for a laser.

6.2.3.3.3 Standard Uncertainty Due to Uncertainty in Temperature Measurement. When a temperature is

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measured, there is uncertainty associated with this measurement. This uncertainty may come from the calibration of the thermometer, thermometer mounting procedures, and electronic variations. This uncertainty can be estimated by various methods. Examples follow:

(a) Option (a). The estimate may be based on the distribution found among results of actual measurements conducted on a number of like objects, using the same thermometers and the same procedures.

(b) Option (b). The estimate may be based on the distribution found in published data regarding the use of such thermometers and specific procedures.

(c) Option (c). The estimate may be made from prior judgment regarding the range of possible error. For the purposes of this Standard, in the absence of other information, it is recommended to estimate the temperature measurement uncertainty as being represented by a rectangular distribution with bounds of ±1°C when using thermocouples and ±0.5°C when using thermistors or platinum resistance thermometers (RTDs).

For Option (c), where the error is estimated by a rectangular (uniform) distribution, the standard uncertainty in temperature measurement is given by

$$u(T) = \sqrt{\frac{(a^+ - a^-)^2}{12}} \tag{6-9}$$

where a^+ and a^- are the upper and lower ranges of the rectangular distribution, respectively.

NOTE: When using a laser as the standard, the uncertainty in temperature measurement of the standard applies to the measurement of air temperature.

6.2.3.4 Derating Procedure Using Expanded Thermal Uncertainty. If the expanded thermal uncertainty exceeds 25% of the specification zone for a particular test in Table 6.1, the machine environment does not conform to the Supplier's guidelines, and the User chooses not to upgrade the environment, permissible specification zone limits for those tests shall be increased. The increase shall be equal to the amount by which the expanded thermal uncertainty exceeds 25% of the specification zone. The following formula shall apply:

$$\begin{aligned}\text{Permissible specification zone} &= \text{specification zone} \\ &\quad + [U_T(L) - 0.25\ \text{specification zone}]\end{aligned} \tag{6-10}$$

If the expanded thermal uncertainty exceeds 25% but the environment conforms to the Supplier's guidelines, no derating of the permissible specification zones for the tests given in Table 6.1 is allowed. Methods for testing compliance of the thermal environment to the Supplier's guidelines are given in Appendix B.

Table 6.2 gives example derating results based on the ETVE results of Fig. 6.2 and with the noted parameters and assumptions.

6.2.3.5 Derating Procedure Using Angular Expanded Thermal Uncertainty. If the angular expanded thermal uncertainty exceeds 25% of the specification zone for a particular test in Table 6.3, the machine environment does not conform to the Supplier's guidelines, and the User chooses not to upgrade the environment, permissible specification zone limits for those tests shall be increased. The increase shall be equal to the amount by which the angular expanded thermal uncertainty exceeds 25% of the specification zone. The following formula shall apply:

$$\begin{aligned}\text{Permissible specification zone} &= \text{specification zone} \\ &\quad + [U_T(A) - 0.25\ \text{specification zone}]\end{aligned} \tag{6-11}$$

If the angular expanded thermal uncertainty exceeds 25% but the environment conforms to the Supplier's guidelines, no derating of the specification zones for the tests given in Table 6.3 is allowed. Methods for testing compliance of the thermal environment to the Supplier's guidelines are given in Appendix B.

6.2.4 Discussion Note: Displacement Sensors for ETVE Test

The choice of probe for the ETVE test strongly depends upon the machine thermal environment. For example, some machines use oil showers. In this case, inductance probes or LVDTs, meeting the requirements of Chapter 11, are preferred because capacitance gages can give erratic results in the presence of oil. It is also possible, using such gages, to conduct this test with the machine cutting fluid on. Although the test with cutting fluid on is not a requirement of this Standard, it can provide significant information regarding its effects on the machine performance.

6.2.5 Discussion Note: Effects of Machine Tool Systems

Although the machine is in the feed-hold condition for the ETVE test, there may be effects that can be misinterpreted as thermal drift due to air temperature. Variation in supplied air and hydraulic pressures can cause changes in machine squareness and positional drift. Also, inadequate temperature regulation of circulating fluids may cause angular or linear motions that are not related to the environmental temperatures. Care should be taken to interpret results and correctly diagnose the source of any problem.

6.2.6 Discussion Note: Effects of Mean Air Temperature

It is possible for errors caused by differential expansion to be induced in machines when they are operated at mean temperatures significantly different from the temperature at which they were aligned and calibrated. It is not within the current state of the art to develop

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Table 6.1 Specification Zones Derated Due to an Excessive Expanded Thermal Uncertainty

Parameter	ETVE Used for Uncertainty Calculation	Lengths Used for Uncertainty Calculation	Paragraph
Linear Positioning (per Axis)	...	...	7.3
Bidirectional systematic deviation of positioning	Per axis	$L = L_s$ = axis length	7.3.4
Bidirectional accuracy of positioning	Per axis	$L = L_s$ = axis length	7.3.4
Unidirectional systematic deviations of positioning	Per axis	$L = L_s$ = axis length	7.3.4
Unidirectional accuracies of positioning	Per axis	$L = L_s$ = axis length	7.3.4
Thermal Tests	...	...	7.6
Spindle thermal stability test	Per axis	$L = L_s = 0$	7.6.2
Thermal distortion caused by moving linear axes	Per axis	$L = L_s$ = axis length	7.6.3
Composite thermal error	Per axis	$L = L_s$ = axis length	7.6.4
Circular Tests	...	...	7.11
Radial deviations	Zero (0)	Ball bar length or circular contour radius	7.11.3
Diagonal Displacement Accuracy	RSS of per axis ETVE values [Note (1)]	$L = L_D$ = diagonal length	7.7.2
Linear Measurement Accuracy	Per axis	$L = L_s$ = axis length	7.9.3

NOTE:
(1) Square root of the sum of the squares, sometimes known as root sum squares (RSS).

simple tests for these effects. If a machine is to be accepted at a mean temperature which is significantly different from that used during alignment and calibration, the linear displacement accuracy and circular tests described in paras. 7.3.2.1 and 7.11 shall be repeated for each temperature. It is the requirement of this Standard that the Supplier specify quantitatively the magnitude of temperature change that is significant, the significant mean temperature change (SMTC), for a given machine of given working tolerance. Furthermore, the Supplier shall specify a safe operating temperature range (SOTR) within which the machine should be kept to prevent physical damage to the machine.

6.3 RELATIVE VIBRATION TESTS

6.3.1 General

The relative vibration tests are used to assess the effects of environmental vibration on the performance tests and machine performance. In all cases, the vibration of interest is between the workpiece-holding part of the machine and the tool-holding part of the machine.

6.3.2 Test Procedure

6.3.2.1 Suggested Equipment

(a) high-resolution, high-bandwidth displacement indicator

(b) test ball or test artifact

(c) gage holding fixture

(d) data recording system/software (as required)

6.3.2.2 Machine Warm-Up. No specific machine stabilization is required for the relative vibration tests. After initial setup, the machine shall be turned off. However, any vibration isolation features of the machine shall be on unless otherwise agreed.

6.3.2.3 Test Location. In the absence of other guidance, the position used for the relative vibration test shall be the same position used for the ETVE test.

6.3.2.4 Measurement Procedure

(a) Attach the test ball or other artifact to the machine spindle.

(b) Attach indicator(s) to the work-holding machine table.

(c) Align displacement indicator(s) with one (the) nominal machine axis direction(s).

(d) Sample the displacement indicators at a minimum rate of 1 kHz for a period of between 1 sec and 5 sec.

(e) Record the displacement amplitude as a range of values.

(f) Repeat the sampling and recording at least 10 times over a period of 10 min.

(g) Repeat for all nominal axis directions as required.

6.3.3 Data Analysis

(a) The maximum range of the displacement indicator(s) reading over any of the 5 sec test periods along each machine axis direction shall be reported as the relative vibration for that axis direction.

(b) The test environment shall be considered acceptable if the relative vibration amplitude is less than 25% of the machine specification zone for bidirectional repeatability for the appropriate axis.

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Table 6.2 Example Calculations for Derating of Specification Zones Due to Thermal Uncertainty

Parameter	Parameters Used for Uncertainty and Derating Calculations													
	Test Time, hr	Specification Zone, μm	*ETVE*, μm	Length, mm	α Used, μm, m°C	u (α), μm, m°C	α_s Used, μm, m°C	u (α_s), μm, m°C	$u(T)$, °C	$u(T_s)$, °C	$u_{cT}(L)$, μm	$\pm U_T(L)$, μm	Permissible Specification Zone, μm	Amount Derated, μm
Linear Positioning (*Z*-Axis)														
Bidirectional systematic deviation of positioning	1	60	8	300	11.7	0.68	0.93	0	0.58	0.58	3.1	12	60	0
Bidirectional accuracy of positioning	1	60	8	300	11.7	0.68	0.93	0	0.58	0.58	3.1	12	60	0
Unidirectional systematic deviations of positioning	1	40	8	300	11.7	0.68	0.93	0	0.58	0.58	3.1	12	42	2
Unidirectional accuracies of positioning	1	40	8	300	11.7	0.68	0.93	0	0.58	0.58	3.1	12	42	2
Thermal Tests (*Z* Direction Only)														
Spindle thermal stability test	2	40	16	0	N/A	0	N/A	0	0.58	0.58	4.6	18	48	8
Thermal distortion caused by moving linear axes	2.5	40	20	300	11.7	0.68	0.93	0	0.58	0.58	6.1	25	55	15
Composite thermal error	3.5	40	28	300	11.7	0.68	0.93	0	0.58	0.58	8.3	33	63	23
Circular Tests														
Radial deviations	0.5	30	0	150	11.7	0.68	11.7	0.68	0.58	0.58	1.1	6	30	0
Linear Measurement Accuracy (*Z*-Axis)	0.5	60	4	300	11.7	0.68	0.93	0	0.58	0.58	2.4	9	60	0
Diagonal Displacement Accuracy	4	60	35	1 591	11.7	0.68	0.93	0	0.58	0.58	14.9	60	105	45

GENERAL NOTES:
(a) Vertical machine center work volume 1 000 × 1 200 × 300 mm (*X*, *Y*, *Z*).
(b) Ball bar length 150 mm for radial deviations test; ball bar material: steel.
(c) From graph of Fig. 6.2, $ETVE_X = 8$ μm, $ETVE_Y = 10$ μm, $ETVE_Z = 32$ μm.
(d) Mean temperature for machine and standards is 22°C during all tests.
(e) Temperatures of machine scale, atmosphere, and ball bar measured with thermocouples with accuracy of ±1°C.
(f) Coverage factor of 2 used for expanded thermal uncertainty in all cases of this example table.
(g) Calculations for other directions can be done in similar fashion.

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Table 6.3 Specification Zones Derated Due to an Excessive Angular Expanded Thermal Uncertainty

Parameter	Paragraph
Angular error	7.4.2.3
Squareness between linear axes	7.4.4.1
Parallelism	7.4.4.2
Alignment between a linear and a rotary axis	7.4.4.3

Table 6.4 Performance Parameters Derated Due to Excessive Environmental Vibration

Parameter	Paragraph
Positioning Accuracy and Repeatability	7.3
Unidirectional accuracies of positioning	7.3.4
Bidirectional accuracy of positioning	7.3.4
Bidirectional repeatability	7.3.4
Unidirectional repeatabilities	7.3.4
Spindle Axis of Rotation (per Spindle)	7.5
Radial error motion	7.5.3.1
Axial error motion	7.5.3.3
Circular Test	7.7.3
Diagonal displacement	7.7.2
Subsystems repeatability	7.8
Tool change repeatability	7.8.2
Pallet change repeatability	7.8.3
Tool-setting repeatability	7.8.4
Machine Performance as a Measuring Tool	7.9
Feature location repeatability	7.9.2
Probe lobing	7.9.2.4
Workpiece location	7.9.5

Permissible specification zone limits for specific tests in this Standard, given in Table 6.4, shall be automatically increased to 4 times the measured vibration amplitude if

(1) the relative vibration amplitude, measured with the machine off, exceeds 25% of the specification zone of the machine for a particular test

(2) the machine vibration environment does not conform to the Supplier's guidelines

(3) the User chooses not to upgrade the environment

The vibration will then be 25% of the new specification zone.

NOTE: This test does not measure vibrations caused by machine electronics, hydraulics, axis drives, etc. Further tests given in this Standard will provide this information (see para. 7.5.2).

6.3.4 Discussion

The relative vibration tests should be conducted to include both the steady-state vibrations and any transients that might occur during normal use. In principle, such tests should run for a complete daily cycle. For practicality, however, only a minimum duration is recommended. The minimum duration is 10 min. These tests do not constitute a well-defined measurement of the forced vibration amplitude, but rather some complicated function that only relates in a very general way to that amplitude. If the machine does not pass the functional test, Appendix C provides recommended procedures for accurate measurement of the vibration spectra at the User–Supplier interface for determining conformance to the Supplier's specifications. The vibration tests described above do not assess the classical dynamic performance of the machine tool when subjected to cutting conditions, which lead to regenerative chatter.

6.4 ELECTRICAL TESTS

Well-defined procedures and highly developed instruments exist to characterize the electrical power supplied to a machine. It is, however, the position of this Standard that such tests are, in the general case, not required and should be undertaken only if the machine does not meet performance specifications and there is reason to suspect the electrical power. Failures due to electrical power usually become apparent as intermittent control or readout failures, which are difficult to link to mechanical causes. In the case that the power is suspect, this Standard provides Appendix D, which describes the recommended procedure for determining the conformance of the electrical environment to the Supplier's guidelines. It should be noted that particular attention must be given to the proper grounding of the machine in accordance with the Supplier's guidelines, provided that these guidelines do not contradict local and national codes such as the latest edition of the National Electric Code (NEC). An example of this contradiction would be to install an isolated ground rod (not physically connected to the power system ground system) at the machine. Improper grounding of electrical equipment is one of the most common causes of improper electrical performance.

6.5 UTILITY AIR AND OTHER TESTS

As with electrical power tests, there also exist many complicated procedures for determining the quality of the utility air, hydraulics, or other services to the machine when such services are required. It is the position of this Standard that exhaustive tests should not be required for checking conformance to specification unless a problem traced to the air or other supply is evident. As stated previously, variations in the mean value of the supplied air pressure can, on certain machines, cause changes in machine squareness and

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positional drifts, so that if such changes occur air pressure is a possible suspect. It shall therefore be the responsibility of the Supplier to examine, using the gages supplied with the machine, the mean pressure and pressure variations of air or other services at the input to the machine. If, in the Supplier's judgment, such fluctuations are excessive, then further tests shall be performed for determining conformance of User-supplied air or other services to the Supplier's specification. If, however, the Supplier judges such fluctuations to be insignificant, then the utility air and/or other services shall be judged as conforming to specification, without further testing.

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Chapter 7
Machine Performance

7.1 GENERAL

The Supplier shall be responsible for providing a machine that meets all performance specifications agreed upon between the Supplier and User when the machine is installed according to the Supplier's recommendations in any environment meeting the requirements of Chapter 5. If required, derating of the acceptable specification zones is applied as described in Chapter 6. Note that the specification zone for any given test is the value given in para. 1.1. If a machine meets the performance specifications and other conditions agreed upon between the Supplier and the User, then the User should accept the machine.

7.1.1 Test Conditions

7.1.1.1 Environment. Where the temperature of the environment can be controlled, it shall be set to 20°C. Otherwise, the measuring instrument output and the machine nominal readings shall be adjusted to yield results corrected to 20°C, where applicable. This means that for material standards, a nominal differential expansion (NDE) correction shall be applied (see para. 4.1) and other instruments, such as laser interferometers, shall be compensated for environmental conditions. Those tests where environmental compensation and NDE correction shall be used are listed in Table 6.1 (see para. 6.2).

The machine and, if relevant, the measuring instrument or artifact standard shall have been in the test environment long enough (preferably overnight) to have reached a thermally stable condition before testing. They shall be protected from drafts and external radiation such as sunlight, overhead heaters, machine lights, etc. All tests should be run under the lighting conditions that will be used during normal machine operation; that is, if the machine is to be run with its internal lights on, it should be tested with the lights on. (For a thorough discussion of thermal effects, see ASME B89.6.2.)

7.1.1.2 Sign Conventions. In addition to magnitude, the signs of machine performance parameters can be important when communicating and analyzing measurement results and when making compensations and adjustments. Recommendations are given in Appendix N.

7.1.1.3 Machine to Be Tested. The machine shall be completely assembled and fully operational. All the necessary leveling operations, geometric alignments, and Supplier-specified functional checks shall be completed before starting performance testing. A minimal set of functional checks is given in Appendix E. All performance tests in Chapter 7 of this Standard shall be carried out with the machine in an unloaded condition (i.e., without a workpiece, unless specified otherwise; e.g., para. 7.9.5).

Users should be aware that changing machine parameters or adjustments of any kind may affect the results of various performance tests. When using this Standard for machine acceptance, these parameter changes and adjustments should be made prior to the commencement of acceptance testing.

7.1.1.4 Compensation Systems. Some machines are equipped with computer-controlled compensation systems for geometric and/or thermal errors. If the machine is so equipped, tests should be run with the compensation system ON. Users desiring to see uncompensated errors may request, as part of the original specification, that these tests also be performed with the compensation system OFF.

7.1.1.5 Machine Warm-Up. The tests shall be preceded by an appropriate warm-up procedure. If the procedure is not specified in this Standard for a particular test, it may be specified by the Supplier of the machine and/or agreed between the Supplier and the User. If no conditions are specified, the preliminary machine movements shall be restricted to only those necessary to set up the measurement instrument.

7.1.2 Foundation Checks and Machine Alignment

Before performing any measurements, it is advisable to align the machine following the Supplier's recommended procedures. If the machine has more than three supports, particular attention should be paid to checking that the foundation is properly cured and meets the Supplier's specifications.

7.1.3 Tool Holders

Several of the performance tests described in this Standard require the use of a tool holder to attach instrumentation to the machine. Unless otherwise agreed upon between Supplier and User, the tool holder to be used for these tests shall be the one supplied with the machine and used during the normal machine operation.

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7.1.4 Test Setup and Instrumentation

7.1.4.1 General. Most measurements prescribed in this Standard are carried out to measure motion between the table of the machine that holds the workpiece and the spindle that holds the cutting tool. All test setups normally involve two fixtures: one that establishes the reference point or surface and one that holds some type of indicator to read against this reference point or surface.[1] The specific setups and instrumentation are provided for suggestions only. Other instrumentation and setups providing comparable results can be used as well. However, before starting any of the measurements, the User of this Standard has to make sure that the particular setup and instrumentation function properly within the machine tool environment. Two main tests are recommended for such checks: setup hysteresis and stability.

7.1.4.2 Setup Hysteresis Test. The goal of this test is to discover any hysteresis effects, which may be caused by loose bolts in test setups, insufficient structural strength in the brackets, etc. Any hysteresis is normally revealed as a lack of repeatability in machine performance testing.

Setup hysteresis is measured by applying a suitable force,[2] in the direction of the intended measurement, between these two fixtures and observing the resulting deflection.

The procedure is as follows:

(a) Set up and zero an indicator between the two fixtures in the direction and location of the intended axis performance test.

(b) Apply the force, by hand, to the fixture holding the datum reference.

(c) After the force is applied, gradually decrease this force to zero and read the indicator.

(d) Apply a force by hand in the opposite direction, gradually decrease the force to zero, and read the indicator.

(e) The difference in readings is the datum hysteresis.

(f) Apply the force to the fixture holding the indicator.

(g) Gradually decrease this force to zero and read the indicator.

(h) Apply a force by hand in the opposite direction, gradually decrease the force to zero, and read the indicator.

(i) The difference in readings is the indicator fixture hysteresis.

(j) The arithmetic sum of the hysteresis values for the datum fixture and indicator fixture is the total test setup hysteresis.

The sensitivity of the result to the magnitude of the force is, in general, insignificant. If significant hysteresis[3] is measured, and if this hysteresis cannot be reduced by increasing the stiffness of the test setup, it may be caused by the machine itself. In such cases, further testing shall be discontinued until this condition is corrected.

7.1.4.3 Setup Stability Tests. Machine tools are subject to a wide variety of vibrations from both internal and external sources. These vibrations vary in both frequency and amplitude, depending on time and location within the machine and machine axis positions. The stiffness and damping characteristics of machines may exclude these vibrations from having an effect on the actual performance of the machine. However, improper mounting of test equipment may also make the instrument/test sensitive to these vibrations. The setup stability test is designed to ensure that the mounting of instruments does not significantly affect the uncertainty of measurements.

The procedure is as follows:

(a) Mount the measuring instrument in the manner used for the performance test.

(b) Position the machine in the middle of travel for the performance test.

(c) Set the instrument to zero and sample the output at a rate and time equal to those used in the test,[4] without moving the machine.

The mounting of instruments can be altered to reduce the range of sampled data. Mountings preferably should be stiffened; however, softening of mounts can also reduce the sensitivity to certain vibrations. If changes to the mounting do not reduce the range, the machine itself may be responsible. Check seismic vibration and continue testing.

7.2 MACHINE COMPLIANCE AND HYSTERESIS

7.2.1 General

This test is designed to estimate machine compliance and hysteresis when a static load is applied between the tool and the workpiece. It provides a simplified indication of what more rigorous compliance testing would measure. Compliance values vary as functions of the position of the machine tool axes. The linear compliance is measured near the center of the work zone at a point defined by the Supplier and is measured for each linear positioning axis. In general, the Supplier shall specify

[1] The reference point can be the ball (ETVE test) or the retroreflector (linear displacement accuracy test). The indicator can be a capacitance gage, an eddy current probe, a laser interferometer, or a dial indicator.

[2] The range of forces can be between 22 N (5 lb) and 220 N (50 lb), depending upon the test setup and the resolution of the indicator. The forces applied should not threaten damage to the machine or the metrology setups. Forces of less than 44 N (10 lb) are recommended to avoid causing machine hysteresis. No attempt is made to measure the forces.

[3] Conventional practice is that the setup hysteresis be less than one-tenth of the desired measurement repeatability.

[4] The range of the data sampled should not exceed 10% of the specification zone for the performance test.

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Table 7.1 Suggested Maximum Loads for the Machine Compliance and Hysteresis Test (Not for Spindles With More Than 10,000 rpm)

Spindle Torque		Force	
N-m	lb-ft	N	lb
20	15	1,100	250
50	40	2,200	500
100	75	4,500	1,000
150	110	6,650	1,500
200	150	8,900	2,000
250 [Note (1)]	185 [Note (1)]	8,900	2,000

NOTE:
(1) Includes torque greater than this number at 600 rpm.

the maximum load and provide appropriate fixturing.[5] If a load is not specified, suggested values are given in Table 7.1.

Angular compliance for machines with rotary axes is measured similarly, but at positions as defined in the text below and at loads to be specified by the machine Supplier.

Two test procedures are included in this section for measurement of compliance and machine hysteresis. The first method (para. 7.2.2) is the preferred method. The situations in which the alternate method may be appropriate are described in the scope of that section (para. 7.2.3). It must be emphasized that the alternate method should only be considered for machines with scale feedback.

WARNING: The suggested loads given in Table 7.1 do not apply to spindles with a maximum speed of more than 10,000 rpm. In the case where such spindles are supplied, the User shall negotiate appropriate compliance and machine hysteresis tests with the Supplier.

7.2.2 Machine Compliance and Hysteresis Test: Linear Axes

7.2.2.1 Test Setup. Typical setups for horizontal and vertical axes are shown in Fig. 7.1 and Fig. 7.2, respectively. A displacement sensor such as an electronic indicator, dial gage, or laser interferometer is set to read the relative motion between the tool holder and the table along the linear axis. A load cell is aligned with the machine axis to be tested and rigidly fixtured between the machine table and the spindle. It is recommended that the setup should be such that the load cell will function under tension and compression. If the machine has backlash compensation, this test is conducted with the backlash compensation on.

7.2.2.2 Test Procedure

[5] Since the loads applied are large, appropriately tested and Supplier-approved fixturing is essential for the safety of personnel and the machine.

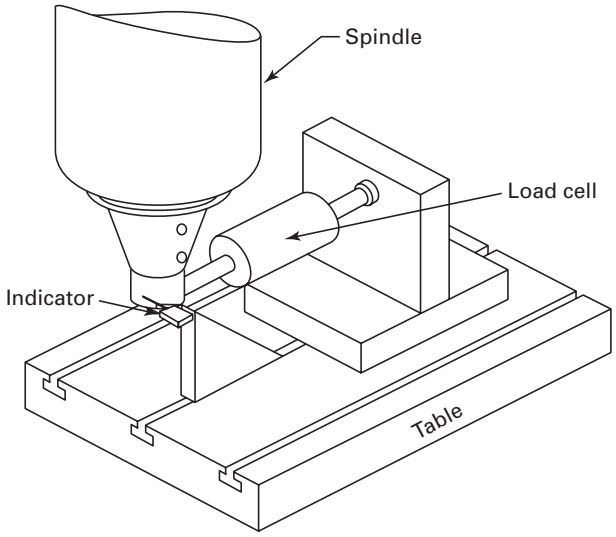


Fig. 7.1 Setup for Measuring the Compliance and Machine Hysteresis of a Linear Axis

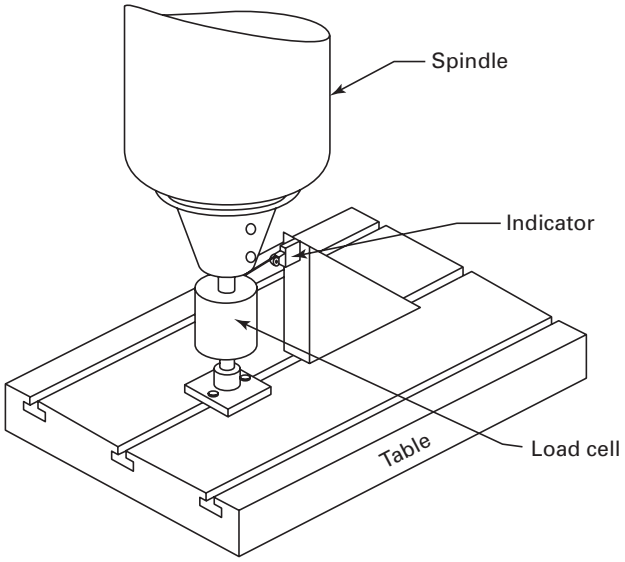


Fig. 7.2 Setup for Measuring the Compliance and Machine Hysteresis of a Linear Axis in a Vertical Direction

7.2.2.2.1 Equipment
(a) displacement indicator
(b) force gage (load cell)

7.2.2.2.2 Machine Warm-Up. No warm-up condition is required.

7.2.2.2.3 Test Location. The machine axes shall be positioned in the center of their respective ranges.

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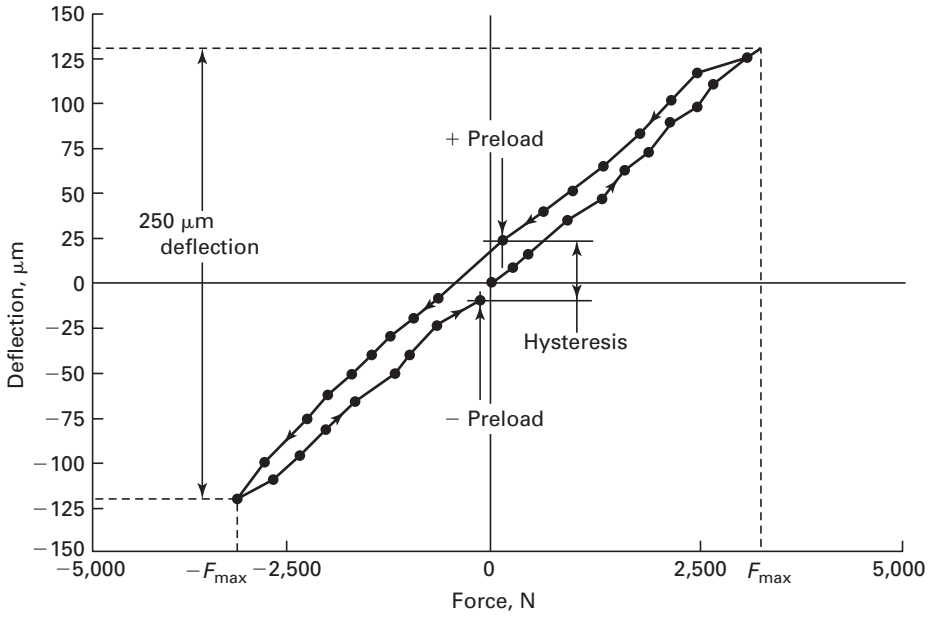


Fig. 7.3 Typical Plot Showing Results of a Compliance and Axis Hysteresis Test

7.2.2.2.4 Measurement Procedure[6]

(a) Zero the indicator at the beginning of each test.

(b) Move the machine axis under test in small increments until the maximum force specified or a maximum deflection[7] of 250 μm (approximately 0.01 in.) has been reached. Call this the positive direction.

(c) Record the command position, actual position, and force.

(d) Jog the axis in the opposite (negative) direction until the force drops to 1% of the maximum force (positive preload).

(e) Record the command position, actual position, and force.

(f) Continue jogging in the same (negative) direction until the force (or deflection) reaches its maximum value.

(g) Record the command position, actual position, and force.

(h) Jog the axis back in the plus direction until the force drops to 1% of the maximum force (negative preload).

(i) Record the command position, actual position, and force.

7.2.2.3 Data Analysis. To evaluate machine compliance and hysteresis, the deflection (actual position minus command position) at each of the four measurement points is computed. The compliance in the direction of the axis is computed as the total range of the deflections divided by the total range of force (expressed as mm/N or in./lb). The machine hysteresis for the axis is computed as the range of deflection between the positive preload and negative preload points (expressed as millimeters or inches). The values to be used for these computations are indicated in Fig. 7.3.

7.2.3 Alternate Machine Compliance and Hysteresis Test: Linear Axes

7.2.3.1 Scope. The alternate compliance and machine hysteresis test procedure may produce different results compared to those obtained following the primary procedure. For machine axes with rotary encoder feedback, the compliance and hysteresis values computed will probably be less. Thus, the machine performance will be overestimated using the alternate method.

For machine axes with scale feedback, the alternate test procedure will likely produce similar results compared with the primary method for both compliance and hysteresis. In this case, the alternate method may be preferred as it generally requires less range on the displacement indicator. Therefore, it allows the use of a higher resolution displacement indicator. In addition, the resolution of the machine display does not affect the resolution of the measurement.

7.2.3.2 Test Procedure

7.2.3.2.1 Equipment

(a) displacement indicator

(b) force gage (load cell)

(c) linear actuator (e.g., differential screw, hydraulic jack)

[6] Performing the test in this fashion removes any effects due to clearance in the test fixtures or deflections of the load cell.

[7] The deflection is defined as the difference between the actual position and the command position.

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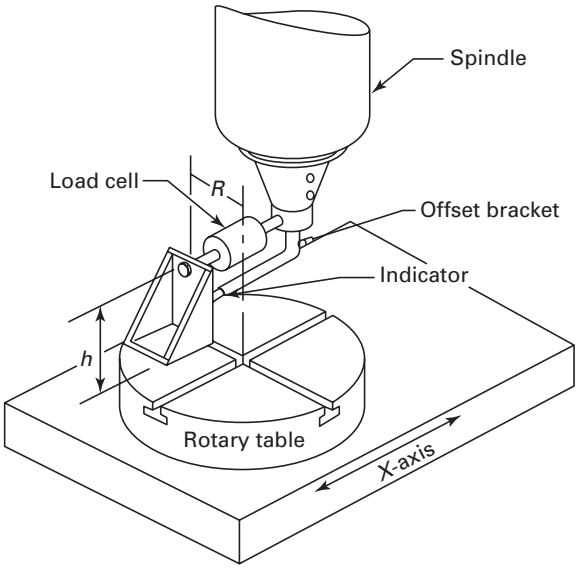


Fig. 7.4 Setup for Angular Compliance Measurement on a Rotary Positioning Axis

7.2.3.2.2 Machine Warm-Up. No warm-up condition is required.

7.2.3.2.3 Test Location. The machine axes shall be positioned in the center of their respective ranges for this test.

7.2.3.2.4 Measurement Procedure

(a) Connect linear actuator and force gage in series between spindle and worktable.

(b) Set up displacement indicator to record relative displacement between spindle and worktable.

CAUTION: Place the displacement indicator as near as possible to the point of force to minimize the effects of tilt errors.

(c) Create a zero-force condition with the linear actuator.

(d) Set zero on the displacement indicator.

(e) Operate the actuator to achieve the maximum test load (or maximum deflection of 250 μm). Call this the positive direction.

(f) Record the force and displacement.

(g) Operate the actuator in the opposite direction until the force drops to 1% of the maximum force (positive preload).

(h) Record the force and displacement.

(i) Continue operating the actuator in the same (negative) direction until the force (or deflection) reaches its maximum value.

(j) Record the force and displacement.

(k) Operate the actuator in the opposite (positive) direction until the force drops to 1% of the maximum force (negative preload).

(l) Record the force and displacement.

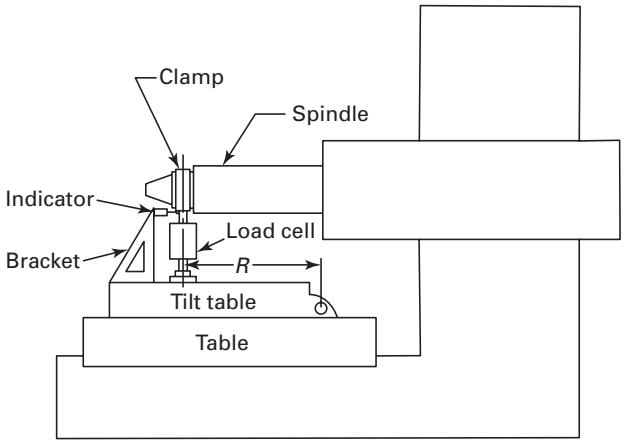


Fig. 7.5 Setup for Angular Compliance Measurement on a Tilt Table

(m) Repeat the measurement procedure for each axis direction.

7.2.3.3 Data Analysis. The compliance for each axis is reported as the total range of recorded displacements divided by the total range of recorded forces.

The machine hysteresis for each axis is computed as the range of measured displacements between the positive preload and negative preload points (expressed as micrometers or microinches).

7.2.4 Machine Compliance and Hysteresis Test: Rotary Machining Axes

7.2.4.1 Test Setup. Two typical setups for measuring the compliance and hysteresis of the rotary axis are shown in Figs. 7.4 and 7.5. A load cell is aligned parallel with one of the linear axes of the machine that has been previously tested and rigidly fixtured between the machine table and the spindle at a distance, R, from the center of rotation of the rotary axis. The distance, R, and the maximum force shall be specified by the Supplier. An indicator is set to read the relative linear displacement between the bracket on the rotary table and the spindle. If the machine has compensation for backlash, this test is conducted with the compensation on.

7.2.4.2 Test Procedure

7.2.4.2.1 Equipment

(a) displacement indicator

(b) force gage (load cell)

7.2.4.2.2 Machine Warm-Up. No warm-up condition is required.

7.2.4.2.3 Test Location. The machine axes shall be positioned in the center of their respective ranges for this test.

7.2.4.2.4 Measurement Procedure

(a) Zero the indicator at the beginning of each test.

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(b) Move the rotary axis in small increments until the maximum force specified has been reached.

(c) Record the angular command position, actual position (indicator reading), and force.

(d) Jog the axis in the opposite (negative) direction until the force drops to 1% of the maximum force (positive preload).

(e) Record the angular command position, actual position, and force.

(f) Continue jogging in the same (negative) direction until the force (or deflection) reaches its maximum value.

(g) Record the angular command position, actual position, and force.

(h) Jog the axis back in the plus direction until the force drops to 1% of the maximum force (negative preload).

(i) Record the angular command position, actual position, and force.

7.2.4.3 Data Analysis. To evaluate compliance[8] and machine hysteresis, the deflection (actual position minus command position) at each of the four measurement points is computed. The command position is obtained from the angular command position using the following formula:

$$CM = 0.01746 \times A \times R \quad (7\text{-}1)$$

where

A = angle command (decimal degrees)
CM = command position
R = distance of the point of load application from the center of rotation

The hysteresis for the axis is similarly computed as the range of deflection between the positive preload and negative preload points (expressed as micrometers or microinches).

NOTE: The compliance for each axis is reported as the total range of recorded displacements divided by the total range of recorded force.

7.2.5 Machine Compliance and Hysteresis Test: Rotary Positioning Axes

The procedure and analysis described in para. 7.2.4 should be applied for this test, except for the following differences in the test procedure:

(a) Before commencing the test, the rotary axis should be positioned and any clamping or braking mechanism used when machining should be applied to this axis.

(b) The motion necessary to produce a load in the rotary direction shall be applied by the appropriate linear axis rather than the rotary axis.

[8] The composite of the compliance of the rotary axis and the other machine elements in the structural loop.

For rotary machining axes with clamping capability that will also be used as rotary positioning axes, this test shall also be performed.

7.2.6 Alternate Machine Compliance and Hysteresis Test: Rotary Axes (Machining or Positioning)

7.2.6.1 General. The alternate compliance and machine hysteresis test procedure may produce different results compared to those obtained following the primary procedure. For machines with indirect rotary position feedback, the computed compliance and hysteresis values will probably be less. Thus, the machine performance will be overestimated using the alternate method.

For machines with feedback that directly measures the position of the rotary axis, the alternate test procedure will likely produce similar results. In this case, the alternate method may be preferred, as it generally requires less range on the displacement indicator. Therefore, it allows the use of a higher-resolution displacement indicator. In addition, the resolution of the machine display does not affect the resolution of the measurement.

7.2.6.2 Test Procedure

7.2.6.2.1 Equipment

(a) displacement indicator

(b) force gage (load cell)

(c) linear actuator (e.g., differential screw, hydraulic jack)

7.2.6.2.2 Machine Warm-Up. No warm-up condition is required.

7.2.6.2.3 Test Location. The machine axes shall be positioned in the center of their respective ranges for this test.

7.2.6.2.4 Measurement Procedure

(a) Connect linear actuator and force gage in series between spindle and worktable as described in para. 7.2.4.1.

(b) Set up displacement indicator to record relative displacement between spindle and worktable.

CAUTION: Place the displacement indicator as near as possible to the point of force to minimize the effects of tilt errors.

(c) Create zero-force condition with the linear actuator.

(d) Set zero on the displacement indicator.

(e) Operate the actuator to achieve the maximum test load (or maximum deflection of 250 μm). Call this the positive direction.

(f) Record the force and displacement.

(g) Operate the actuator in the opposite direction until the force drops to 1% of the maximum force (positive preload).

(h) Record the force and displacement.

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(i) Continue operating the actuator in the same (negative) direction until the force (or deflection) reaches its maximum value.

(j) Record the force and displacement.

(k) Operate the actuator in the opposite (positive) direction until the force drops to 1% of the maximum force (negative preload).

(l) Record the force and displacement.

(m) Repeat the measurement procedure for each axis direction.

7.2.6.3 Data Analysis. The compliance for each axis is reported as the total range of recorded displacements divided by the total range of recorded forces calculated as shown in para. 7.2.4.3.

7.3 POSITIONING ACCURACY AND REPEATABILITY

This paragraph of the Standard specifies the tests to evaluate the accuracy and repeatability of positioning of numerically controlled machine tool axes. The tests address deviations in the direction of motion of an axis at stationary target positions. The methods described apply to linear and rotary axes, including servoed spindle axes and indexing axes. Paragraph 7.3.5 describes a test that focuses on the periodic term of the deviations.

7.3.1 Mode of Operation

The machine shall be programmed to move the axis under test and to position it at a series of target positions. At a target position, the machine will remain at rest long enough for the actual position reached to be measured and recorded.

For linear axes, target positions are required over the full travel range. The measuring intervals shall be no larger than 25 mm for axes of 250 mm or less. For longer axes, the intervals shall be no more than $^1/_{10}$ of the axis length. When the measurement reference of the machine axis consists of several segments, additional target positions may be selected to ensure that each segment has at least one target position. For rotary axes, a minimum set of nine target positions is required over the full travel range. For axes exceeding 360 deg, the total measurement travel of the axis up to 1,800 deg (five revolutions) shall be tested at intervals not exceeding 180 deg. Over an angle of 360 deg in the normal working area, additional target positions may have to be added such that within this angle the intervals do not exceed 45 deg. For indexing axes, the number of target positions may equal the number of indexing positions.

It is recommended that the target points should not be the points used by the Supplier to acquire data used for error compensation. Furthermore, it is desirable to either choose a nonuniform spacing of the target points or to select an interval that is not an even fraction of the pitch of the axis measurement system. This ensures that periodic errors, such as errors caused by the pitch of the ball screw, are adequately sampled. Paragraph 7.3.5 describes a test for periodic error.

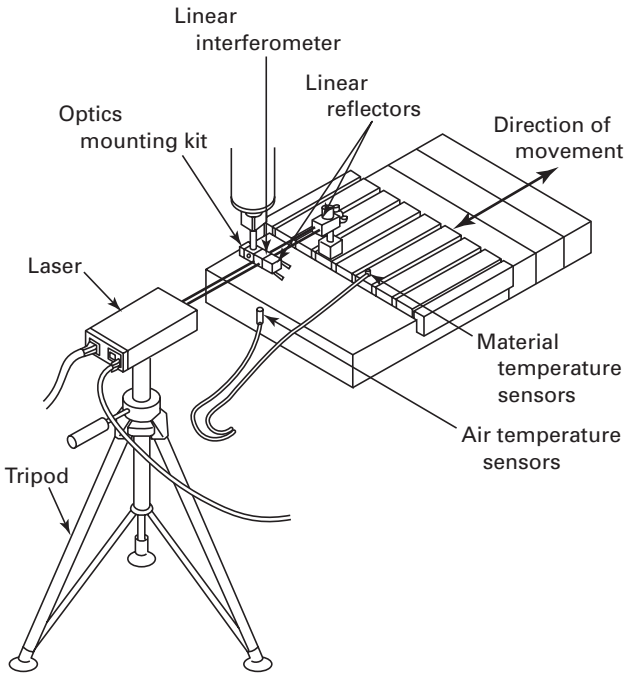


Fig. 7.6 Application of a Laser Interferometer to Test the Positioning Accuracy of a Linear Axis

7.3.2 Test Procedure

The measurement setup is designed to measure the relative displacements between the component that holds the tool and the component that holds the workpiece in the direction of motion of the axis under test.

7.3.2.1 Linear Axes. The displacement shall be measured along a line through the center of the workspace, parallel to the axis under test. Alignment of the measuring instrument to the axis motion should be such that the cosine error is less than 1% of the specification zone of the axis under test. A laser interferometer is the preferred measuring instrument. A typical setup for a moving table machine is shown in Fig. 7.6. If possible, the retroreflector should always be the moving element, particularly on very accurate machines. The optics associated with the tool should be mounted in the spindle. However, on machines where the spindle cannot be locked, a bracket should be made to position the optics near the point where a tool would be, with the bracket attached to the spindle housing.

This Standard requires that the nominal differential expansion (NDE) correction be performed for linear displacement measurements. In addition, an interferometer must be compensated for air pressure and air humidity. The environmental compensation unit supplied with the laser interferometer must be used for all these corrections. The part temperature sensor must be placed in a

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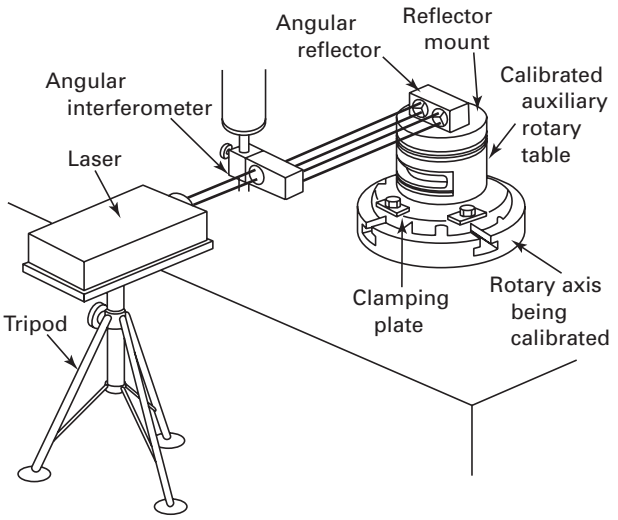


Fig. 7.7 Setup for Measuring the Positioning Accuracy of a Rotary Table With a Laser Angle Interferometer and a Calibrated Indexing Table

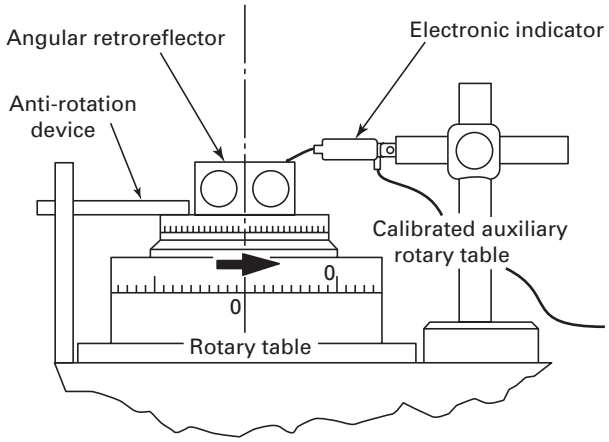


Fig. 7.8 Setup for Adjusting the Alignment of an Indexing Table and a Laser Angle Interferometer

position where the temperature corresponds, as closely as possible, to the temperature of the machine scale or its equivalent. The position of the temperature sensor(s) on the machine components and the type of compensation routine shall be stated on the test sheet. The correct effective coefficient of expansion for the machine axes shall be used (see para. 1.1). If the laser system does not provide for environmental correction, both laser readings and machine readings shall be corrected manually (see Appendix H).

7.3.2.2 Rotary Axes

7.3.2.2.1 Setup With an Auxiliary Rotary Table. This method uses an auxiliary calibrated rotary table to extend the range of a small-angle indicator. Suitable indicators are a laser interferometer with angular optics, an autocollimator, and electronic levels. Electronic levels can only be applied to test horizontal axes. A diagram for a typical setup using a laser interferometer is given in Fig. 7.7. An auxiliary calibrated rotary table is attached to the face of the rotary axis to be measured. The axis of rotation of the auxiliary table must be aligned to the rotary axis being measured. The angular interferometer is attached to the spindle with the double retroreflector mounted on the center of the auxiliary rotary table. The machine axis is commanded to move in steps smaller than the measuring range of the interferometer. After each step, the auxiliary table is moved in the opposite direction to maintain a condition of approximate parallelism between the retroreflectors and the interferometer. The actual angular displacement of the machine axis equals the observed indicator reading minus the sum of the auxiliary table displacements. For both the autocollimator and the electronic levels, steps can be used that exceed the measuring range of the instruments.

Most angular indicators can have large errors if not properly aligned and need to be corrected for nonlinearity if the measurement angle exceeds a few degrees. In such cases, the indicator supplier's recommendations should be followed. In the case of an angular interferometer, the centerline of the double retroreflector must be square with the axis of rotation. Figure 7.8 illustrates a test for verifying this alignment. An indicator is bracketed to the machine slide and adjusted so that the stylus contacts the outer edge of the double retroreflector. The indicator is zeroed at this point. The linear axes of the machine are moved so that the indicator is clear of the corner cube. The auxiliary rotary table is lifted, and the rotary axis is rotated 180 deg with the anti-rotation bar in place on the auxiliary table. The table is then reclamped and the machine slides are returned to their original position. The procedure is repeated for a 90-deg and a 270-deg rotation. For each pair of rotations, the reading of the indicator should be within 50 μm (0.002 in.) to ensure an error less than 1 part in 1,000 of the measured angle. Such a procedure assumes that the side faces of the angular retroreflector assembly are parallel to the plane defined by the centerline of the two reflectors to within 5 μm (0.0002 in.).

7.3.2.2.2 Setup With a Polygon. This test is performed using a calibrated optical polygon with a minimum of nine faces. For an indexing axis, the faces may correspond to the positions of the axis. A setup is shown in Fig. 7.9. The polygon is fixtured to the face of the rotary axis to be measured. Special attention should be given to the attachment of the polygon in order to minimize any fixture-induced stresses that might distort the polygon. An autocollimator should then be placed so that an image is obtained from one of the polygon faces. The setup allows readings on the angular position

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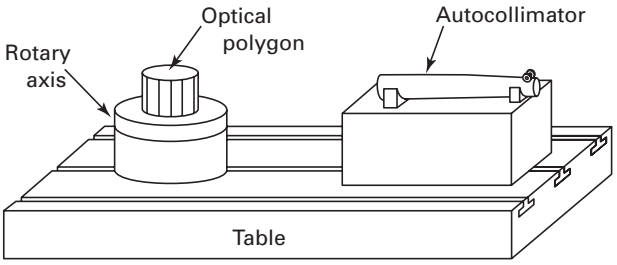


Fig. 7.9 Setup for the Positioning Accuracy of a Rotary Axis Showing the Polygon, Autocollimator, and Rotary Table

7.3.3 Measurement Procedure

(a) Before commencing measurements, the machine shall be run through an exercise sequence of two back-and-forth movements between the first and last target points.

(b) The next five sets of bidirectional measurements are made at all the target positions using the cycle depicted in Fig. 7.11. The default traverse speed shall be the machine's maximum programmable feed rate. Other feed rates may be negotiated between User and Supplier.

(c) At each target position, the machine motion is halted for a short duration, 1 to 5 sec, after which a measurement is taken. On some large machines, longer settling times may be required. In this case, the settling time should be negotiated between the User and Supplier. It is recommended that the instrument readings be averaged for about 0.25 sec and at least 120 readings be taken to compute this average. The data shall be acquired without rezeroing the measurement instrument. A set of measurements shall consist of the target positions and the corresponding instrument readings.

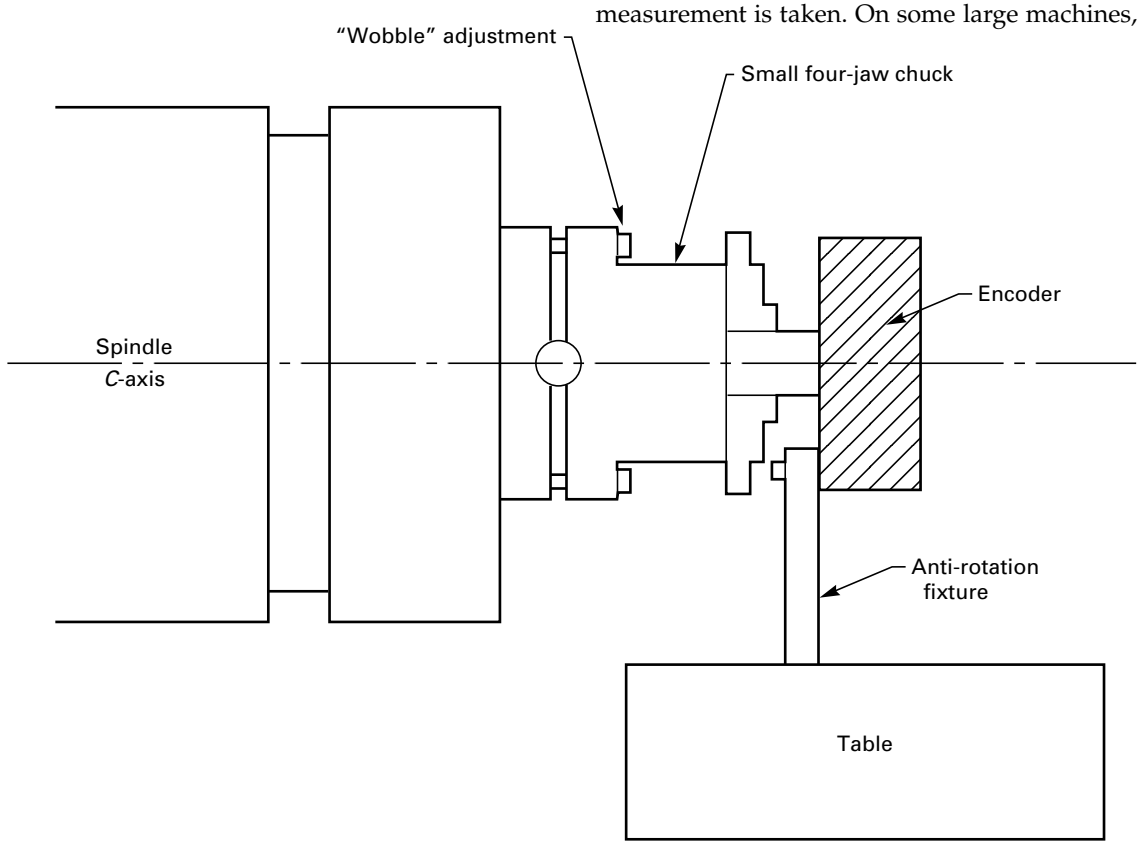


Fig. 7.10 Setup for Measuring the Positioning Accuracy of a Rotary Axis With a Calibrated Rotary Encoder

of the machine table corresponding to each of the polygon faces.[9]

7.3.2.2.3 Setup With a Rotary Encoder. This method employs a calibrated rotary encoder to measure the angular displacement. A typical setup is shown in Fig. 7.10.

[9] Particular attention must be paid to obtain the correct sign (±) for the autocollimator reading when performing this test.

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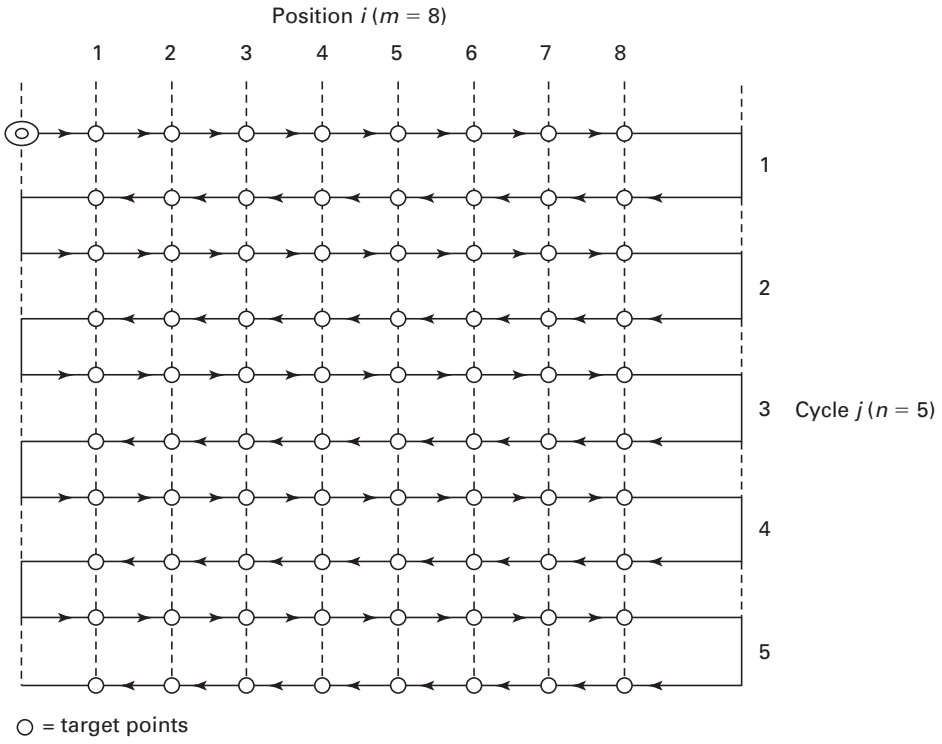


Fig. 7.11 Standard Test Cycle

(d) For each target point there will be ten measurements, five in each direction.

7.3.4 Data Analysis

(a) For each measurement, the respective deviation of position is calculated as the measured actual position minus the target position. For each axis, the calculated deviations shall be plotted as shown in Fig. 7.12. For clarity, the forward data are shown separately in Fig. 7.13. On both figures the data averages are shown as dark lines. From these data, the following parameters shall be computed for each axis and compared to the appropriate specification zones:

(1) the unidirectional systematic deviations of positioning, $E\uparrow$ and $E\downarrow$

(2) the bidirectional systematic deviation of positioning, E

(3) the unidirectional repeatabilities, $R\uparrow$ and $R\downarrow$

(4) the bidirectional repeatability, R

(b) The computations for these and other parameters are summarized in Table 7.2 and consist of the following steps:

(1) The positional deviation, $x_{ij}\uparrow$ or $x_{ij}\downarrow$, equals the actual position reached by the moving part minus the target position. It is calculated for each approach j to target position i. The symbols $\uparrow$ and $\downarrow$ are used to indicate a positive and negative approach direction.

(2) The mean unidirectional positional deviation at a position, $\bar{x}_i\uparrow$ or $\bar{x}_i\downarrow$, is the mean of the positional deviations for a series of n unidirectional approaches to a target position. It is calculated as

$$\bar{x}_i\uparrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\uparrow \tag{7-2}$$

and

$$\bar{x}_i\downarrow = \frac{1}{n}\sum_{j=1}^{n} x_{ij}\downarrow \tag{7-3}$$

(3) The estimator of the unidirectional standard uncertainty of positioning at a position, $s_i\uparrow$ or $s_i\downarrow$, is the standard deviation of the positional deviations obtained by the series of n unidirectional approaches at a target position. It is calculated for each position as:

$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n} (x_{ij}\uparrow - \bar{x}_i\uparrow)^2} \tag{7-4}$$

and

$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n} (x_{ij}\downarrow - \bar{x}_i\uparrow)^2} \tag{7-5}$$

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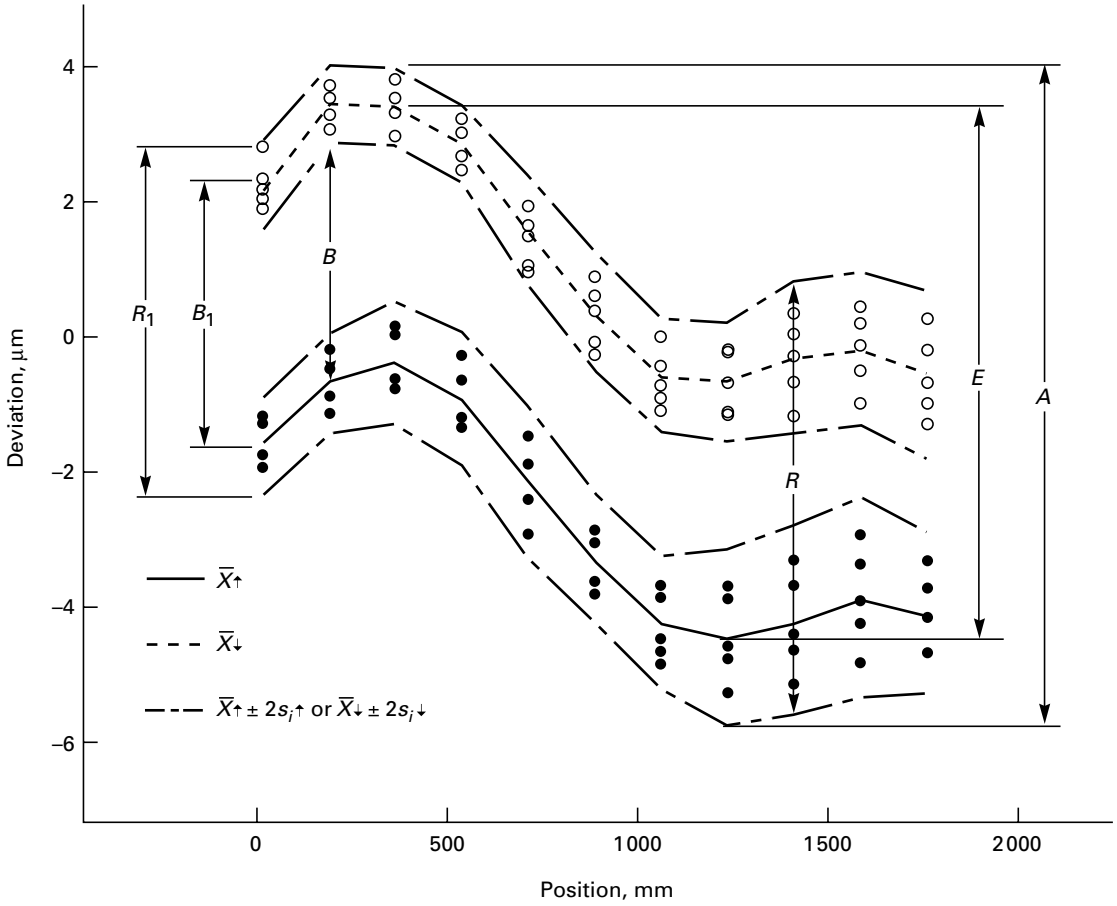


Fig. 7.12 Full Data Set for the Positioning Deviations of an Axis, Bidirectional

(4) The unidirectional repeatability at a position, $R_i\uparrow$ or $R_i\downarrow$, is the range derived from the expanded uncertainty of unidirectional positional deviations at a position using a coverage factor of two. It is calculated for each position as

$$R_i\uparrow = 4s_i\uparrow \tag{7-6}$$

and

$$R_i\downarrow = 4s_i\downarrow \tag{7-7}$$

(5) The reversal deviation at a position, B_i, is the difference between the mean unidirectional positional deviations, and $\overline{x}_i\uparrow$ and $\overline{x}_i\downarrow$, obtained from the two directions of approach at a target position. It is calculated as

$$B_i = \overline{x}_i\uparrow - \overline{x}_i\downarrow \tag{7-8}$$

(6) The bidirectional repeatability at a position, R_i, is the range derived from an estimate for the expanded uncertainty of bidirectional positional deviations at a position. It is calculated for each position as

$$R_i = \text{max. } [2s_i\uparrow + 2s_i\downarrow + |B_i|;\ R_i\uparrow;\ R_i\downarrow] \tag{7-9}$$

(7) The mean bidirectional positional deviation at a position, $\overline{x}_i$, is the mean of the mean unidirectional positional deviations, $\overline{x}_i\uparrow$ and $\overline{x}_i\downarrow$, obtained from the two approach directions at a target position. That is,

$$\overline{x}_i = \frac{\overline{x}_i\uparrow + \overline{x}_i\downarrow}{2} \tag{7-10}$$

(8) The reversal deviation of an axis, B, is the maximum of the absolute mean reversal deviations, $|B_i|$, at all target positions,

$$B = \text{max. } [|B_i|] \tag{7-11}$$

(9) The mean reversal value of an axis, $\overline{B}$, is the mean of the reversal deviations, B_i, at all m target positions,

$$\overline{B} = \frac{1}{m}\sum_{i=1}^{m} B_i \tag{7-12}$$

(10) The unidirectional systematic deviation of positioning of an axis, $E\uparrow$ or $E\downarrow$, is the difference between the maximum and minimum of the mean unidirectional positional deviations for an approach direction, $\overline{x}_i\uparrow$ or

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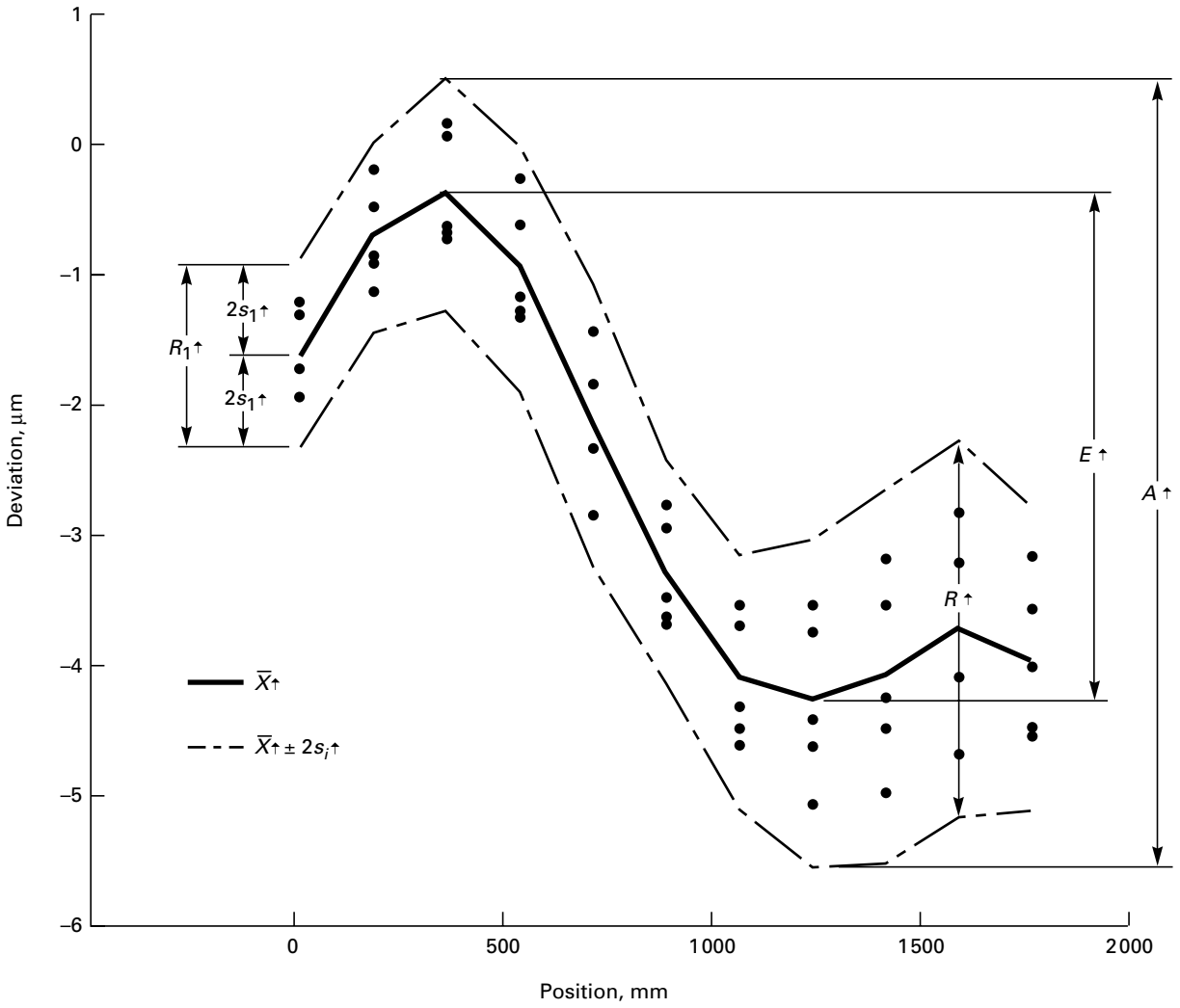


Fig. 7.13 Positioning Deviations of an Axis, Forward Direction Only

$\bar{x}_i\downarrow$, at any position along or around an axis. It is the range of the average plot in the forward or reverse direction and is calculated as

$$E\uparrow = \text{max. } [\bar{x}_i\uparrow] - \text{min. } [\bar{x}_i\uparrow] \quad (7\text{-}13)$$

and

$$E\downarrow = \text{max. } [\bar{x}_i\downarrow] - \text{min.}[\bar{x}_i\downarrow] \quad (7\text{-}14)$$

(11) The bidirectional systematic deviation of positioning of an axis,[10] E, is the difference between the maximum and minimum of the mean unidirectional positional deviations for both approach directions, i.e., $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$, at any position along or around the axis (that is, the range of the average values as shown in Fig. 7.12). The equation is

$$E = \text{max. } [\bar{x}_i\uparrow; \bar{x}_i\downarrow] - \text{min. } [\bar{x}_i\uparrow; \bar{x}_i\downarrow] \quad (7\text{-}15)$$

(12) The unidirectional repeatability of an axis, $R\uparrow$ or $R\downarrow$, is the maximum value of the repeatability at any position. That is,

$$R\uparrow = \text{max. } [R_i\uparrow] \quad (7\text{-}16)$$

and

$$R\downarrow = \text{max. } [R_i\downarrow] \quad (7\text{-}17)$$

(13) The bidirectional repeatability of an axis, R, is the maximum value of the bidirectional repeatability at any position. That is,

$$R = \text{max. } [R_i] \quad (7\text{-}18)$$

[10] The bidirectional systematic review of positioning of an axis is the preferred method for measuring positioning capability. It is the same as the linear displacement accuracy in ASME B5.54-1992.

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Table 7.2 Typical Test Results for the Positioning and Repeatability of a Linear Axis (Measured in μm)

Parameter	Target Position, i																					
	1		2		3		4		5		6		7		8		9		10		11	
	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑
Positional deviations, $j = 1$	2.3	−1.2	3.6	−0.50	3.5	0.20	3.0	−0.60	1.7	−1.9	0.40	−3.0	−0.40	−3.7	−0.20	−3.7	0.20	−3.5	0.30	−3.2	−0.10	−3.6
Positional deviations, $j = 2$	2.1	−1.7	3.5	−0.90	3.3	−0.60	2.7	−1.2	1.5	−2.3	0.20	−3.5	−0.70	−4.3	−0.60	−4.4	−0.20	−4.3	−0.10	−3.8	−0.60	−4.0
Positional deviations, $j = 3$	1.9	−1.9	3.1	−1.1	3.0	−0.70	2.4	−1.3	1.0	−2.9	−0.20	−3.7	−1.0	−4.6	−1.0	−5.1	−1.0	−5.0	−0.90	−4.7	−1.2	−4.5
Positional deviations, $j = 4$	2.8	−1.3	3.7	−0.20	3.8	0.10	3.6	−0.70	1.9	−1.4	0.90	−2.8	0.00	−3.6	−0.20	−3.6	0.50	−3.2	0.50	−2.8	0.40	−3.2
Positional deviations, $j = 5$	2.2	−1.9	3.2	−0.80	3.5	−0.70	2.6	−1.3	1.1	−2.3	−0.10	−3.7	−0.90	−4.5	−1.1	−4.6	−0.50	−4.5	−0.40	−4.1	−0.90	−4.5
Mean unidirectional positional deviation, $\bar{x}_i \uparrow$; $\bar{x}_i \downarrow$	2.3	−1.6	**3.4**	−0.70	3.4	**−0.30**	2.9	−1.0	1.4	−2.2	0.20	−3.3	−0.60	−4.1	**−0.60**	**−4.3**	−0.20	−4.1	−0.10	−3.7	−0.50	−4.0
"Estimator of standard uncertainty," $s_i \uparrow$; $s_i \downarrow$	0.34	0.33	0.26	0.35	0.30	0.45	0.47	0.34	0.39	0.56	0.44	0.42	0.41	0.46	0.43	0.63	0.59	0.74	0.56	0.75	0.64	0.57
$2s_i \uparrow$; $2s_i \downarrow$	0.68	0.66	0.52	0.70	0.60	0.90	0.94	0.68	0.78	1.1	0.88	0.84	0.82	0.92	0.86	1.3	1.2	1.5	1.1	1.5	1.3	1.1
$\bar{x}_i \uparrow - 2s_i \uparrow$; $\bar{x}_i \downarrow - 2s_i \downarrow$	1.6	−2.3	2.9	−1.4	2.8	−1.2	2.0	−1.7	0.62	−3.3	−0.68	−4.1	−1.4	−5.0	−1.5	**−5.6**	−1.4	−5.6	−1.2	−5.2	**−1.8**	−5.1
$\bar{x}_i \uparrow + 2s_i \uparrow$; $\bar{x}_i \downarrow + 2s_i \downarrow$	3.0	−0.94	3.9	0.00	**4.0**	**0.60**	3.8	−0.32	2.2	−1.1	1.1	−2.5	0.22	−3.2	0.26	−3.0	0.98	−2.6	1.0	−2.2	0.78	−2.9
Unidirectional repeatability at a position, $R_i \uparrow = 4s_i \uparrow$; $R_i \downarrow = 4s_i \downarrow$	1.4	1.3	1.0	1.4	1.2	1.8	1.9	1.4	1.6	2.2	1.8	1.7	1.6	1.8	1.7	2.5	2.4	3.0	2.2	**3.0**	**2.6**	2.3
Reversal deviation at a position	−3.9		**−4.1**		−3.7		−3.9		−3.6		−3.5		−3.5		−3.7		−3.9		−3.6		−3.5	
Bidirectional repeatability at a position, R_i	5.2		5.3		5.2		5.5		5.5		5.2		5.2		5.8		**6.6**		6.2		5.9	

Axis Deviation	Unidirectional, ↓	Unidirectional, ↑	Bidirectional
Reversal deviation, B	Not applicable	Not applicable	4.1 (at $i = 2$)
Mean reversal value, $\bar{B}$	Not applicable	Not applicable	−3.7
Systematic deviation of positioning, $E \downarrow$, $E \uparrow$, E	4.0 [from 3.4 − (−0.60)]	4.0 [from (−0.30) − (−4.3)]	7.7 [from 3.4 − (−4.3)]
Repeatability of positioning, $R \downarrow$, $R \uparrow$, R	2.6 (at $i = 11$)	3.0 (at $i = 10$)	6.6 (at $i = 9$)
Accuracy of positioning, $A \downarrow$, $A \uparrow$, A	5.8 [from 4.0 − (−1.8)]	6.2 [from 0.60 − (−5.6)]	9.6 [from 4.0 − (−5.6)]

GENERAL NOTES:

(a) The down arrows (↓) and up arrows (↑) represent approach direction.

(b) Boldface numbers in main body of table are used in last three rows of four-column portion of table.

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(14) The unidirectional accuracy of positioning of an axis, $A\uparrow$ or $A\downarrow$, is a range derived from the combination of the unidirectional systematic deviation and the estimator of the standard uncertainty of unidirectional positioning using a coverage factor of 2. It is the range of the uncertainty envelope shown in Fig. 7.13 and is calculated as

$$A\uparrow = \text{max. } [\bar{x}_i\uparrow + 2s_i\uparrow] - \text{min. } [\bar{x}_i\uparrow + 2s_i\uparrow] \quad (7\text{-}19)$$

and

$$A\downarrow = \text{max. } [\bar{x}_i\downarrow + 2s_i\downarrow] - \text{min. } [\bar{x}_i\downarrow + 2s_i\downarrow] \quad (7\text{-}20)$$

(15) The bidirectional accuracy of positioning, A, is a range derived from the combination of the bidirectional systematic deviation and the estimator of the standard uncertainty of bidirectional positioning using a coverage factor of 2. It is the total range of the uncertainty envelopes shown in Fig. 7.12 and is calculated as:

$$\begin{aligned} A = {} & \text{max. } [\bar{x}_i\uparrow + 2s_i\uparrow; \bar{x}_i\downarrow + 2s_i\downarrow] \\ & - \text{min. } [\bar{x}_i\uparrow - 2s_i\uparrow; \bar{x}_i\downarrow - 2s_i\downarrow] \end{aligned} \quad (7\text{-}21)$$

7.3.5 Periodic Error

This paragraph addresses the periodic term of the positioning error by selecting a set of closely spaced target points on a small range of the axis motion. The test does not apply to positioning axes.

7.3.5.1 Target Points. A set of at least 20 evenly spaced target points is selected over two periods of the expected periodic error. For a machine with a leadscrew this would be the screw pitch, for a linear scale or angular encoder it is the line spacing, and for laser interferometer scales it is the wavelength of light or a fraction thereof. On rotary tables whose angular position is measured by the position of a worm gear drive, the interval shall at least correspond to two rotations of the worm.

7.3.5.2 Setup and Instrumentation. The setup and instrumentation can be identical to that used for the positioning accuracy test over the full axis range (para. 7.3.2). Because of the small range of motion, the auxiliary rotary table or polygon is often not needed when testing a rotary axis. Periodic angular positioning can also be measured using a displacement indicator. A setup using a micrometer and an appropriate electronic or mechanical indicator with a spherical stylus is shown in Fig. 7.14. At each target point the indicator is re-zeroed using the micrometer. A laser displacement-measuring interferometer, or other long-range displacement indicator, can also be substituted for the micrometer and indicator shown. The angular motion, θ (in radians), is approximately the ratio of the measured displacement divided by the radius, *MR*, as shown in the figure. This approximation is only valid for small angles, and corrections shall be applied if the measured angle exceeds a few degrees.

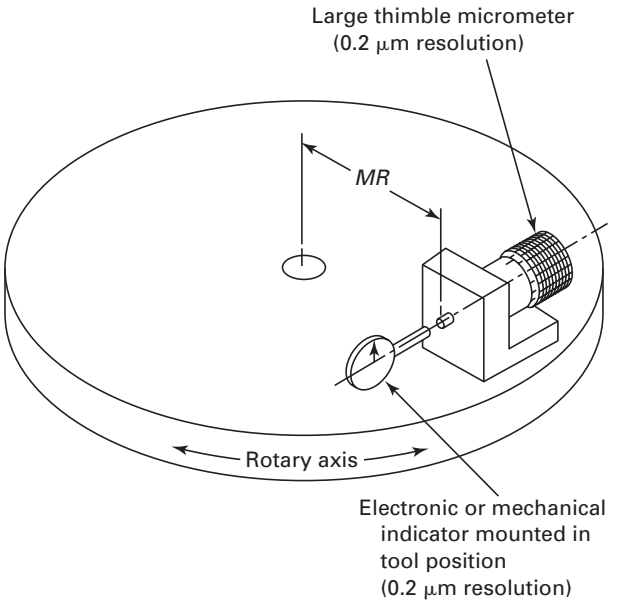


Fig. 7.14 Setup for the Measurement of the Periodic Angular Error With a Displacement Indicator

7.3.5.3 Measurement Procedure. Before commencing measurements, the machine shall be run through an exercise sequence of two back-and-forth movements between the first and last target points. The next five sets of unidirectional measurements are made at all the target positions using the same procedure as for the positioning accuracy test over the full axis range (para. 7.3.3).

7.3.5.4 Data Analysis and Reported Parameters. The calculated deviations shall be plotted as shown in Fig. 7.15. The periodic error, *P*, is the total range of the average of the deviations as shown in the figure. It is computed precisely the same as the unidirectional systematic deviation of positioning, $E\uparrow$, as described in para. 7.3.4; that is,

$$P = \text{max. } [x_j\uparrow] - \text{min. } [x_j\uparrow] \quad (7\text{-}22)$$

7.4 GEOMETRIC ACCURACY TESTS

7.4.1 General

All machine tools are composed of moving carriages, tables, or other elements whose purpose is to change the position of the workpiece with respect to the cutting tool. It is customary to design each element to behave as a rigid body with five of its six degrees of freedom virtually eliminated, and drive that element in the remaining direction while measuring its motion in that direction as accurately as possible. Traditionally, the motion desired is the pure linear or rotary motion leading to linear and rotary machine axes. The measurement

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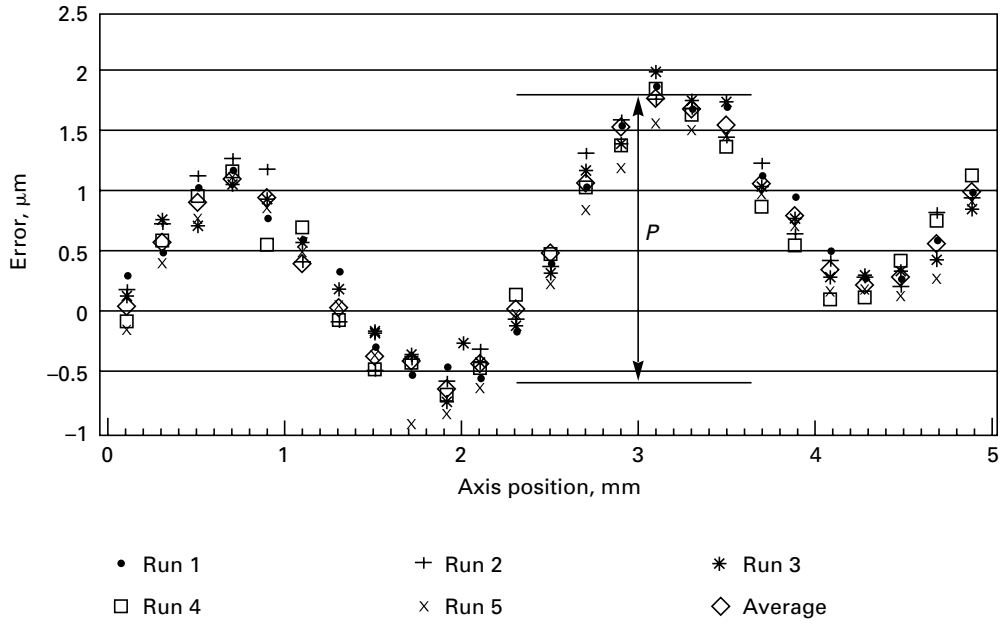


Fig. 7.15 Periodic Error, *P*, of a Linear Axis

of how well the individual machine elements conform to their ideal geometric behavior is the purpose of this section. A typical linear carriage moving in the *X* direction is shown in Fig. 7.16. One can measure six error terms associated with its motion. These measurements are the linear displacement error (positioning accuracy and repeatability) along the intended direction of travel (*X*); two straightness errors, in this case the *Y* straightness of *X* and the *Z* straightness of *X*; and three angular errors, rotations about the *X*-, *Y*-, and *Z*-axes, called roll, pitch and yaw, respectively.[11] Therefore, for a three-axis machine, there are six error terms per axis to measure plus three error terms to define the squareness of the axes with respect to each other, yielding 21 different error terms.

All measurements must be made with respect to the same reference system to measure the relative displacements between the component that holds the tool and the component that holds the workpiece in the appropriate direction with respect to error term of interest. There are many acceptable ways to perform these measurements. It is important that the chosen method be consistent with the above-mentioned principle.

[11] Although the definition of these errors appears straightforward, there are some ambiguities. First, the value obtained for the positioning accuracy and for the straightness errors depends upon the location of the measurement, due to the effects of angular errors and nonrigid body behavior. Furthermore, there are two equally valid definitions and methods for measuring straightness (see para. 4.1), and the choice of which to measure depends on how the data are to be used. Finally, the terms pitch and yaw are ambiguous when dealing with axes that are not in the horizontal direction.

When machines with more than three axes are considered, other geometric interrelationships between multiple axes, such as parallelism and coaxiality of rotary axes, become important to machine function. Such special cases will not be considered here. Some machine tool test codes also require measurement of such parameters as table flatness, alignment of T-slots, etc. Since the effects of such errors can be eliminated by the machine operator following proper procedures, these geometric measurements are not included in this Standard.

7.4.2 Individual Linear Axes

For each individual axis of the machine, six error terms should be measured. For each of the linear error terms, measurements shall be made at at least the same number of points specified for the positioning accuracy and repeatability test defined in para. 7.3.1.

7.4.2.1 Linear Displacement Error. See para. 7.3.

7.4.2.2 Straightness Error. Straightness of a linear axis is measured by positioning a straightedge in the workpiece position, aligned to the motion axis, and measuring the lateral motion in the two directions orthogonal to the traverse direction, using an indicator in the tool position. The best positions for performing the straightness measurement in the machine work zone are those that most commonly reflect the normal position of the workpiece in the work zone.

7.4.2.2.1 Test Procedure. Common methods of straightness measurement use mechanical straightedges, "optical" straightedges, taut wires, geometry

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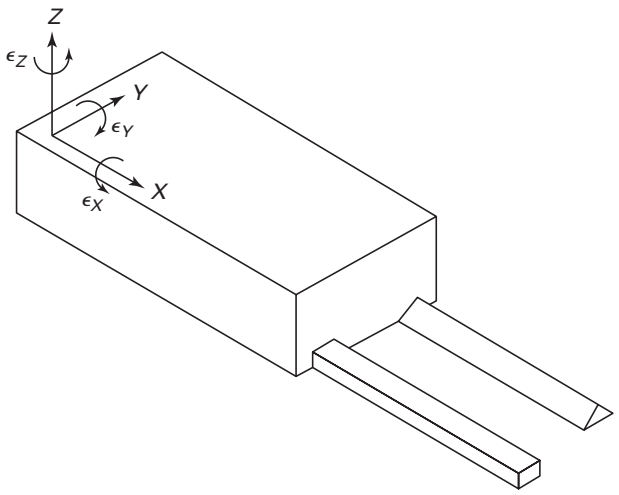


Fig. 7.16 Typical Linear Carriage Designed for Motion in the *X* Direction

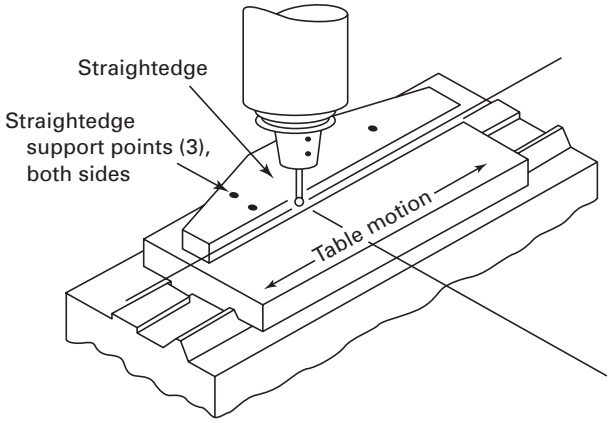


Fig. 7.17 Setup for Measuring Straightness Using an Electronic Indicator and a Mechanical Straightedge

lasers, and laser straightness interferometers.

(a) Mechanical Straightedges. The straightedge is fixtured in the position where a part would be placed during machining and is aligned approximately parallel to an axis motion.[12] The straightness error is measured with a mechanical or electronic indicator or a plane mirror interferometer (if the straightedge has an optical quality reflective surface) mounted in the machine's tool position. This situation is depicted in Fig. 7.17.

WARNING: The calibration chart of the straightedge should be used to determine if its accuracy is adequate enough compared to the straightness specification of the slide under test (see Chapter 11). If the straightedge is not accurate enough, the calibration chart or a technique called straightedge reversal should be used to eliminate the effects of straightedge errors from the measurements (see Appendix L). However, the straightedge reversal technique does not work when measuring the vertical straightness of a horizontal axis when the sag of the straightedge due to gravity is important.

When an interferometer is used as the measurement sensor, the air gap between the interferometer and the straightedge should be kept as small as possible to avoid effects of air turbulence. Since the measurement is differential and the air gap is small, it is usually not necessary to make corrections for errors in laser wavelength due to atmospheric conditions such as temperature and pressure. For the highest measurement accuracy, however, these corrections should be made as described in para. 5.5.2.3.

(b) Taut Wire. Taut wires are often used for measuring the horizontal straightness on large machines. The wire is stretched along the axis direction and measurements of wire position are made with a sensor (proximity sensor or microscope) mounted in the machine spindle. (See Fig. 7.18.)

(c) Geometry Laser. A laser head is mounted in the position where a part would normally be fixtured and the laser beam aligned along the axis of motion as shown in Fig. 7.19. A sensor[13] (either a lateral effect photodiode or a quadrant photodiode) capable of measuring the lateral motion of the spindle from the laser beam is attached in the nominal tool position.

WARNING: When using this method, care must be taken due to "wandering" of the laser beam and to intensity variations over the beam cross-section as a function of distance, which are caused by interference, diffraction, and thermal effects. For best results, averaging should be performed at every point, the air in the laser path should be vigorously mixed using fans, and an adequate number of repetitions should be performed.

(d) Laser Straightness Interferometers. The most commonly used laser straightness interferometers consist of a Wollaston prism and a straightness reflector. The straightness reflector should be mounted in the position where the part will be fixtured and the Wollaston prism should be mounted in the tool position[14] (see Fig. 7.20).

WARNING: The centerline of the straightness reflector can be thought of analogously to the mechanical straightedge. Thus, extreme care must be taken in the fixturing of this reflector,

[12] For large machines, either a very long straightedge is required or the straightedge must be staged. To improve relative alignment between stages, larger overlap of gage positions is required, but this increases the number of gage positions. It is thus difficult and time-consuming to make accurate straightness measurements on a large machine using a short straightedge (cases exist where mechanical straightedges have been used successfully for distances up to 2 m).

[13] Interference filters are often used at the sensor to reduce the effects of changes in ambient illumination.

[14] If, due to the difficulty of setup, the positions of the Wollaston and the straightness reflector are reversed, then the measured parameter is called "lateral deviation." This value can be converted into straightness as defined in this Standard by mathematically combining the effects of the angular motions of the slide at the measurement line to this measured value. Users not familiar with these calculations should avoid such setups.

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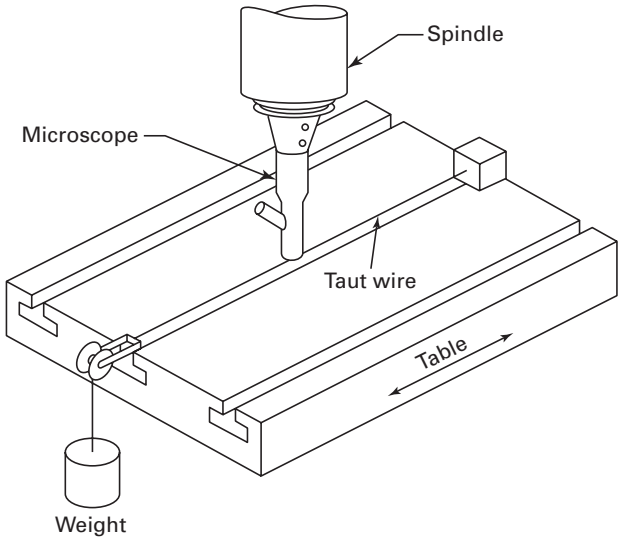


Fig. 7.18 Test Setup for Measuring Straightness Using Taut Wire

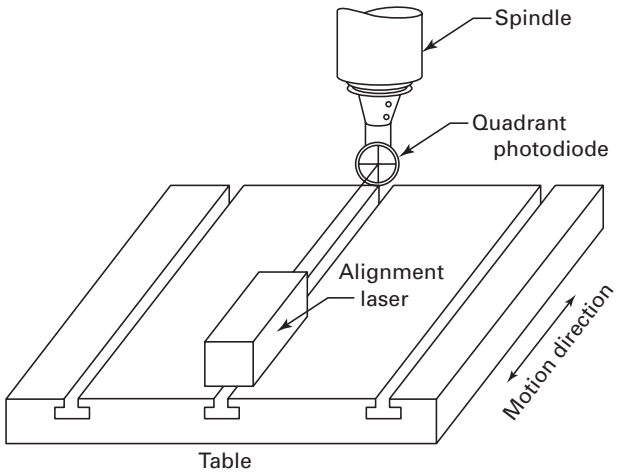


Fig. 7.19 Straightness Setup Showing an Alignment Laser

particularly in situations where table bending is suspect. Any local bending will cause the centerline of the reflector to change its position (see Fig. 7.20), and the result obtained will not reflect the straightness one would obtain on a part fixtured at multiple points over the table surface. This situation can be partially rectified by mounting the reflector to a secondary surface which is kinematically supported over the table.

Laser straightness interferometers, like alignment and geometry lasers, are sensitive to changes in the properties of the air. Mixing and averaging should be used to minimize the effects of these changes.

Flatness errors of the mirrors of the straightness reflector are also sources of measurement errors. Reversing the straightness reflector, as shown in Fig. 7.20, and averaging the results from the two positions is conceptually similar to straightedge reversal and can cancel this error.

(e) Measurement Procedure

(1) Before commencing measurements, the machine shall be run through an exercise sequence of two back-and-forth movements between the first and last target points.

(2) The machine shall be programmed to move the axis under test, and to position it at a series of target positions.

(3) At a target position, the data can be recorded with the machine stationary or during continuous motion. The target positions are required over the full travel range of the axis. The measuring intervals shall be no larger than 25 mm for axes of 250 mm or less. For longer axes, the interval shall be no more than $^{1}/_{10}$ of the axis length.

(4) Five sets of bidirectional measurements are made at all the target positions. The default traverse speed shall be the machine's maximum programmable feed rate. Other feed rates may be negotiated between User and Supplier. A set of measurements shall consist of the target positions and the corresponding instrument readings.

7.4.2.2.2 Data Analysis. For each set of bidirectional measurements, the best-fit line corresponding to the data is drawn or determined by software using the least-squares method. For the purposes of this Standard, the minimum distance between the two lines parallel to this least-squares best-fit line that are enveloping the straightness data will be considered the straightness value for that measurement. The average and the standard uncertainty of the five straightness values calculated as such are reported as the straightness error of the axis. Straightness errors should also be plotted.

7.4.2.3 Angular Error. For each linear axis, three angular errors about the *X*-, *Y*-, and *Z*-axes, commonly called roll, pitch, and yaw, should be measured.

7.4.2.3.1 Test Procedure. The common methods of angular error measurement use (1) laser angular interferometers or autocollimators to measure pitch and yaw of an axis (rotations about axes orthogonal to the direction of axis motion), and (2) differential levels to measure the roll (rotation about the axis of linear motion) of horizontal axes. Differential straightness measurements are used to assess the roll of vertical axes. Differential levels may also be used for measuring the pitch of horizontal axes and the yaw and pitch of vertical axes. Geometry lasers are also capable of measuring angular errors.

(a) Laser Angle Interferometer. The laser angle interferometer is used for measuring rotations about the axes perpendicular to the axis of motion (i.e., pitch and yaw).

A typical setup using the laser angle interferometer is shown in Fig. 7.21, where the pitch of a horizontal

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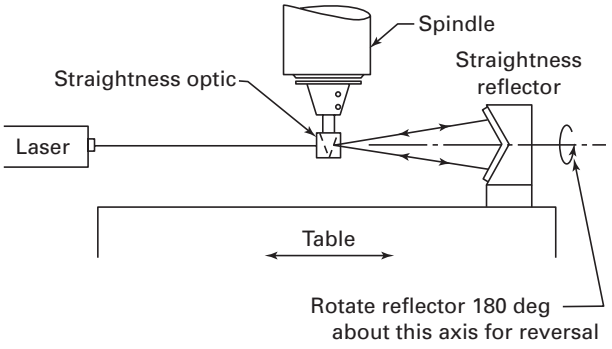


Fig. 7.20 Typical Straightness Interferometer of the Most Common Type

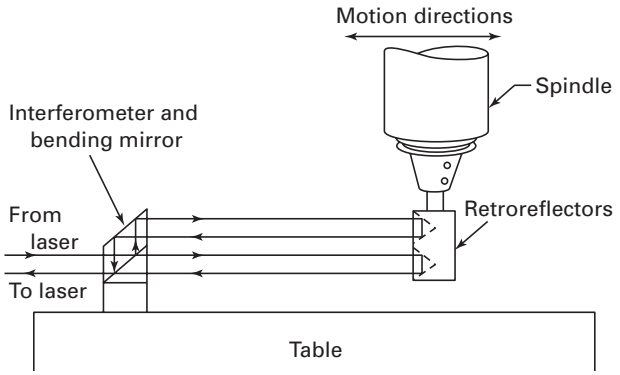


Fig. 7.21 An Angular Interferometer Setup to Measure Pitch on a Machine Where the Spindle Moves Relative to the Table

axis is being measured. In this figure the spindle is being moved relative to a fixed table. The position of the retroreflector pair and the interferometer[15] should be reversed if the table is the moving element.

WARNING: The angular interferometer, like a straightness interferometer, is extremely sensitive to local bending of the table. If the table is bent as a function of spindle motion, then the measured pitch will be greatly different than the average pitch of the spindle with respect to the table. Therefore, when bending is suspected, care should be taken in mounting the interferometer in order to obtain average results.

For yaw measurements, the retroreflector and interferometer should be rotated 90 deg about the beam axis.

On machines where the spindle cannot be locked, external brackets should be used to fixture either the retroreflector or the interferometer in the spindle to prevent instability.

(b) Autocollimator. Angular error measurement setup with an autocollimator is conceptually identical to that with a laser interferometer. The interferometer is replaced by the autocollimator and the retroreflector by an accurate, flat mirror of appropriate size.

WARNING: Autocollimators are sensitive to refraction in the air and thus fans and averaging are the accepted method for reducing these effects.

(c) Differential Levels. Differential levels can be used for measuring roll and pitch of horizontal axes and yaw and pitch of vertical axes, as shown in Fig. 7.22. One level is placed in the part position and a second measuring level in a fixture attached to the machine spindle. The readout device is set to display the difference between the two readings of the levels.

Differential levels are required, since most machines exhibit some tilt with respect to gravity as their axes are moved, and this tilt has no effect on the relative position between tool and workpiece so must be removed from the measurement results.

WARNING: When using differential levels on machines that have large tilts with respect to gravity, care must be taken that both levels are properly calibrated[16] (see Chapter 11) and that their weight does not affect the measurement result.

(d) Differential Straightness Measurements. This measurement is performed by carrying out two parallel sets of straightness measurements. The principle is illustrated in Fig. 7.23, which shows the setup for measuring the roll of a vertical axis using a mechanical square and one or two electronic indicators. Different straightness-measuring instruments may be substituted.

The instrumentation is set to measure straightness perpendicular to the line of motion of the carriage. The carriage is moved along its axis normal to the direction of the straightness measurement and straightness data are recorded. The indicator is next mounted on an extension and the straightness is remeasured, being careful to follow the same measurement line along the straightedge. The roll in any particular vertical position is the difference between the two measured straightness values at that position divided by the distance between the two spindle positions.

[15] If the interferometer and bending mirror are assembled by the User, a great deal of care must be taken to assure that the beams are parallel. Nonparallelism can lead to large errors.

[16] The level calibration is particularly important on machines that have large tilts with respect to gravity, where errors in the calibration of the individual levels may be significant compared with the differential angular error being measured. In all cases they should be checked by placing the levels side by side and inducing a controlled tilt to assure that there is no difference. In highest accuracy calibrations, the levels should be reversed and two runs made, with the levels interchanged between runs and the results averaged. Like straightedges, levels also can be compared to themselves by a 180-deg rotation. For the most accurate calibration, both reversals should be performed; that is, reversal of the level position and 180-deg reversal of each level at each position, which would yield four complete sets of data for each measurement run on each axis. Averaging of these results will reduce many of these effects.

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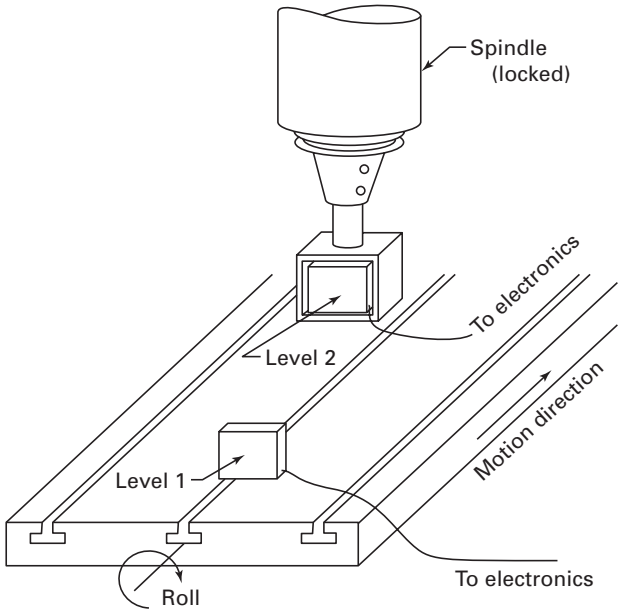


Fig. 7.22 Typical Setup Showing Differential Levels to Measure the Roll of a Horizontal Axis

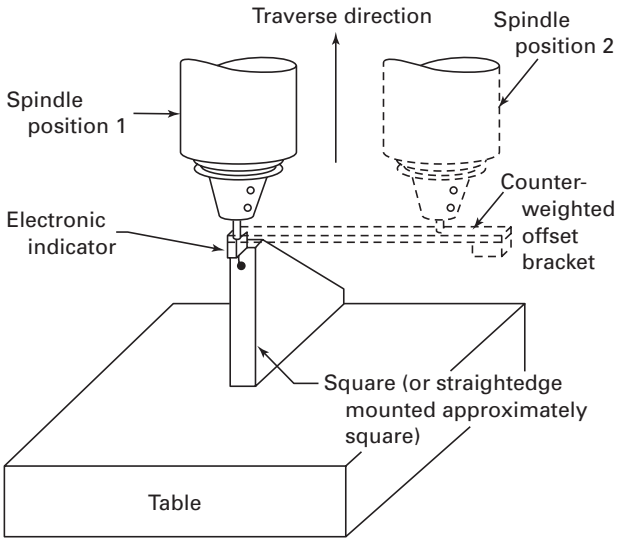


Fig. 7.23 Differential Straightness Measurement Used to Measure the Roll of a Vertical Axis

WARNING: Because one carriage has to be moved to accommodate the extension fixture (either table or spindle) in a direction other than the vertical during this measurement procedure, the roll measurement of the vertical axis must be corrected for the change in angular orientation of the table or spindle caused by this motion. The effect of this angular orientation is illustrated in Fig. 7.24.

(e) Measurement Procedure. This is similar to the procedure for straightness errors; see para. 7.4.2.2.1.

7.4.2.3.2 Data Analysis. The data shall be analyzed and reported as given in para. 7.3.4, except that the names of the parameters shall be as follows:

(a) bidirectional systematic angular error, E_{ae}

(b) bidirectional total angular error, A_{ae}

(c) unidirectional systematic angular error, $E_{ae}\uparrow$ and $E_{ae}\downarrow$

(d) unidirectional total angular error, $A_{ae}\uparrow$ and $A_{ae}\downarrow$

(e) bidirectional repeatability of angular error, R_{ae}

(f) unidirectional repeatabilities of angular error, $R_{ae}\uparrow$ and $R_{ae}\downarrow$

(g) reversal deviation of angular error, B_{ae}

7.4.3 Individual Rotary Axes

The six error terms to be measured for each rotary axis are the

(a) angular displacement accuracy and repeatability

(b) axial and radial motion in two orthogonal directions

(c) two tilt motions

The measurement of angular displacement accuracy and repeatability is described in para. 7.3. The measurement of axial and radial errors and the tilt errors are covered in para. 7.5.

Each of these errors should be measured using the procedure (the number of points with the number of repetitions and directions of approach) specified for the displacement accuracy (see para. 7.3.1).

7.4.4 Interrelationships Between Axes

Depending upon the machine configuration, the measurement of alignment between machine axes can be quite complex. This Standard provides only general comments for the most commonly encountered cases. Users requiring different measurement procedures shall make such procedures a part of the machine specification.

7.4.4.1 Squareness Between Linear Axes. Squareness is measured with a variety of instruments as described below. The procedure is similar in all these cases. Two nominally square reference lines are established in the middle of the work zone where possible, each nominally parallel to one of the axes whose squareness to each other is to be measured. For each axis in turn, the machine is traversed along its motion axis and the lateral motion between the nominal tool point and the reference surface is measured in a direction orthogonal to the traverse direction using an indicator in the tool position.

7.4.4.1.1 Test Procedure

(a) Mechanical Square. The square is placed in such a way that its reference surfaces are nominally aligned with the two axes whose squareness is to be measured. A mechanical indicator is used to trace the reference

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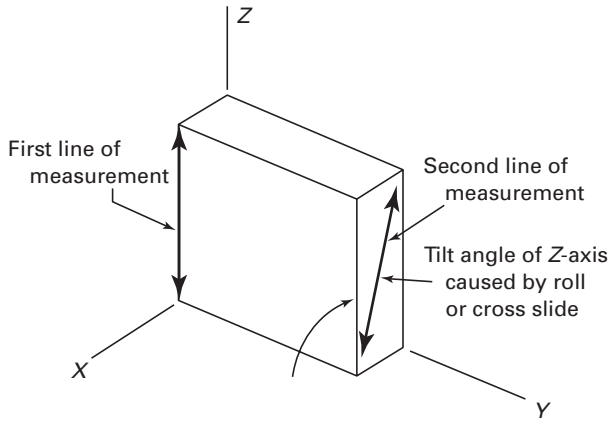


Fig. 7.24 Diagram Showing the Effect of Cross-Axial Roll on the Measurement of Roll of a Vertical Axis Using Differential Straightness

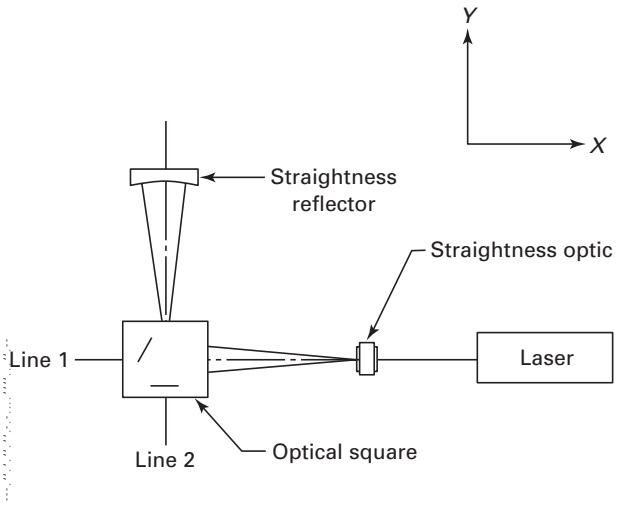


Fig. 7.25 Setup for Measuring Squareness With an Optical Square and a Straightness Interferometer: Line 1

surfaces of the square along the axes of travel.

(b) Straightedge and an Indexing Table.[17] The straightedge is mounted to an indexing table, which is rigidly attached to the table of the machine. The straightedge is aligned initially along one machine axis and this reference surface is measured as in para. 7.4.2.2. The table is then indexed 90 deg and the measurement repeated for the second axis. Either a mechanical or optical straightedge may be used.

(c) Optical Square and Straightness Interferometer. The measurements may be performed in at least two ways. In the first method, the straightness of the first axis (labeled 1 in Fig. 7.25) is measured by aligning the laser

[17] The indexing table should meet the accuracy requirements specified in Chapter 11.

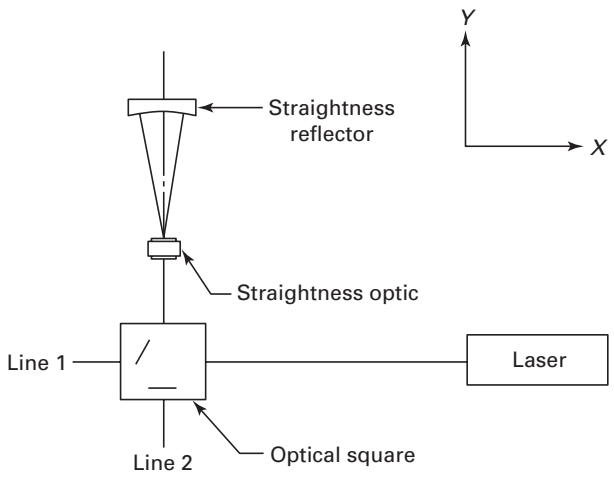


Fig. 7.26 Setup for Measuring Squareness With an Optical Square and a Straightness Interferometer: Line 2

to the straightness reflector through the optical square. Next the straightness optics are moved and the straightness of line 2 is measured (see Fig. 7.26) without moving the optical square, straightness reflector, or laser. In the second method, the straightness of the first axis is measured, as previously. The optical square is then removed, and the laser is realigned with the straightness reflector by moving the laser only. The straightness reflector must not be moved during this procedure.

7.4.4.1.2 Data Analysis. The measurements obtained are first plotted as shown in Fig. 7.27. Lines through the measured data are obtained by a least-squares fit.

The slopes of these lines are calculated. These slopes are the angular deviations between the traverse line and the reference line for each axis.

Depending upon the sign convention chosen for the measurement, these two angles should be either subtracted or added to determine the initial out-of-squareness. For the purposes of this Standard, positive squareness will indicate greater than 90 deg, and the negative squareness will indicate less than 90 deg.

Next the correction for the out-of-squareness of the reference square should be applied. This must be determined from the calibration certificate of a mechanical square[18] or the indexing table.

The locations of reference lines within the work zone must be reported along with the calculated squareness value.

WARNING: Since there is no established convention for the sign of the out-of-squareness of a reference square, careful attention should be given in applying this correction.

[18] A form of reversal technique can be used to calibrate a mechanical square in situ and optical squares can also be calibrated by reversal.

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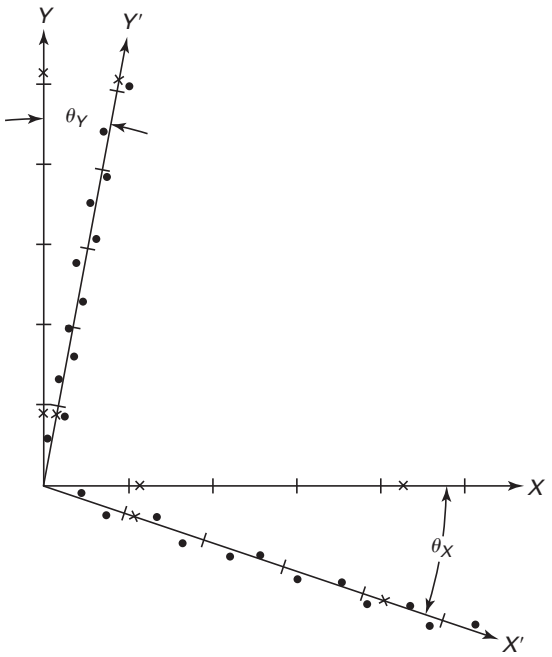


Fig. 7.27 Conceptual Diagram Showing the Angles Obtained in a Squareness Measurement

7.4.4.2 Parallelism Between Linear Axes. It is often necessary to measure parallelism between linear axes where there are more than the traditional three linear axes. For example, parallelism may be checked between the *Z*- and *W*-axes on a machining center, where the *W* is an extending spindle.

7.4.4.2.1 Test Procedure. This test is performed by using any straightness measurement device. Straightness of each axis is measured using the procedure described in para. 7.4.2.2.1.

7.4.4.2.2 Data Analysis. The parallelism between two linear axes shall be calculated and reported for two orthogonal planes. For each plane, the least-squares best-fit lines of their respective straightness data should be compared to a common reference line (e.g., laser beam, plane, etc.). The slope of the best-fit line is the angular deviation between the traverse line and the reference line for each axis. The basic analysis is to compare the angular deviation of the slope of the best-fit data line for the *Z*-axis from the *Z* reference to the angular deviation of the best-fit slope line of the *W*-axis from the same *Z* reference. The deviation can be expressed in millimeters per meter or arcseconds. This is depicted in Fig. 7.28. More specifically, the analysis is as follows:

The parallelism of the *Z*-axis to the *W*-axis, Parallelism_{ZW}, is defined by

$$\text{Parallelism}_{ZW} = \theta_Z - \theta_W \qquad (7\text{-}23)$$

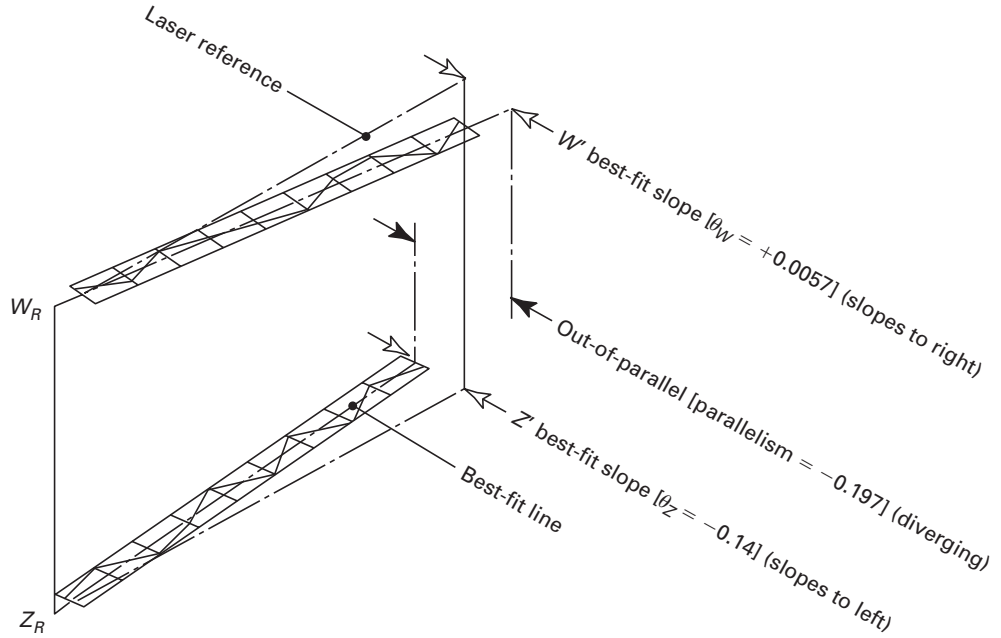
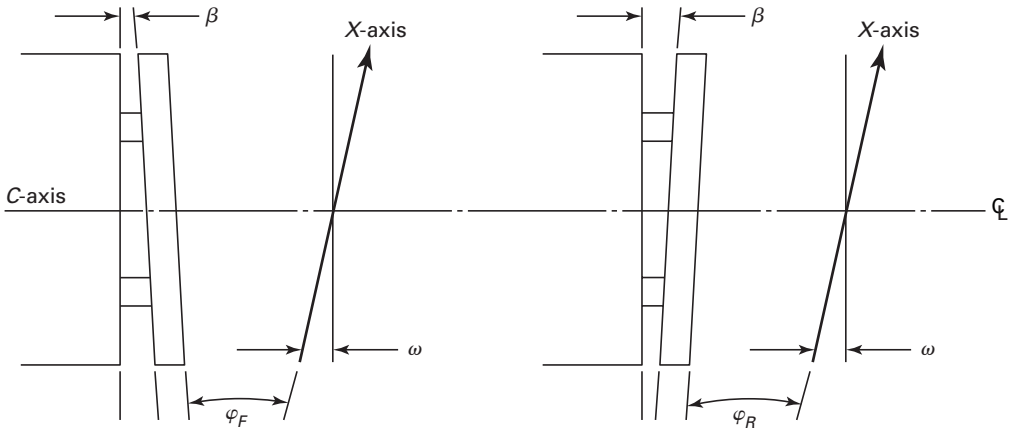


Fig. 7.28 Analysis of Parallelism Between Two Linear Axes (Parallelism Is Calculated From the Differences in Best-Fit Slopes of Each Profile)

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(a) Forward, $\theta = 0$ deg (b) Reverse, $\theta = 180$ deg

Fig. 7.29 Measurement of Rotary Axis Squareness Using a Mechanical or Optical Straightedge

where

W' = least-squares best-fit line to the straightness data for the W-axis
Z' = least-squares best-fit line to the straightness data for the Z-axis
Z_R = reference line for the Z-axis
θ_W = angular deviation of W' from Z_R, expressed in millimeters per meter or seconds
θ_Z = angular deviation of Z' from Z_R, expressed in millimeters per meter or seconds

7.4.4.3 Alignment Between a Linear Axis and the Axis of Rotation of a Rotary Axis or a Machine Spindle. The relationship between the axis of rotation of a rotary axis or machine spindle and a linear axis is conceptually determined by first establishing a reference line corresponding to the axis of rotation. Then the motion of the linear axis is measured against this reference line. The axis of rotation reference line in the plane of measurement (plane containing both the axis of rotation and the linear axis) is determined by averaging straightness measurements at two positions of the rotary axis that are 180 deg apart over the 180-deg rotation of the axis. To indirectly represent the axis of rotation reference, sometimes a reference line perpendicular to the axis of rotation can be established. Mechanical artifacts or optical methods can be used to generate these axis of rotation reference lines. The following equipment-specific test setups are for examples only; any other instrument providing comparable results can be used instead.

7.4.4.3.1 Measurement of Squareness Using a Mechanical Straightedge. A typical setup for such a measurement is shown in Fig. 7.29.

The straightedge is mounted so as to straddle the rotary axis center, and the change in separation between the gaging surface of the straightedge and an appropriate machine axis, called X in the figure, is measured either optically or mechanically. A least-squares fit to the data yields a line whose slope is equal to the angle between the X-axis and the straightedge gaging surface.

Next the rotary axis is rotated 180 deg and a similar measurement performed. In the figure we depict an arbitrary "forward direction" with the rotary axis at zero angle, and the "reverse direction" with the rotary axis rotated 180 deg.

The angle, β, in the figure is the squareness error between the straightedge and the rotary table axis resulting from supporting fixtures, while the angle, ω, is the desired squareness error. We denote the measured angles and the respective orientations by φ_F and φ_R. Examination of the figure yields the relationship $\omega = \frac{1}{2}(\varphi_F + \varphi_R)$.

By performing these measurements again, beginning with the first measurement at 90 deg with respect to the first measurement in the initial step, squareness with an orthogonal linear axis can be determined.

7.4.4.3.2 Measurement of Parallelism Using a Straightness Interferometer. The setup for such a measurement is shown in Fig. 7.30. The measurement is conceptually similar to the squareness measurement discussed above.

A straightness reflector is mounted to the table and aligned so that its measurement axis is close to the table's axis of rotation. Straightness measurement is made with the straightness reflector in one position and then rotated 180 deg in the other direction. The actual angle deviation is one-half the algebraic sum of the slopes measured in the two orientations. Again, by changing the phase of this measurement 90 deg the parallelism in the other plane may also be obtained. This procedure

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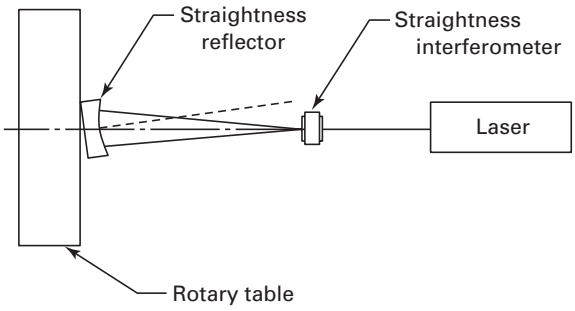


Fig. 7.30 Measurement of Rotary Axis Squareness (or Parallelism) Using a Straightness Interferometer

can also be performed with a mechanical straightedge.

7.4.4.3.3 Measurement of Parallelism Using Mechanical Artifacts. The parallelism between a rotary axis and a linear axis may also be measured with a simple mechanical setup using an indicator and a precision test ball as shown in Fig. 7.31 for a vertically oriented rotary axis.

The precision test ball is mounted on the linear axis and the indicator mounted to the table. The position of the ball is moved using the machine's controls, while the table with the indicator reading against the ball is rotated in order to center the ball along the table axis of rotation close to the table surface. This position is recorded.

Next the ball is moved to a height, h, above the table and the indicator re-bracketed to read against the test ball. The procedure of centering the test ball is repeated.

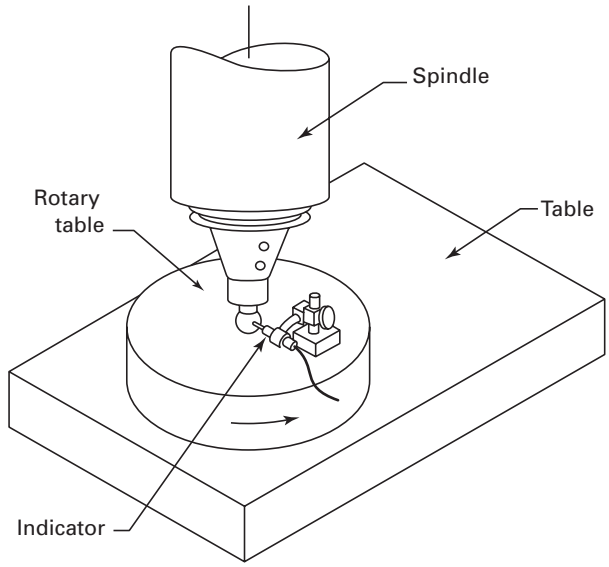
The angles of the rotary axis with respect to the linear axis are computed by dividing the differences between the coordinates obtained by centering the ball in the first and the second positions by the height difference between the two setups. Two angles can be obtained simultaneously.

The parallelism of the axis of rotation of a machine spindle to a linear axis can be measured by inserting a precision test mandrel into the machine spindle taper or collet. A mechanical or electronic indicator is mounted to the linear axis to contact the side of the test mandrel.

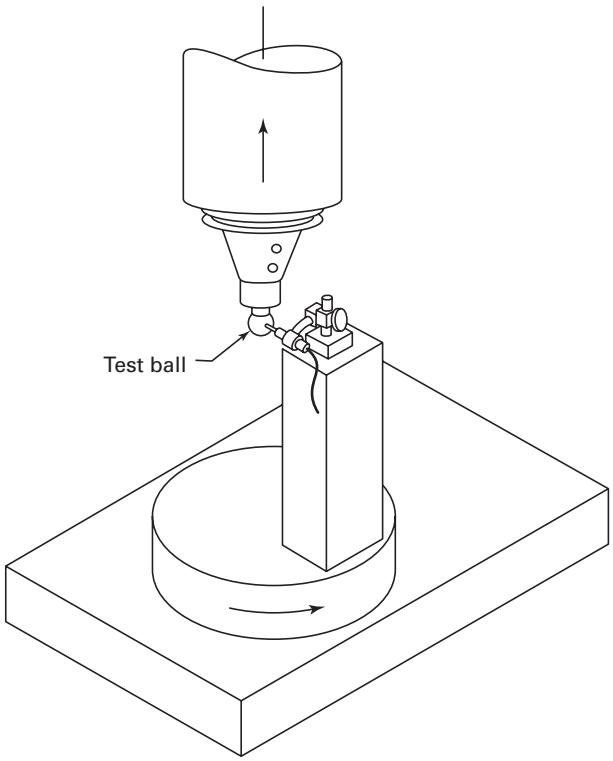
Indicator readings are recorded while traversing the linear axis along the length of the mandrel.

By rotating the machine spindle with mandrel 180 deg and recording a second set of readings, the misalignment of the test mandrel to the machine spindle can be eliminated by calculation similar to the straightedge method described in para. 7.4.4.3.1.

By performing these measurements again with the indicator contacting the test mandrel at 90 deg with respect to the first set of measurements, the spindle parallelism in the orthogonal direction can be determined.



(a) First Position



(b) Second Position

Fig. 7.31 Measurement of Parallelism of the *Z*-Axis With a Rotary Table

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7.4.4.3.4 Data Analysis. The squareness data shall be analyzed and reported according to para. 7.4.4.1.2. The parallelism data shall be analyzed and reported according to para. 7.4.4.2.2.

7.5 SPINDLE AXIS OF ROTATION

7.5.1 General

The general problem of the specifying and testing of axes of rotation is thoroughly treated in ASME B89.3.4M. This Standard defines a minimum set of tests necessary for ensuring spindle performance. Only the case of rotating sensitive direction will be treated (see para. 4.1).

For axes of rotation, the general term, *error motion,* will be used herein to refer to the relative displacement in the sensitive direction between the tool (or gage head) and the workpiece. Error motions in the sensitive direction cause one-for-one form errors to be cut into the workpiece and thus are most significant for machine-tool performance characterization. Error motions perpendicular to the sensitive direction are considered to be in the nonsensitive direction and are not evaluated. The measurements required by this Standard include

(a) structural motion with the spindle off

(b) average and asynchronous error motions for rotating sensitive direction

(c) average and asynchronous tilt error motions for rotating sensitive direction

(d) total axial error motion

Optional measurements include static error motion (see Appendix O).

7.5.2 Structural Motion, Spindle Off

7.5.2.1 General. Before commencing spindle error testing, assessing structural motions of the machine with the spindle off is required. These tests are designed to point out relative motion between the spindle and the workpiece, which is caused by the machine itself, and the environment. The structural motion value is the peak-to-valley displacement observed over a relatively short time period (such as 1 sec).

7.5.2.2 Test Procedure

7.5.2.2.1 Equipment

(a) spindle analyzer or oscilloscope

(b) artifact

(c) displacement sensors (2, 3, or 5)

7.5.2.2.2 Measurement Procedure. The test setup is the same as for the ETVE test described in para. 6.2.2.

(a) First, measure structural motion with the machine's power and auxiliary systems, such as hydraulics, turned on, but with the machine drives off (i.e., the emergency stop position).

(b) Second, measure the structural motion with the machine's power, auxiliary systems, and machine drives on (i.e, with the machine in the feed-hold mode).

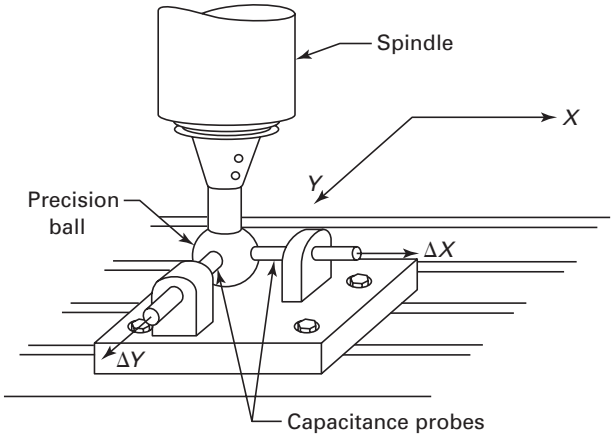


Fig. 7.32 Schematic of the Test Setup for Radial Error Motion With a Rotating Sensitive Direction

7.5.2.3 Data Analysis. If the structural motion in either condition exceeds 25% of the specification zone for unidirectional repeatability (see para. 7.3.4) and the User has met the Supplier's guidelines regarding vibration and environment (para. 5.3), the Supplier shall be responsible for rectifying the situation.

7.5.3 Spindle Tests, Rotating Sensitive Direction

7.5.3.1 Radial Error Motion

7.5.3.1.1 General. The radial error motion shall be measured by computing and displaying the error motion polar plot according to the following formula:

$$r(\theta) = r_0 + \Delta X(\theta) \cos \theta + \Delta Y(\theta) \sin \theta \qquad (7\text{-}24)$$

where

r_0 = value of the offset of the center of the test ball relative to the center of rotation

$\Delta X(\theta)$ = output of the gage oriented with the X-axis

$\Delta Y(\theta)$ = output of the gage oriented with the Y-axis

θ = angle of rotation of the spindle

7.5.3.1.2 Test Procedure. Figure 7.32 schematically represents a test setup for the measurement of the spindle error motions for the case of rotating sensitive direction. In this setup, a precision test ball or other suitable artifact such as a cylinder is mounted in the machine spindle. Indicators are mounted to the table of the machine in orthogonal orientations. The ball may be centered on the axis of rotation to minimize eccentricity, in which case a signal proportional to the spindle rotation angle is required. The ball may be mounted slightly eccentrically, and this eccentricity is used to generate the signals necessary for a polar plot. The setup for this latter case is shown in Fig. 7.33, and both cases are described in detail in ASME B89.3.4M.

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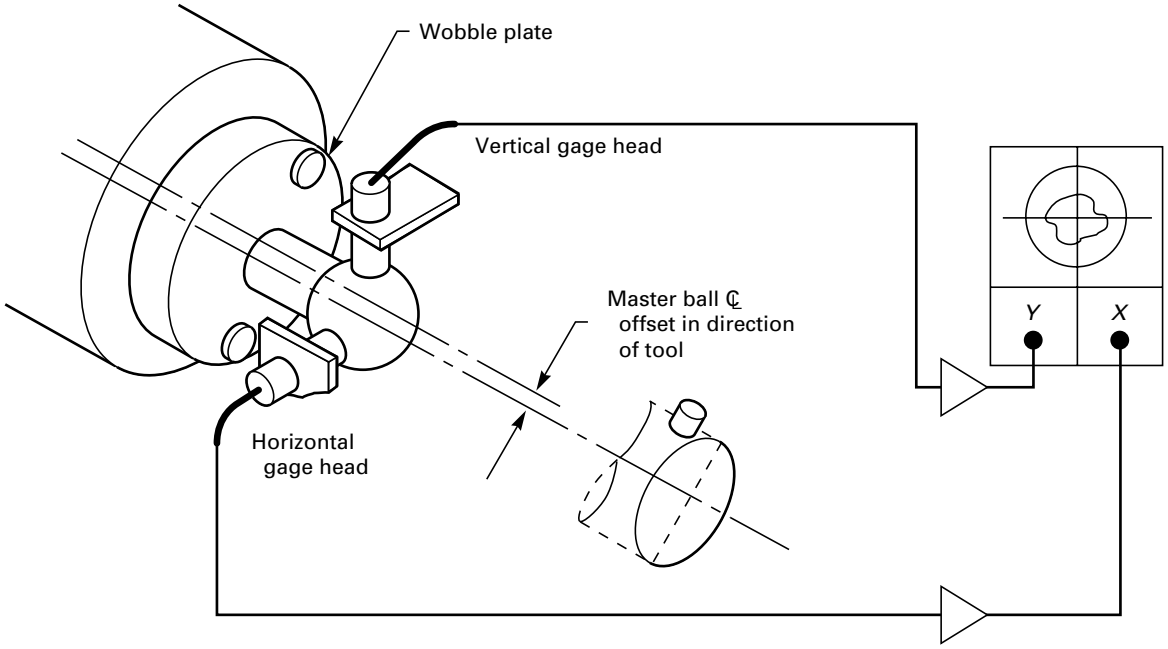


Fig. 7.33 Test Method for Radial Motion With a Rotating Sensitive Direction and the Ball Mounted Eccentric to the Spindle

7.5.3.1.2.1 Equipment. The equipment includes a spindle analyzer, or oscilloscope with indicators of the noncontacting type, such as capacitance, with a bandwidth sufficient to cover the revolutions per minute range specified. The bandwidth required depends upon the number of undulations per revolution that one desires to resolve and the revolutions per minute range of the spindle. For most machining centers, a bandwidth of 10 kHz is acceptable for rotational speeds of up to 6,000 rpm and scaling of this value can be used for other spindle speeds. The displacement indicator and test artifact should meet the specifications outlined in Chapter 11. For more detailed descriptions and background, see ASME B89.3.4M.

7.5.3.1.2.2 Machine Warm-Up. Radial error motion measurements shall be carried out at three spindle speeds after the spindle has been allowed to warm up at half of the maximum speed for a minimum of 10 min or after performing the short-term thermal stability test.

7.5.3.1.2.3 Measurement Procedure

(a) Rotate spindle at 10% of maximum speed and record measured average radial error motion and asynchronous radial error motion.

(b) Rotate spindle at 50% of maximum speed and record measured average radial error motion and asynchronous radial error motion.

(c) Rotate spindle at 100% of maximum speed and record measured average radial error motion and asynchronous radial error motion.

7.5.3.1.3 Data Analysis. At each speed a polar plot of the spindle error motion shall be made for a minimum of 20 revolutions. A typical plot for a single spindle speed is shown in Fig. 7.34. For the purposes of this Standard, only two error-motion values will be computed from the error motion plot. The asynchronous error motion value shall be the maximum scaled width of the total error motion polar plot (before averaging), measured along a radial line through the polar chart center, as shown in Fig. 7.34. Next, the average error motion polar plot shall be computed by averaging the total error motion polar plot results for the total number of revolutions. A typical average error motion polar plot is shown as the dark line in the figure. The average radial error motion value is the scaled difference in radii of two concentric circles, centered at the LSC center, just sufficient to contain the average error motion polar plot.

7.5.3.2 Tilt Error Motion

7.5.3.2.1 General. Measurement of the tilt error motion requires simultaneous measurement of the radial error motion at two spatially separated points, as shown in Fig. 7.35, using radial displacement indicators 1 and 4, and also 2 and 5 (test method 2). A commercial spindle error analyzer can be used for this purpose, or a test fixture with two balls with their centers spaced some distance apart (50 mm is adequate; or a precision test mandrel or other artifact) may be attached to the spindle nose and aligned with high precision to the axis of spindle rotation, in order to minimize eccentricity. As stated previously, the balls (or mandrel, or any master in the

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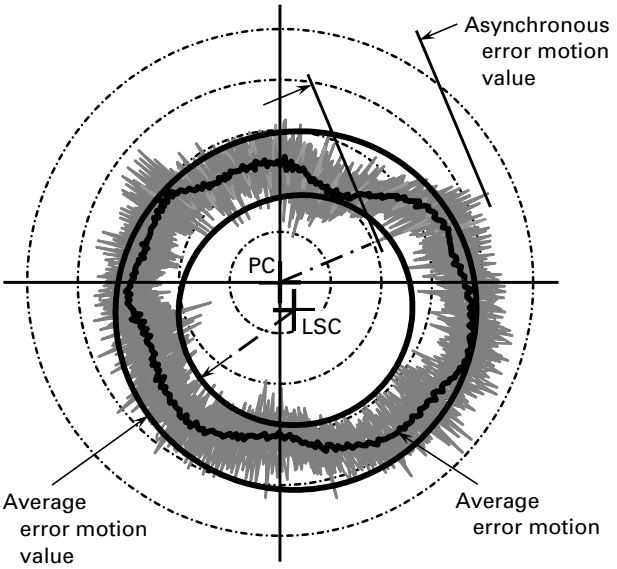


Fig. 7.34 Typical Total Error Motion Polar Plot Showing Asynchronous Error Motion and Average Error Motion Value as Utilized in This Standard

commercial system) shall have a roundness such that any error in their form is less than the value of error expected in the machine (see Chapter 11). Otherwise, procedures taken from ASME B89.3.4M should be used to extract artifact out-of-roundness of the artifact from the measurement.

Two methods are discussed for measuring tilt error motion. Method 1 describes the use of two indicators and method 2 describes using four indicators for measuring tilt. Both procedures are acceptable methods of measuring average tilt error motion.

7.5.3.2.2 Test Procedure Method 1

(a) First a test ball or other artifact and displacement indicators are fixtured as shown in Fig. 7.32, and the average radial error motion and the asynchronous radial error motion are measured.

(b) Rotate the spindle at 10% of maximum speed and measure the average radial error motion and the asynchronous radial error motion.

(c) Rotate the spindle at 50% of maximum speed and measure the average radial error motion and the asynchronous radial error motion.

(d) Rotate the spindle at 100% of maximum speed and measure the average radial error motion and the asynchronous radial error motion.

(e) Next, refixture the ball or other artifact a distance of at least 50 mm (approximately 2 in.) from the previous position and a second set of measurements is taken at 10%, 50%, and 100% of maximum speed. Note that both sets of measurements before and after refixture of the artifact should be performed at the same spindle angles (phase lock using marker or spindle encoder).

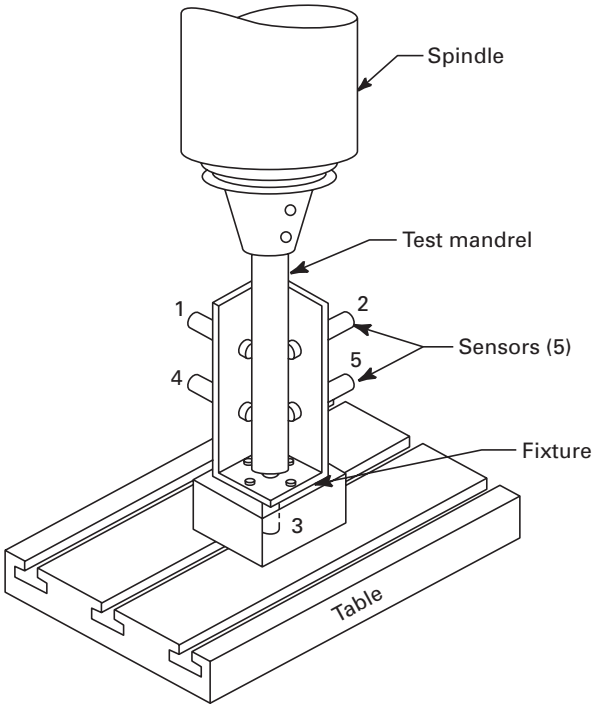


Fig. 7.35 Five-Sensor Test System for Tilt Error Motion Test on a Machining Center

7.5.3.2.3 Data Analysis Method 1.

For each spindle speed, the average tilt error motion polar plot is constructed as the difference between the average error motion polar plots obtained at different tool offsets, divided by the distance between the two measurements (nominally 50 mm). The average tilt error motion value, calculated in radians,[19] is the scaled difference in radii of two concentric circles centered at the LSC center just sufficient to contain the average tilt error motion polar plot. This method is not reliable to assess the asynchronous tilt motion error.

7.5.3.2.4 Test Procedure Method 2

(a) First a test ball or other artifact and displacement indicators are fixtured as shown in Fig. 7.35, and the average radial error motion and the asynchronous radial error motion are measured.

(b) Rotate the spindle at 10% of maximum speed and calculate the average and asynchronous tilt error motions as described below.

(c) Rotate the spindle at 50% of maximum speed and calculate the average and asynchronous tilt error motions as described below.

(d) Rotate the spindle at 100% of maximum speed and calculate the average and asynchronous tilt error motions as described below.

[19] Note that in performance forms (para. 1.2), the spindle tilt error motion is presented in the unit of seconds. One second is approximately equal to 5×10^{-6} radians.

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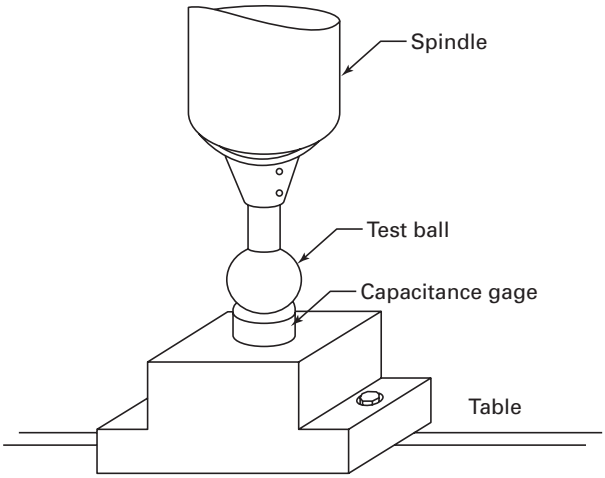


Fig. 7.36 Setup for Axial Error Motion Measurement for Rotating Sensitive Direction

7.5.3.2.5 Data Analysis Method 2. The differences between the outputs of sensors 1 and 4 and sensors 2 and 5 are used as the ΔX and ΔY in the equation and r_0 is set equal to zero (note that sensor number 3 is not required). The average tilt motion, in radians,[19] is obtained by dividing the average error by the distance between the sensors in the test setup. A polar plot is constructed and analyzed as in para. 7.5.3.1.3. The asynchronous error motion, in radians, is obtained by dividing the asynchronous error by the distance between the sensors in the test setup.

7.5.3.3 Axial Error Motion

7.5.3.3.1 General. To measure axial error, synchronization to the spindle angular position and sophisticated data analysis are not required. The measurement can be done with an oscilloscope. This test is optional, since for many applications, such as boring, axial motion is in the nonsensitive direction. For certain other applications, such as contour milling, fly cutting, and die sinking, however, it can contribute significantly to machining error and degradation of surface finish. For these applications it is strongly recommended that these tests be performed.

NOTE: Fundamental, residual, average, and asynchronous axial error motions are described in ASME B89.3.4M.

7.5.3.3.2 Test Procedure

7.5.3.3.2.1 Equipment

(a) spindle analyzer or oscilloscope
(b) artifact
(c) displacement probe

7.5.3.3.2.2 Measurement Procedure

(a) Position capacitance gage as indicated in the axial position as shown in Fig. 7.36.

(b) Rotate the spindle at 10%, 50%, and 100% of maximum speed and record the total axial motion.

7.5.3.3.3 Data Analysis. At each speed, the maximum range of the displacement over approximately 20 revolutions of the spindle shall be used as a measurement of total axial error motion.

7.6 MACHINE THERMAL TESTS

7.6.1 General

For the thermal tests described in this paragraph, the machine shall be powered up with auxiliary services operating and axis in the "feed-hold" position, with no spindle rotation, for a period sufficient to stabilize the effects of internal sources. The machine and measuring instrument shall be protected from drafts and external radiation such as that from overhead heaters or sunlight. If the machine is equipped with an enclosure and the machine will be operated with this enclosure closed, then these thermal tests shall be done in this configuration.

All tests shall be carried out with the machine in the unloaded condition. In all cases, the tests shall be between a nominal workpiece location and a nominal tool location. If any compensation capability or facilities for minimizing thermal effects, such as air or oil showers, are available on the machine tool, they shall be used during the tests and their existence recorded.

All measuring instruments described in this paragraph must conform to instrumentation and test equipment requirements given in Chapter 11 and also be "cap" tested according to the procedures outlined in Appendix I. The results of the cap test on the instrument should be no greater than 10% of the expected range of deviations during the test. Otherwise, the instrument should be modified or replaced.

7.6.2 Spindle Thermal Stability Test

This test is carried out to identify the effects of the internal heat generated by rotation of the spindle and the resultant temperature gradients on the distortion of the machine structure observed between the workpiece and the cutting tool. This test should be performed for all spindles.

Before proceeding with this test, the machine should be in a quiescent state as described in para. 7.6.1, after a soak-out period of at least 12 hr.

7.6.2.1 Spindle Warm-Up Test. A test fixture, such as that used for the spindle error analysis tests (Fig. 7.35), is used.[20] This fixture, in which the displacement sensors are mounted, shall be securely fixed to the nonrotating

[20] If desired, the fixturing for the gage nest and for the test ball may be made of low-expansion material. The concept here is, insofar as possible, to check the thermal stability of the spindle and not the thermal stability of the test fixture(s).

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workholding zone of the machine to measure the following:

(a) the relative displacements between the component that holds the cutting tool and the component that holds the workpiece along the three orthogonal axes parallel to the linear axes of travel of the machine

(b) tilt or rotation around the *X*- and *Y*-axes of the machine tool

The sensors should be of similar sensitivity to those used in the ETVE and spindle error tests and be of the noncontacting type (see Chapter 11). A test mandrel shall be mounted on the spindle and adjusted to minimize radial runout. The sensors shall be set to read positive for deflections of the mandrel toward them.

This test should be performed in a configuration suggested by the Supplier; that is, if the machine has active spindle thermal control, as in a liquid shower machine, it should be on during this test. The test may also be performed with both coolant on and coolant off.[21]

7.6.2.1.1 Procedure

(a) The spindle is turned on to 75% of its maximum rpm.

(b) Data from the five sensors are taken at intervals of a maximum of 5 min (shorter intervals than 5 min are acceptable).

(c) The data at each interval should be averaged for at least 5 sec to remove dynamic effects. If a digital measurement system is used, a minimum of four samples per revolution for 20 revolutions, at any time during the 5-min period, is sufficient.

(d) During the first 30 min of the test, the range of the data at all sensor locations shall be noted.

The test shall continue until the maximum change in any sensor reading over any 30-min period, at all of the sensor locations, has reduced to 15% of the maximum change of that sensor reading over the first 30 min of the test. However, if this condition is not achieved, the test will stop after 4 hr.

The data shall be plotted as shown in Fig. 7.37. The zero for this figure is established by reading the sensors immediately after spindle rotation has commenced.

7.6.2.1.2 Data Analysis. The thermal tilts of the spindle axis average line (refer to Fig. 7.35 for gage designations) in two orthogonal planes are calculated using the following formulae:

$$D_{XZ} = \frac{D_5 - D_2}{L_d} \tag{7-25}$$

and

$$D_{YZ} = \frac{D_4 - D_1}{L_d} \tag{7-26}$$

where

D_{XZ} = tilt in the XZ plane
D_{YZ} = tilt in the YZ plane
D_1 = reading of gage 1
D_2 = reading of gage 2
D_4 = reading of gage 4
D_5 = reading of gage 5
L_d = distance between gages 2 and 5 or 1 and 4

(Note that the tilt angles are in radians,[22] defined with respect to the gages and not to the machine's axes. Positive tilts indicate tilting towards the lower gage pair 4 and 5 used in the computation.) Based on these calculations, tilt drifts of the axis average line are plotted as shown in Fig. 7.38.

To facilitate comparison between machines, this Standard requires reporting the thermal drift of the spindle axis average line as close to the face of the spindle as possible. The displacements of the axis average line at the face of the spindle are calculated by

$$D_X = D_2 - L_{1,2} \times D_{XZ} \tag{7-27}$$

$$D_Y = D_1 - L_{1,2} \times D_{YZ} \tag{7-28}$$

$$D_Z = D_3 \tag{7-29}$$

where

D_X = displacement of the axis average line at the face of the spindle in the X-direction
D_Y = displacement of the axis average line at the face of the spindle in the Y-direction
D_Z = displacement of the axis average line at the face of the spindle in the Z-direction
D_3 = the reading of gage 3
$L_{1,2}$ = measured distance between the centerlines of sensors 1 or 2 and the face of the spindle

The displacements are positive in the direction of the corresponding sensors, not necessarily in machine coordinates. The ranges of average displacements in each direction shall be reported.

7.6.2.2 Transient Shutoff Test.[23] This test is performed with the same setup used for spindle warm-up tests. At the end of the spindle warm-up test described in para. 7.6.2.1, the spindle is turned off and the sensors are read for a period equal to that of the spindle warm-up test. The data are taken at maximum intervals of 5 min, with each data point being an average of all the readings

[21] When tests are performed using cutting lubricant, capacitance sensors should not be used.

[22] Note that in performance forms (para. 1.2), the spindle thermal tilt error motion is presented in the unit of seconds. One second is approximately equal to 5×10^{-6} radians.

[23] The behavior of a spindle during warm-up is often dramatically different from its behavior during cool-down. This can lead to significant problems when using machines in intermittent duty cycles. It is therefore recommended that a transient shutoff thermal stability be measured.

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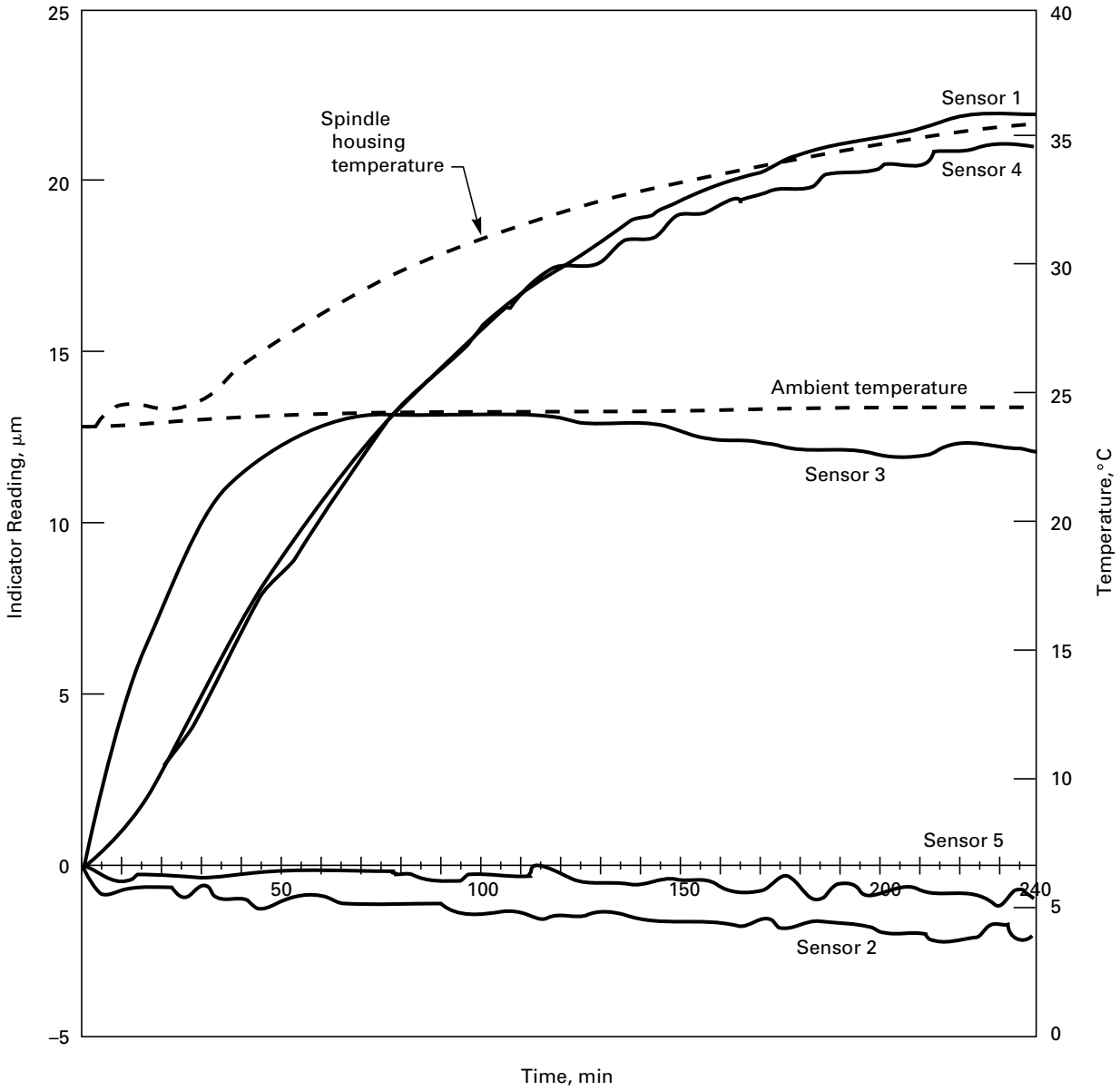


Fig. 7.37 Sensor Data From a Typical Spindle Thermal Warm-Up Test

obtained for a minimum of 5 sec within the 5-min interval. For a more-detailed discussion of the sampling required, see para. 7.6.2.1. The data are analyzed as described in para. 7.6.2.1.2.

The transient shutoff thermal stability, as the total range of the linear (and tilt) readings for a period of 1 hr after spindle shutdown, shall be reported.

7.6.3 Thermal Distortion Caused by Moving Linear Axes

This test is carried out to identify the effects of internal heat generated by the machine positioning system (linear axes only) on the machine structure observed as displacements between a nominal workpiece and a nominal tool. The test indicates the amount of drift in the machine axis "home" position as well as the amount of elongation of machine scales or equivalent during the warm-up period.

7.6.3.1 Test Procedure. A displacement-measuring instrument, usually a laser interferometer, shall be set so as to measure the distance traversed by the axis under test (corresponding to the relative motion between the nominal tool and the nominal workpiece of the machine) between two target positions. Note that the laser interferometer should have been "cap" tested as specified in

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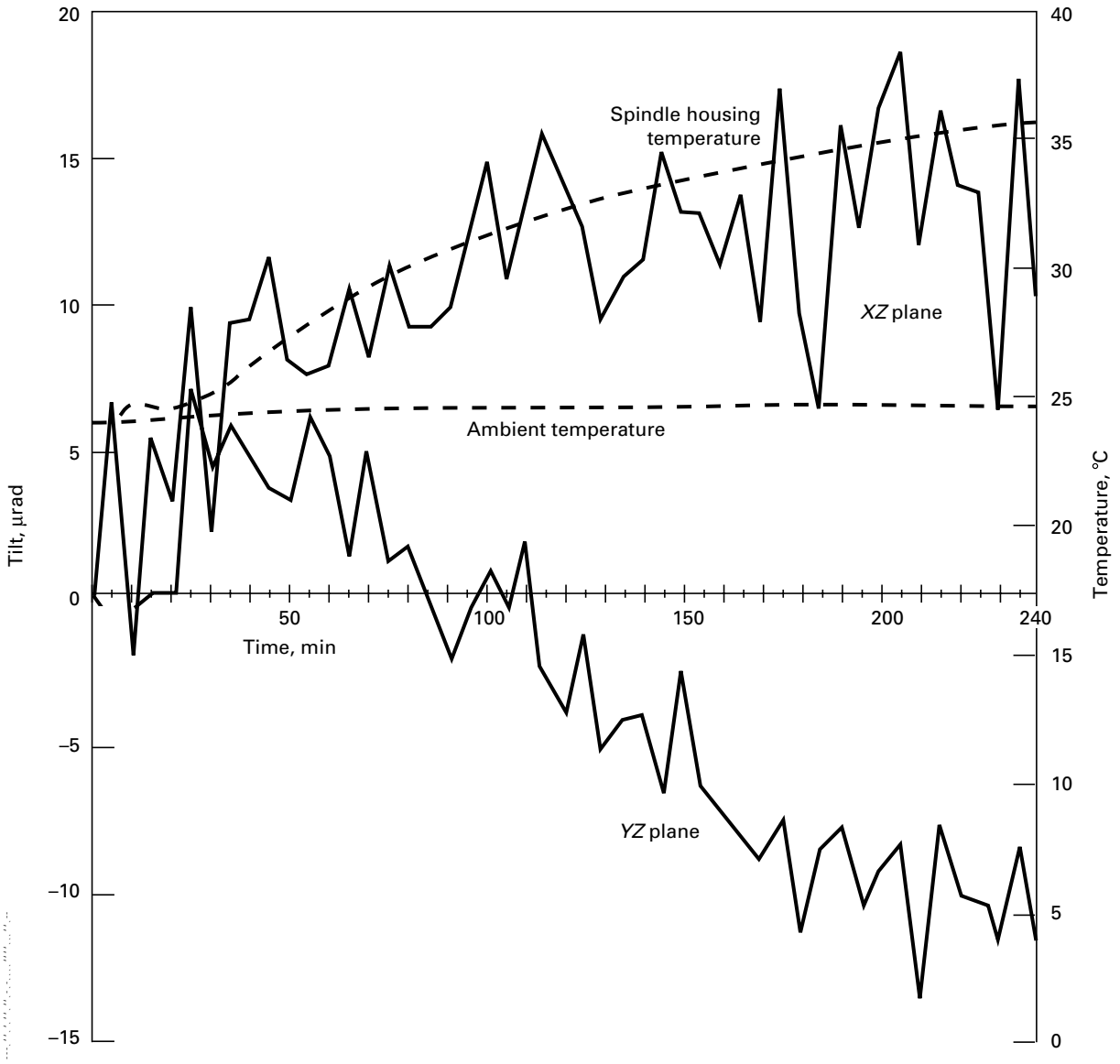


Fig. 7.38 Tilts of the Axis Average Line, Spindle Warm-Up Test

Appendix I. If the measuring instrument incorporates compensation for environmental factors, such as air temperature and pressure, then these shall be used. If the measuring instrument incorporates facilities by which the measured data can be modified for the part temperature, then the part sensor shall not be used. For machines using lasers for positioning feedback, environmental compensation for air temperature, pressure, and humidity should be used, if available, as part of the normal machine configuration as supplied by the Supplier. An example of a typical test setup is shown in Fig. 7.6. The two target positions should be selected close to the end points of travel, where applicable. Two additional reversal positions should be selected outside this test range to allow for bidirectional measurement. Measuring instrumentation shall be located such as to allow for minimum opening in the machine enclosure (if supplied) during the measurements.

Starting from one of the reversal positions, the machine shall be programmed to move the axis to target position 1, where it will remain at rest long enough for the actual position reached to be measured and recorded.

The axis shall then move in the same direction to target position 2, where the second reading will be taken. The motion should then continue to reach the second reversal point, where the direction will be reversed. The readings at target position 2 and target position 1 shall then be measured and recorded during this motion in the reverse direction.

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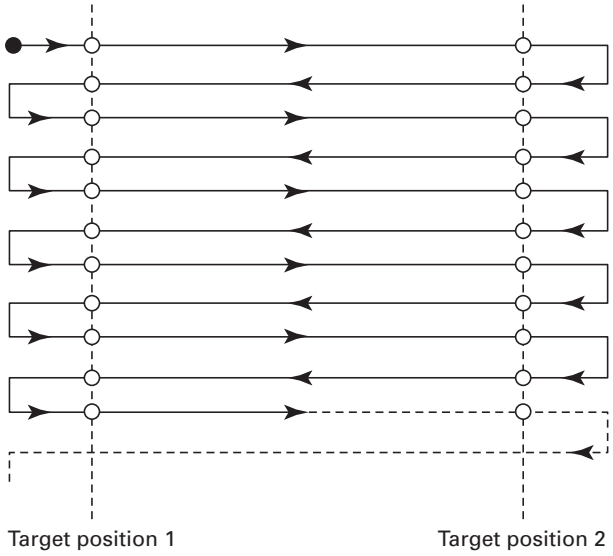


Fig. 7.39 Path for Measuring Thermal Distortion Caused by Moving Linear Axes

A diagram showing this procedure is given in Fig. 7.39. The programmed traverse rate shall be 0.5 times the rapid traverse rate and the dwell time shall be the settling time used for the positioning accuracy and repeatability tests (para. 7.3). Different dwell times and traverse rates produce different heat inputs; therefore, they cause different axis drifts. If other dwell times and traverse rates are to be specified, they shall be the subject of prior agreement between User and Supplier.

The test sequence described above shall then be repeated, recording data bidirectionally at the two target positions. During the first 30 min of the test, the range of the data for each axis shall be reported at each target position for both directions of motion. The test shall proceed until the maximum change in any axis reading over any 30-min period at both end points has reduced to 15% of the maximum of either end point change over the first 30 min of the test, with a maximum test period of 4 hr, whichever is smaller.

Before commencing the test on another axis, sufficient time should be allocated to allow for the machine to cool down. The ambient temperature shall be continuously monitored during these tests.[24] Note that on a machine of normal size, a very large number of data will be produced by this test which may last as long as 4 hr. It is recommended that the average value over 10-min intervals be retained, rather than the full data set. The average position values will then be used to compute the thermal drift. Note that this test does not fully assess the machine's thermal behavior, but rather indicates thermal problems and can be effective for machine comparison.

7.6.3.2 Data Analysis. At the end of the test period, the error at the two target positions for each direction shall be calculated at 10-min intervals. This shall be done by subtracting the first average position reading from all subsequent readings. The data sets shall be plotted in the form of position error versus time graphs, an example of which is shown in Fig. 7.40. With reference to this figure, error $e(X_1\uparrow)$ is the total range of thermal drift of target position 1 in the X direction for the forward direction, and error $e(X_2\uparrow)$ is the total range of thermal drift of target position 2 in the X direction for the forward direction. The drifts in the reverse direction will be noted similarly, using the down arrow ($\downarrow$).

The dwell (settling) times, traverse rates, setup positions, position of the air temperature sensor, type of test equipment, and target positions shall be recorded with the test results.

7.6.4 Composite Thermal Error

This test is carried out to identify the combined effects of the internal heat generated by the main spindle(s) and the positioning systems on the relative position between the workpiece and the tool. It should be noted that the results of this test cannot be derived from the results of the two types of tests described in paras. 7.6.2 and 7.6.3 of this Standard.

7.6.4.1 Test Procedure. Figure 7.35 shows a typical measurement setup for a machining center. Five displacement indicators shall be rigidly mounted to the worktable, so as to be able to measure changes in position and tilt between the structure that holds the tool and the structure that holds the workpiece.

Wherever possible, all the other axes and spindles should be exercised during the test.

The temperature of the machine structure, as close as possible to the front spindle bearing housing, along with the ambient temperature, shall be continuously monitored. Although these temperatures do not exactly correlate to the measured displacements, they are indications of the thermal changes of the machine structure.

The recommended test position is at the center of the work zone. After reading the displacement indicators, all machine axes are exercised over their full travel at half the maximum rapid traverse rate while taking care to avoid collisions with the test setup. Next the test mandrel is returned to the test position and a new reading is taken after a dwell equal to the settling time as specified in the positioning accuracy and repeatability test (para. 7.3). The final 5-mm approach to the test position should be carried out at a low feed rate, and the direction of approach should not be changed throughout

[24] It is useful to measure the drift during the cool-down period. To do this, at the end of the test period, the machine should be at the target position which indicated the largest drift and the drift at this position is periodically recorded as the machine cools down.

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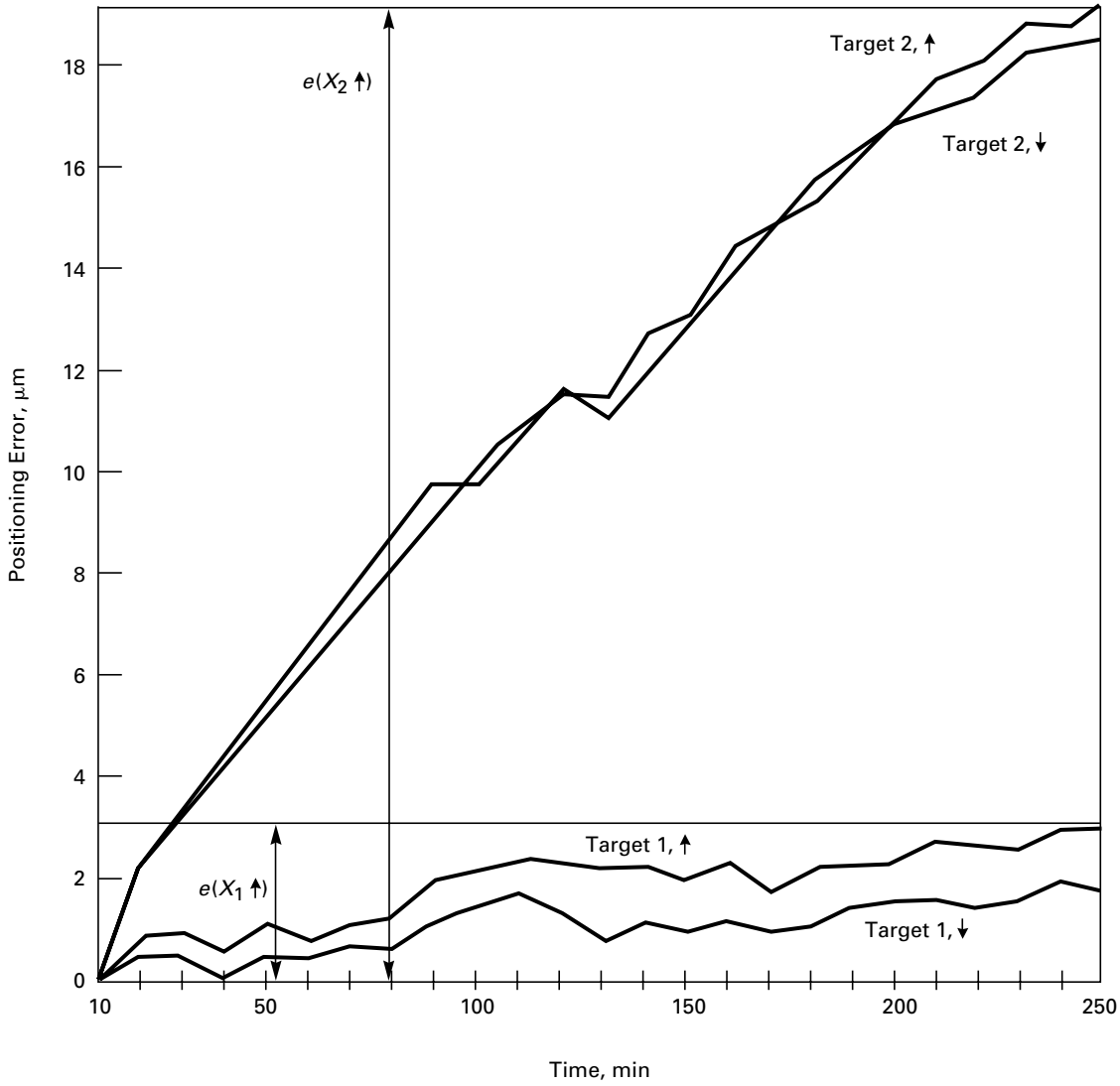


Fig. 7.40 Position Error Versus Time for a Typical Test for Thermal Distortion Caused by a Moving Linear Axis

the test. It is recommended to run the spindle continuously at half the maximum speed throughout the test. Other test conditions, including variable spindle speed spectra, may be specified by prior agreement between User and Supplier. The dwell time, spindle speed spectrum, traverse rate, sequence of axis movements, and travel ranges change heat input and therefore can cause different drift rates.

The test shall proceed in this manner until the change in the position over any 30-min period, at all the measurement locations, has reduced to less than 15% of the maximum position change over the first 30 min of the test, with a maximum test time of 4 hr. The results should be plotted in graphs of deflection and temperature versus time, as shown in the example given in Fig. 7.41. Note that, as in the preceding test, a large number of data points may be generated by this test. Again it is recommended that only the average value over a reasonable period of time, say 5 to 10 min, be retained for the purposes of analysis.

7.6.4.2 Data Analysis. The effect of warming up the machine structure on the ability of the machine to maintain the position of the tool relative to the workpiece can be assessed from the deflections versus time graphs. The results are influenced by the positional repeatability of the machine axis.

The range of displacements measured by each indicator shall be reported for the first 30 min and for the

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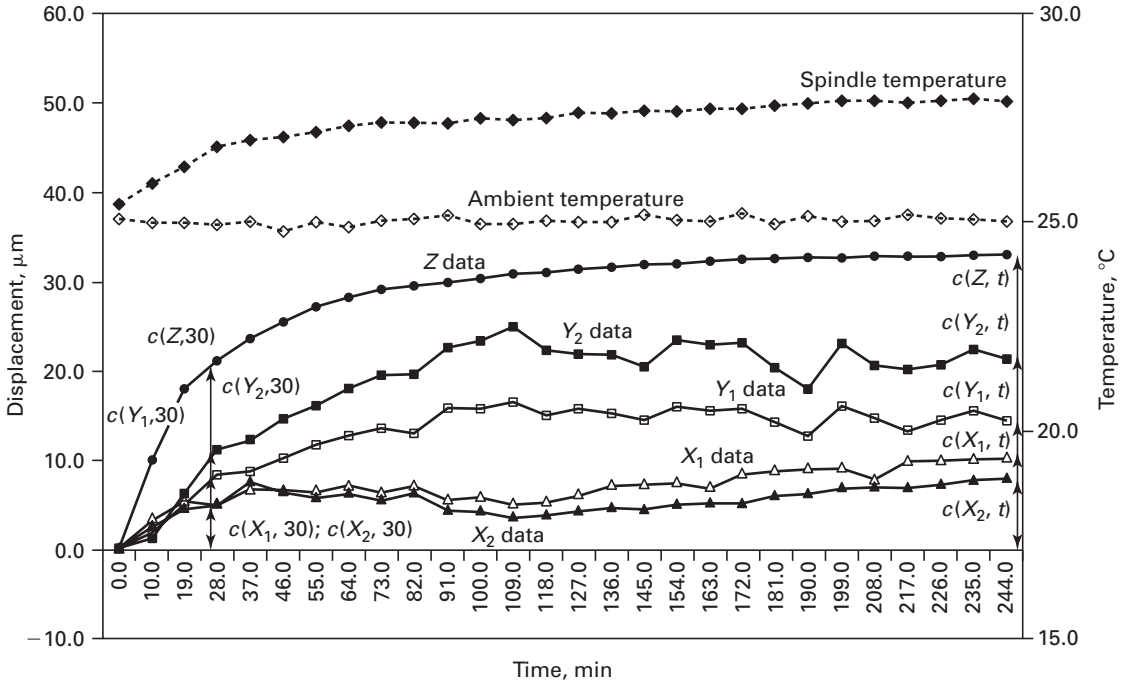


Fig. 7.41 Typical Results From a Composite Thermal Error Test

duration of the test (see para. 1.1). Furthermore, deflection versus time graphs shall be provided. The test procedure, traverse rate, dwell time, sequence of axes movements, location of target positions, location of the measurement setup, including the locations of the temperature sensors, and spindle speed should also be reported with the results of the tests.

7.7 DIAGONAL DISPLACEMENT TEST

7.7.1 General

These tests are used to determine displacement accuracy of the machine along body or face diagonals. To obtain an estimate of the volumetric positioning capability of the machine, one has to combine the results of these tests with those of linear displacement tests. The linear displacement tests are preferably executed at different Abbe offsets to assess effects of yaw and pitch errors. A more complete estimate can be obtained using the tests in para. 7.4, which may be required for certain applications and machine configurations.

7.7.2 Volumetric Performance Using Diagonal Displacement Measurements

7.7.2.1 General. The procedure is similar to that described in the section for linear displacement accuracy, except that displacement measurements are done along the work volume's four body diagonals. For performing these measurements, the average scale temperature shall be assumed to be the mean temperature of the table of the machine at the center of the work zone or any suitable location. The measurements shall be carried out along the four body diagonals of the working volume of the machine. To adequately characterize the working volume, the measured diagonals shall be of a maximized length with recorded start and end points.

NOTE: On machines with large aspect ratios, the diagonal displacement measurement test can be insensitive to certain errors. One should take particular care when interpreting results in the case of large aspect ratio machines. For these large aspect ratio machines, additional measurement of face diagonals can be useful.

7.7.2.2 Test Procedure

7.7.2.2.1 Equipment

(a) laser interferometer

(b) optics for diagonal displacement measurements (optics for linear displacement measurements and optics for beam alignment)

(c) environmental compensation measurement sensors

(d) machine temperature sensors

7.7.2.2.2 Measurement Procedure

(a) Measurements shall be made at all the target positions according to the standard test cycle described in the positioning accuracy and repeatability test (paras. 7.3.1 and 7.3.3) for measuring intervals and feed rates. If, for practical reasons, the feed rate must be reduced to perform this test, the percentage reduction shall be reported as part of the test results.

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(b) The measuring instrument is set up approximately along a diagonal of the work volume. The start and end points are aligned when a measuring signal is obtained after jogging the machine tool axes.

7.7.2.3 Data Analysis. The data obtained for each of the diagonals shall be analyzed in a similar manner to that used for the positioning accuracy and repeatability, with the exception that only the bidirectional systematic deviation, E, and the reversal deviation, B, are evaluated and reported.

7.8 SUBSYSTEMS REPEATABILITY

7.8.1 General

Machining centers are complex systems and contain many subsystems, which also contribute to the accuracy and performance of the machine. Three important subsystems that affect accuracy are the tool changer, pallet changer, and the tool setting system.

In the computation of the tool change repeatability and the pallet change repeatability, the standard uncertainty of measurement for the combined effect of the machine's linear axis repeatability and the test instrument repeatability should be determined first. Next, the standard uncertainty of measurement for the combined effect of the machine's linear axis repeatability, test instrument repeatability, and subsystem repeatability should be determined. Finally, the subsystem repeatability is computed from the difference between the two squared standard uncertainties. Tests for the three subsystems are addressed in the following paragraphs.

7.8.2 Tool Change Repeatability

7.8.2.1 General. Tool change repeatability is checked using two tool holders selected from a Supplier's specified tooling package. Precision test spheres are to be mounted in these tool holders in a manner similar to that shown in Fig. 7.42. One of the test spheres is at the minimum possible distance from the tool holder or spindle gage line, and the second test sphere is mounted on a rigid column at a distance of 250 mm (approximately 10 in.) from the first sphere. These tool lengths[25] are default options, and the User is free to select other lengths appropriate to his or her application, if required.

7.8.2.2 Test Procedure. The tool holders with their test spheres are to be inserted in User-selectable positions in the tool magazine, and a displacement indicator nest, such as the three-sensor nest[26] shown in Fig. 7.43, is to be rigidly attached to the machine table or pallet in the nominal position of the part. The test then proceeds as follows. The first sphere is loaded into the spindle and the machine jogged into position such that the three displacement indicators are nulled. This position is recorded. This procedure is repeated on the second sphere.

An automatic cycle is established to place sphere 1 into the spindle and position it to its established null in the displacement indicator nest, withdraw it safely from the nest, and move the spindle to the tool change position at the tool change feed rate. Note that the tool holder is not to be removed from the spindle. This cycle is repeated ten times in rapid succession and the X, Y, and Z indicator readings for each trial are recorded. The estimate of standard uncertainty for the combined effect

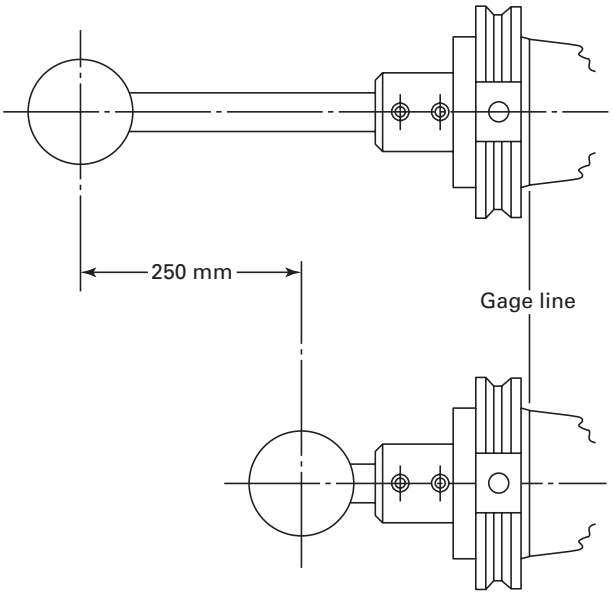


Fig. 7.42 Tool Holders Used for Tool Change Repeatability

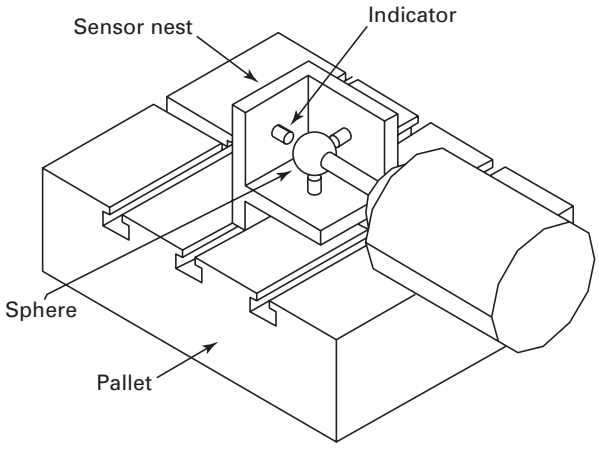


Fig. 7.43 Three-Sensor Nest Setup for Tool Change Repeatability

[25] Result for long and short tool length provides a basis for estimating the tilt motions of the tool.

[26] This test can, if required, be performed on an axis-by-axis basis using a single sensor.

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of the machine's linear axis repeatability and the test instrument repeatability is now calculated for each axis as

$$u_{tx} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_{txj} - \bar{x}_{tx})^2} \quad (7\text{-}30)$$

where

n = 10 is the default value for this test
u_{tx} = standard uncertainty for combined effect of machine linear axis repeatability and test instrument repeatability
$\bar{x}_{tx}$ = average of the ten readings in the X direction
x_{txj} = jth reading in the X direction

Another automatic cycle is established to place sphere 1 into the spindle and position it to its established null in the displacement sensor nest, withdraw it safely from the nest, interchange it with sphere 2, position sphere 2 to its null position in the nest, and then withdraw and return sphere 2 safely to the tool magazine. This program is executed ten times in rapid succession at the tool change feed rate, and the X, Y, and Z indicator readings of each sphere are recorded for each trial.

The estimate of standard uncertainty for the combined effect of the machine's linear axis repeatability, test instrument repeatability, and tool change repeatability is now calculated for each axis as

$$u_{tcx} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_{tcxj} - \bar{x}_{tcx})^2} \quad (7\text{-}31)$$

where

n = 10 is the default value for this test
u_{tcx} = standard uncertainty for combined effect of machine linear axis repeatability, test instrument repeatability, and tool change repeatability
$\bar{x}_{tcx}$ = average of the ten readings in the X direction
x_{tcxj} = jth reading in the X direction

7.8.2.3 Data Analysis. Tool change repeatabilities in the X, Y, and Z directions are reported for each tool length. For example, the tool change repeatability for the short tool length in the X direction is reported as

$$R_{xts} = 4\sqrt{(u_{tcx}^2 - u_{tx}^2)} \quad (7\text{-}32)$$

where

R_{xts} = tool change repeatability for the short tool length in the X direction

Note that these results include any thermal errors induced by traversing the machine spindle to and from the tool change location.

7.8.3 Pallet Change Repeatability

7.8.3.1 General. A suitably sized precision angle bracket is securely bolted to the pallet such that the corner of the bracket is located as close as possible to the center of the pallet as shown in Fig. 7.44. The size of the angle bracket should be slightly less than half the shortest length of the pallet. Six measurement points are required on the angle bracket and these points are numbered 1 through 6. In addition to pallet-change positioning repeatability along the X-, Y-, and Z-axes, the three tilt motions about the three axes are also determined. For ease of measurement, the use of a spindle probe is recommended.

7.8.3.2 Test Procedure. The pallet carrying the angle bracket is loaded onto the machine table pallet receiver. The face of the angle bracket is aligned to the X-axis travel of the machine. An automatic cycle is established to probe the six measurement points. The cycle is repeated ten times in rapid succession, and the X, Y, and Z probe readings are recorded. Note that the pallet carrying the angle bracket is not removed from the table pallet receiver. This preliminary step establishes the standard uncertainty that includes the combined effect of the machine's linear axis repeatability and the probe system repeatability for both linear and tilt motion measurements. For example,

$$u_{px2} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_{p2j} - \bar{x}_{p2})^2} \quad (7\text{-}33)$$

where

n = 10 is the default value for this test
u_{px2} = standard uncertainty for the pallet linear positioning error along the X-axis that includes the combined effect of machine's linear axis repeatability and probe system repeatability
$\bar{x}_{p2}$ = average of the ten readings for measurement point 2 in the X direction
x_{p2j} = jth reading in the X direction for measurement point 2

Similar calculations are performed for measurement points 1 and 3. Next, the standard uncertainty of the tilt motion measurement in the XY plane is computed.

$$\beta_{pxyj} = \frac{(x_{p6j} - x_{p2j})}{L_d} \quad (7\text{-}34)$$

$$u_{p\beta xy} = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(\beta_{pxyj} - \bar{\beta}_{pxy})^2} \quad (7\text{-}35)$$

where

L_d = nominal distance between measurement points 2 and 6
n = 10 is the default value for this test
$u_{p\beta xy}$ = standard uncertainty of the tilt motion measurement that includes the combined effect of machine's linear axis repeatability and probe system repeatability
x_{p2j} = jth reading in the X direction for measurement point 2

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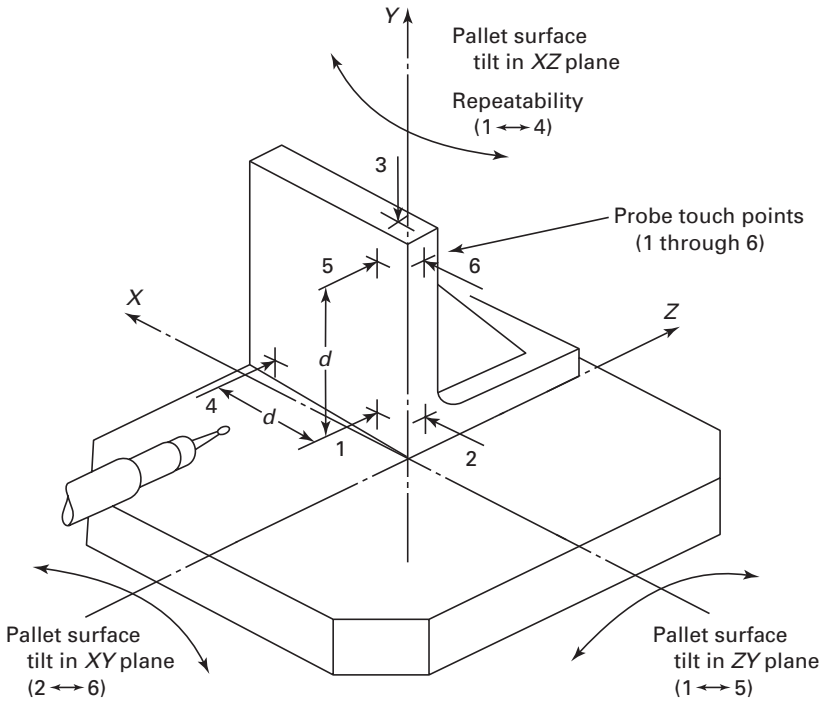


Fig. 7.44 Test Setup for Pallet Change Repeatability

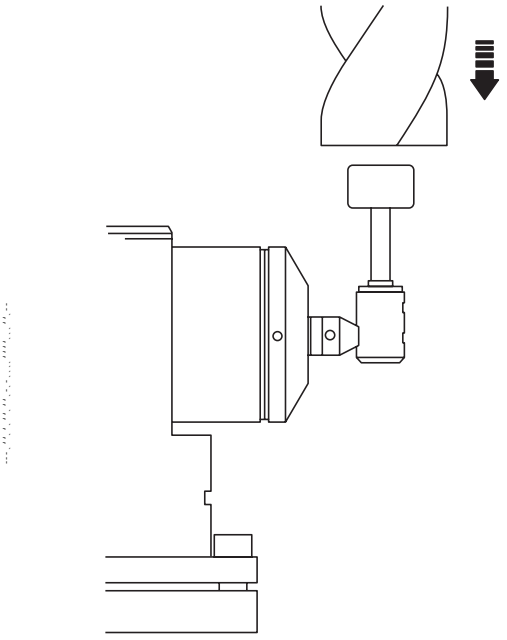


Fig. 7.45 Tool Length Measurement With No Spindle Rotation

x_{p6j} = jth reading in the X direction for measurement point 6

$\overline{\beta}_{pxy}$ = average tilt motion of the pallet in the XY plane

β_{pxyj} = jth reading of the tilt motion of the pallet in the XY plane

Similar calculations are performed for measurement points 1 and 4, and for points 1 and 5.

Another automatic cycle is now established to place the pallet carrying the angle bracket onto the machine table pallet receiver, probe and record the readings at measurement points 1 through 6, shuttle the pallet from the machine table receiver to the pallet stand, and return the same pallet to the machine table pallet receiver. This cycle is repeated ten times in rapid succession. The estimates of the standard uncertainties that include the combined effect of the machine's linear axis repeatability, probe system repeatability, and pallet change repeatability for linear and tilt motion errors are evaluated as shown before.

7.8.3.4 Data Analysis. Six pallet change repeatabilities are reported; they are the three linear errors in pallet change positioning along the X-, Y-, and Z-axes, and three tilt motion errors in pallet-change positioning about the X-, Y-, and Z-axes. For example, the linear error in pallet change positioning in the X direction is given by

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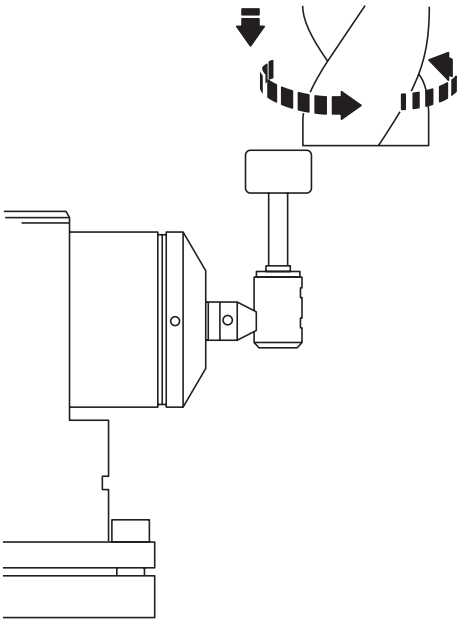


Fig. 7.46 Tool Length Measurement With Rotating Spindle

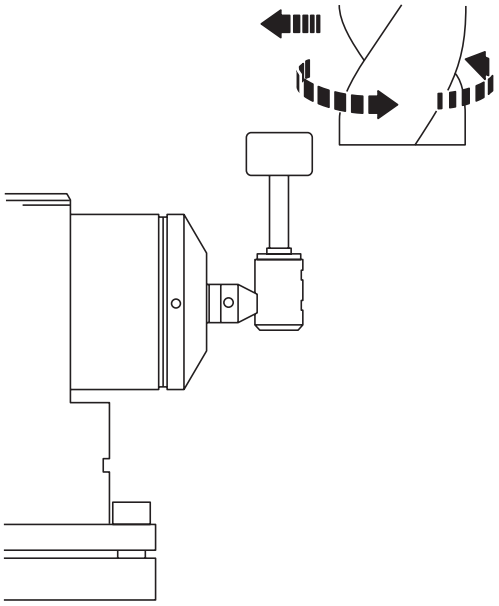


Fig. 7.47 Tool Diameter Measurement

$$R_{pcx} = 4\sqrt{u_{pcx2}^2 - u_{px2}^2} \quad (7\text{-}36)$$

where

R_{pcx} = pallet change repeatability along the X-axis

u_{pcx2} = standard uncertainty for the pallet linear positioning error along the X-axis that includes the combined effect of machine's linear axis repeatability, probe system repeatability, and pallet change repeatability

u_{px2} = standard uncertainty for the pallet linear positioning error along the X-axis that includes the combined effect of machine's linear axis repeatability and probe system repeatability

Similarly, R_{pcy} and R_{pcz} are determined using readings from measurement points 3 and 1, respectively. Next, the tilt error motion of the pallet change positioning in the three planes is computed. For example, the pallet surface tilt motion in the XY plane is given by:

$$R_{pcxy} = 4\sqrt{u_{pc\beta xy}^2 - u_{p\beta xy}^2} \quad (7\text{-}37)$$

where

R_{pcxy} = pallet surface tilt motion repeatability in the XY plane

$u_{pc\beta xy}$ = standard uncertainty for the pallet tilt motion error in the XY plane that includes the combined effect of machine's linear axis repeatability, probe system repeatability, and pallet change repeatability

$u_{p\beta xy}$ = standard uncertainty for the pallet tilt motion error in the XY plane that includes the combined effect of machine's linear axis repeatability and probe system repeatability

Similarly, R_{pcxz} is determined using readings from measurement points 1 and 4, and R_{pcyz} is determined using readings from measurement points 1 and 5. Note that the tilt motion errors are in radians, and may be converted into seconds using the relation 4.85 μrad = 1 sec.

7.8.4 Tool Setting Repeatability

7.8.4.1 General. Some machining centers are equipped with a sensor/probe system designed to set, under machine control, the length and/or diameter of a variety of tools. The performance of these sensors can vary considerably depending on their design and functionality (e.g., single axis measurement, 3D probe, and noncontact optical systems).

7.8.4.2 Scope. Some sensors can only measure tool length without the spindle rotating. Others are capable of measuring length and diameter with the spindle rotating. This test will evaluate the performance of these systems in three modes of operation with a single tool type and will make use of the software control routines provided by the manufacturer and/or the machine OEM.

The tool will be a 50-mm diameter two flute end mill of 150-mm length. If the machine is incapable of using a tool of this size, then a similar tool type of half the diameter and length should be used.

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7.8.4.3 No Spindle Rotation (Length Measurement Only). Position the spindle center over the sensor/probe, without the spindle rotating. Using the cycle provided by the equipment Supplier, measure the end mill length ten times. The repeatability is reported as 4 times the standard uncertainty of the measured length. See Fig. 7.45.

7.8.4.4 Spindle Rotation (Length Measurement Only). On systems that allow length measurement with the spindle rotating, select the recommended speed. Position the spindle center offset from the sensor center by 25 mm. Using the cycle provided by the equipment Supplier, measure the slot drill length ten times. The repeatability is reported as 4 times the standard uncertainty of the measured length. See Fig. 7.46.

NOTE: These systems allow for the automated length setting of discrete cutting inserts located off the spindle axis.

7.8.4.5 Diameter Setting. Using the cycle provided by the equipment Supplier, measure the diameter of the end mill ten times. The repeatability is reported as 4 times the standard uncertainty of the diameter recorded. See Fig. 7.47.

7.9 MACHINE PERFORMANCE AS A MEASURING TOOL

7.9.1 General

The following procedures have been designed to evaluate the performance of a machine tool, equipped with a suitable probing system, as a measuring machine. The tests below are meant to apply to machines equipped to measure in the point-to-point mode. The results of these tests do not reflect on the performance of the machine tool in a metal-cutting mode. The following tests address the issue of measuring performance in discrete stages that depend on the level of software capability provided by the Supplier and the intended use of the measuring system. Testing shall be performed in a manner that most closely represents the way in which the machine measurement system will be used after acceptance. Prior to commencing these tests, the machine probe shall be calibrated and qualified according to the Supplier's recommendations for normal operation of the machine when measuring parts. Qualification on the test artifact to be used for this test is specifically excluded. It is also assumed that prior to performing these tests, the machine performance has been assessed as described in Chapter 7.

7.9.2 Feature Location Repeatability (FLR) and Feature Measurement Accuracy (FMA)

7.9.2.1 General. The concept of feature location repeatability testing requires that the test must evaluate the complete system, which may include effects due to machine characteristics, computer algorithms, control systems, etc. To reduce the time required for testing, this Standard also incorporates into the repeatability test the measurement of a simple artifact.

Two tests are specified. The test chosen for a particular machine shall be the test for the principal mode of operation and probe type specified for that machine. The artifact chosen for the test depends on this principal mode of operation. A precision 25-mm (approximately 1-in.) diameter ring gage is used for machines whose software allows only planar measurement. A precision 25-mm (approximately 1-in.) diameter reference sphere is used for machines whose software allows 3D measurement. Regardless of which artifact is chosen, it must conform to the requirements of Chapter 11. Its nominal coefficient of thermal expansion is also required for this test.

Unless otherwise specified by the User, the feature location repeatability and feature measurement accuracy tests shall be performed at the center of the work zone with a default stylus length of 50 mm (approximately 2 in.). It should be noted that the size value for feature location repeatability and feature measurement accuracy is position-dependent; therefore, the User may specify other locations or several locations, if required.

7.9.2.2 Common Features. In these tests, the requirement in the definition of repeatability to sense the same quantity is satisfied by measuring the center coordinates of the precision artifact rigidly mounted on the workpiece supporting surface near the center of the work zone multiple times. Ten determinations of the reference artifact's center shall be made as rapidly as practical to determine feature location repeatability. Feature location repeatability will be reported on a per-axis basis. To determine the feature measurement accuracy, the same data will be used to determine the size of the artifact being measured.

7.9.2.3 Standard Tests for Feature Location Repeatability and Feature Measurement Accuracy. The following tests are designed to assess the ability of the machine to repeat a measurement and to accurately measure features that are within the capability of the machine software.

7.9.2.3.1 Tests Where Software Allows for Only Planar Measurements

(a) A 25-mm (approximately 1-in.) reference ring gage shall be rigidly mounted on a fixture in the part position such that the axis of the ring is aligned with the spindle axis.

(b) A thermometer shall be coupled tightly to the ring gage to measure its temperature, and a second thermometer shall be placed at the position designated by the Supplier to be representative of the mean scale temperature of the machine.

(c) After alignment, the machine shall be set in its normal automatic cycle to be used for the measurement

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of a bore. (If such a normal program cycle is not available, then the machine shall be set in an automatic cycle to make ten sets of up to ten readings on the inner diameter of the reference ring. Contact points for each automatic cycle shall be spaced as widely as possible, but shall be in the same plane.)

(d) For each set of these data, the center coordinates (X, Y) and the diameter of the ring gage shall be computed.

(e) Feature location repeatability shall be reported as follows:

(1) Feature Location Repeatability FLR_X. Four times the standard uncertainty of the mean X coordinate.

(2) Feature Location Repeatability FLR_Y. Four times the standard uncertainty of the mean Y coordinate.

The feature measurement accuracy (FMA) for each axis shall be the difference between the average diameter obtained from the ten sets of measurements, corrected for temperature, and the calibrated diameter of the gage. The diameter of the gage, corrected for machine and gage temperatures, is given as follows:

$$CD = MD[1 + \alpha(T - 20) - \alpha_s(T_s - 20)] \qquad (7\text{-}38)$$

where

CD = corrected diameter
MD = measured diameter
T = average temperature of point selected as representative of the mean scale temperature
T_s = average temperature of gage during measurement (degrees Celsius)
α = nominal thermal expansion coefficient of the machine scales
α_s = thermal expansion coefficient of calibration gage

The Z-axis repeatability shall be determined by taking ten measurements of the position of the top face reference surface on the precision ring without moving the other two machine axes. Feature location repeatability FLR_Z will be reported as 4 times the standard uncertainty of the mean Z-axis coordinate. (For the case of machines having only planar measurements, there is no three-dimensional feature measurement accuracy.)

7.9.2.3.2 Tests Where Software Allows for 3D Measurements

(a) The precision reference sphere shall be rigidly mounted to a fixture in the part position such that it is readily accessible for machine probing.

(b) A thermometer conforming to the requirements of Chapter 10 shall be appropriately thermally contacted with the test sphere in a position that does not interfere with probing and a second thermometer placed in a position designated by the Supplier as being representative of the mean scale temperature.

(c) Ten sets of up to 15 readings shall be made on the reference sphere. Contact points for each set shall be as widely spaced as possible and not all on the same plane.

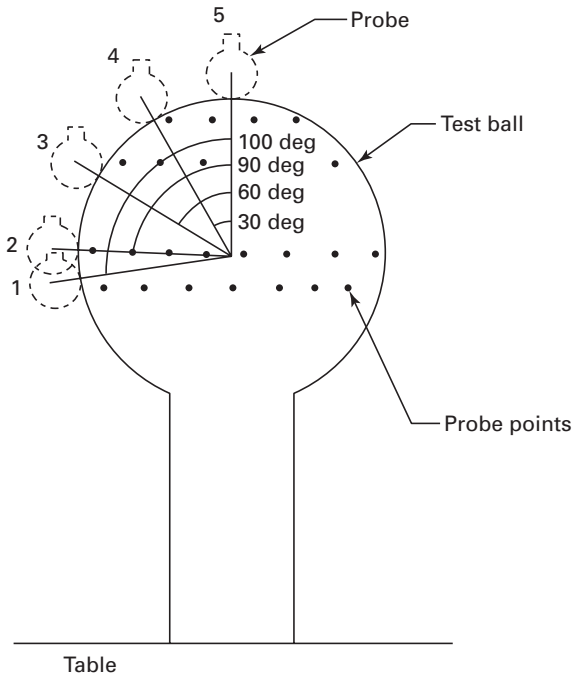


Fig. 7.48 Illustration of the Probing Pattern Used for Determining Three-Dimensional Probing Capability

(d) Coordinates of the center of the ball shall be computed for each set of readings and the feature location repeatability values FLR_X, FLR_Y, and FLR_Z computed as described in para. 7.9.2.3.1.

(e) The same data shall be used to calculate the diameter of the precision sphere.

(f) The average diameter of the sphere, corrected for temperature, shall be computed.

The feature measurement accuracy (FMA) shall be the difference between the corrected sphere diameter, as measured, and the calibrated diameter.

7.9.2.4 Standard Test for Probe Lobing. While the machine is still set up for the repeatability and feature measurement accuracy test, it is optional that a probe lobing test be performed. For the purposes of this Standard, probe lobing is tested in two different ways. The first way is for machines which only allow probing in a plane. The second, for machines which have three-dimensional measurement capability, is identical to those tests used for coordinate measuring machines as specified in ASME B89.4.1.

7.9.2.4.1 Test for Probe Lobing Where Software Allows Only for Planar Measurements. Care should be taken to ensure that the ring gage is aligned to the XY

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plane of the machine. Before commencing the test, the approximate center of the ring gage is determined by probing at the axis coordinate directions. Next, the ring gage is probed in the radial direction at 36 points uniformly distributed around the circumference. For machines that allow only single-axis probing, four points spaced 90 deg apart shall be sufficient. The measured X and Y coordinates of each point shall be recorded. The center of the thus-measured circle is calculated as the average of these coordinates. The coordinates of this center shall be subtracted from the X, Y coordinates of each point and the vector distance, the square root of the sum of the squares of the coordinate differences, calculated for each of the 36 touches. The range of the distances is reported as the specification zone for the probe lobing. Probe lobing can be further analyzed by plotting these data on a polar plot.

7.9.2.4.2 Test for Probe Lobing Where Software Allows for Three-Dimensional Measurements. A precision reference ball shall be rigidly mounted on the workpiece-supporting surface in the work zone of the machine on a fixture that allows access by the machine probing system. Any position may be chosen for this mounting, with the default position being the ETVE position. A single probing test shall be performed on this ball using a 50-mm (approximately 2-in.) long, straight stylus probe. Other lengths may be specified, as long as specification is made as a detailed part of the machine procurement.

Before commencing the test, the approximate center of the sphere is determined by probing at the axis coordinate directions. Next, 49 points are probed on the test ball (at four different heights and 12 points around the circumference at each height, in addition to the point at the pole of the ball) as shown in Fig 7.48. In all cases, the manufacturer's probe approach distance, probe approach rate, and settling time, as shown in performance forms (para. 1.1), shall be used.

7.9.2.4.2.1 Data Analysis on Machines With Three-Dimensional Measuring Capability. From the set of 49 readings, a sphere center is computed using the manufacturer's recommended algorithms. From this center, a radius is then determined for each measurement point. (The minimum radius is subtracted from the maximum radius to produce the point-to-point probe lobing.) The range of the magnitudes of these vectors is reported as the specification zone for 3D-probe lobing.

7.9.3 Linear Measurement Accuracy (LMA)

7.9.3.1 General. The procedure described in this section of the Standard represents a minimum requirement to ensure conformance to linear measurement accuracy specifications. Linear measurement accuracy can be considered a combination of the positioning accuracy of the machine, the ability of the measurement system to repeat a measurement, and any offsets introduced by probe performance. Since the bidirectional systematic deviation of positioning (E; para. 7.3.4) and the feature measurement accuracy (para. 7.9.2) have been previously measured, the values obtained for these measurements will be used in the computation of the LMA.

7.9.3.2 Estimate of Linear Measurement Accuracy. The estimate of the LMA will be reported for each linear axis. It is the sum of the feature location repeatability (FLR) for an axis (para. 7.9.2.3), the feature measurement accuracy (FMA; para. 7.9.2.3) for the machine, and the bidirectional systematic deviation of positioning (E; para. 7.3.4) for an axis.

$$LMA_X = FLR_X + FMA + E_X \tag{7-39}$$

7.9.4 Volumetric Measuring Performance (VMP)

7.9.4.1 General. The volumetric measuring performance is determined using principles similar to those outlined in para. 7.11. That is, the volumetric measuring performance is obtained from the addition of the volumetric positioning performance data, the feature location repeatability data, and the feature measurement accuracy.

7.9.4.2 Calculation of Volumetric Measuring Performance. The VMP will be reported as the maximum range of error over the work zone of the machine. This shall be defined as the sum of the largest of the bidirectional systematic deviation in positioning of diagonals, E_d (para. 7.11), the vector repeatability error (VRE), and the feature measurement accuracy (FMA; para. 7.9.2). The VRE is determined as follows:

$$VRE = (FLR_X^2 + FLR_Y^2 + FLR_Z^2)^{1/2} \tag{7-40}$$

where

FLR_X = feature location repeatability for the X-axis
FLR_Y = feature location repeatability for the Y-axis
FLR_Z = feature location repeatability for the Z-axis

The volumetric measuring performance is then

$$VMP = E_d + VRE + FMA \tag{7-41}$$

7.9.5 Workpiece Location Tests

7.9.5.1 General. In many cases, probing on a machine is used to locate a workpiece in the machine reference system in order to alter machine programs. This test is designed to evaluate the ability of the measuring system to locate the position of a workpiece relative to the spindle centerline. Before performing this test, a calibration of the probe system for stylus eccentricity and ball radius must be performed according to the Supplier's recommendations.

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7.9.5.2 Procedure

7.9.5.2.1 The workpiece location specification zone is defined as the maximum deviation from the defined datum (zero) point established in both *X* and *Y* axes.

[If desired, the User may defer this test until the machining tests are performed, as one of the bores on the precision positioning machining test part (Chapter 8) can be used to perform this analysis.]

(a) A test part of at least 25-mm (approximately 1-in.) thickness is rigidly mounted to the machine table in preparation for machining. The part material shall be 7075-T6 Al, as specified in the section on machining tests (para. 8.4).

(b) A hole at least 25 mm (approximately 1 in.) in diameter is bored in the part following predrilling of a hole 1.25 mm (approximately 0.050 in.) undersized, in order to obtain a high-quality bore with surface finish better than the specification zone for repeatability of the probing system.

(c) Without moving the machine, the *XY* position of the bore is established as a datum. This ensures that the axis of rotation of the spindle is coincident with the hole centerline.

(d) The precalibrated probe is introduced into the measuring position by a procedure which duplicates the normal method of the machine in the production mode (that is, either manually or with a tool changer, whichever is standard procedure).

(e) The machined bore is probed using the Supplier's recommended software for bore measurement, as described in para. 7.9.2.4.1, and the center coordinates of the hole computed.

(f) The deviations of the coordinates of the center of the hole from the datum are noted.

(g) The probe is removed from the measuring position, returned to the tool changer, reintroduced into the measuring position, and the bore remeasured. Before the probe is returned to the spindle, the tool changer shall be indexed at least one position and returned in order to check the repeatability of this system.

(h) This procedure is repeated ten times.

7.9.5.2.2 The *Z*-axis workpiece location specification zone is assessed in a similar manner as follows:

(a) The previously bored part shall be faced with an appropriate facing tool, either over its complete surface or at a spot.[27]

(b) This faced surface is now probed ten times to determine its *Z* offset, returning the probe to the tool changer after each probing. Before the probe is returned to the spindle, the tool changer shall be indexed at least one position and returned in order to check the repeatability of this system.

The workpiece location specification zone for the *Z* direction is defined as the maximum deviation from the defined datum (zero) point established in the *Z*-axis, as determined by the probing system. Note that during this test the *X* and *Y* coordinates are to be the same each time the part is probed.

7.10 CNC PERFORMANCE TESTS

7.10.1 General

The following tests are designed to check the function of the machine tool controller and the programming limitation of the system.

7.10.2 Minimum Block Execution Time

The minimum block execution time (MBET) is a measure of the time it takes for the CNC to translate a G-code command, input the translation into the servo algorithms, and execute the command in the servo loop. Factors that impact MBET are number of axes programmed, number of characters per block, and buffer size of the CNC.

7.10.2.1 Test Procedure

7.10.2.1.1 Suggested Equipment. Laser interferometer.

7.10.2.1.2 Machine Warm-Up. No warm-up condition is required.

7.10.2.1.3 Test Location. No test location is specified.

7.10.2.1.4 Measurement Procedure

(a) Prepare a part program to run the machine tool in 3D (along the diagonal of the work volume), using linear interpolation.

(1) The overall travel length shall be at least three times the square of the maximum feed rate divided by the maximum machine acceleration.[28]

(2) Set the length of the line segments to 0.2 mm.

(3) The number of blocks in the part program is equal to the overall travel length divided by the length of the line segments (0.2 mm).

(4) The size of the program should exceed the buffer size of the CNC.

(b) Begin the test by running the program at 10% of maximum feed rate. Measure the actual feed rate with a laser interferometer set in the velocity mode as described in para. 7.10.5.

(c) If the feed rate is constant over the axis travel, increase the programmed feed rate. Continue to do this

[27] If desired, any appropriately flat surface properly fixtured may be used for this test.

[28] This condition assures that the overall travel length is long enough for the programmed feed rate to be reached.

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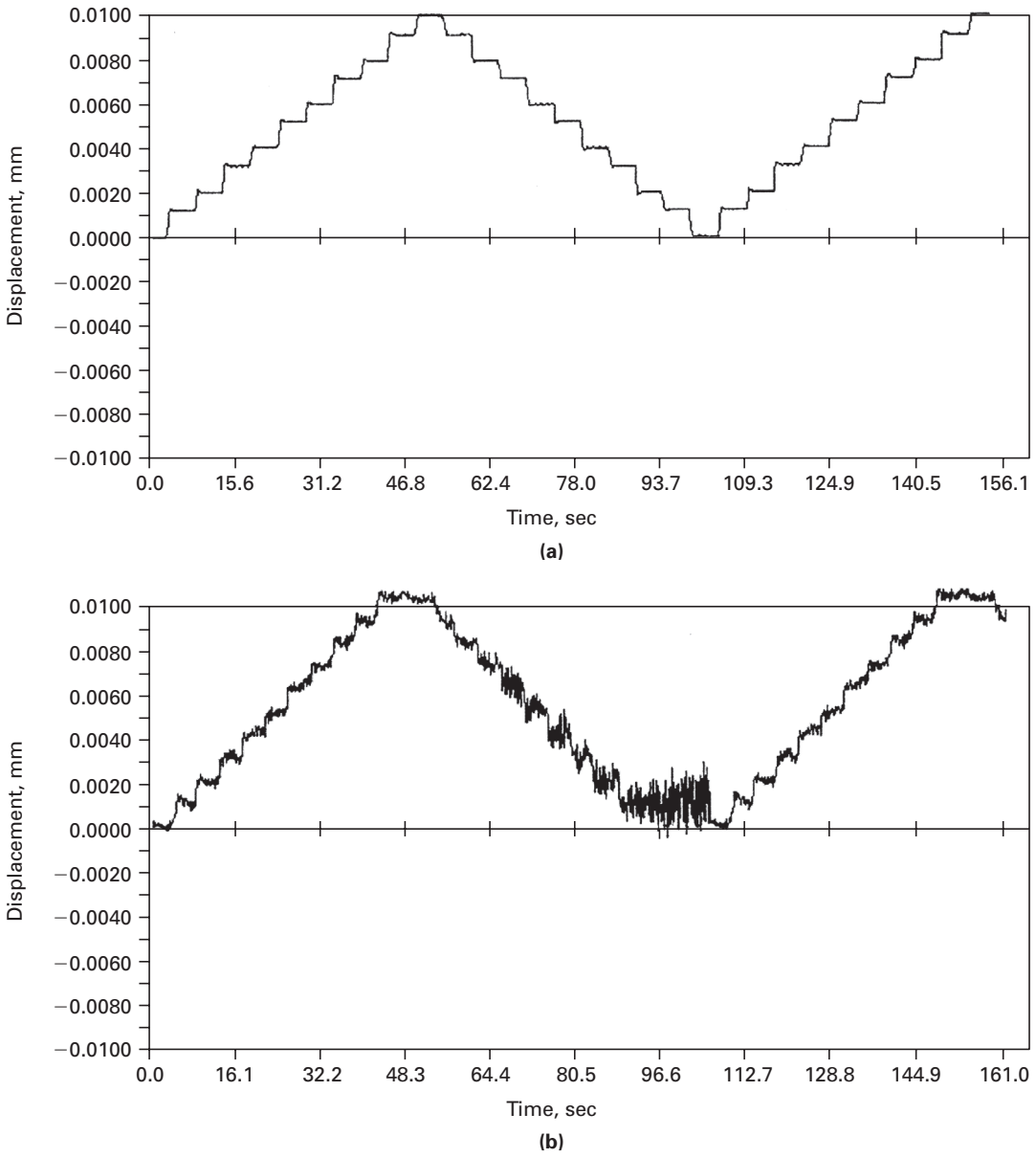


Fig. 7.49 Sample Results From the Small Increment Tests

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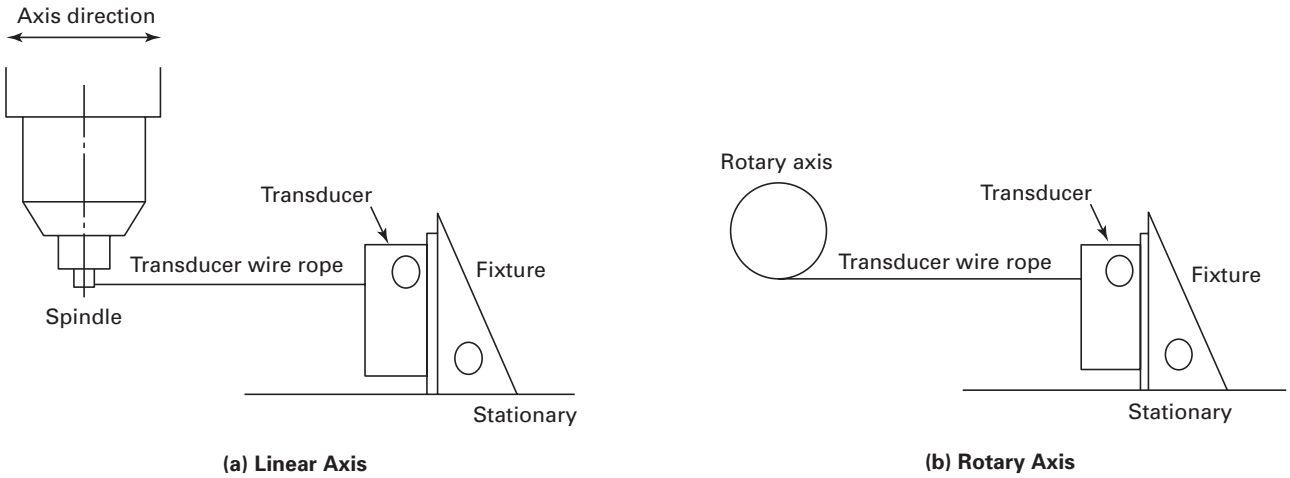


Fig. 7.50 Test Setup

until the feed rate begins to vary over the total distance.

The test program should be run from the CNC memory to determine the CNC MBET. Direct numerical control (DNC) or direct CNC networking (DCN) affects the minimum block execution time. Therefore, transfer the test program to the CNC using DNC or DCN in order to determine the overall system MBET also.

7.10.2.2 Data Analysis. Use the maximum steady feed rate measured (less than 5% fluctuation), $V_{\max,}$ to compute the block execution time (MBET) with the following equation:

$$MBET = INCR/V_{\max} \quad (7\text{-}42)$$

7.10.3 Test for Varying Segment Lengths

As in para. 7.10.2, this test moves the three cutting axes at once. The program is made up of varying line segment lengths. The line segment lengths shall range from 50% to 150% of the test line segment length used in the test in para. 7.10.2 in a random pattern. The feed rate shall be the maximum steady feed rate observed in para. 7.10.2 for the machine.

The feed rate is measured by a laser interferometer set in the velocity mode. If the feed rate varies by more than 5% during the total axis travel, the feed rate should be reduced by 5% increments until it does not vary by more than 5%. This steady feed rate should be recorded as the varying segment feed rate (VSFR). Realistic line segments and feed rates shall be negotiated between the User and Supplier.

7.10.4 Least Increment Tests

7.10.4.1 General. Machine tools are designed to operate over a wide range of feed rates and distances. Positioning accuracy and repeatability can vary greatly depending on these variables and the machine construction. The least increment test is used to determine the effect of these variations. In this test, the smallest increment at which the machine can position in a specified period of time is determined. This test also quantifies the machine's ability to make small corrections in position, which are necessary for thermal, reversal, and taper compensations. The test procedure described below applies to linear axes. However, a similar procedure can be applied for rotary machining axes. The setup for such tests is similar to the periodic angular positioning test described in para. 7.3.5.2.

7.10.4.2 Test Procedure

7.10.4.2.1 Equipment

(a) electronic gage or laser interferometer system
(b) optics for linear displacement test
(c) temperature, pressure, and humidity sensors
(d) personal computer for data gathering and analysis

7.10.4.2.2 Measurement Procedure

(a) Position the electronic gage or laser retroreflector along the axis to be measured. The distance from the spindle gage line should be measured and recorded. Note that the gage or retroreflector are placed on the spindle centerline to reduce sensitivity to spindle axis roll, and the spindle should be locked. If the spindle cannot be locked, brackets, as described in para. 7.3.2.1, should be used.

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(b) The ten positive, ten negative, and ten positive increments shall start at the resolution of the machine and shall be increased until the machine positions clearly definable steps to the commanded increment.

7.10.4.3 Data Analysis. The specification zones for the least increment test shall be defined by two parameters: least increment step and reversal errors. The least increment step is the commanded increment at which the ten negative and the second ten positive steps can be counted and overshoot does not exceed the step. The least increment reversal error shall be the amplitude of the first negative step minus the commanded increment. See Fig. 7.49.

7.10.5 Linear and Rotary Axes Feed Rate and Acceleration Tests[29]

7.10.5.1 Scope. This test is designed to measure the axis feed rate characteristics of accuracy and variability from a target value. This test is also designed to check the machine velocity profile, from which the User can identify

(a) the actual acceleration and deceleration rates of the machine

(b) the stability of the machine when changing feed rates

Rotary axis tests are only applicable for machine tools that have rotary machining axes. See Figs. 7.50 and 7.51.

7.10.5.2 Test Procedure

7.10.5.2.1 Equipment

(a) Laser interferometer with suitable dynamic data acquisition and analysis software (see Fig. 7.6 for linear axis tests only).

(b) Alternative displacement transducers with adequate frequency response, such as pullout wire positioning and velocity transducer with sampling rate of at least 200 Hz (see Fig. 7.50 for linear and rotary axes).

7.10.5.2.2 Machine Warm-Up and Test Location. These tests should be carried in similar conditions to those for positioning accuracy and repeatability tests (see para. 7.3). For rotary axis tests, the rotary axis shall be positioned at 0 deg.

7.10.5.2.3 Measurement Procedure. For each moving axis to be evaluated, two different tests shall be conducted at 10% and 100% of the maximum programmable feed rate (G01):

(a) Align the measuring equipment with the axis under test as described in para. 7.3.2.1 for linear axes, and as shown in Fig. 7.50, illustration (b), for rotary axes.

(b) The linear axis must be commanded, using two points only, to execute a simple motion.[30] The travel distance of about half the axis travel or 500 mm, whichever is the shortest, should allow the axis to accelerate, then move at constant feed rate for a distance equal to at least 10% of its total range, and then decelerate to stop.[31] The same travel distance should be used for both feed rates. For rotary axis tests, the rotary axis shall be programmed to rotate from 0-deg position to 360-deg position (one complete revolution).

(c) The test should be carried out in both positive and negative directions.

(d) Data acquisition should be made at approximately 0.01 mm intervals (for linear axis tests); alternative sampling rates are to be agreed between User and Supplier. No smoothing or averaging techniques should be used.

(e) The tests must be repeated a minimum of three times.

NOTE: The above-described test specifies that all linear axis tests shall be run using linear move (G01). This addresses the effect of acceleration and deceleration seen during contour machining. However, if acceleration and deceleration rates need to be known for point-to-point positioning cycle time evaluation, a test using positioning moves (G00) will need to be added. To see the effect of acceleration/deceleration, the added test will have to be conducted in a stop-and-go series along each axis separately. The moves will need to be of short duration but long enough to allow the maximum feed rate to be reached before deceleration starts.

7.10.5.3 Data Analysis

(a) Plot the measured velocity versus time for each test as shown in Fig. 7.51, showing positive and negative direction separately.

(b) For each direction, calculate the mean velocity and state the range of the variation as a value and percentage of the target.

(c) For each test, determine the time it takes to reach 63.2% of the programmed feed rate.

(d) Calculate the acceleration for each test by dividing the 63.2% of the programmed feed rate by the time in para. 7.10.5.3(c).

(e) The average acceleration of the machine is the average of all accelerations calculated in para. 7.10.5.3(d).

(f) Similar analysis should be done for computing average deceleration.

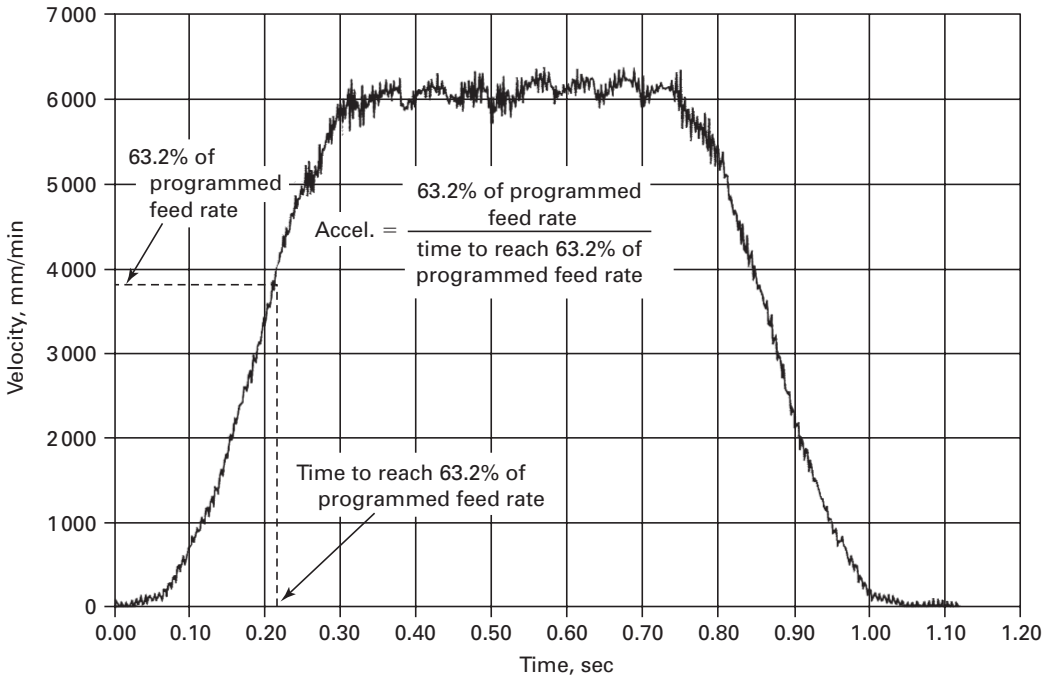
For acceptance purposes of a new machine, Supplier and customer must agree beforehand on the specifications to be met for these tests.

[29] These tests are not intended to measure the time required to index a rotary axis. This parameter is measured using a suitable timing device as the average indexing time during ten repeated back-and-forth indexing operations.

[30] In some instances, the CNC has a feature of automatically reducing feed rate and/or acceleration in order to meet the specified cutting accuracy for complex cutting paths. In this case, the selection of a straight line defined with two points only (start–end) should allow the test to be performed without the interference of this feature.

[31] Prior to these tests, two preliminary tests may be done in such a way that the distance to be traveled is not enough to allow the two programmed feed rates (10% and 100%) to be reached.

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GENERAL NOTE: Only the feature tolerances shown are to be inspected for machine acceptance.

Fig. 7.51 Sample Acceleration Plot

NOTE: A useful additional analysis would be to evaluate the data in the frequency domain by carrying out a fast fourier transform (FFT) and showing if there is any dominant frequency content in the results.

7.11 CONTOURING PERFORMANCE USING CIRCULAR TESTS

7.11.1 General

Circular contours provide one of the best checks for contouring performance evaluation. When contouring a circle, a machine is running with multiple axes along a circular path and each axis goes through sinusoidal acceleration, velocity, and position changes. Circular tests can be performed using telescoping ball bars, grid encoders, or precision disks. Each test specified shall be run at two speeds. These two speeds are approximately 10% and 80% of maximum programmable feed rate. Other feed rates may be used if agreed to by the User and Supplier. On some machines the controller will automatically slow the feed rate in order to compensate for errors. It is therefore required that the User measure the time required to perform the circular test and report the actual feed rate computed from the circle circumference and time. The radius recommended for this test is slightly less than one-half of the range of travel of the shortest axis under test or 250 mm, whichever is smaller.

During this test, the temperature sensor location shall be agreed upon between the manufacturer and User.

7.11.2 Test Procedure: All Machining Centers

7.11.2.1 Equipment

(a) machine temperature sensors

(b) circular test device (telescoping ball bar, precision disk, grid encoder, etc.)

7.11.2.2 Measurement Procedure. An NC program using circular interpolation (linear interpolation can be used as an option to the circular interpolation) is now prepared to move the machine in a 360-deg circle in the test plane. Examples of circle test setups are shown in Fig. 7.52. Although full circle is strongly recommended, for some machine configurations only partial circles may be possible. The acquired circular test data must be reduced to a polar plot so that the residual eccentricity of the measuring instrument can be eliminated. All circular tests shall be carried out with the machine in the unloaded condition (without workpiece).

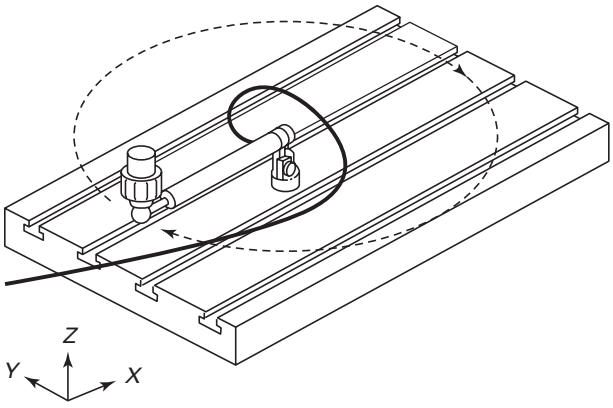
7.11.2.3 Parameters. Parameters of the test are

(a) diameter (or radius) of the nominal path

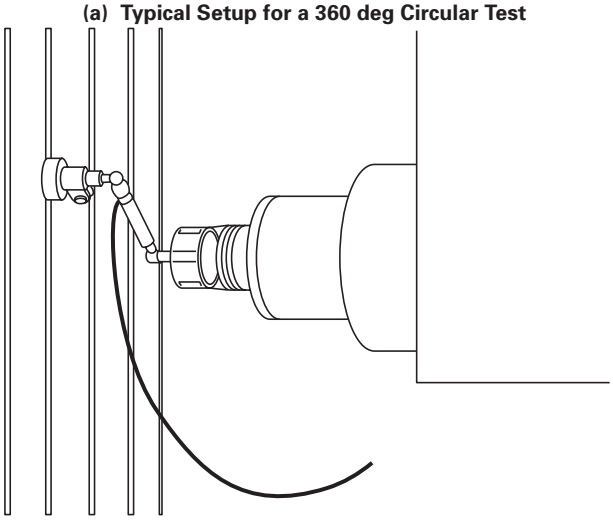
(b) contouring feed

(c) contouring direction (clockwise or counterclockwise)

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(a) Typical Setup for a 360 deg Circular Test



(b) Example of Setup for Horizontal Spindle Machine

Fig. 7.52 Examples of Circle Test Setups

(d) machine axes moved to produce the actual path

(e) location of the measuring instrument in the machine working zone

(f) temperature (measuring instrument and machine temperature[32]) for the radial deviation measurement only

(g) data acquisition method (data capture range if different from 360 deg, starting and ending points of the actual movement, number of measuring points taken for digital data acquisition)

(h) any machine compensation routines used during the test cycle

(i) position of slides or moving elements on the axes which are being tested

(j) programming techniques (G01, G02, G03)

7.11.3 Data Analysis

For each circular test, the circular deviations for clockwise, $G\uparrow$, and counterclockwise, $G\downarrow$, contouring, and the radial deviations, F_{max} and F_{min}, for clockwise ($\uparrow$) and counterclockwise ($\downarrow$) contouring, shall be reported, as well as the measured feed rates in the clockwise and counterclockwise directions (see Fig. 7.53). The circular deviation is the minimum radial separation of two concentric circles that will envelop the actual path. Finally, the radial deviations are the maximum deviation from the true ball bar length, corrected to 20°C using the NDE correction. (See Chapter 4.) For the purpose of this

[32] A better estimate of the machine representative temperature for this test will be obtained if the temperatures of the relevant machine scales were measured during this test. Any of the two scale temperatures can be used for the NDE correction.

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ASME B5.54 (2002)
Example Data
Operator: A. N. Other
Date: Mar-20-2002 Time: 13:50

Machine: Example machine
Instrument: Dynamic ball bar

Circular Deviation	
Value (CW)	100.0 μm
Value (CCW)	106.6 μm
Radial Deviation	
Min. value (CW)	-150.7 μm
Max. value (CW)	-50.7 μm
Min. value (CCW)	-159.4 μm
Max. value (CCW)	-52.8 μm
Calculated Feed Rate	
Value (CW)	3012.0 mm/min
Value (CCW)	3012.0 mm/min
Test Parameters	
Radius	150.0000 mm
Sample rate	18.750 Hz
Feed rate	3000.0 mm/min
Run sequence	CCW CW
Plane under test	*XY*
Test position	
Start angle	0 deg
End angle	360 deg
Overshoot angle	180 deg

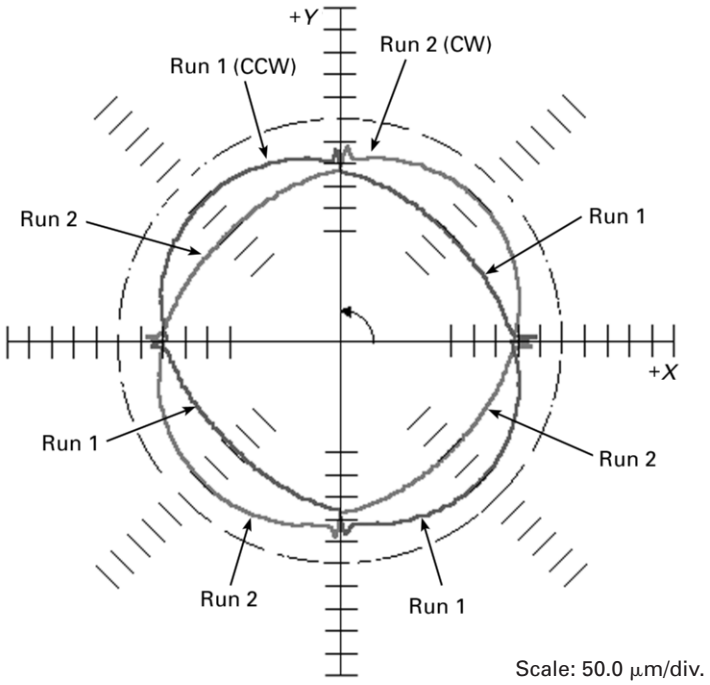


Fig. 7.53 Typical Results From a 360 deg Circular Test

Standard, the manufacturer of the circular test instrument shall supply an effective coefficient of the thermal expansion for the instrument and recommendations as to appropriate calibration procedures, where applicable.

7.11.4 Additional Measurement Procedures: Four- and Five-Axis Machining Centers

Four- and five-axis machines can be built in a wide variety of configurations. Because of this high variability, a simple test suited for all these machine types has not been developed. It is recommended that circular tests for three-axis machines be used on these machines, exercising the rotary as well as the linear axes wherever possible. Users are advised to work closely with the Supplier of such machines and develop tests suitable for the particular geometry required. Appendix J shows a set of recommended patterns. These tests shall be specified in detail equivalent to that of the other circular tests in this Standard, as part of the initial machine specification.

7.11.5 Other

At the time of issuance of this Standard, other circular test instruments were in the process of development and testing. The use of any of these instruments is suitable, as long as the instrument system is able to perform the same task with the required accuracy defined in this Standard.

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Chapter 8
Machining Test Parts

8.1 GENERAL

Machining test parts has an important role in the acceptance testing of machining centers. The machining accuracy is checked under a limited set of machining conditions, to arrive at standard means of machine comparison. Since such tests necessarily include factors that may not have any direct relation to the machine tool, such as materials variation, tooling variations, thermal effects of cutting, and fixturing variations, careful attention must be paid to the minimization of these effects for accurate comparison of different machining centers.

The User of this Standard may require testing of the machine on the specific parts (referred to as production-part runoffs) for which it is initially purchased, as discussed in para. 8.4. The User may also specify other machining tests, provided specifications are supplied in equivalent detail.

Test parts may be used simply to provide assurance that the machine is functioning as expected or can be used as a part of the machine specification for establishing the conditions of machine acceptance. The acceptance specifications on all of the features in the test part shall be supplied as part of the initial machine specification for each of the test parts to be machined.

Using test parts alone to determine machine accuracy and acceptance is not recommended. The machine performance is best tested by the procedures outlined in the preceding chapters of this Standard. It is recommended that the test parts machining is done as one of the last acceptance tests, after the machine passes all the other acceptance tests agreed upon between the User and the Supplier. Any change in machine performance would affect the results obtained from machining test parts.

8.1.1 Types and Sizes of Test Parts

There are five types of test parts in this Standard, as shown in Table 8.1. One or more of these test parts could be used based on agreement between the User and the Supplier.

The sizes of test parts can be scaled or modified to suit the applications of the User. The test part(s) shall be selected so that the size is appropriate for the machine size, with the size of the test part approximating the size of parts that will be produced on the machine. If the machine is extremely large and if the cost of the test part or the time involved in machining is prohibitive, then it is recommended that more than one part be utilized for these tests, with these parts placed in more than one location on the machine. If the size is modified, appropriate tooling and process parameters should be used to suit the modified test part. Whenever the test parts specified in the Standard are modified or new test part(s) have been agreed upon by the User and the Supplier, procedures and acceptance specifications for machining such test parts should be provided in equivalent detail.

8.1.2 Location of Test Parts

In general, the test part shall be placed as close as possible to the position where operations will be performed on the machine in production. The test parts, however, shall be machined at different locations based on the applications of the User, subject to agreement by the User and the Supplier. For example, on a long-bed machine, parts could be placed at each end and at the center of the bed to provide some coverage of the entire work zone, whereas on some machines, the test parts could be placed only at the center of the work zone.

8.1.3 Material of Test Parts

The material of the test parts is subject to agreement between Supplier and User and shall be recorded. Depending on the material chosen for test parts, appropriate process parameters and tooling shall be selected.

8.1.4 Tooling and Fixturing

The tooling used for machining test parts in this Standard shall be standard tooling, thoroughly inspected to ensure tool accuracy. If agreed to by Supplier and User, inserts can be changed between cuts to minimize the effects of tool wear. The inspection of the tool shall include all components of the system, such as tool, tool holders, adapters, etc., to ensure that any deviation from requirements is either noted or corrected before commencing machining tests. The fixtures should be designed so that the effect on part accuracy from fixture-induced deflections is insignificant.

8.1.5 Procedure

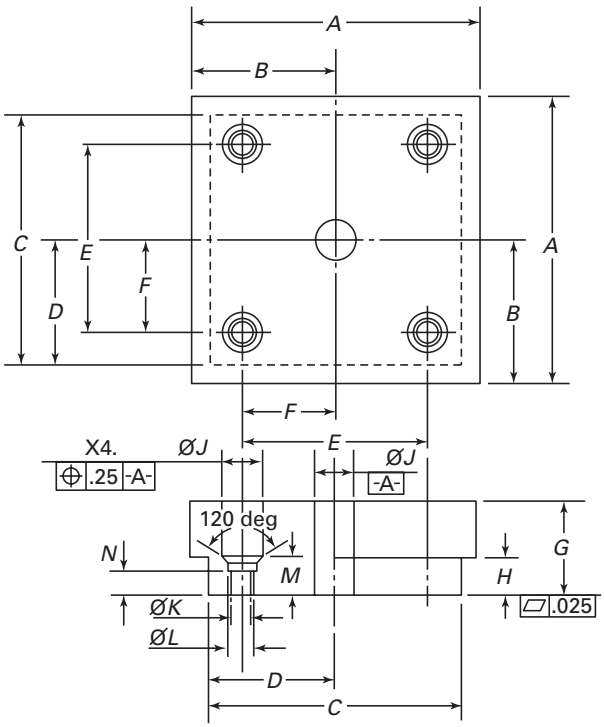
Procedures shall be thoroughly defined and agreed upon by both Supplier and User. Test part material, tools, process parameters (feeds, speeds, depths of cut), and the part program shall be thoroughly documented and tested before commencing any test. The machine should be warmed up by moving the machine axes for

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Table 8.1 Types and Sizes of Test Parts

Paragraph	Test Part Name	Referenced Standard	Applicable Machining Center Type
8.2	Precision contouring test part	ISO 10791-7 [Note (1)]	Machining centers with 3 or more axes
8.3	Transverse tilt machining test part	NAS 979, Section 4.3.3.6.1	Machining centers with 4 or more axes
8.3	Longitudinal tilt machining test part	NAS 979, Section 4.3.3.7.1	Machining centers with 4 or more axes
8.3	Profile cone frustum machining test part	NAS 979, Section 4.3.3.8.1	Machining centers with 5 or more axes
8.4	Production parts	. . .	All machining centers

NOTE:
(1) Modifications have been made to the part and inspection procedure.



Dimension	Size 1, 160 mm Square	Size 2, 320 mm Square
A	170	330
B	85	165
C	140	280
D	70	140
E	104	200
F	52	100
G	55	85
H	20	42
J	22	41
K	11	17
L	18	26
M	18	40
N	10	26

Fig. 8.1 Precision Contouring Test Part Test Piece Blank

a minimum of 1 hr before starting this test. The test setup(s) should be constructed and tested before beginning the machining tests. Furthermore, attention should be paid to the temperature at which the part is machined so that the dimensions of the part are correct at 20°C. This documentation shall be retained as part of the test record.

8.1.6 Inspection

Measurement of the temperature of the test part, the machine, and the ambient air is recommended, and corrections for thermal expansion shall be applied when differences exist between the inspection temperature and 20°C.

Test equipment and instrumentation used to inspect all test parts shall comply with the requirements in para. 11.11.

8.2 PRECISION CONTOURING MACHINING TEST: ALL MACHINING CENTERS

This machining test and procedures for inspection are designed to provide data to determine the following characteristics of the machine tool:

(a) positioning accuracy and repeatability in the *X*-, *Y*-, and *Z*-axes

(b) deflection of the machine head under cutting load

(c) squareness of the *X*- and *Y*-axes

(d) angular and circular profiling capability in the *X*- and *Y*-axes

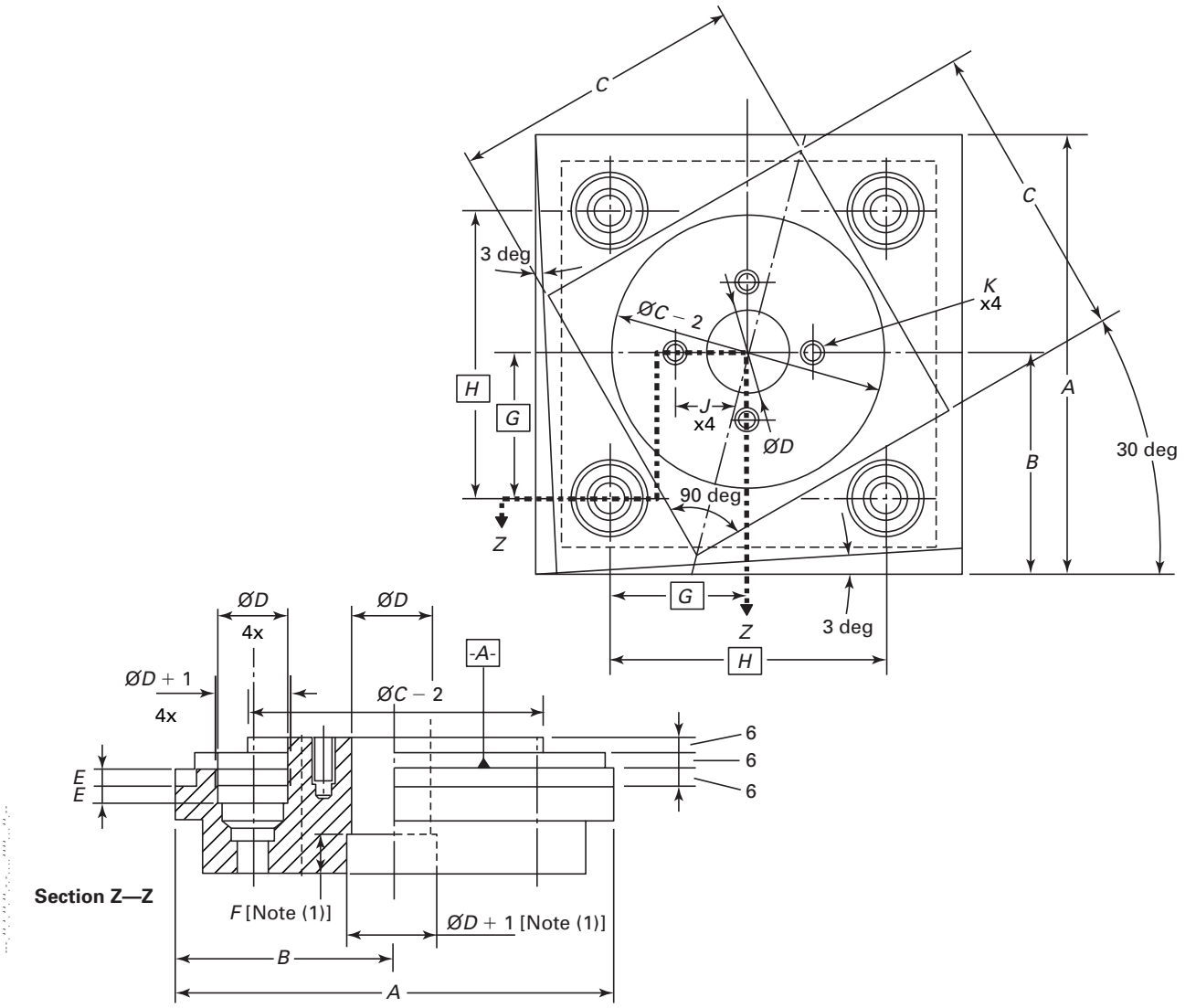
The test piece blank (see Fig. 8.1) may be mounted on a subplate, angle bracket, or tombstone fixture, depending on the configuration of the machining center being tested.

Two sizes of test piece are shown in this Standard, size 1 (160-mm square) and size 2 (320-mm square). See Figs. 8.2 and 8.3. The choice of the test piece size and material to be used for machine acceptance should be determined at the contract stage of purchase and will depend on the size of the machine and its intended use.

8.2.1 Location of Test Pieces

Extreme location positions for the test piece should only be adopted by agreement between the Supplier and the User. Unless otherwise specified, the test piece

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Dimension	Size 1, 160 mm Square	Size 2, 320 mm Square	Dimension	Size 1, 160 mm Square	Size 2, 320 mm Square
A	160	320	*F*	25	40
B	80	160	*G*	52	100
C	110	220	*H*	104	200
D	26	45	*J*	35	65
E	6	10	*K*	M4 X 0.7 8 deep	M12 X 1.75 20 deep

GENERAL NOTE: Only the features dimensioned in the above figure are machined during the test cut. See Fig. 8.3 for geometric control features.

NOTE:

(1) Only on machines where test part is mounted on a rotary or index table.

Fig. 8.2 Precision Contouring Test Part Machining Dimensions

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should be placed approximately at mid-travel of the *X*-axis and in positions along the *Y*- and *Z*-axes suitable for the location of the test piece and/or fixture and for the tool lengths employed.

8.2.2 Number of Test Pieces

In principle, no more than one test piece should be machined for acceptance purposes. In case of special requirements, such as statistical assessment of the machine performance, the machining of more test pieces is to be submitted to the agreement between Supplier and User.

8.2.3 Multiple Usage of Test Piece Blanks

The same contouring test piece may be machined several times, with the consequent reduction of external dimensions and increase of hole diameters. When such a test piece is used for acceptance purposes, it is recommended that the final test piece should comply with the dimensions specified in the present Standard, so as to represent the cutting accuracy of the machine.

If the contouring test piece comes from previous cutting tests and is reused, its characteristic dimensions should remain within ±10% of those indicated in this Standard. When the test pieces are reused, a shallow cut shall be made to clean up all surfaces before new finishing cuts are taken.

It is also recommended that type and serial number of the machine, date of the test and designations, and orientation of the axes be marked on the test piece and that they be delivered with the machine for reference purposes.

8.2.4 Temperature Measurement

Temperature difference has a significant effect when testing machine tools and must always be considered.

8.2.5 Inspection Method and Requirements

Inspection methods for test pieces shall be agreed upon between the User and the Supplier. Test equipment and instrumentation used to inspect the precision contouring test part shall comply with requirements in para. 11.11.

Figure 8.2, Fig. 8.3, and Form 8.1 specify the machined features of the test part to be inspected, and the results are to be used to evaluate the accuracy and acceptability of the machine tool. These are the only features to be measured for evaluation purposes. There are no surface finish requirements applied to these tests.

8.2.6 Programming and Cutting Techniques

Acceptable programming and cutting techniques, consistent with the test part material, the cutting tools employed, and the machine tool's design capabilities, shall be used.

The four bored holes, datums (-*D*1- through -*D*4-) shall be approached in the positive *X*- and *Y*-axes directions to the final boring location. Their counterbore (*D*+1) locations shall be approached in the negative *X*- and *Y*-axes directions.

Also, to test the effect of tool change repeatability on the size of bored holes, the boring tool producing the four counterbored holes (*D*+1) shall be returned to the tool storage after machining each of the four counterbores.

8.3 MACHINING TESTS FOR FOUR- AND FIVE-AXIS MACHINING CENTERS

To verify the accuracy of four- and five-axis machining centers under cutting loads, for the purposes of this Standard, the following tests as given in NAS 979 shall be performed:[1]

(a) transverse tilt machining test (NAS 979, para. 4.3.3.6.1, Transverse Tilt Test)

(b) longitudinal tilt machining test (NAS 979, para. 4.3.3.7.1, Longitudinal Tilt Test)

(c) cone frustum machining test (NAS 979, para. 4.3.3.8.1, Profile — Cone Frustum)

Other tests may be substituted if they are specified in equivalent detail.

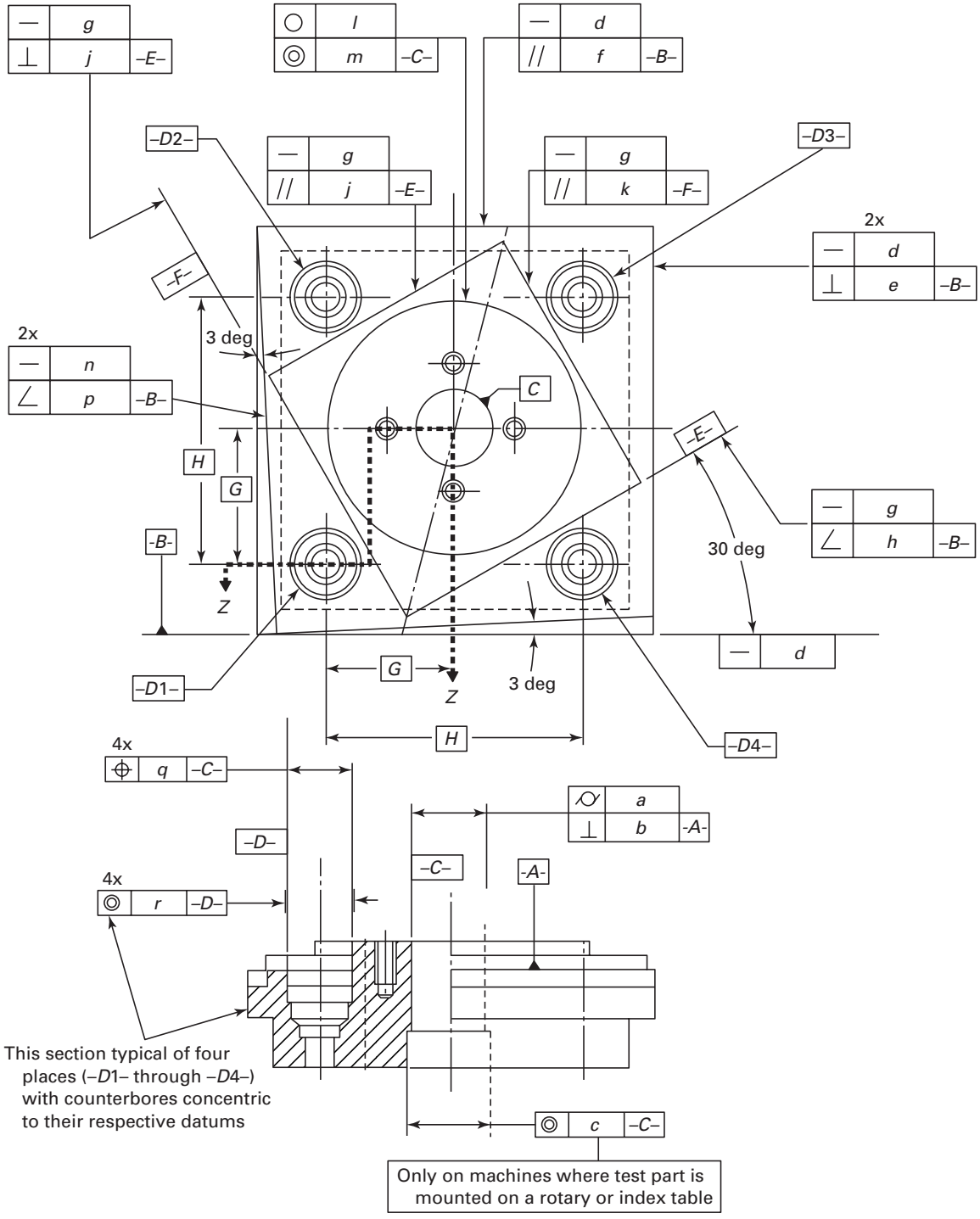
8.4 PRODUCTION PARTS

Where the machine is to be used in producing a single part or a family of parts, the best machining test to determine machine capability would be a run of production parts or parts that are as close to the production part as possible. This paragraph is included to allow the machine User to specify the machine performance on selected parts, with the performance criteria on these parts specified in equivalent detail to the other machining test parts specifications in this Standard. Such tests are not of great value in assessing machine performance over the long term, except for dedicated equipment. They do, however, provide the User with more rapid start-up and thus are of significant economic value.

In this case, the machine shall be started and allowed 1 hr for warm-up. The first part shall be cut and checked and any corrections to the tooling or programming made at that time. A minimum of 30 parts is recommended to obtain statistically valid information. This shall be subject, however, to agreement between the User and the Supplier. The machine shall be kept running between the various test cuts in a dry cycle to increase thermal stability of the machine without requiring an excessive amount of material to be run and inspected for test cutting.

[1] Tolerances to be agreed between the User and Supplier.

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GENERAL NOTES:

(a) Only the feature tolerances shown are to be inspected for machine acceptance.

(b) See Table 8.2 to record predetermined tolerance and inspection results.

Fig. 8.3 Precision Contouring Test Part Inspection Requirements

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Form 8.1 Precision Contouring Test Part Inspection Results

Inspection Feature	To Be Agreed Between Supplier and Customer			Actual Test Results	
	Feature Tolerance	Size 1 160 mm	Size 2 320 mm	Size 1 160 mm	Size 2 320 mm
Cylindricity /O/ of bore datum -*C*-	*a*				
Squareness ⊥ of bore datum -*C*- to surface datum -*A*-	*b*				
Concentricity ⊙ of *C*/bore to bore datum -*C*-	*c*				
Straightness — of all (4) sides of square	*d*				
Squareness ⊥ of (2) adjacent sides of square to datum -*B*-	*e*				
Parallelism // of opposite face of square to datum -*B*-	*f*				
Straightness — of (4) sides of canted square	*g*				
Angularity ∠ of 30 deg face, datum -*E*- to datum -*B*-	*h*				
Squareness ⊥ of datum -*F*- to datum -*E*-	*j*				
Parallelism // of opposite faces of datums -*E*- and -*F*-	*k*				
Circularity, O, of contoured circle	*l*				
Concentricity ⊙ of contoured circle to datum -*C*-	*m*				
Straightness — of two 3 deg angular faces	*n*				
Angularity ∠ of two 3 deg faces to datum -*B*-	*p*				
True position ⊕ of (4) bored holes, datums -*D*1- through -*D*4- to datum -*C*-	*q*				
Concentricity ⊙ of (4) *C*/bored holes to their respective datums -*D*1- thru -*D*4-	*r*				
(4) *C*/bored holes (*D*+1) same size diameter within given tolerance(s) (*D*+1) max. – (*D*+1) min.	*s*				

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Chapter 9
Cutting Performance Tests

9.1 GENERAL

In the performance of a cutting operation, the following types of "errors," or limitations, may arise:

(a) The drive cannot deliver the necessary torque, and it either stalls or the machine breaks. This leads to a test of the ability to use the rated torque. A preliminary to this test is the test of spindle idle run losses.

(b) Chatter occurs. In roughing cuts this leads to excessive vibratory forces that may damage the tool and cause chatter marks on the surface in finishing cuts.

(c) In stable cuts (without chatter), the deflections in the tool/spindle/structure/fixture/workpiece system cause errors of position and profile of the machined surface.

(d) Other kinds of problems may arise, such as failures of the coolant delivery system, leakage of oil from the spindle lubricating system, clogging of chips in the chip removal system, etc., that cannot be quantified and constitute what is distinguished from tests by calling them simple checks. These are not discussed any further in this Standard.

The limitations in paras. 9.1(a) through (c) must be determined in well-organized tests performed under carefully selected conditions. For practical reasons, the tests are organized in the following sequence:

Step 1. *Spindle Idle Run Loss Test.* This test is carried out first to measure the power available for the cutting tests.

Step 2. *Chatter Limits and Full Torque Test.* Measurements of these two limitations are combined in a series of tests during which one or the other limitation prevails. Both these limitations occur decisively in milling (particularly in end milling), and these limitations do not have to be tested in any other of the various cutting operations, such as boring and drilling, commonly performed on machining centers.

Step 3. *Cutting Force Induced Error Tests.* These test the errors of position and flatness of the machined surface due to deflections in the system and their imprint on the surface. Two tests are specified: the end milling deflection test and the face milling deflection test.

9.1.1 Conversion Factors

This Chapter is completely in metric. Because of the complexity of the tables, our usual practice of including the English approximation immediately following the metric number will be deviated from here. Instead, Table 9.1, which has conversion factors from metric to English for all of the units used in this Chapter, has been provided.

Table 9.1 Metric to English Conversion Used in This Standard

Metric	English
25.4 mm	1.00 in. (exact)
746 W	1 hp (U.S.)
750 W	1 hp (metric)
1 mm/N	0.175 in./lb approximate
1 N/mm^2	145 $lb/in.^2$ approximate

9.2 COMPLETE SET OF TESTS

A complete set of tests of a machine's dynamic performance is summarized in Appendix G. These include measurements of the machine's structural dynamics as well as cutting performance. If the machine tool Supplier has investigated the particular model of the machine tool concerned in considerable detail and has established the complete set of characteristics, then these shall be offered to the User upon request. These characteristics are assumed to be repeatable for all the individual machines of a particular model. It is further assumed that the User will want a limited selection of the complete set of tests to be carried out for verification that the machine being supplied possesses characteristics close enough to those being specified. It is these limited verification tests that are fully defined in this Standard. If the Supplier cannot provide the data described above and in Appendix G, two options are possible: either the Supplier provides a limited set of data as described below or default values of the required parameters are used.

9.2.1 Limited Data Set From the Complete Set

At the present stage of general practice of machine tool testing, it is not considered possible to require the Supplier to provide all the machine characteristics described in Appendix G. However, to obtain some guidance for the cutting performance tests, the following data should be supplied by the machine tool Supplier. (If this limited data set is not available, default values for the test parameters are given; however, this may

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sometimes lead to unsatisfactory results.)

For each of the tool/tool holder combinations selected for a cutting performance test (see para. 9.5), a limited set of structural dynamic parameters should be supplied to the customer. These parameters have been defined in Appendix G. They are the natural frequency of the dominant mode, f_n, and its dynamic compliance (the amplitude of the imaginary part of the transfer function at f_n), H_c, in each of the two feed directions orthogonal to the spindle axis of rotation.[1] These two feed directions are called X and Y in this Standard. The natural frequency data will be used for choosing the spindle speeds for the chatter test and the accuracy test. The magnitude will be used for estimating the initial depth of cut in the chatter test. Four examples of measured transfer functions are presented in Fig. 9.1. In each case the imaginary part of the transfer function, Im(G), is plotted on a linear scale of compliance, in micrometers per newton, versus frequency. In graph (a), a simple transfer function in one direction is shown that contains only one dominant mode. In this case the choice of the frequency and the magnitude of the compliance to be chosen is clear. In graph (b), an example is shown of a transfer function where there are two modes of approximately equal compliance. In this case the lower frequency mode shall be chosen. In cases (c) and (d), the transfer functions are rather complicated and differ significantly in the two basic directions. In cases such as these, the procedure referred to in footnote 1 shall be followed.

9.3 MACHINING CENTER RANGES

For selecting tools, workpiece materials, and spindle speeds, machining centers are classified into several ranges according to available spindle speed and torque. These classifications are given in Table 9.2. In general, chatter and accuracy depend on the same cutting parameters as the torque. Their limits also depend on the dynamic stiffness between the tool and workpiece. Therefore, it is proper to require more stiffness from machines with higher torques. These machines will have larger diameter spindles and generally heavier structures. The torque, T_q, is related to the power, P_w, by

$$T_q = \frac{60P_w}{2\pi n_{rpm}} \tag{9-1}$$

where

n_{rpm} = spindle speed, rpm
P_w = power, W
T_q = torque, N-m

[1] In some cases there will be a number of closely spaced natural frequencies. In such cases the Supplier shall supply the complete real and imaginary parts of the transfer function, or a separate agreement should be reached between User and Supplier. (See Appendix G.)

9.4 SPINDLE IDLE RUN LOSS TEST

This test is performed first. It measures the economy of the drive and potential heat sources. It is also useful, for the cutting tests, to know the actual power available on the spindle at the various speeds.

In this test the spindle is run idle in five steps over its total speed range and, using a wattmeter, the power required is recorded and a graph like the one in Fig. 9.2 is produced. The measured lost power includes losses in the electric drive as well as those in the transmissions and bearings. It has been sufficiently established that these losses are little affected by the useful load on the spindle. The net available power shall correspond to that provided in the specifications of the machine tool.

9.5 CHATTER LIMITS TESTS AND FULL TORQUE TEST

In general machine tools, their spindles and their tool holders shall be so designed as to provide enough dynamic stiffness to allow chatter-free milling within the whole range of available torque, speed, and power. Machines should not be equipped with drives with more torque and power than is utilizable in stable chatter-free cuts.

However, it is conceivable that chatter-free machining is obtainable under most conditions with short rigid holders, but not under some exceptional circumstances. At other times it also happens that machines are not rigid enough and chatter limits the metal removal rates under almost any conditions. The purpose of the chatter test is to distinguish between machines with equal torque and power but different degrees of rigidity and stability.

Before the actual test procedure is discussed, the conditions for the test are described. Conceptually, the test is rather simple. The machine is used to mill test parts of different materials using standard tools. The depth of cut is varied at different radial immersions until chatter is perceived. The depth of cut where chatter occurs at the different radial immersions is used as the cutting performance criterion. The major complexity comes in establishing the cutting conditions and the spindle speeds to obtain comparable results.

9.5.1 Materials for the Chatter Limit Test and Full Torque Test

The chatter limit test is conducted using 4340 steel, 300–350 Brinell hardness number (BHN), with a face mill and an end mill with inserts, and 7075-T6 aluminum using a solid end mill. The full torque test is carried out using face milling 4340 steel (300–350 BHN) only. Details of the tooling, other machining parameters, and the test part geometry are given in the following paragraphs.

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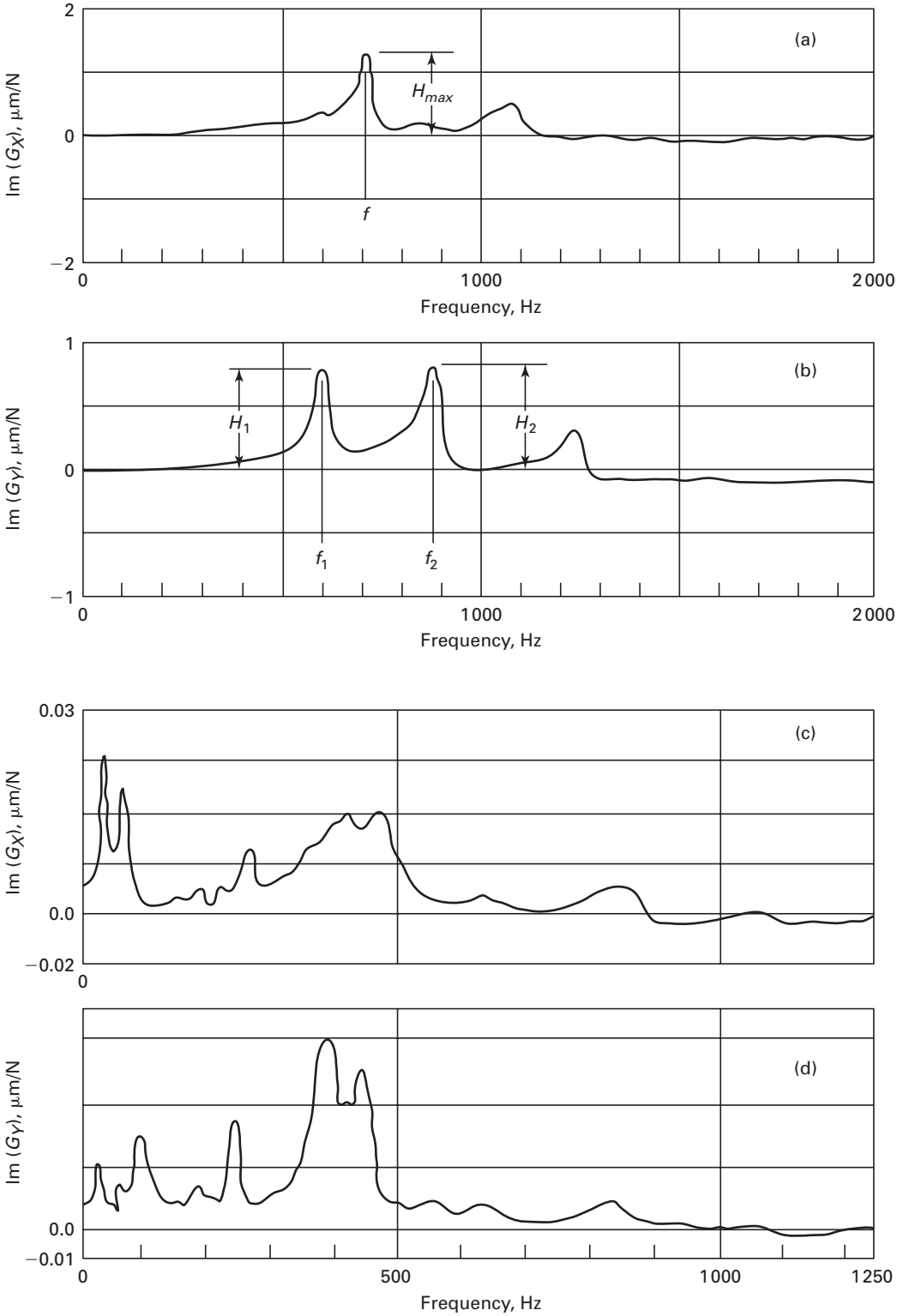


Fig. 9.1 Typical Transfer Functions

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Table 9.2 Machine Center Ranges

Machine Range	Maximum Torque, N-m
A. Very light	‹10
B. Light	10–25
C. Medium light	25–65
D. Medium	65–150
E. Medium heavy	150–375
F. Heavy	375-750 [Note (1)]

NOTE:
(1) For machines with higher torque spindles, no recommendations for tool dimensions and test conditions are given in this Standard. For these machines, the Supplier shall provide recommendations for appropriate parameters, and they chould be specified in equivalent detail to those given in this Standard.

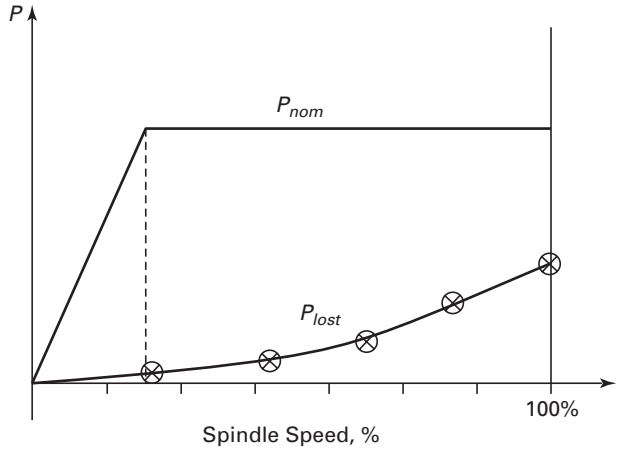


Fig. 9.2 Typical Plot of the Power Loss in the Spindle Idle Run Loss Test

9.5.2 Coolant

The chatter tests and the full torque test are designed to be run without coolant; however, in the case of machining of aluminum, coolant may be used if desired by the machine User.

9.5.3 Chip Load

Chatter limits do not depend on chip load. Therefore, the test is carried out with light chip loads, $c = 0.15$ mm for the face mills and $c = 0.1$ mm for the end mills. Even so, it is necessary to watch for torque (or power) overload during the chatter test. Once the chatter limits are found without reaching full torque (or power), the full torque test is carried out in face milling at double the chip load, $c = 0.3$ mm. For convenience, these chip loads are summarized in Table 9.3.

9.5.4 Spindle Speeds

The choice of spindle speed is, first of all, dictated by empirical tool life data. This limits the spindle speed so as not to exceed a particular cutting speed on the periphery of a cutter that is known, for a particular combination of workpiece/tool materials, to give satisfactory tool life. From a practical point of view, this limitation does not exist for aluminum because both high-speed steel tools and carbide tools can cut aluminum at very high speeds with little wear. For the 4340 steel (300–350 BHN) we choose a cutting speed of 120 m/min. The corresponding spindle speed, n_T, is then

Table 9.3 Chip Loads for Cutting Performance Test

Cutting Test	Chip Load, mm/Tooth
Chatter: face mills	0.15
Chatter: end mills	0.10
Full torque	0.30

$$n_T = \frac{120{,}000}{\pi d} \tag{9-2}$$

where
d = tool diameter, mm
n_T = maximum spindle speed, rpm, for acceptable tool life

From the point of view of chatter, there are two further limitations as follows:

(a) Tests shall not be done at such low speeds that chatter is suppressed by process damping. This would be a way of avoiding chatter by sacrificing metal removal rate. This rule leads to the requirement of a minimum spindle speed $n_{\min}$ for the chatter tests (see Appendix G). To determine $n_{\min}$, it is necessary to know the natural frequency, f_n, of the dominant mode in each axis direction, as specified in para. 9.2.1. For our purposes:

$$n_{\min} = \frac{29 f_n}{d} \tag{9-3}$$

where
d = tool diameter, mm
f_n = natural frequency, Hz, of the dominant mode
$n_{\min}$ = minimum speed, rpm, for the chatter test

(b) On the upper side, the choice of spindle speed is complicated by "lobing effects" (see Appendix G). At higher speeds, chatter may strongly depend on spindle speed and stable regimes are possible. Although this is definitely beneficial for the process, it may produce test results on the better side and obscure the potential of much less stability at different speeds. Therefore, unless the lobing diagram is available, it is recommended to use a speed, $n_{\max}$, as a general limitation for the test speed. This speed is chosen to have a cutting frequency of 0.8 of a third of the natural frequency of the dominant mode. That is,

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Table 9.4 Standard Tools and Default Machine and Cutting Parameters for the Face Milling Chatter Test(s)

Workpiece Material: Steel 4340 (Chip Load $c = 0.15$ mm/Tooth)

	Machine Class									
Variable	B		C		D		E		F	
d, mm	50		75		100		100		150	
m	4		6		8		8		12	
	Holder									
Variable	R	L	R	L	R	L	R	L	R	L
L, mm	0	N/A	0	50	0	100	0	125	0	150
H_c, μm/N	0.80	N/A	0.50	0.90	0.20	0.55	0.10	0.30	0.08	0.25
f_n, Hz	600	N/A	550	400	500	350	500	350	550	380
n_{min}, rpm	340	N/A	210	160	145	100	145	100	100	75
n_{max}, rpm	2 400	N/A	1 500	1 100	1 000	700	1 000	700	740	500
n_s, rpm	9 000	N/A	5 500	4 000	3 750	2 650	3 750	2 650	2 750	1 900
n_T, rpm	763	N/A	510	510	380	380	380	380	250	250
b_{cr}, mm	0.45	N/A	0.5	0.3	0.95	0.35	1.9	0.65	1.5	0.5
T_{cr}, N-m	4.5	N/A	11.5	6.5	37.5	13.5	75	25	140	45
P_{cr}, W	344	N/A	585	331	1 425	513	2 850	950	3 500	1 125

GENERAL NOTES:

(a) In all instances the n_T speed must be chosen.

(b) Class A machine is not included. It is designed for end milling and drilling only, no face milling.

$$n_{max} = \frac{16 f_n}{m} \tag{9-4}$$

where

f_n = natural frequency, Hz, of the dominant mode
m = number of teeth on the cutter
n_{max} = maximum spindle speed for normal testing, rpm

With these values of n_{min} and n_{max}, we may now formulate the following rules for the choice of spindle speeds for the tests. This choice depends on the extent of the dynamic characteristics supplied by the Supplier of the machine tool. The rules are labeled spindle speed rules 1 through 4.

9.5.4.1 Spindle Speed Rule 1. The characteristic data, as described in Appendix G, are available in a general form such that they apply to the use of the standard set of tools and to other tools and feed directions, or else there is a provision for an automatic regulation to stable speeds. In this case, use only the most stable speed available. (Because the stability of such a machine type is well characterized, only one spindle speed is required for the chatter test in this case.) If a separate test is required to check the recommendations or the functioning of the speed regulating system, such a test shall be negotiated between Supplier and User, as part of the initial machine specification.

9.5.4.2 Spindle Speed Rule 2. The characteristic data as discussed above are available, including the lobing diagrams for only the standard tools, radial immersions, and feed directions. Use the formula to determine n_{min} and avoid process damping. Then choose two speeds, both greater than n_{min}, with the first one, n_1, coinciding with the highest speed available of the "stable speeds." The stable speeds, n_s, are given by

$$n_s = \frac{60 f_n}{jm} \tag{9-5}$$

where

f_n = frequency of the dominant mode, Hz
j = an integer ($j = 1, 2, 3...$)
m = number of teeth on the cutter
n_s = stable speed, rpm

This choice also must not violate the acceptable tool life criterion when machining steel. The second speed, n_2, shall be the first "critical" speed lower than n_1. A "critical" speed is a speed that corresponds to the frequency at the bottom of a lobe, as described in Appendix G. In this way, the range between the "critical" stability (the minimum expected stability) and the stability at stable speeds is determined.

9.5.4.3 Spindle Speed Rule 3. Only the minimum characteristics are available, as specified in para. 9.2.1.

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Table 9.5 Standard Tools and Default Machine and Cutting Parameters for the Chatter Tests Using Solid (HSS or Carbide) End Mills

Workpiece Material: Aluminum 7075-T6 (Chip Load $c = 0.1$ mm/Tooth)

	Machine Class											
Variable	A		B		C		D		E		F	
d, mm	12.5		19		25		38		50		50	
l, mm	30		50		75		75		75		125	
m	2		4		4		6		6		6	
	Holder											
Variable	R	S	R	S	R	S	R	S	R	S	R	S
H_c, μm/N	1.0	0.5	3.6	0.6	2.4	0.4	1.4	0.26	0.36	0.14	0.17	0.07
f_n, Hz	1 400	1 600	700	1 300	450	1 300	600	840	600	800	900	1 000
n_{min}, rpm	3 250	3 700	1 100	2 000	520	1 400	460	640	350	460	520	580
n_{max}, rpm	11 200	12 800	2 800	5 200	2 100	5 600	1 600	2 200	1 600	2 200	2 400	2 700
n_s, rpm	42 000	48 000	10 500	19 500	7 875	21 000	6 000	8 250	6 000	8 250	9 000	10 125
b_{lim}, mm	2	4	0.25	1.65	0.4	2.5	0.5	2.55	1.85	4.75	3.9	19
T_{lim}, N-m	0.65	1.3	0.25	1.65	0.5	3.15	1.35	7.5	7	17.5	15	70

GENERAL NOTES:

(a) In machining aluminum, none of the n_{max} speeds is too high to endanger tool life.

(b) Obviously, T_{max} cannot be exceeded in any of the cases.

Use the f_n data for each of the feed directions, X and Y. Determine n_{min} and n_{max} from formulas. Choose a speed, n_1, in this interval, the highest one permissible from the point of view of tool life. Again, as in the case of spindle speed rule 1, only one spindle speed is required. For machining of steel this will probably be the n_T speed and for aluminum it will be the n_{max} speed. **If the speed n_1 is not available, do not perform the chatter test.**

It is also possible, in a way analogous to rule 2 above, to use two speeds higher than n_{max} such that $mn_1 = 60\ f_n$ or $mn_1 = 60\ f_n/2$, and $n_2 = 1.33\ n_1$ or $n_2 = 0.57\ n_1$; the higher of the two that is available. If such an option is selected, it shall be made part of the original machine specification as agreed upon by Supplier and User.

9.5.4.4 Spindle Speed Rule 4. No dynamic characteristics are available at all. In this case, use the default spindle speeds as given in Tables 9.4, 9.5, and 9.6.

Again, it is possible to use two speeds higher than n_{max}, in the same way as defined in spindle speed rule 3. In such a case, this option must be agreed upon as part of the original machine specification, as discussed in spindle speed rule 3.

Table 9.6 Standard Tools and Default Machine and Cutting Parameters for the Chatter Test for End Mills With Carbide Inserts

Workpiece Material: Steel 4340
(Chip Load $c = 0.15$ mm/Tooth)

	Machine Class		
Variable	D	E	F
d, mm	50	50	67.5
l, mm	75	100	150
m	4	4	6
H_c, μm/N	0.26	0.15	0.10
f_n, Hz	600	700	900
n_{min}, rpm	350	400	400
n_{max}, rpm	2 400	2 800	2 400
n_T, rpm	760	760	570
b_{cr}, mm	1.9	2.5	2.5
T_{cr}, N-m	19	25	50

GENERAL NOTES:

(a) These tools are equivalent in stiffness to the end mills of Table 9.5 in the short (S) holders.

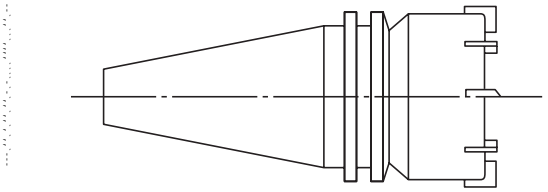
(b) Machine classes A, B, and C do not qualify for these tools.

9.5.5 Tools and Cutting Conditions

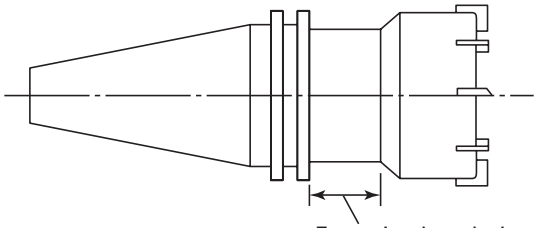
On most machining centers, the most flexible part of the structural system is the tool holder/spindle/bearing system and, if used, the end mill. In some instances, the mass of the workpiece together with the mounting of the rotary table may also have significant compliance. Finally, the mass of the headstock on the "springs" of the guideway may also contribute to the machine compliance.

With tool/holder/spindle being most significant, the overhang of the cutting edge from the spindle bearing plays an important role. The currently common V-flange holders provide a rather large overhang for face mills and even more so for end mills. For the latter, the set-screw type clamping of the cutter is much stiffer than most of the collets, but its length contributes significantly to the tool overhang. New tool holders have been developed that provide lesser overhangs than the standard

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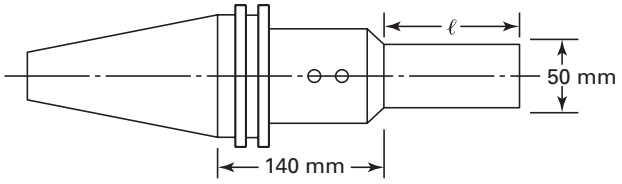


(a) Regular Face Mill

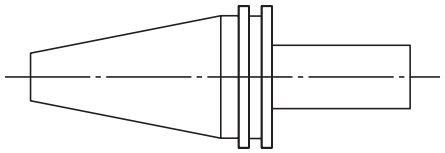


(b) Face Mill With Extension

Fig. 9.3 Typical Face Mills



(a) Set Screw Type Holder



(b) Special Short Overhang Holder (Shrunk Fit)

Fig. 9.4 Typical End Mills

V-flange holders. These may be included in the test program. They are designated S for short. For example, end mills may be made integral with the tapered holder or clamped directly into the spindle.

For the standard tests, the holders to use are the shortest V-flange holder for face mills and the V-flange set-screw type holder for end mills.[2] These will be designated R, for regular. However, in many instances, for practical purposes, the face mill must be clamped on a 100-mm or a 150-mm extension holder. In that case they may be used for these tests if such use is clearly specified in the machine specification. They are designated L (for long) in the tables. For end mills, the smaller diameter, longer cutters may overwhelm the rest of the structure and provide the major part of the resulting compliance. Because it is the machine that is to be tested, they are excluded from the tests. (An exception may be made if there is a provision to stabilize cutting with slender end mills, like an automatic system for regulation into stable speeds. In such a case, these tools may be included in this test, as long as their expected performance in the machine is made part of the original machine specification and is given in equivalent detail to other cutting performance tests in this Standard.)

Based on these considerations, the following tools are specified for the standard tests.

9.5.5.1 Face Mills. Face mills (see Fig. 9.3 and Table 9.4) with negative square carbide inserts will be used, with negative/negative geometry, 0.5-mm nose radius, a small lead angle (3 deg or 10 deg), and uniform pitch. The regular (R) tools are such that they are clamped on the regular V-flange type holder. The long (L) ones are clamped on a holder that is, by the amount of extension, L longer.

9.5.5.2 High Speed Steel (HSS) and Solid Carbide End Mills. End mills of high speed steel or carbide (see Fig. 9.4) with smooth continuous edges and uniform tooth pitch shall be used. The length, l, given in the table (Table 9.5) is measured as the total overhang from the face of the holder to the tool end (see Fig. 9.4). It shall be maintained within ±5%. The standard set-screw type tool holder is used as the regular (R) holder. The alternative short (S) holder is one where the clamping of the tool is much closer to the spindle face than with the regular holder. An extreme case is the example of a "shrink-fit" holder, where the face of the holder extends only about 30 mm out of the spindle. Such a short holder may be used if recommended by the Supplier or requested by the User, and made part of the original machine specification. The default values of stiffness for the S holders in Tables 9.5 and 9.6 apply to the shrink-fit holder.

9.5.5.3 End Mills With Carbide Inserts. These cutter bodies are made one piece with the tapered holder and in stiffness they are similar to the S holders in Table 9.5. When possible, such a design is to be used where the inserts virtually fill the cutting edge completely. The top end mill in Fig. 9.5 shows a typical end mill with overlapping inserts. However, commonly these cutters do not have edges completely filled, as there are gaps between the inserts along the edge. For these cutters, the number m will still express the number of cutters per circumference, but the axial depth of cut b will be expressed as the actual depth of cut times the average filling factor on the edge: $p = b_1/b$, where b_1 is the cumulative length of the cutting edges. The bottom end

[2] Other tool holders may be used for this test as agreed between Supplier and User and made part of the original machine specification. However, in such cases it must be warned that the tables supplied in the Chapter may not fully apply.

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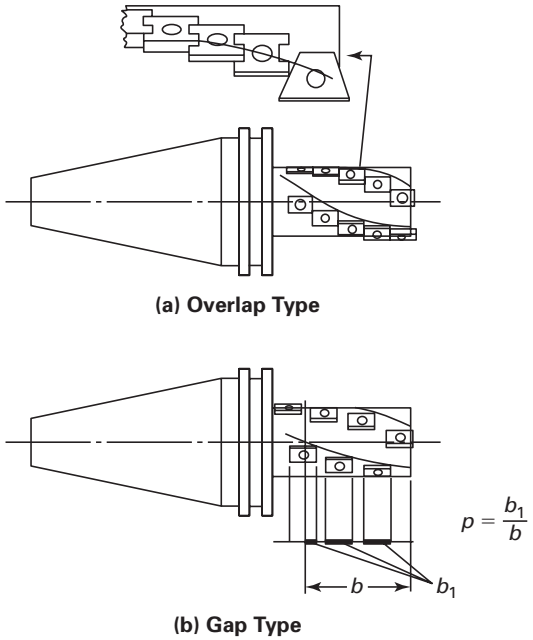


Fig. 9.5 Typical End Mills With Carbide Inserts

mill in Fig. 9.5 shows these types of end mills with gaps between the inserts.

Machine tool and cutting tool parameters are given in Tables 9.5 and 9.6. The speeds, n_{min} and n_{max}, the dynamic stiffness, and the expected chatter limits are given as default values to be used whenever the f_n and H_c parameters are not available. The default values are based on accumulated experimental data from measurements on a large number of spindles. The parameters are

(a) d (mm), tool diameter

(b) m, number of effective teeth or flutes

(c) l (mm), end mill length

(d) L (mm), extension length for "long" face mill holders

(e) H_c (μm/N), dynamic compliance of the dominant mode. Here it is assumed that all the other structural parts are stiff, this value is the same in both the basic directions, and it results from the compliances of the system

(f) f_n, frequency of such a dominant mode

(g) n_{min}, minimum spindle speed, below which process damping would affect the results; derived from f_n

(h) n_{max}, maximum spindle speed, above which the "lobing" affects a few of the results

(i) n_s, the spindle speed for best stability, to be used if spindle speed rule 1 applies

(j) n_T, maximum spindle speed for satisfactory tool life; for carbide tools and steel 4340 this will correspond to a cutting speed of $v = 120$ m/min

(k) b_{cr}, limit depth of cut for a "slotting" cut, where radial depth (width) of cut $a = d$. The value given applies to the standard number of effective teeth, m. If, for any reason, a different number of effective teeth (flutes) is specified, the value of b_{cr} will be affected. The value of b_{cr} in the slotting cut represents the shallowest possible milling pass without chatter, and it helps to set the initial depth of cut in the test. For radial immersions $a/d < 1.0$, the limit depths will be larger.

(l) T_{cr} (N-m), the cutting torque in a slotting cut at b_{cr}

(m) P_{cr} (kW), the power in a slotting cut at the depth b_{cr} and spindle speed n_{max} or n_T when applicable

The values of T_{cr} and P_{cr} are given for face mills only to give guidance regarding the potential for exceeding the available torque and power.

9.5.6 General Procedure for Chatter Testing

The chatter tests are to be performed on 4340 steel (300–350 BHN) using the face mills and the end mills with carbide inserts and on 7075-T6 aluminum using only the solid end mills. To perform each test, first select a machine class (Table 9.2); then choose the tool from the appropriate table (Tables 9.4, 9.5, and 9.6). If the table does not contain a reference to your machine class, do not perform the test. Next, select the axis for the test. Select the spindle speed(s) for that axis using one of the four spindle speed rules (see para. 9.5.4). Compute the feed rate. The feed rate is given by

$$F = cmn \tag{9-6}$$

where

c = chip load, mm/tooth
F = feed rate, mm/min
m = number of teeth on the cutter
n = spindle speed for the test, rpm

Then follow the procedure in para. 9.5.7 for each of the tests.

9.5.7 The Chatter Test Procedure for Both End and Face Mills

For the chatter tests, a workpiece in the form of a solid block is used. For face mills this block has the following nominal dimensions: width, $w = d$; length, $l = 3d$; and height, $h = 0.75d$; where d is the tool diameter. For end mills, the workpiece nominal dimensions are $w = 100$ mm, $l = 200$ mm, and $h = 75$ mm. These workpieces are illustrated in Fig. 9.6.

For vertical spindle machines, the workpiece is clamped directly to the surface of the table of the machine. For horizontal spindle machines, the workpiece is clamped to a rigid block or an angle plate at a height $H_{clamp} = d$ above the table. Furthermore, the face of the test block shall be on the edge of the table (pallet) closest to the spindle to minimize extension of the quill. Some modifications of the workpiece will be required to provide proper clamping. Possible configurations are illustrated in Fig. 9.6.

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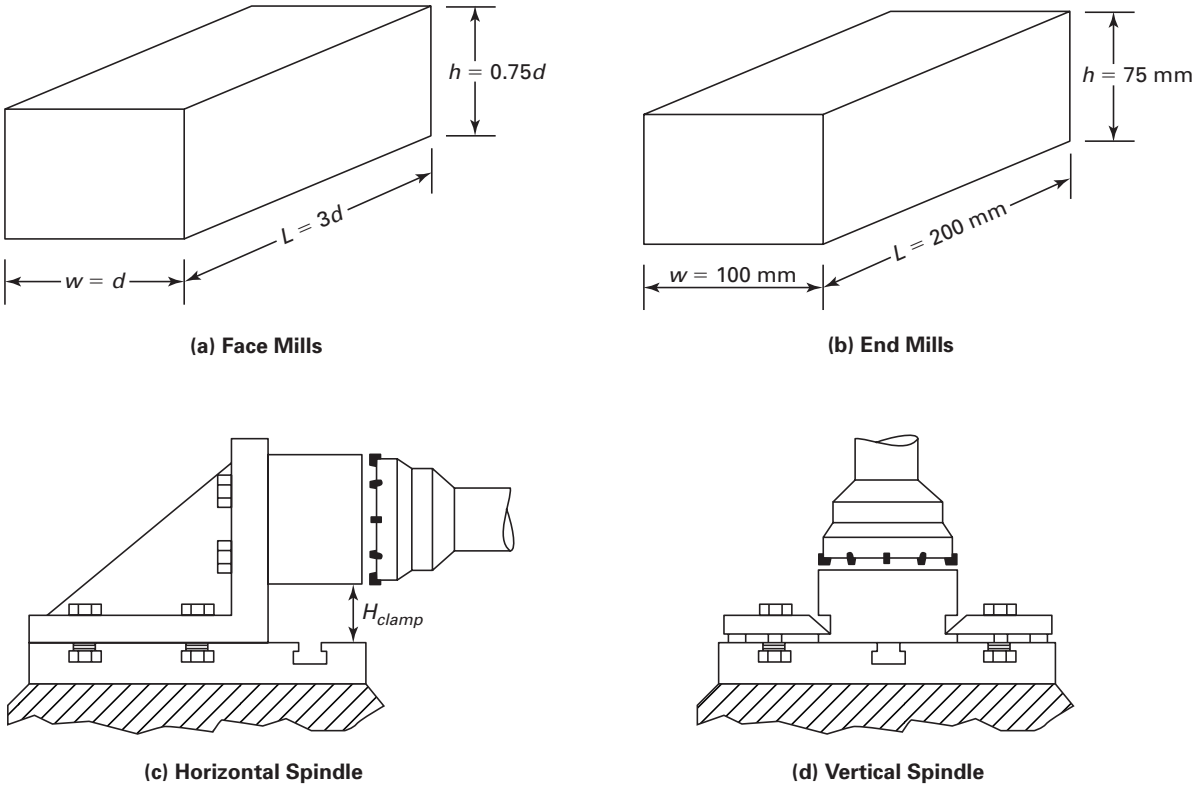


Fig. 9.6 Typical Test Parts for the Chatter Tests

The chatter limits will be tested in the two feed directions orthogonal to the spindle axis, X and Y, for three radial immersions (radial immersion $i = a/d$, where a is the dimension of the tool actually in the cut). The radial immersions shall be $i = 1.0$ (slotting cuts), $i = 0.5$, and $i = 0.25$. The test shall also be performed for both up and down milling when the radial immersion is not equal to 1. Each test shall also be performed for all of the spindle speeds selected in para. 9.5.4. For each test, the chatter limit will be defined as the limiting depth of cut, b_{lim}, where chatter occurs for that particular radial immersion, milling direction, feed direction, and spindle speed.

During these tests, chatter is most easily recognized by the characteristic sound and by the examination of the machine surface for chatter marks. However, as an aid in recognizing the limit, the spectrum of vibrations obtained from an accelerometer on the spindle or the spectrum of sound obtained from a microphone can be used.[3]

During each test, it is necessary to watch to ensure that the available torque is not exceeded. It is recommended that prior to the tests, the conditions at which it is expected to reach the rated torque, T_R, be calculated from the following formula:

$$T_R = \frac{K_s abmc}{1{,}000(2\pi)} \tag{9-7}$$

where

a = radial depth of cut, mm
b = axial depth of cut, mm
c = "chip load" or feed per tooth, mm
K_s = "specific force" for the given material, N/mm^2 [K_s = 2 000 for 4340 steel (300–350 BHN) and 750 for 7075-T6 aluminum]
m = number of teeth on the cutter

Furthermore, for each given spindle speed used there is a corresponding rated power, P_w (see para. 9.3). The spindle shall be connected to an appropriate wattmeter so that it is possible to monitor the spindle power. If the rated power or the rated torque is exceeded, the test shall be immediately stopped. In addition, it is recommended, but not required, that a circuit be installed that constantly monitors the speed slow-down of the spindle and stops the feed as soon as the actual spindle speed drops below the commanded speed by more than a specified percentage. This percentage speed reduction shall be given by the machine Supplier. If such a value is not supplied, the default speed reduction is 6%. If the rated power is

[3] It also can be valuable to measure the chatter frequencies along with the limiting depth of cut b_{lim}, and report these results also. This is explained in Appendix G but is not a requirement of this Standard.

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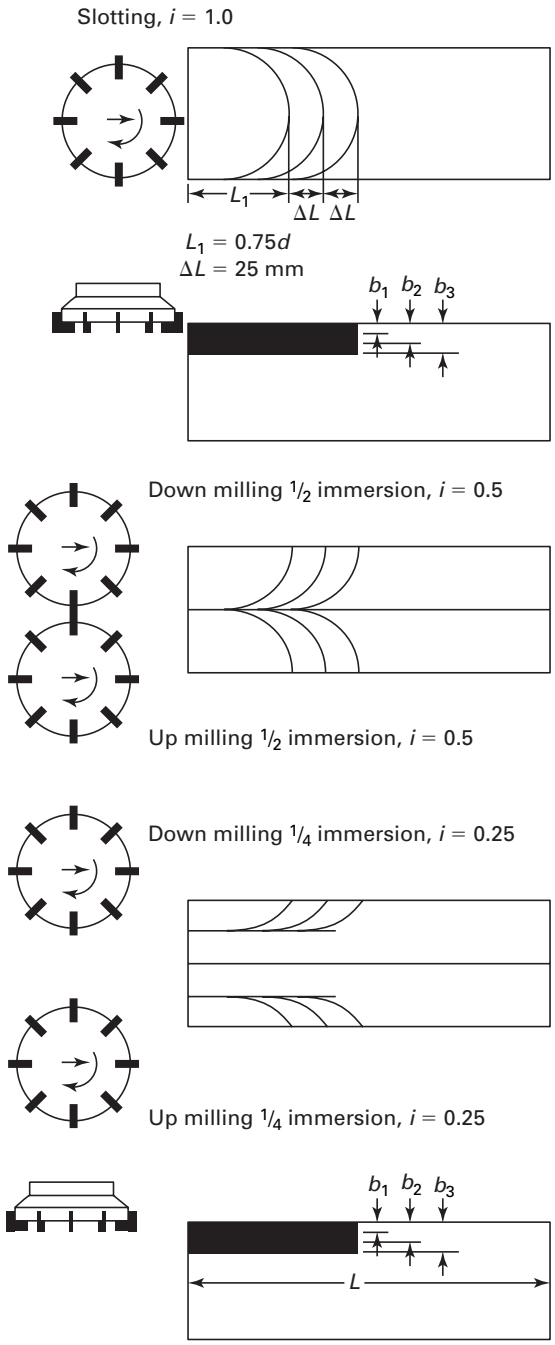


Fig. 9.7 Chatter Test for Face Mills

exceeded at cutting conditions where the predicted rated power is less than that specified for the machine, or the spindle slows down more than the specified speed reduction percentage or stalls, the Supplier shall be responsible for correcting this condition.

The test procedure is as follows. For each spindle speed, a radial immersion is selected. A sequence of milling passes is carried out, starting with a small depth of cut, b_1, at which chatter does not occur. The depth of cut is gradually increased in subsequent passes to $b_2 = 2b_1$, $b_3 = 3b_1$, etc., until chatter occurs. The depth of cut at which chatter first occurs shall be designated b_{lim} for the particular spindle speed, radial immersion, direction of feed, and milling direction (up or down). The starting depth, b_1, is related to the estimated chatter limit depth of cut for slotting, b_{cr}. For the materials here, b_{cr} is given by

Table 9.7 Record of the Chatter Test

Direction	Case	b_{lim}, mm	$a–b$, mm^2
X	0.25U	4.5	56.25
	0.50U	1.9	47.50
	1.00	1.1	55.00
	0.50D	1.8	45.00
	0.25D	3.2	40.00
Y	0.25U	3.4	42.50
	0.50U	2.3	57.50
	1.00	1.6	80.00
	0.50D	2.6	65.00
	0.25D	4.7	58.75

$$b_{cr} = \frac{1.5}{H_c m} \text{ [4340 steel (300–350 BHN)]} \quad (9\text{-}8)$$

$$b_{cr} = \frac{4}{H_c m} \text{ (7075-T6 aluminum)} \quad (9\text{-}9)$$

where

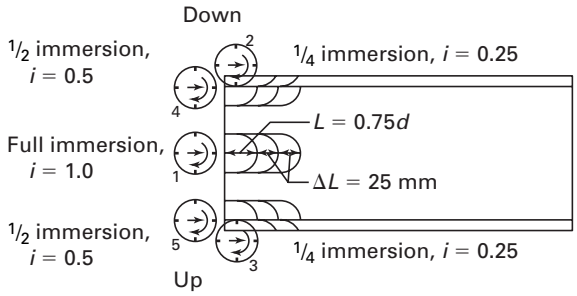
b_{cr} = estimated chatter limit depth of cut for slotting
H_c = dynamic compliance (see para. 9.2.1), μm/N, for the particular cutting direction
m = number of teeth on the cutter

In the case where the dominant natural frequencies and compliances are not given, b_{cr} shall be chosen to be equal to b_{cr} in the appropriate table (see Tables 9.4, 9.5, and 9.6).

Two variations of the tests are described in the procedure below. The first procedure assumes that the initial depth of cut is such that chatter does not occur and subsequent depths of cut are increased. The second procedure is to be used if the initial estimate of a chatter-free depth of cut, b_1, is incorrect and chatter occurs on the first pass. In this case, the sequence is reversed and successive cuts are made at decreasing depths.

9.5.7.1 Regular Procedure. Commence machining with $b_1 = b_{cr}/2i$, where i is the radial immersion. Feed ahead a length, L_1, where $L_1 = 0.75d$ and d is the cutter diameter. If chatter occurs, discontinue this procedure and follow the reverse procedure. If chatter does not occur, return the tool to the starting position, increase

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GENERAL NOTE: The top surface is remachined after the 0.25 immersion cuts (2 and 3).

Fig. 9.8 Chatter Test With End Mills

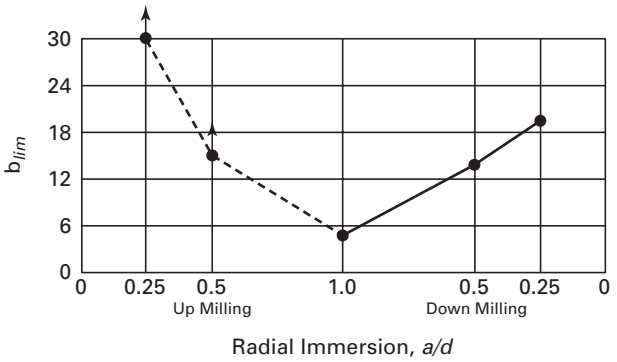


Fig. 9.9 Typical Results of the Chatter Test in One Axis Direction

the depth of cut by b_1, and then feed into the workpiece to a length, $L_1 + \Delta L$, where $\Delta L = 25$ mm. During the cut of the additional length, the depth of cut will be $b_2 = 2b_1$. If chatter occurs, stop the procedure; if it does not, return feed down by b_1 again, then feed ahead by an amount ΔL past the end of the previous cut. In this last part of the motion, the depth of cut will be $b_3 = 3b_1$. Continue this procedure until chatter occurs or the torque limit is exceeded. The depth at which chatter first occurs is the limit depth of cut for the particular radial immersion, milling direction, feed direction, and spindle speed. If chatter does not occur before the rated torque is exceeded, then b_{lim} is designated as $b_{lim} > b_i$, where b_i is the depth of cut at which the rated torque is exceeded.

9.5.7.2 Reverse Procedure. The reverse procedure is used when chatter occurs at the initial depth of cut, b_1. If chatter occurs at this depth, the tool is returned and withdrawn from the workpiece by the amount $b_1/4$. The next pass is taken to a length, $L = L_1 + \Delta L$, as in the regular procedure. If chatter still occurs, the tool is returned and withdrawn again by the same amount, $b_1/4$. The procedure is repeated until no chatter occurs. The last depth of cut at which chatter occurs is designed as b_{lim}. If chatter still occurs, even at the minimum depth (which is $b_1/4$), the test is concluded and the limit depth of cut is considered to be $b_{lim} < b_1/4$.

The sequence of tests with face mills shall be such that the slotting cut (radial immersion $i = 1.0$) is done first. After this test, mill the surface flat. Then proceed with the radial immersion equal to 0.5 in the down milling direction, followed by the up milling at the same radial immersion. After this test, mill the surface flat once again and then perform the up and down milling tests with a radial immersion of 0.25. This is illustrated in Fig. 9.7 and is performed for each axis direction. For end milling, start with a radial immersion of 1 in the center of the workpiece (see Fig. 9.8), follow this cut by the 0.25 radial immersion cuts in the up and down directions on the sides of the workpiece, and then clean the sides of the workpiece. The 0.5 radial immersion cuts in the up and down directions follow to complete the test.

After both the X and Y directions have been tested for each tool and spindle speed, the values of b_{lim} for all the cuts are recorded as shown in Table 9.7. For each machining axis, the limit depth of cut will be plotted versus the radial immersion as shown in Fig. 9.9. The cross-sectional area of the cut (the product of the radial depth of cut, a, and the limit depth of cut, b_{lim}) shall also be plotted versus the radial immersion as shown in Fig. 9.10. The area is indicative of the metal-removal rate. The condition where the maximum rated torque is reached before chatter occurs shall be indicated on the figure by an arrow pointed upward and by the connection of that point to the other points by a dashed line. This is illustrated in Fig. 9.9.

9.5.8 The Full Torque Test

This test is carried out face milling 4340 steel (300–350 BHN) using the regular (R) holders only (see para. 9.5.5), under the same conditions as for the face milling chatter test (see Table 9.4), except that the chip load, c, is 0.3 mm per tooth. The spindle speed shall be n_T (see para. 9.5.4). Before commencing this test, check the graphs obtained of the limit cross-sectional area and torque versus radial immersion in the end milling chatter test (see Fig. 9.10) for both the X and Y directions. If the rated torque was reached in any one of these tests, no additional test is necessary. If this is not the case, a full torque test shall be performed using any one of the radial immersions and feed directions in the chatter test where half the rated torque of the machine ($T_R/2$) was exceeded. The other conditions of this test are as follows: First the chip load is increased to 0.3 mm and the depth of cut is set at one-half the depth of cut at which $T_R/2$ was reached. A series of cuts is now initiated. After each cut, the axial depth of cut, b, is increased by the same amount as used previously in the chatter test (para. 9.5.7) until T_R is obtained. If, while performing the chatter

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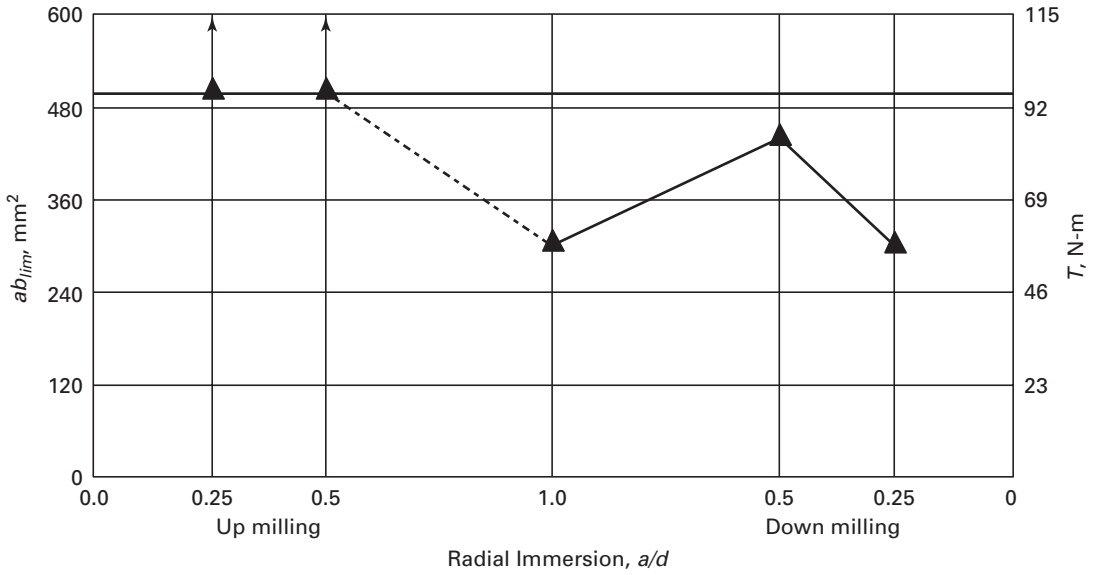


Fig. 9.10 Plot of the Limit Cross-Sectional Area of Cut Versus the Radial Immersion for a Typical Chatter Test

Form 9.1 Record of the Fill Torque Test

Direction	Up/Down	*a*, mm	*b*, mm	T_{ex}	P_{meas}	T_{meas}
X or *Y* (User-selectable)	Up or down					

test, there was no case where half the rated torque (T_R/2) was reached without chatter, do not perform this test. Note that because the chip load was changed to 0.3 mm per tooth, a new feed must be computed (see para. 9.5.6) before initiating this test. The power is measured on a wattmeter or other such measuring device as recommended by the machine Supplier. The results of the test will be expressed in a form as shown in Form 9.1.

T_{ex} is the expected torque for the test (see para. 9.5.7).

T_{meas} is obtained from the measured power minus idle loss power as

$$T_{meas} = \frac{(P_{meas} - P_{idle})}{(2\pi n/60)} \quad (9\text{-}10)$$

where

P = spindle power, W

9.5.9 The End Milling Deflection Test[4]

This test is performed by feeding in one axis at a time. Figure 9.11 shows a schematic of the test for the *X* direction. The other axis will be tested in the same manner. The workpiece shall be premachined with two inclined surfaces so that the radial depth of cut will continuously increase for the cuts in the positive *X* (down milling) and negative *X* (up milling) directions. In this figure, an end mill of diameter *d* is illustrated. The same type end mill is used as in the chatter test, as given in Table 9.5. Furthermore, the material, spindle speeds, and feed rates are to be the same as those used previously in the end milling cutting performance test (para. 9.5.7). Also, the workpiece shall be fixtured in the same location as the chatter test with the same quill extension. The values of *P*, *R*, and *h*, which define the geometry of the premachined workpiece, are selected as 125 mm, 1.2*d* mm, and 1.6 mm, respectively. The axial immersion of the cut *b* is selected from the results of the solid end milling test (para. 9.5.7) to ensure the maximum possible depth of cut without producing chatter.

The cutting pass is programmed so that the ideal surface produced is 0.1 mm above the lowest point of the inclined surface. This means that the tool will first start cutting when its center has traveled about 8 mm from the beginning of the workpiece. The radial immersion at any given time during the cut is measured at the point at which a tooth enters the cut (for down milling) or the point at which a tooth leaves the cut (for up milling). The program first feeds the tool in the positive *X* direction until the midpoint of the workpiece is reached, then

[4] Note that the end mill for this test must have a corner radius smaller than 0.025 mm.

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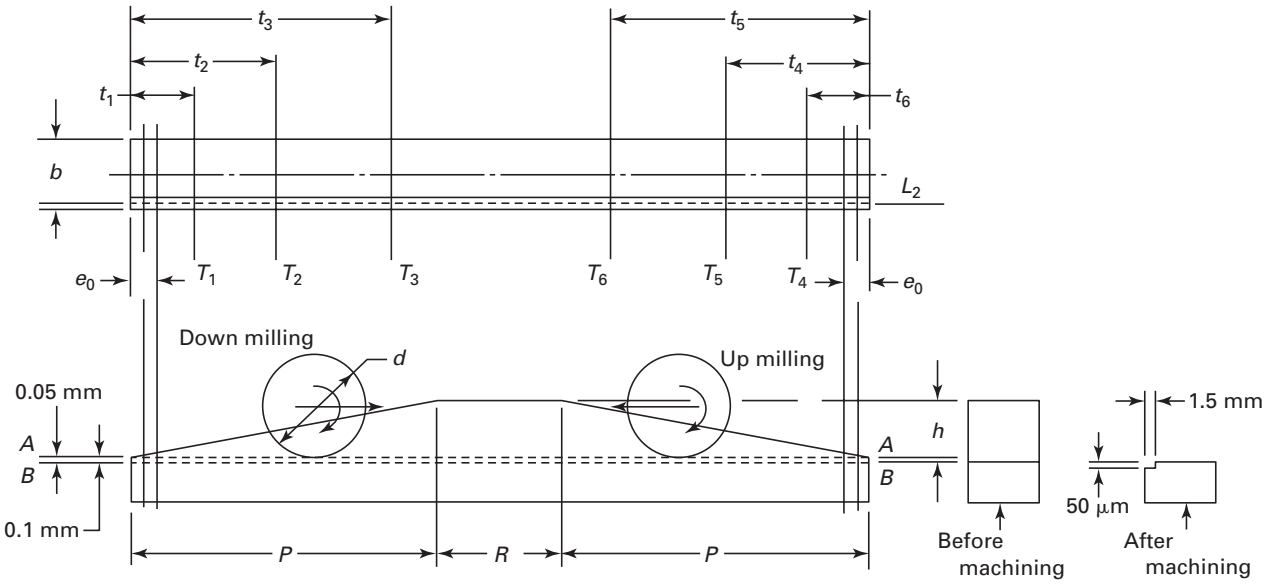


Fig. 9.11 Test Part and Test Procedure for the End Milling Deflection Test

repositions the tool and runs a similar cut in the negative X direction. The ideal surface left behind by these cuts is shown as line A–A in Fig. 9.11. A reference surface is then machined (line B–B), which is 50 μm below the ideal surface using an axial depth of cut of 1.5 mm. Because of the small immersions, the deflections due to the cutting forces are assumed minimal in the reference surface.

The errors produced during the test are evaluated using a displacement probe mounted in the headstock of the machine. The probe traces the machined and reference surfaces over lines T1 to T6 in the transverse direction.[5] In Fig. 9.11, lines T1, T2, and T3 represent this position for radial depths of cut of 0.05 mm, 0.5 mm, and 1.5 mm, respectively, for the down milling case. Lines T4, T5, and T6 represent similar positions for the up milling case. Table 9.8 shows typical measurement results for this end milling deflection test and Table 9.9 lists the location of the measurement lines used to obtain these results for different tool diameters. Figure 9.12 shows examples of the displacement measurements

Table 9.8 Typical Results From an End Milling Deflection Test

Direction	Up/Down	a, μm	e_{max}, μm	Δe, μm
X	Up	50	−20	27
		500	+22	35
		1 500	+32	38
	Down	50	−20	20
		500	+43	43
		1 500	+91	67
Y	Up	50	+48	23
		500	+46	23
		1 500	+48	30
	Down	50	+40	28
		500	+50	28
		1 500	+86	48

Table 9.9 Location of Measurements for the End Milling Deflection Test

d, mm	e_0, mm	T1, T6, mm	T2, T5, mm	T3, T4, mm
12.50	7.8	10.9	44.4	120.9
18.75	7.8	10.7	43.9	119.9
25.00	7.8	10.6	43.4	119.1
37.50	7.8	10.3	42.6	117.7
50.00	7.8	10.1	42.0	116.5

[5] Using a machine tool to probe against a workpiece that has been machined on that machine is generally called a "part trace test" to distinguish the results that would be obtained from a separate inspection. The machine probing that is described in the end and face milling deflection tests is neither a part trace test nor a separate inspection, because the axis of the machine that is used for the probing in the Z in the case of end milling, and X and Y in the case of face milling, was not used during milling. Nonparallelism of the Z-axis with the spindle axis of rotation could affect the results. Any taper in the end mill itself or conical shape in the face mill will also affect the results. The Committee is aware of these factors, but in the interests of keeping the instrumentation and time required to a minimum and because the magnitude of the milling deflection is expected to be large with respect to the potential errors in metrology, the test is recommended.

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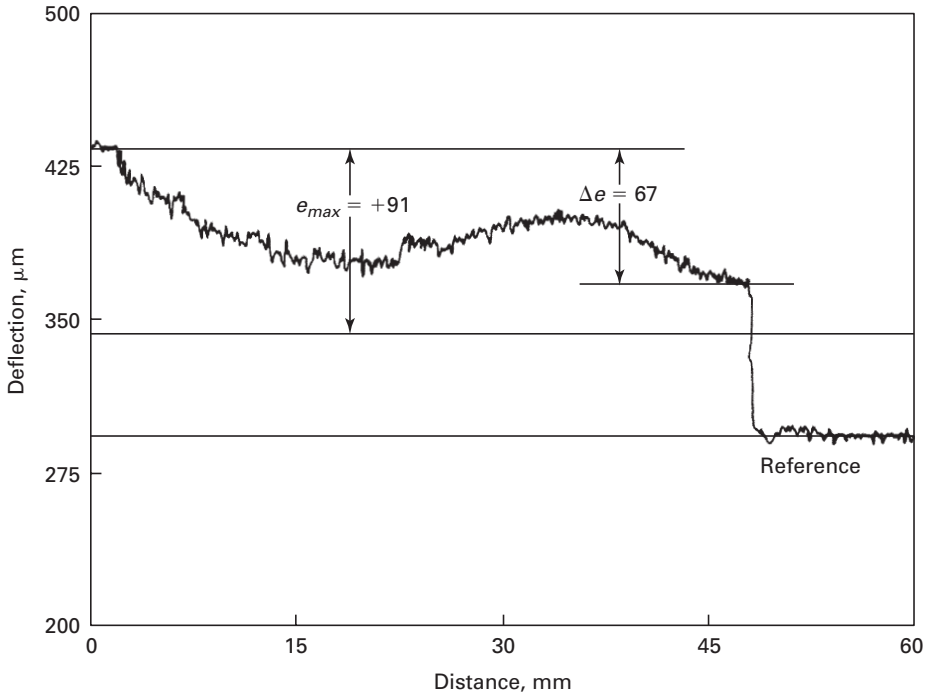


Fig. 9.12 Sample Measurements of the Part Profile in the End Milling Deflection Test

obtained along lines T3 and T4, respectively. These plots show the errors of location plus surface profile (nonflatness) errors that arise due to the helix of the tool and its relationship to the vibration. The error could be positive (more material was left behind) or negative (more material was removed). These errors are expressed as a maximum error $e_{\max}$ and an error range Δe. These are found by using the reference surface to locate the position of the ideal surface from which these errors can be directly measured. The error is taken as positive if it represents deviation out of the material. Table 9.8 shows an example of the listing of the errors of position for the conditions T1 to T6 for the *X*- and *Y*-axes for a typical machine.

The parameters used in defining the workpiece geometry, as well as the positions at which the displacement probe should be used, change with the tool diameter. Table 9.9 lists the values of e_0 and T1 to T6 for common tool diameters.

9.5.10 The Face Milling Deflection Test

This test is analogous to the end milling deflection test and will also be run one axis at a time. The same tool as in the chatter test according to Table 9.4 is used cutting steel 4340. Speed n_T is used and chip load c = 0.15 mm. The block workpiece does not require premachining in this case. Instead of machining an inclined surface, a horizontal plane in two steps is machined. The dimensions of the workpiece depend on the tool diameter, d. The minimum length required is 3.5d and the minimum width is 1d. The workpiece dimensions as well as some of the tool path are presented in Fig. 9.13. The machine is tested in the full radial immersion and in half immersion up and down milling. The tool path is programmed to first cut a step 2d long with 1 mm axial depth of cut as shown in the figure. Then the tool is repositioned and the whole workpiece is milled with an additional 1 mm axial depth of cut. The axial depth then increases from 1 mm to 2 mm at the point at which the step occurs. The tool is further programmed to generate reference surfaces on both sides of the workpiece as shown in Fig. 9.13. These reference surfaces are machined 50 μm below the ideal surface of the test with 2 mm radial immersions.

Once the machining is completed, the errors are measured using a displacement probe. The locations for measurements are selected at positions where no distortions due to entry and exit phenomena occurred. The locations T1 and T2 are selected at 0.55d and 2.05d from the beginning of the workpiece. Examples of results from testing a machine type *E* are presented in Form 9.2. Plots of the errors for the slotting case are presented in Fig. 9.14. In these plots, the vertical axis is reversed so that the material is above the trace and the air over the workpiece below it. These plots are strongly affected by the error of perpendicularity of the spindle axis with respect to the base plane of the workpiece. This is shown in Fig. 9.13. This error causes a difference in the level of the

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Form 9.2 Deflection Errors in Face Milling

Direction	Case	e_{max} at 1 mm (μm)	Δe (μm)	e_{max} at 2 mm (μm)	Δe (μm)
X	Slot	+27	18	+24	44
	1/2 up	+15	22	+11	15
	1/2 down	−38	38	−42	31
Y	Slot				
	1/2 up				
	1/2 down				

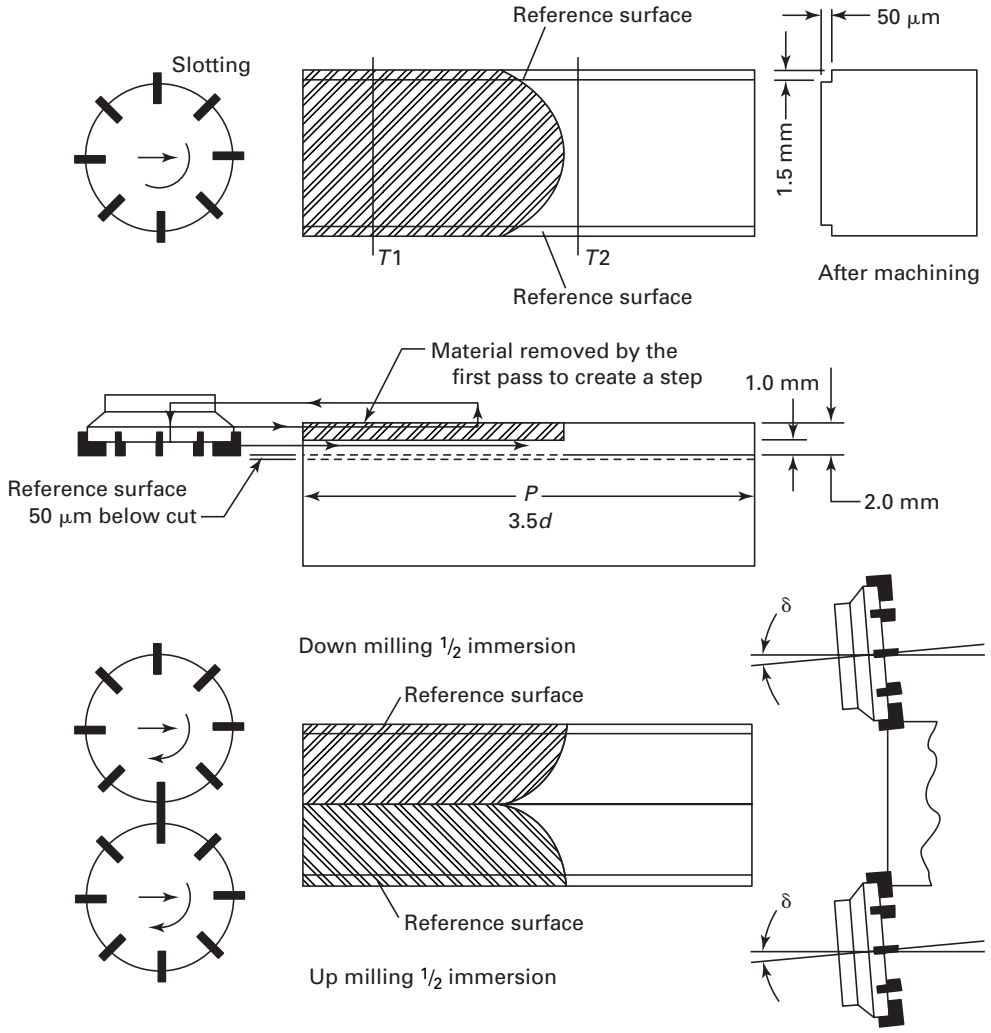


Fig. 9.13 Face Milling Deflection Test

two reference ledges. To exclude this effect from the result of this test and to make sure that the test expresses mainly the effects of deflections due to the cutting forces, a reference line is drawn in the graph; the reference line is constructed by projecting the right reference surface to the left-hand axis and the left reference surface to the right-hand axis. The line is drawn between the two points where these projections cross the respective axes. Then, a line parallel to the reference is drawn 50 μm above the reference and it represents the ideal location of the surface. The maximum error e_{max} and the error range Δe are measured from this line. The error is taken as positive if it represents a deviation out of the material.

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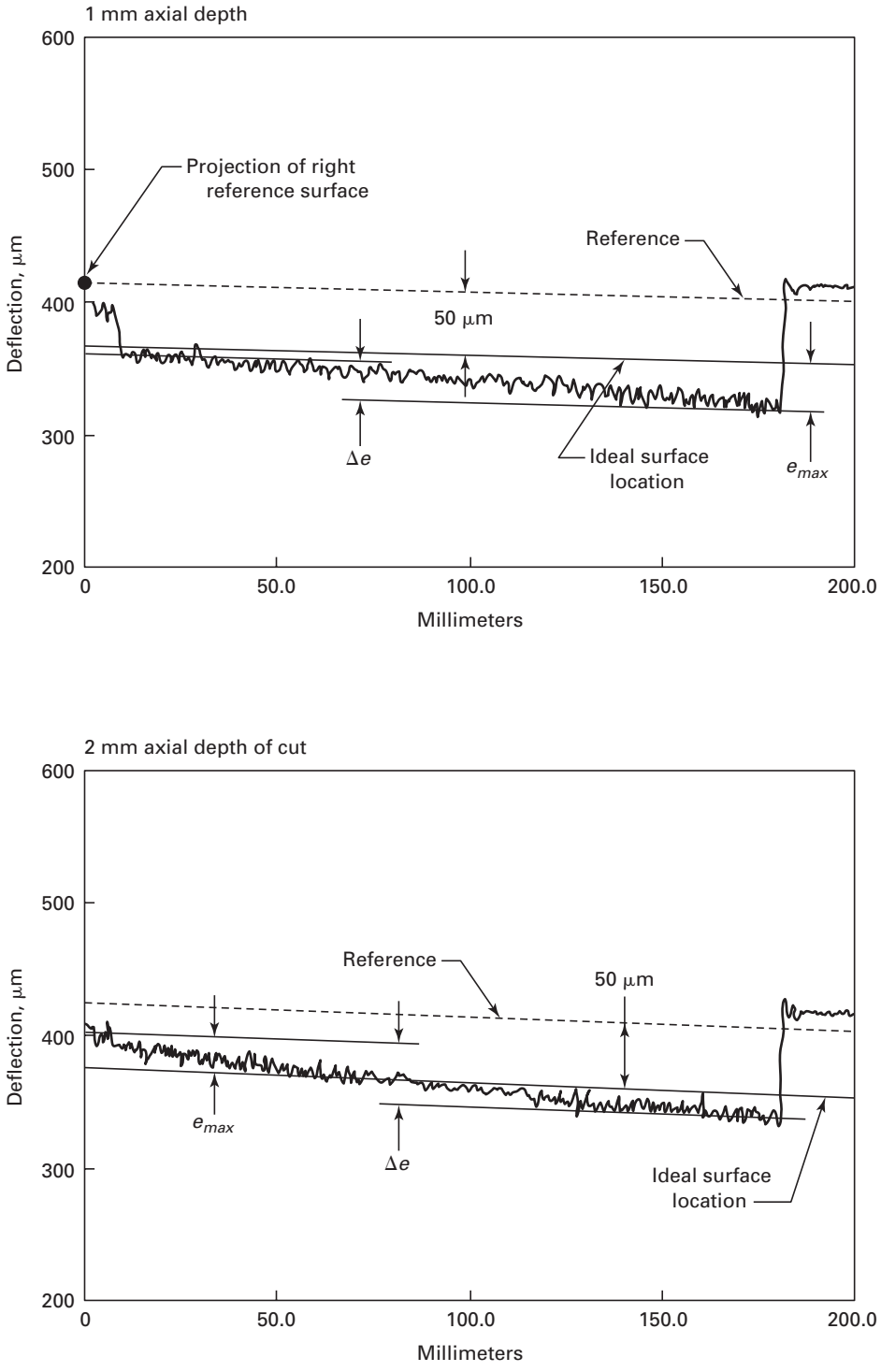


Fig. 9.14 Sample Displacement Measurements for the Face Milling Deflection Test When "Slotting" (Radial Immersion = 1)

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Chapter 10
Multifunction Cycle Test

10.1 GENERAL

The machine shall be cycled through all basic machine functions (see para. 10.2) for a specified time period to demonstrate its complexity, capability, and short-term reliability. Preceding this test, a subsidiary test shall be performed to check the function of the machine limit switches, coolant cycling, etc.

10.2 PROCEDURE

The machine and control shall cycle automatically under numerical control for a specified time period and for a specified set of functions agreed upon between Supplier and User. The program used for the cycling test must position the machine over its entire work zone and shall include all basic machine functions, such as tool changes, traverse and feed motions, contouring, G-code canned cycles, etc. The spindle shall operate through its entire speed range during the test. A complete program run (cycle) time shall not exceed 15 min, unless specifically negotiated between Supplier and User.

10.3 FUNCTIONAL CHECK

The machine and control shall cycle as specified in para. 10.2 with only one failure over the complete specified test period. Correction of the failure shall not take more than ½ hr. If more than one failure occurs and/or the correction takes more than ½ hr, the cycle test must be repeated, from the beginning, until the above condition is satisfied.

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Chapter 11
Test Equipment and Instrumentation

11.1 GENERAL

The instruments specified in this Standard are for recommendation only. Other instruments with similar capabilities and accuracy are acceptable for use with this Standard. It is recommended that the accuracy of the instruments and artifacts being used shall be such that the resulting measurement uncertainty is less than 25% of the specified value for the performance parameter being measured, unless otherwise specified. In the paragraphs below, simplified guidelines are given to approximate this condition for individual cases.

11.2 TEMPERATURE

The time constant of thermometers shall be no more than $\frac{1}{10}$ of the cycle time of the highest frequency component of the temperature variation of interest in a test. The time constant is the time required for the thermometer to indicate 63.2% of its final change due to a step change in temperature (see ASME B89.6.2 for further clarification).

The resolution of thermometers shall be no greater than $\frac{1}{10}$ of the amplitude of the lowest-amplitude component of temperature variation of interest in a test.

Thermometers used for nominal differential expansion correction or laser wavelength correction shall be calibrated by suitable means to an accuracy of ±0.1°C over the temperature range of use. Calibrations traceable to the National Institute of Standards and Technology (NIST) are preferred. Calibration frequency shall be that recommended by NIST for the particular sensor.

11.3 RELATIVE VIBRATION

Relative vibration shall be measured using a high-resolution, undamped displacement indicator. Resolution of 0.1 μm (approximately 0.000004 in.) or better is recommended. Such indicators should also have a bandwidth of at least 1 kHz.

11.4 DISPLACEMENT

11.4.1 Laser Interferometers

Laser interferometers shall have a frequency stability of such that this long-term stability represents an error less than $\frac{1}{4}$ of the unidirectional repeatability, linear axes, of the machine (in meters), divided by the length of the longest machine axis (in meters). The resolution of such a system shall be better than $\frac{1}{4}$ of the unidirectional repeatability, linear axes.[1]

11.4.2 Grid Encoders

Grid encoders used for contouring performance testing shall be calibrated with an error of less than $\frac{1}{4}$ of the unidirectional repeatability, linear axes, of the machine. Calibrations traceable to NIST are preferred.

11.4.3 Precision Reference Ball(s)

The precision reference ball(s) for ETVE, tool change and turret repeatability, and machine performance as a measuring tool test shall be spherical to within $\frac{1}{4}$ of the unidirectional repeatability, linear axes, of the machine tool. Reference balls used for the feature measurement accuracy test shall be calibrated for their diameter to within $\frac{1}{4}$ of the unidirectional repeatability, linear axes, of the machine. Diameter calibration, where required, shall be traceable to NIST.

11.4.4 Precision Disks

The precision disk(s) used for the contouring test shall be calibrated to an accuracy of $\frac{1}{4}$ of the unidirectional repeatability, linear axes. Calibrations traceable to NIST are preferred.

11.4.5 Telescoping Ball Bars

The balls on the end of the telescoping ball bar shall be spherical to within $\frac{1}{4}$ of the unidirectional repeatability, linear axes, of the machine tool and equal in diameter to within $\frac{1}{4}$ of the unidirectional repeatability, linear axes, of the machine. The length variation due to sag of the telescoping ball bar in any position shall be less than the resolution of the machine being tested, and the resolution of the ball bar indicator shall be equal to or better than the machine resolution. Any ball bar system conforming to the requirements of this Standard shall state, as part of the output data, the angular interval used for ball bar length measurement during circular contouring. The ball bar shall be calibrated to an accuracy of $\frac{1}{4}$ of the unidirectional repeatability, linear axes. Calibrations traceable to NIST are preferred.

[1] Users concerned with the suitability and accuracy of a laser system for their application should contact the Precision Engineering Division, NIST, Gaithersburg, MD 20899.

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11.4.6 Displacement Indicators

Displacement indicators used for the ETVE test, machine thermal tests, critical alignment, rotary axis alignments, tool change repeatability, and repeatability in drift of tool-setting systems, as specified in this Standard, shall be calibrated to within ¼ of the unidirectional repeatability, linear axes, of the machine. Capacitance probes, laser interferometers, linear variable differential transformers (including air-bearing types[2]), fiber-optic proximity sensors, dial gages, or other developed instrumentation that accurately measures displacement throughout the range of machine displacement variation, are acceptable. The bandwidth of the probe(s) to be used for these tests is unspecified, as these tests are sufficiently slow that a bandwidth of a few hertz is sufficient. Users are cautioned to make sure the bandwidth of the indicator being used is sufficient for the intended purpose.

11.5 ANGLE

11.5.1 Autocollimators

Autocollimators used for the positioning accuracy and repeatability, rotary axes, and the periodic angle positioning accuracy shall be calibrated to within ¼ of the unidirectional repeatability, rotary axes, of the axis to be measured. Calibration shall be traceable to NIST and performed on a regular basis or after any suspected instrumental damage.

11.5.2 Polygons

Polygons used for the positioning accuracy and repeatability, rotary axes, shall be calibrated to within ¼ of the unidirectional repeatability, rotary axes, of the axis to be measured.

11.5.3 Indexing Tables

Indexing tables shall be calibrated to within ¼ of the unidirectional repeatability, rotary axes. The calibration may be performed by an appropriate agency, traceable to NIST, or by subdivision (a self-calibration procedure).

11.5.4 Rotary Encoders

Rotary encoders shall be calibrated to within ¼ of the unidirectional repeatability, rotary axes. The calibration may be performed by an appropriate agency, traceable to NIST, or by subdivision (a self-calibration procedure).

11.5.5 Angle-Measuring Interferometers

Several manufacturers offer differential interferometers for the measurement of small angles. For the use of these interferometers, the instrument manufacturer's recommendations and constants regarding the conversion of differential displacement to angle shall be followed, with particular attention to the nonlinear corrections required for large angles. Special attention should also be paid to the alignment of the optical elements when such alignment is performed by the User.

11.5.6 Differential Levels

Differential levels shall be calibrated to within ¼ of the unidirectional repeatability, angular positioning. Calibrations shall be performed on a regular basis, with traceability to NIST being highly recommended.

11.6 PRESSURE

The accuracy and repeatability of the pressure sensor used for correction of the laser interferometer shall be at least ±1 mm Hg. Calibration traceable to national standards shall be performed at an interval recommended by NIST for that particular sensor.

11.7 HUMIDITY

Humidity measurement for correction of the laser interferometer wavelength shall be sufficiently accurate that it contributes no more than ¼ of the unidirectional repeatability, linear axes, to laser measurement error.

11.8 UTILITY AIR

The utility air pressure shall be measured using the gages supplied with the machine, unless specified as part of the original machine specification.

11.9 SPINDLE ERROR MEASUREMENT

At the time of this writing, the only suitable indicators for spindle error measurement are high bandwidth capacitance gages. Such gages shall be calibrated to within ¼ of the unidirectional repeatability, linear axes, and shall have a bandwidth of at least 10 kHz. The User shall specify for particular applications if a higher bandwidth is required. Other indicators of equivalent bandwidth may be substituted, with the warning that some such indicators may be sensitive to parameters other than displacement, and this condition must be investigated.[3]

11.9.1 Commercial Instruments

Commercial instruments that measure spindle error motion shall have sensors that conform to the requirements for spindle error measurement given in para. 7.5.3.1.2. Furthermore, such instruments shall provide

[2] Air-bearing LVDTs are preferred for the part-trace tests on high-precision machines.

[3] In particular, inductive sensors are also sensitive to the metallurgy of the mandrel or ball used as a reference artifact when testing spindles.

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documentation to ensure that any internal algorithms conform to the measurement procedures as described in this Standard.

11.10 INDICATORS FOR STRAIGHTNESS MEASUREMENTS

Indicators for straightness measurements shall conform to the requirements of para. 11.4.6.

11.11 TEST PART MEASUREMENT

If a coordinate measuring machine is used for a test part measurement it shall conform to the requirements of ASME B89.4.1 and have a working tolerance for volumetric performance less than $\frac{1}{4}$ of the specification zone for the specific machining test(s). If other inspection methods are used, all instruments, gages, and procedures required for these measurements shall have calibrations to ensure that individually the error component that they introduce shall be at least $\frac{1}{10}$ of the specified measurement accuracy for the test part.

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NONMANDATORY APPENDIX A
GUIDE FOR USING THIS STANDARD

A1 GENERAL

The primary purpose of this Standard is to aid in purchasing of machines to specification. When purchasing a new machine, the User should clearly specify the desired machine classification (para. 4.2) and the machine performance (Forms 1.1 through 1.5). If desired, the User may also describe the proposed machine environment on Forms 1.1 through 1.5; however, it is the responsibility of the Supplier to provide these environmental guidelines with the machine quote. When the machine is received, it should be tested and, subject to environmental derating, the measured values for the tests described should be less than or equal to the specification zones in the original machine specification. Note that the machine should be tested in the environment in which it will be used. Testing at the Supplier's plant is recommended, but is not a substitute for testing after machine installation.

A2 RECOMMENDED TESTS

The tests described in this Standard are in logical sequence but not necessarily the most rapid sequence in machine testing. The most rapid sequence groups tests in terms of similar instrumentation. The following is a suggested procedure for testing that the Committee currently believes would minimize the testing time, by grouping tests. It is assumed that programs and all necessary fixtures have been prepared in advance.

A2.1 Group 1

(a) relative vibration test (para. 6.3)
(b) ETVE test (para. 6.2)
(c) structural motion test (para. 7.5.2)
(d) spindle thermal stability test (para. 7.6.2)
(e) spindle error motions: rotating sensitive direction (para. 7.5.3)
(f) composite thermal error (para. 7.6.4)

Note that the composite thermal error test requires 4 hr to perform. After this test, the machine must be allowed to come to equilibrium before other testing can proceed.

A2.2 Group 2

(a) contouring performance using circular tests (para. 7.11)
(b) positioning accuracy and repeatability, *X*-axis (para. 7.3)
(c) angular error motion, *X*-axis (para. 7.4.2.3)
(d) positioning accuracy and repeatability, *Z*-axis (para. 7.3)
(e) angular error motion, *Z*-axis (para. 7.4.2.3)
(f) thermal distortion caused by moving linear axes (para. 7.6.3)

Again, after completion of these tests, the machine will be in a warmed-up thermal state and needs to be allowed to come to equilibrium.

A2.3 Group 3

(a) interrelationship between axes (para. 7.4.4)
(b) spindle idle run loss test (para. 9.4)
(c) multifunction cycle test (Chapter 10)

A2.4 Group 4

(a) chatter limits test and full torque test (para. 9.5)
(b) other test parts, as specified

A3 RECOMMENDED MINIMUM SET

When it is desired to estimate machine performance in a relatively short period of time, the following set of tests, taken from the body of the Standard, is recommended. These tests are for machines with only three linear axes. Machines with more than three axes will require additional tests. The minimum set of tests also requires advanced preparation of the machine, tooling, fixturing, NC programming, and test equipment.

A3.1 Contouring Performance Using Circular Tests (Para. 7.11)

The telescoping ball bar provides a rapid and efficient way of measuring a machine tool's contouring accuracy along a circular contour. Contouring performance shall be measured in three different planes following the procedures in para. 7.11.2. For four- and five-axis machines, refer to Appendix J, para. J1.

A3.2 Positioning Accuracy and Repeatability (Para. 7.3)

Positioning accuracy and repeatability shall be measured for all three axes following the procedures outlined in para. 7.3.2.1.

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A3.3 Diagonal Displacement Measurements (Para. 7.7)

For this test, the diagonal displacement shall be measured along all four body diagonals, following the procedures outlined in para. 7.7.2.

A3.4 Precision Contouring Machining Test (Para. 8.2)

For the purposes of the machine performance evaluation, test parts will be machined to provide assurance that the machine is functioning as expected. For this test, a modified version of ISO 10791-7 is recommended, as shown in para. 8.2.

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NONMANDATORY APPENDIX B
THERMAL ENVIRONMENT VERIFICATION TESTS

B1 PURPOSE

The performance of machine tools is strongly affected by the detailed characteristics of the thermal environment that surrounds them. Parameters of importance include cooling medium (usually, but not always, air), velocity of cooling medium, frequency and amplitude of temperature variations of the cooling medium, mean temperature of that medium, and temperature gradients within that medium. The effects of these parameters and others are discussed in detail in ASME B89.6.2. It is the thesis of ASME B89.6.2 and of this Standard that currently it is not possible to specify a thermal environment that will ensure a specific value for the expanded thermal uncertainty, $U_T(L)$, para. 6.2.3. For a thorough discussion of the technical situation, refer to ASME B89.6.2. The purpose of this Appendix is, however, to specify procedures and responsibilities for testing the thermal environment if the ETVE, as measured in para. 6.2.2, is excessive. That is, the expanded thermal uncertainty exceeds that required for the machine, and the machine User contends that his/her environment meets the Supplier's parameters. For this Standard, these parameters include cooling medium velocity, nominal mean temperature, frequency and amplitude range of temperature variation, and horizontal and vertical temperature gradients. The following tests are designed to measure these parameters for the purposes of assuring conformance to the Supplier's parameters.[1]

B2 TEST METHOD

To ensure that the environment itself is tested rather than any characteristic of the machine tool supplied, these tests are to be conducted with the machine tool, support computers (if supplied), and any other auxiliary equipment related to the machine tool, turned off for 24 hr preceding the test, to allow adequate soak-out of machine tool induced thermal gradients. Normal activity, however, should be continued about the machine as this constitutes part of the User-supplied environment. With these constraints, the following tests should be performed.

B2.1 Velocity

Since air is the most widely used cooling medium in dimensional metrology laboratories, the following tests are structured for measuring air velocity. If some other medium is to be used for heat transfer, then methods for testing its properties should be part of the machine specifications.

For the measurement of velocity, several types of instruments could be suitable. These instruments and a discussion of the measurement problems are given in Tables B1 and B2 of ASME B89.6.2. It is recommended that the instruments used are properly calibrated and the test personnel are aware of both the limitations of their instruments and their operation.

Using appropriate instruments, the velocity of the cooling medium around the machine shall be measured. Measurements shall be made at the corners of a cubic volume that completely encompasses the machine, and the velocity shall be computed as the average of these eight measurements.

B2.2 Mean Ambient Temperature

The mean ambient temperature shall be measured using a thermometer with characteristics as specified in Chapter 11. The mean ambient temperature shall be the time-average temperature of five readings taken at the center of the machine work zone over a period of time spanning the longest test. (The use of five readings, rather than two, for the measurement of the mean ambient temperature is justified here for diagnostic purposes.)

B2.3 Frequency and Amplitude of Temperature Variation

The range of frequencies of temperature variation and the amplitude of those variations shall be determined by measuring and continuously recording the temperature at the center of the work zone over a period of time that should, at a minimum, be representative of a daily cycle (i.e., 24 hr). The maximum peak-to-valley temperature variation shall be determined from the recorded data. The data shall be analyzed to determine the range of temperature variation for a daily cycle and an hourly cycle, subject to the condition that isolated disturbances that are shorter in duration than the minimum period

[1] This Appendix discusses only measurements of air temperature, and the User is warned that sometimes thermal effects are caused by coupling of infrared and visible radiation to the machine. If the environment appears to conform to the Supplier's parameters after performing the tests in these appendices and the ETVE of the machine is still not within specification, radiation coupling should be seriously examined.

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(maximum frequency) specified by the Supplier shall be ignored. The daily variation shall be defined as the maximum range of temperature readings in 24 hr, subject to the condition on transients mentioned above. The amplitude of the superimposed hourly cycle shall be defined as the maximum range of temperature variation in any 1-hr interval, subject to the same condition.

B2.4 Thermal Gradients

Thermal gradients shall be determined by measuring the temperature at the extreme corners of the machine in a horizontal plane and also at the highest and lowest locations of the machine. These temperatures shall be defined as the average value of no less than five readings over an interval of 10 min. The vertical gradient shall be determined to be the difference between the maximum and the minimum temperatures anywhere along a vertical line through the machine divided by the distance between the measurement point of these extreme temperatures. The horizontal gradient is defined to be the difference between the maximum and the minimum temperatures along any horizontal line through the machine divided by the distance between the measurement points of these extreme temperatures. These readings shall be taken over a period of at least as long as the longest acceptance test (or 24 hr) and the greatest value of the gradient reported.

B3 ANALYSIS

If any of the parameters measured in para. B2 exceed the Supplier's specified parameters, it is the responsibility of the User to correct the problem in order to conform with those specified parameters, or else to be willing to accept the performance derating described in Chapter 6. If the parameters so measured meet the Supplier's specified parameters, it is the Supplier's responsibility to correct the performance of the machine tool to meet the specified working tolerances.

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NONMANDATORY APPENDIX C
SEISMIC VIBRATION VERIFICATION TESTS

C1 SCOPE

The purpose of this Appendix is to recommend vibration measurement instrumentation and procedures for measuring vibration at machine installation sites. Vibration levels shall be measured at the proposed machine site(s) to compare to allowable site vibration limits established by the machine Supplier. This document also defines the instrumentation and measurement procedures to establish vibration on the machine for additional analysis. This Appendix does not address the determination of vibration sources or reduction of vibration levels. This task is usually involved and requires the knowledge of vibration specialists.

C2 DEFINITIONS

To the extent possible, this document is intended to be self-defining. It is written for individuals with an engineering background. Definitions for specific vibration terminology may be found in IEST-RP-CC024.1.

C3 VIBRATION ACCEPTANCE CRITERIA

The machine Supplier is to provide site vibration criteria of acceptability. Below these levels the machine can operate successfully, and above these levels problems may occur. Each machine Supplier has different formats and levels of acceptance. The type of vibration measurements to be taken will depend on format and vibration units specified by the machine Supplier. Based on the type of criteria, the vibration specialist should determine the necessary measurement units, frequency range, measurement locations, and instrumentation.

C3.1 Criteria Units

Vibration is characterized by amplitude versus time or frequency. The amplitude can be defined in displacement, velocity, acceleration, or power spectral density.

Since the machine is a cutting tool, units of displacement are most useful in relation to machine performance. Velocity and acceleration, however, are more appropriate parameters for measuring machine site vibration. Displacement may be suitable for specific situations, but it is not recommended for general vibration measurements.

The use of time or frequency for the amplitude will depend on the acceptance criteria format of the machine Supplier. Time-based criteria are referred to as a time history, which provides measurement of transient or very low frequency vibratory events, such as beat signals. The frequency domain allows measurement over a very short time range that provides ability to diagnose many dynamic events.

C3.2 Criteria Format

As defined in para. 5.3, the Supplier shall provide, as part of the machine specification, a statement of acceptable vibration. The criteria should be provided by the Supplier or listed as part of the machine specification form (Form 1.1), if used. At least two criteria format options are presented: frequency response function and time history. The supplied acceptance criteria will define the format to present the vibration data for ease of comparison.

C3.2.1 Frequency Response Function. These types of criteria are specified as a vibration amplitude as a function of specific frequencies. The criteria are usually presented as allowable vibration amplitude versus frequency, in hertz. The frequency range may vary from Supplier to Supplier. In general, seismic vibrations are applicable over a range of 0 (DC) to 100 Hz. Vibration levels have large dynamic range and it is sometimes helpful to present amplitude data in logarithmic scale. If decibels are used, the standard reference values must be used.

C3.2.2 Time History. These measurements represent the vibration during the time period of interest. The Supplier should specify a maximum peak-to-peak acceptable vibration amplitude and a time period over which it applies.

C4 INSTRUMENTATION

This paragraph describes various instruments required to perform on-site vibration measurements. Various types of sensors, signal conditioners, recorders, computer programs, and signal analyzers are available to acquire such data. It is not intended to single out any particular equipment manufacturer, but to recommend types of equipment that meet the requirements of this Standard.

C4.1 Transducers

Many types of transducers exist for various types of vibration measurements. The measurements specified

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in this document require a seismic accelerometer or a specific type of velocity transducer.

C4.1.1 Seismic Accelerometers. The two most important requirements for the accelerometer are frequency response and sensitivity. Site vibration measurements generally require low frequency and high sensitivity. The minimum frequency response linearity should be less than 1 Hz, preferably 0.5 Hz. The frequency response should be greater than 100 Hz. The sensitivity of the accelerometer should be 10 V/g or greater, where g is equal to 9.8 m/sec^2 (386 in./sec^2).

C4.1.2 Velocity Transducers. These sensors are also referred to as geophones. The sensitivity of the geophone should be 4 V/cm/sec (approximately 10 V/in./sec) or greater. The frequency response linearity requirement of the velocity transducer is the same as the accelerometer, 0.5 Hz to 100 Hz.

C4.2 Amplifiers and Signal Conditioners

The transducers require amplifiers and signal conditioners. Most seismic accelerometers require an amplifier, but some models may have built-in electronics that do not require signal conditioning. Velocity transducers may require amplification and signal conditioning, depending upon the sensitivity and signal-to-noise ratio. It is the responsibility of the vibration specialist to use the proper signal conditioners.

C4.3 Signal Recording/Analysis Instruments

The type of instrumentation to use will depend on the type of criteria and format that have been provided by the machine Supplier. The frequency response criteria require a fast Fourier transform (FFT) dynamic signal analyzer or digital recorder. Time history data can be acquired with an oscilloscope, a digital recorder, or an FFT analyzer.

C4.3.1 FFT Signal Analyzers. This type of analyzer is the most sophisticated means of measuring vibration, by providing the greatest amount of information about the vibration signal. In most cases, this additional information is necessary to understand the vibration environment. Many types of FFT analyzers exist, from many different manufacturers. One- and two-channel units, hand-held, and PC-based are formats readily available. It should be noted that using a data recorder, as specified in the following paragraphs, will require the use of an FFT analyzer after the data are acquired. It is the User's responsibility to understand the instrument, its capabilities, and its limitations.

The following list offers guidelines for FFT analysis configuration and specifications.

(a) Noise Floor. 100 dB/$\sqrt{\text{Hz}}$.

(b) A/D Resolution. The resolution of the analog-to-digital converter should be at least 12 bits. The better analyzers will have a 16-bit A/D resolution.

(c) Dynamic Range. The dynamic range should be at least 70 dB. Better spectrum analyzers will have higher dynamic range.

(d) Frequency Resolution. This parameter, as it applies to the analyzer, is denoted in number of lines over which the analysis range is divided. Most analyzers can have selectable resolution from 100 lines to 1,600 lines. The resolution, in hertz, is calculated by dividing the frequency range by the number of lines. For example, a 0- to 100-Hz frequency range acquired with a 400-line analysis will have 0.25-Hz (100/400) resolution. The frequency resolution used must be compatible with the resolution of the frequency response criteria. If the criteria are defined at every 1 Hz, the data must be acquired with a 1-Hz resolution. For example, 0- to 100-Hz criteria defined every $\frac{1}{2}$ Hz would need to be acquired with 200 lines of resolution. This document recommends that 0–100-Hz data be acquired with 400 lines of resolution, producing 0.25-Hz resolution data. The overall frequency resolution will also be dependent on the transducer frequency response. The procedure above should be followed, and modified only when the machine Supplier's specification requests otherwise.

(e) Anti-Aliasing Filter. This filter prevents incorrect reporting of frequency components due to under-sampling of higher frequency signals. This filter is found on most (if not all) FFT analyzers. It should always be used.

(f) Averaging. Most analyzers have this feature. It is used to reduce the effects of transient events such as personnel or vehicular activity. It is recommended that ten averages be taken for all measurements.

Some spectrum analyzers have various types of averaging functions, such as linear, rms, peak hold, or exponential. Linear or summation averaging should be used.

(g) Window Functions. This feature is used to force a generalized vibration signal into discrete time domain periods. When window functions are not used, the frequency response of the vibratory signal is incorrectly distributed throughout the frequency range. There are many types of window functions. The most popular are Hanning, flat top, and uniform. Other windows provide excellent amplitude accuracy and poor frequency accuracy, and vice versa. The Hanning should be used for all measurements specified in this Appendix.

C4.3.2 Data Recorders. For ease of gathering vibration data in the field, the use of a multichannel data recorder is found to be useful and convenient. Such an instrument allows for three or more channels of data to be recorded simultaneously, while providing a permanent record for archives and verbal data annotation during specific events. Additionally, the recorder allows a record of the real-time response that can be most useful. The data can then be processed at a later date using in-house data reduction techniques such as FFT analyzers specified in the section above. The recorder format must be digital and use Digital Audio Tape (DAT), because

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of its excellent signal-to-noise ratio and dynamic range as compared to analog tape.

C4.3.3 Oscilloscopes. This piece of general laboratory equipment may be easily obtained to make an initial set of time-history readings. Most facilities have an oscilloscope and personnel who can operate the equipment, which allows a user to take baseline readings. The oscilloscope is also useful for viewing beat signals, transient events, and hourly and daily vibratory changes. The oscilloscope should be set to AC-coupled and free-run triggering. The vibration amplitude is determined by viewing the signal and determining the peak-to-peak voltage amplitude, and using the transducer sensitivity for converting to appropriate amplitude units.

C5 TEST PROCEDURE

The procedures for making vibration measurements are fairly simple, once the appropriate analysis equipment is selected and configured as required.

C5.1 Calibration

At a minimum, the vibration measurement equipment should have been calibrated by a qualified laboratory, traceable to NIST, in the past 12 months (see Chapter 11). Site calibration of the transducers at the start of the testing is required.

C5.2 Transducer Mounting

For all measurements, the transducers should be mounted directly and firmly to the floor or a common interface for measuring three mutually orthogonal axes. Such mounting arrangements are referred to as triaxial. Some accelerometers incorporate three transducers in one device. When this mounting arrangement is used, all three channels should be acquired simultaneously.

C5.3 Measurement Location

In general, the transducers should be mounted in the general area where the machine will rest. This area should encompass the outer envelope of the machine plus 3 m (approximately 10 ft) beyond its footprint.

C5.4 Acquiring/Recording Data

Vibration measurements should be made during normal operations of the facility. Nearby equipment that will be operating when the machine is expected to be used should be running during the vibration testing. A written test log or voice channel on a data recorder should be maintained by the individual performing the test so that any abnormal events during the test may be recorded. A test should be repeated if abnormal events occur. Normal vehicular traffic should not be excluded. When the environmental conditions are satisfactory, the data should be recorded on tape, saved to memory, and printed or manually recorded.

C5.4.1 Time History. For time-history criteria, simply compare the measured peak-to-peak vibration levels to the permissible level. The machine Supplier may provide criteria for vertical and horizontal directions. It is important to compare the acquired data to the criteria in the appropriate direction.

C5.4.2 Frequency Response Function. Comparison of frequency response function criteria to frequency domain vibration data can be more effort than taking the data. If the criteria have the same level at all frequencies (straight line) or little changes in amplitude, it will be easy enough to draw the criteria over the printed vibration levels. If the criteria are not constant or uniform, it may be easier to compare data and criteria with various software programs. This involves digitizing the criteria, which in some cases requires entering levels at 1-Hz increments. The vibration data stored on the FFT analyzer must be downloaded into a PC. This requires different steps, depending on the analyzer manufacturer. Using a spreadsheet, math, graphing, or special program, the vibration data and criteria are combined into a single graph. Once the data are in a software format, they can be manipulated, graphed, and analyzed in a usable format.

C6 CRITERIA ASSESSMENT

C6.1 Measured Vibration Below Criteria

If the vibration levels measured by the procedure above are within the Supplier's criteria, no additional work is required. It is the sole responsibility of the Supplier to maintain the performance of the machine in order to meet specifications.

C6.2 Measured Vibration Above Criteria

If the vibration levels exceed the Supplier's specifications, it is the responsibility of the User to isolate the vibration to conform to the specification, or else accept a performance derating as described in para. 6.3. This Appendix does not provide information on how to reduce excessive vibration levels, but vibration isolation will reduce the levels. Before the vibration levels can be reduced, the source of the vibration must be determined. It may be easy to do this with the above equipment. Shock and vibration isolator suppliers, who specialize in low-frequency vibration attenuation, should be contacted if vibration isolation or a vibration survey is required.

C7 REPORT

A report should be issued by the vibration specialist within approximately three weeks. The report should include all backup information and analyzed data, with a comparison to the machine specification. The report should include the following as a minimum:

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(a) title
(b) dates (issued and when data were taken)
(c) calibration information
(d) description and diagram of test setup
(e) procedure
(f) analysis
(g) summary

It is important to note that the report should serve to archive the baseline vibration data for later review, if problems arise after machine installation.

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NONMANDATORY APPENDIX D
ELECTRICAL POWER MONITORING TESTS

D1 PURPOSE

The purpose of this Appendix is to specify test procedures for analyzing the electrical power supplied to a machine tool and its support equipment if the electrical power is suspected to be causing inadequate machine performance.

D2 TEST EQUIPMENT

Although the parameters describing the electrical power supplied to a machine can be measured by a variety of instruments (voltmeters, oscilloscopes, and the like), it is the recommendation of this Standard that a power-line monitor be used for these tests. Power-line monitors are designed to monitor a wide range of disturbances and steady-state conditions in an unattended mode of operation. Typical measured parameters include rms variations, transients, harmonics, and frequency.

Definitions of these parameters are not provided in this document. The reader is referred to IEEE 1159 for complete definitions and explanations of each parameter.

D3 METHOD

To ensure proper monitoring, the power supply to the machine should be monitored for a period that includes the normal cycle of machine tool operation. In the one-shift plant, this should include a complete shift. In the three-shift plant, complete 24-hr monitoring is required. Additionally, care should be taken that the power-line monitoring occurs over a representative period, which includes all normal or even intermittent electrical activity within the plant that could affect the machine. (As an obvious example, consider the case when arc welding is done only a few days a week at a location that uses the same feeder as the machine tool. In this case, the power-line monitoring should include a typical arc welding sequence.)

For making these measurements, an approved, calibrated power-line monitor of the type discussed previously should be used. Appropriate thresholds (sag, swell, and transients) should be set at the values corresponding to those levels set by the Supplier in the machine tool specification. Monitoring should continue for a sufficient period to ensure that all of the effects mentioned are included. Seasonal changes, abnormal weather conditions, system operations, and other factors all affect the power environment and the reliability of the power system.

D4 ANALYSIS

Typical power-line monitors provide printouts of both the levels and times at which deviations from the accepted thresholds occur. If the monitor is set with the thresholds described above, any such deviations recorded shall constitute nonconformance with the Supplier's specifications, and it shall be the responsibility of the User to correct such power-line defects. If no deviations from specifications occur, then it is the responsibility of the machine Supplier to correct the performance of the machine tool so that machine specifications are met. For help in interpreting the power monitoring results, refer to Section 8 of IEEE 1159.

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NONMANDATORY APPENDIX E
MACHINE FUNCTIONAL TESTS

E1 GENERAL

The tests described in this Appendix are to verify machine functional specifications that are important, but do not directly influence machine accuracy. These tests influence the machining cycle time estimated based on functional parameters like pallet change time and tool change time, etc.

E2 SPINDLE RPM MEASUREMENTS

This test is intended to verify whether the spindle is running at the commanded revolutions per minute.

E2.1 Test Procedure

E2.1.1 Equipment. A spindle analyzer that is used to measure spindle dynamic errors (para. 7.5) can be used, if available. Other instruments like strobe or rpm indicator can also be used to measure the spindle revolutions per minute.

E2.1.2 Measurement Procedure

(a) The machine shall be programmed to command the spindle to run with no load at five different speeds, equally spaced over the total spindle speed range (including maximum spindle speed[1]), and the spindle speed recorded.

(b) For machines with ranges of spindle speeds, measurements shall be taken at the center of spindle speed range for each range, and at the maximum speed of the spindle.

(c) At each revolution per minute, a minimum of 100 revolutions shall be used to measure an average revolution per minute obtained from the spindle analyzer.

(d) The average revolution per minute shall be recorded for each of the spindle speeds measured.

E2.2 Data Analysis

The spindle speed error (differences between the target and measured spindle speeds) shall be reported for each spindle speed measured.

$$\text{Spindle speed error, \%} = \left[\frac{\text{measured spindle speed} - \text{target spindle speed}}{\text{target spindle speed}} \right] \times 100 \qquad \text{(E-1)}$$

E3 TOOL CHANGE TIME

This test is intended to measure the time taken for the machine tool to perform a tool change operation.

E3.1 Test Procedure

E3.1.1 Equipment. A suitable timing device is used to measure the time taken by the machine tool to perform tool change operations.

E3.1.2 Test Location. The machine shall be positioned at the center of the work zone with the spindle stopped.

E3.1.3 Measurement Procedure

(a) The machine shall be commanded to perform a tool change to pick up the nearest tool in the magazine, and then return to the center of the work zone with that tool.

(b) This process shall be repeated ten times.

(c) The average time period between the start of the machine motion from the center of the work zone and the return of the machine (after picking up the nearest tool) to the center of the work zone shall be reported as the minimum tool change time.

(d) A similar procedure is repeated ten times, with the machine moving from the center of the work zone to pick up the farthest tool and then returning back to the center of the work zone.

(e) The average time period between the start of the machine motion from the center of the work zone and the return of the machine (after picking up the farthest tool) to the center of the work zone shall be reported as the maximum tool change time.[2]

E3.2 Data Analysis

The minimum tool change time error shall be reported as the difference between the nominal minimum tool

[1] Exercise cautionary measures to ensure that measurements at different spindle speeds do not cause any safety concerns.

[2] On most modern machine tool controllers, a look-ahead capability exists, minimizing the tool change time by allowing simultaneous magazine movement while cutting.

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change time and the measured minimum tool change time.

The maximum tool change time error shall be reported as the difference between the nominal maximum tool change time and the measured maximum tool change time.

E4 PALLET CHANGE TIME

This test is intended to measure the time taken for the machine tool to perform a pallet change operation.

E4.1 Test Procedure

E4.1.1 Equipment. A suitable timing device is used to measure the time taken by the machine tool to perform pallet change operations.

E4.1.2 Test Location. The machine shall be positioned at the reference position, P_R, with the spindle stopped.

(a) For horizontal machining centers, the reference position is identified by the following values:

(1) X_R at the mid-travel of the X-axis

(2) Y_R at $\frac{1}{4}$ of the Y travel from its lower limit

(3) Z_R at a position where the spindle nose is at the edge of the table nearest to the column

(b) For vertical machining centers, the reference position has the following values:

(1) X_R at mid-travel of the X-axis

(2) Y_R at mid-travel of the Y-axis

(3) Z_R at mid-travel of the Z-axis

E4.1.3 Measurement Procedure

(a) The machine shall be commanded to perform a pallet change to pick up the nearest pallet in the pallet station, and then return to the reference position with that pallet.

(b) This process shall be repeated ten times.

(c) The average time period between the start of the machine motion from the reference position and the return of the machine (after picking the nearest pallet) to the reference position shall be reported as the pallet change time.

E4.2 Analysis of Results

The pallet change time shall be reported.

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NONMANDATORY APPENDIX F
MACHINE LEVELING AND ALIGNMENT

F1 MACHINE LEVELING

Most machine tools do not have to be leveled. Ships have machine tools and the machines are never level. Schlesinger's book on the *Testing of Machine Tools,* published in 1927, discusses leveling and the use of levels at great length (pages 7, 10, 11, and 12). This emphasis on leveling of machines continues today. Absolute leveling is one method, and often a convenient method, for achieving straightness of travel. It is rarely a requirement, however. Many methods are now available for measuring straightness, squareness, and parallelism that are faster and better. The use of electronic levels for measuring the change in level such as the measurement of pitch or roll is, on the other hand, an important technique in modern machine tool metrology. Installation procedures that require absolute leveling should be questioned.

F2 DISTRIBUTION OF LOADING ON MULTIPOINT SUPPORTED MACHINES

Uniform distribution of loading on multipoint supported machines is rarely a requirement. Such machines are generally mounted on a thick foundation block with adjustable wedges at each point of support. These wedges normally have a hole in their center to accommodate a grouted-in hold-down bolt to hold the machine down to the block. These wedges and hold-down bolts are adjusted "push–pull" to achieve the correct machine geometry. In so doing, the forces between the block and the machine are indeterminate and vary widely from point to point. Optimizing machine geometry should always be the goal. For machines of this type, it is the recommendation of this Standard that the User work closely with the machine Supplier to make sure the foundation is adequate for the machine and is sufficiently cured. Supplier's recommendations regarding machine alignment shall be followed. If such procedures are followed, then the Supplier shall have sole responsibility for meeting the functional specifications of the machine, derated as appropriate for thermal effects and excessive relative vibration (see Chapter 6).

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NONMANDATORY APPENDIX G
CLARIFICATIONS FOR CUTTING PERFORMANCE TESTS

G1 CHOICE OF METHODS

Two fundamentally different approaches have been discussed for both the chatter limits test and the cutting force induced errors test. In one of them, the tests are made by specified machining passes and corresponding observations and measurements. In the other approach, the dynamic compliance between the tool and the workpiece is measured, and the chatter limits and surface errors are calculated using the corresponding formulas and computer simulations. In the latter approach, actually, it might be considered just to accept the main parameters of the dynamic compliance as a measure of the required quality of the machine tool. This dilemma of the two approaches has been called the question of cutting tests versus exciter tests. Each of the two has its own pros and cons. The cutting tests are simpler to understand and interpret, and they do not need much special instrumentation. They have the advantage of "proof of the pudding," but their results may be affected by process damping and tool wear as well as by the location of the chosen spindle speed in the lobing diagram. Additionally, they are more time-consuming than exciter tests and the cost of workpiece material and of tools is not negligible. Cutting tests must therefore be limited to a minimum number of tools and cutting conditions. The exciter tests, once the necessary instrumentation and skill is available, can be done quickly and in many different configurations of the machine tool. Their results can be used in a more general way, and provide information about chatter limits and surface accuracy for various tools over the whole range of speeds. However, because of some tricky effects like those of spindle speed, thermal effects on the dynamic compliance, and nonlinearities in bearings and guideways that need special experience to account for, these tests cannot be simply recommended as fully satisfactory.

The best solution, recommended here, is to carry out the exciter tests and complement and cross-check them with the cutting tests. Such a combination is considered as the complete set. It is then recommended to use a selection of the cutting tests as the verification set. The latter is the subject of this Standard.

G2 THE COMPLETE SET

The contents of the complete set of tests are summarized here. The dynamic compliance is formally represented as a set of direct transfer functions $G_X = X(\omega)/F_X(\omega)$, $G_Y = Y(\omega)/F_Y(\omega)$, where X and Y are generally meant as vibrational displacements in two coordinate axes perpendicular to the spindle axis and F_X and F_Y are periodically variable forces acting in the two axes, respectively. The forces act between the tool and the workpiece, and the relative displacements are measured between tool and workpiece.

The individual components of the complete set are given in the following sections.

G2.1 Measurement of the Transfer Functions

First obtain the transfer functions G_X and G_Y over such frequency ranges as to contain all significant resonances. It is usually sufficient to excite at spindle standstill, without preload. Sometimes it is also necessary to measure with the spindle rotating and with the spindle preloaded at standstill. It is often difficult to eliminate the effects of the excitation device on the results, especially when exciting at a point of low reflected mass, as with an end mill, and special care must be taken. Impact excitation is preferable and preload may be provided by a piano wire stretched between tool and table. The transfer functions must be obtained for a representative selection of tool and tool holder combinations and for all the different basic configurations of the machine. This means, for example, that if the machine has an extendable ram, data for several selected extensions are required. The transfer functions should be curve fitted, and a table of modal parameters k (modal stiffness), m (modal mass), ξ (modal damping ratio) of the most significant modes for each transfer function assembled. Four examples of measured transfer functions are presented in Fig. G1. In each case, the imaginary part, Im(G), of the transfer function is plotted on linear scales of displacement (μm) over force (N) versus frequency (Hz). In illustration (a), a simple transfer function in one direction is shown that contains only one dominant mode. In (b), an example is shown of a transfer function in one direction with two modes of approximately equal compliances. In (c) and (d), rather complicated transfer functions are presented as measured on a tool in the two basic directions and they differ substantially. Only the imaginary parts are shown. These kinds of data are then used for further processing, although they could be used as the final characteristics of the tested machine.

G2.2 Computation of the Chatter Limits

In the next step, the data from para. G2.1 are used to compute the expected chatter limits. For this purpose,

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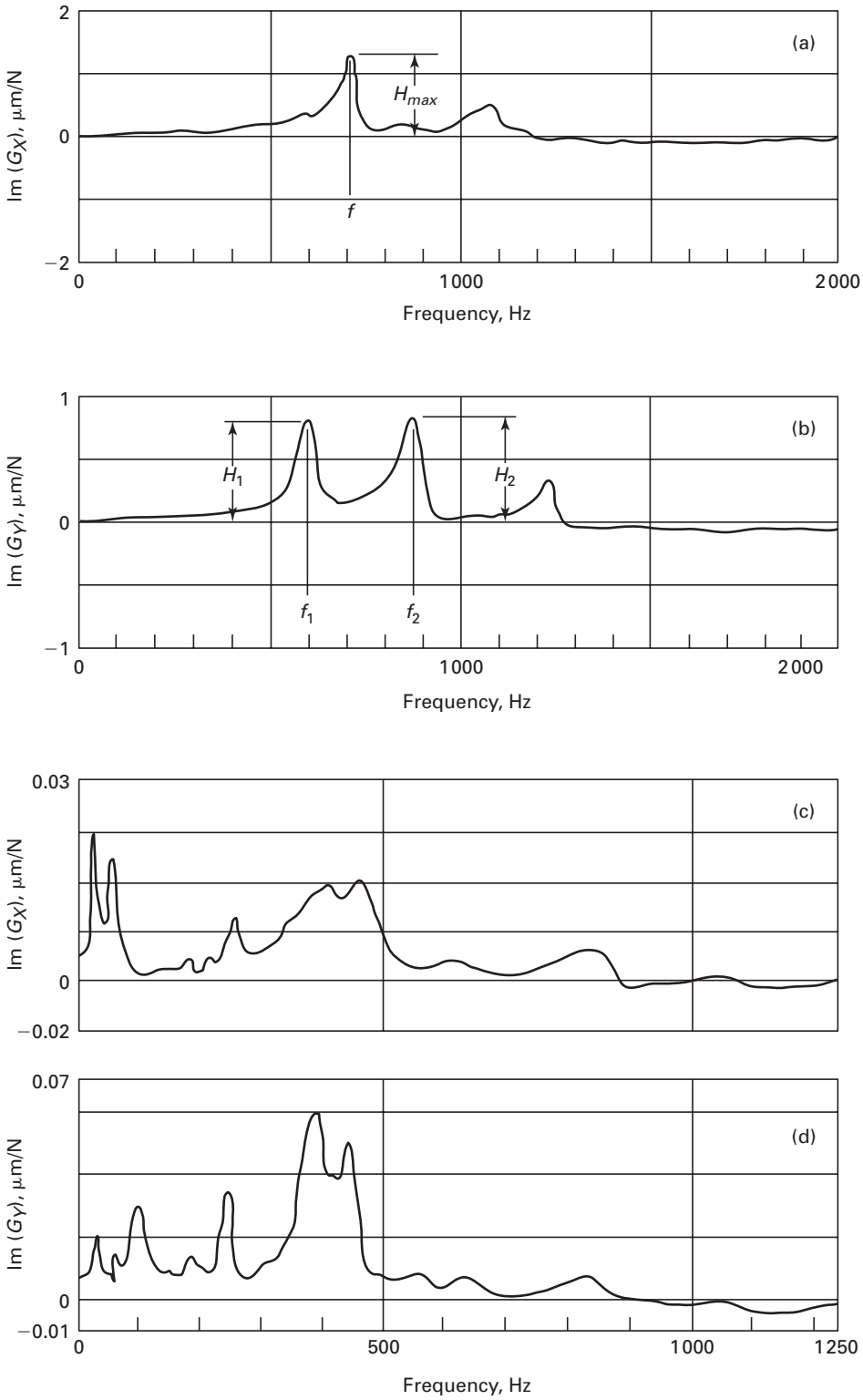


Fig. G1 Typical Transfer Functions

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well-established procedures may be used.[1–3] The state of stability of cutting (i.e., whether chatter vibrations occur) is fundamentally decided on the part of the cutting process by the following parameters: the workpiece material (the specific force, K_s), the axial depth of cut b (mm), the radial depth of cut (width of cut) a (mm), and even more correctly by the "radial immersion" expressed by the ratio $i = a/d$, where d (mm) is cutter diameter, and by the number of teeth on the cutter, m. Increasing any one of these parameters may change cutting from stable to unstable. Actually, in a good approximation it is their product (abm/d) which is decisive. The change of the chip load, c (mm), does not affect the state of stability, but it affects the amplitude of chatter once cutting is in the unstable range. Spindle speed, n, has a special effect to be explained in the following. On the part of the structure, stability is affected by the degree of dynamic compliance as expressed by the two basic transfer functions.

The link between the cutting process and the structural parameters is the directional orientation of cut. Often the transfer functions in X and Y differ if even slightly. By changing the radial immersion, i, the direction of the feed X or Y, or the mode of up or down milling, the cutting force effect on vibrations in X and Y, respectively, varies, as does the effect of these vibrations back on the force.

Considering all of these parameters, it is customary to express their effects in the so-called "stability lobing diagram." It relates the effect of spindle speed, n, and of the axial depth of cut, b, on stability, and it has to be computed for all the values of radial immersion of interest, for the workpiece material of interest, for a selected tool/tool holder combination, and for the corresponding structural dynamics. Computer programs are readily available for plotting the diagram with a high degree of correspondence to reality, by repeated simulations, or to approximate it by using a "simplified method."

Typically, for simple structural dynamics with one single dominant mode, the lobing diagram looks like the one in Fig. G2. It is plotted in coordinates: limit depth of cut, b_{lim}, versus spindle speed, n. Its envelope, shown in a thicker line, separates stable cutting (below the curve) from chatter (above the curve). At the low speed range, chatter generation is limited by "process damping": the wavelength of undulations created by chatter on the cut surface decreases, the slope of these waves increases, and a damping component of the cutting force prevents the regeneration of waviness. Machining at these low speeds is stable (for instance when using high-speed steel end mills on steel) but not very productive. Above a certain speed, $n_{\min}$, dependent on the frequency of the structural mode and on the cutter diameter, the effect of process damping becomes negligible. At the high speed range where the tooth frequency, $f_t = mn/60$, approaches the natural frequency, f_n, of the structural mode, prominent lobes are seen in the graph. They are due to the changes of phasing between the regenerative waves related to subsequent teeth of the cutter. The highest "wedge of stability" is at such spindle speed at which $f_t = f_n$. We will denote it the "stable speed," n_s. Other wedges of increased stability are found at $n = n_s/2$, $n_s/3$, $n_s/4$, etc., but they are smaller and smaller. Over the whole range above $n_{\min}$, stability repeatedly drops to a level called the critical depth of cut, b_{cr}. Below a speed of $n_{\max} = 0.8n_s/3$, stability varies little with speed and settles on $b_{cr.}$

Even for more complex cases than the one with a single dominant mode, the lobing diagram retains these characteristics. See Fig. G3, where lobing diagrams are compared corresponding to (a) a transfer function with a single mode and (b) with one more flexible mode added, for a cutter with $m = 8$ and $f_1 = 300$ Hz, $f_2 = 800$ Hz. In case (a), $n_s = (300/8)60 = 2\,250$ rpm and in case (b), $n_s = (800/8)60 = 6\,000$ rpm. The thick lines were obtained by the more accurate method and the thin lines by the simplified method. The b_{cr}, n_s, and $n_{\max}$ parameters are indicated. The effect of process damping was left out from this graph so as not to clutter it.

In summary, in the complete set of tests these kinds of graphs are generated. If they were available for all the tools to be used, one would know the n_s speeds and they could be used. It would be acceptable to also test the machine tool at these speeds.[4]

Generally, however, it is useful enough to know the value $b_{cr,}$ which is obtainable from a simple formula, and the speeds $n_{\min}$ and $n_{\max,}$ and to arrange the test between them so as to check b_{cr} and be on the "safe side" of stability.

G2.3 Cutting Tests

Cutting tests of chatter limits are then carried out for the individual tool/tool holder and machine configuration combinations to verify the most characteristic features of the chatter limits as determined in para. G2.2.

G2.4 Effects of Deflections on Accuracy

The data from para. G2.1 are further used to calculate the expected effect of deflections on accuracy of the

[1] J. Tlusty, "Machine Dynamics," Handbook of High Speed Machining Technology, R.I. King, ed., Chapman and Hall, New York, 1985.

[2] M. Weck, G. Petuelli, "Static and Dynamic Behaviour of Metal Cutting Machine Tools," Vol. 3, Machine Tool Mechanics, Technology of Machine Tools, MTTF, Oct. 1980, UCRL-52960-3, Lawrence Livermore National Laboratory.

[3] S. Smith, J. Tlusty, "Modeling and Simulation of the Milling Process," Symp. on Sensors and Controls for Manufacturing, PED Vol. 33, ASME 1988 WAM.

[4] S. Smith, T. Delio, "Sensor-Based Control for Chatter-free Milling by Spindle Speed Selection," Symp. on Control Issues in Manufacturing, DSC Vol. 18, ASME 1989 WAM.

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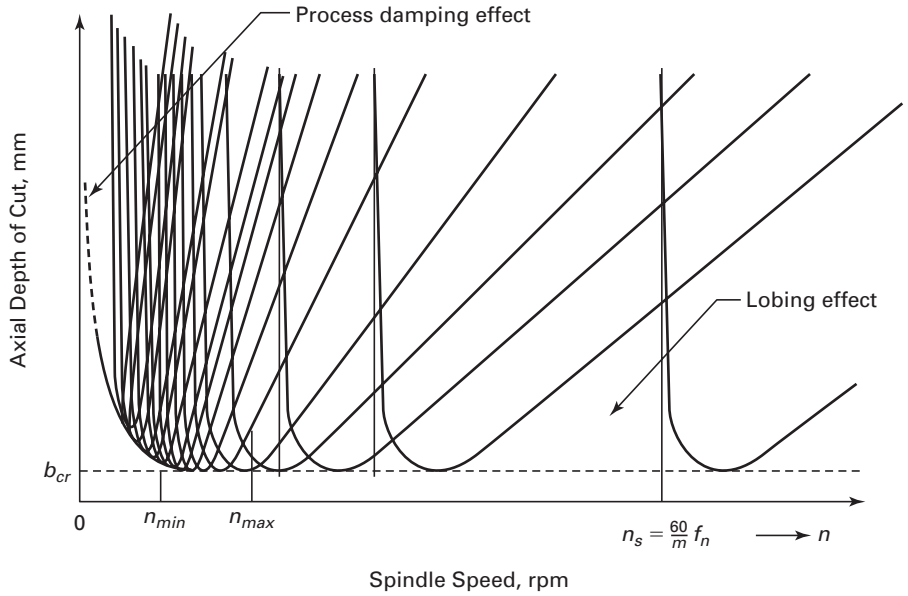


Fig. G2 Lobing Diagram for a System With a Single Dominant Structural Mode

machined surface. The relationship between the cutting force, system deflection, and the error of the surface is not straightforward, but it has been thoroughly explored.[1,5] It is indicated in the graph in Fig. G4, which applies to peripheral milling (contouring) with end mills. These tools commonly have helical teeth. Consider first the diagram (a). The end mill is removing a layer a into a depth, b, and generates surface, S. Although every tooth removes a chip, shown in black, on the way from A to B, it contributes to the surface, S, at only the instant it passes through the line A–A. Actually, with helical teeth the tooth contributes in an instant just one little spot on line A–A. For instance, point 5 is just generated by the tooth edge shown in a thick helical line. As the tooth rotates, it contributes to the surface, S, along 1, 2, ..., 5, 6. The broken lines are snapshots of the edge during the cutter rotation. And as the cutter moves with feed f, tooth by tooth climb subsequently along line A–A, which moves along surface, S. The cutting force, graph (b), has an average value F_{av} and a variation that is periodic in the tooth frequency, f_t. It acts on the structural system and produces an average displacement, y_{av}, and a variational component with amplitude, Y, frequency, f_t, and phase shift, ϕ. During the generating motion of the edge along A–A, the displacement varies through points 1 to 6, synchronized with the cutter motion. At every point on A–A, a different deflection is imprinted on surface S. The section through S is indicated in (d). It has an average shift $\delta_{av} = y_{av}$ and it is not flat but assumes a profile corresponding to the variation of the deflection. The latter part of the error is related to the helical teeth. With straight teeth, all of A–A would be generated in one simple instant, with the shift δ equal to a corresponding instantaneous value of the variable deflection y.

All of this can be computed and graphics like the one in (e) produced. This one shows how the surface error varies with varying radial depth of cut a. Actually, the recommended test procedure is just like this. It is important to realize that the amplitude, Y, of the variable deflection and its phase shift depend on spindle speed and they follow the corresponding transfer function as discussed in para. G2.1. These transfer functions are used as inputs in the simulation program.

G2.5 The Cutting Accuracy Test

The next step in the complete set is the experimental verification of the computations by the cutting accuracy test. In order to avoid the complexity of the speed effect mentioned above and still get an assessment of the significance of the errors produced by the structural deflections under the cutting force, on the particular machine tool to be tested, it is recommended to use a low speed at which the amplitude, Y, remains constant over a wide range of speeds and the phase shift, ϕ, is close to zero. A satisfactory choice is half the $n_{\max}$ speed, or less.

The verification set of tests specified in Chapter 9 of the Standard is formulated as a minimal set of cutting tests with selected tool/tool holder combinations and at cutting speeds most generally applicable as determined by accumulated experience.

G3 ESTIMATING CHATTER LIMITS

To choose correctly the range of the test conditions, it is useful to estimate the test results beforehand using

[5] J. Tlusty, S. Smith, "Forced Vibration, Chatter, Accuracy in High Speed Milling," NAMRC XIII, May 1985, SME.

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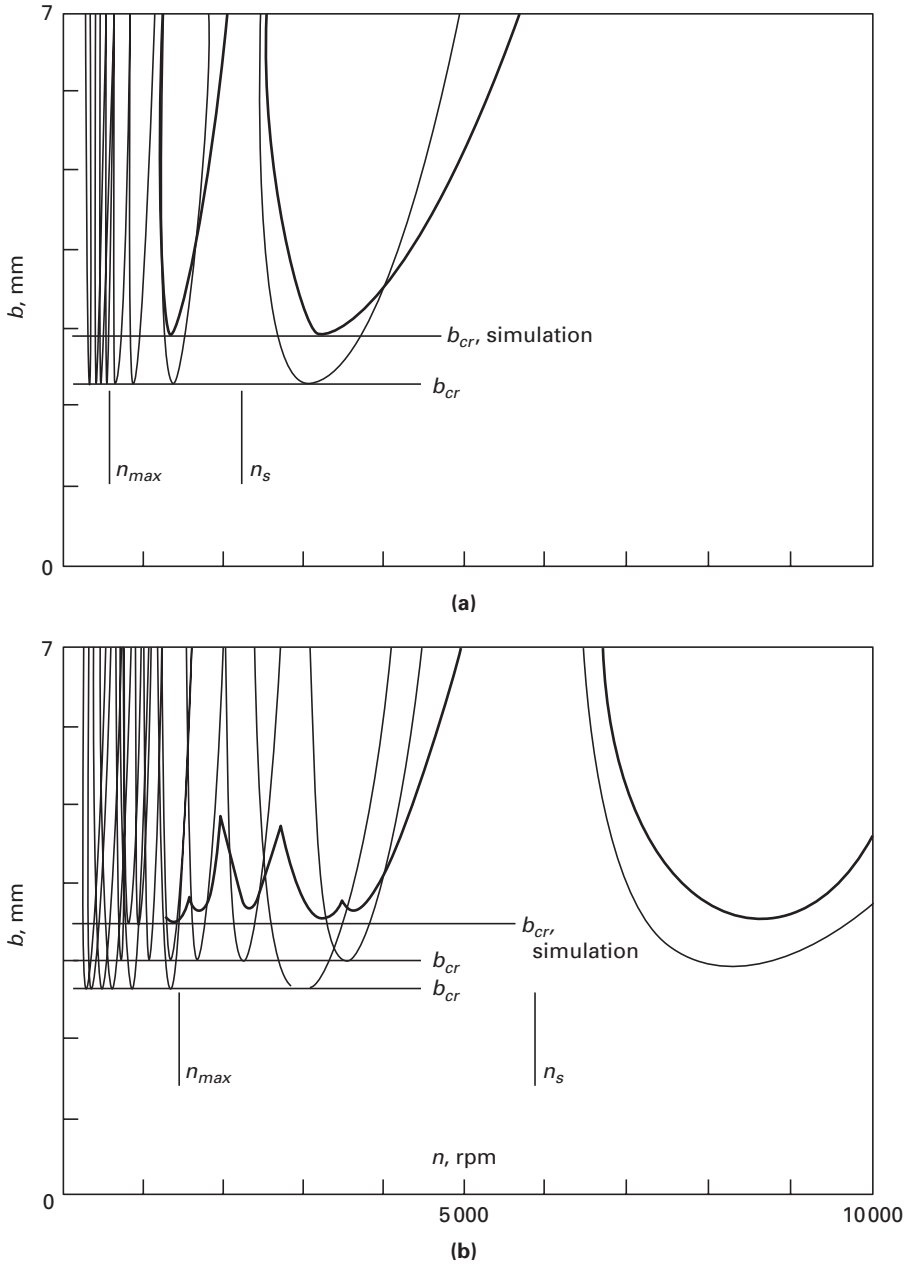


Fig. G3 Lobing Diagram for More Complicated Systems

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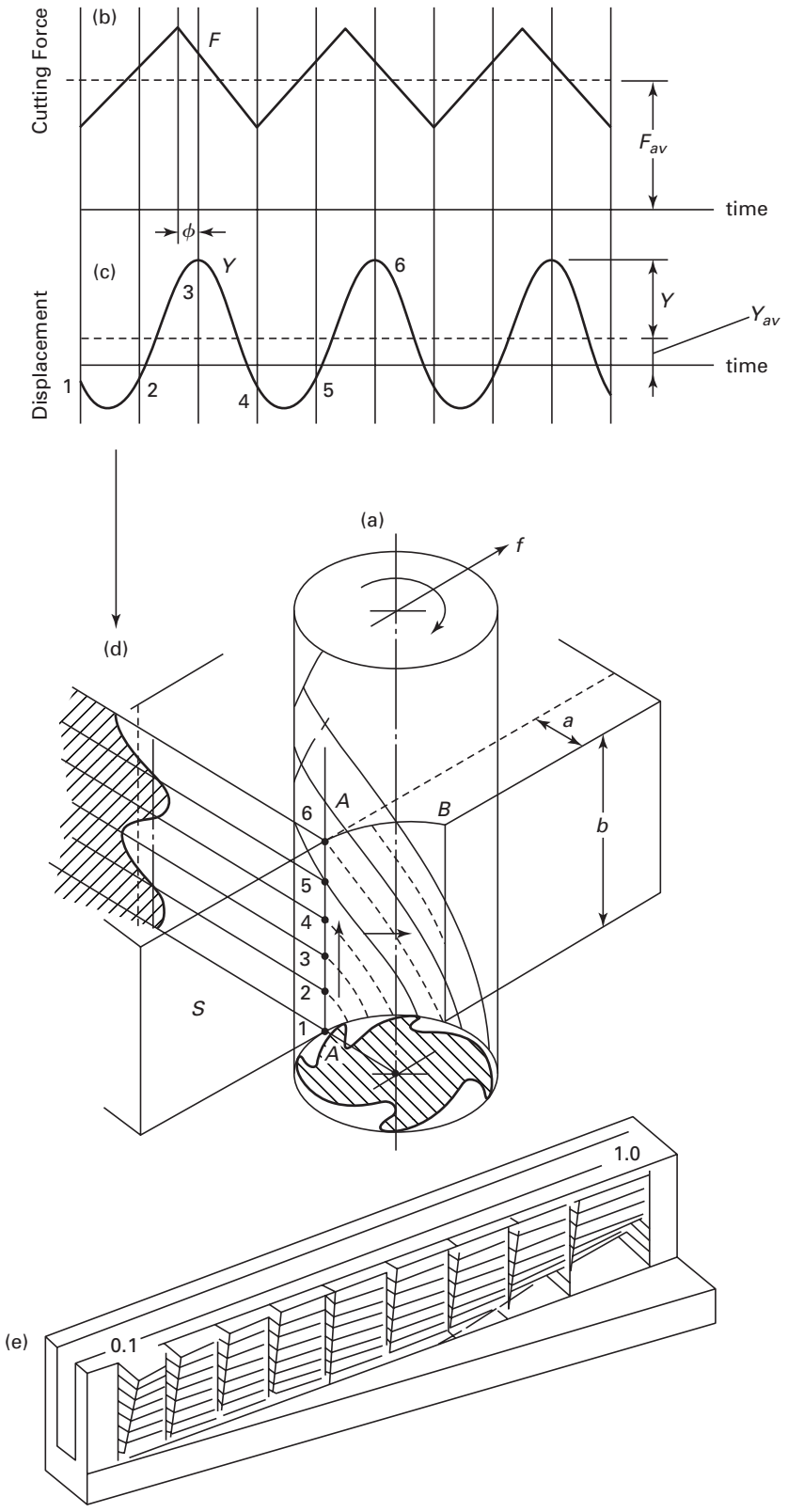


Fig. G4 Effects of Deflection in End Milling

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the minimum dynamic characteristics as specified in para. 9.2.1. We will express the "critical" limits as encountered in the n_{min}, n_{max} range and as they represent the minimum stability in the range above n_{min}. An approximate formula for the limit depth of cut of a full immersion milling pass, $a/d = 1.0$, is

$$b_{cr} = \frac{-[1/(m/2)]}{4K_s u \mathrm{Re}(G)_{min}} \quad \text{(G-1)}$$

where

K_s = specific force, N/mm^2
$m/2$ = number of teeth cutting simultaneously in a slotting cut
$\mathrm{Re}(G)_{min}$ = value of the minimum real part of the transfer function between the tool and the workpiece, measured in the direction of the feed, mm/N
u = directional factor

This formula is based on a rather gross simplification of the actual process and the results may be wrong by a factor of up to two times. However, even so it is extremely useful. Further, assuming $u = 0.33$ and $\mathrm{Re}(G)_{min} = H_{max}/2$,

$$b_{cr}\ (\mathrm{mm}) = \frac{3}{K_s H m} \quad \text{(G-2)}$$

where K_s is expressed in N/mm^2 and H is expressed in mm/N.

For 4340 steel (300-350 BHN), we use $K_s = 2\,000$ and

$$b_{cr}\ (\mathrm{mm}) = \frac{1.5}{Hm} \quad \text{(G-3)}$$

where H is expressed in μm/N.

For aluminum, $K_s = 750$ is used and

$$b_{cr}\ (\mathrm{mm}) = \frac{4}{Hm} \quad \text{(G-4)}$$

where H is expressed in μm/N.

Referring to Eq. (G-9), as given in para. G6, we may now express the estimated limitations imposed by chatter on torque and power limitations in slotting cuts:

$$T_{lim}\ (\mathrm{N\text{-}m}) = \frac{cd}{2H} \quad \text{(G-5)}$$

$$P_{lim}\ (\mathrm{W}) = \frac{0.05cdn}{H} = 0.1T_{lim}n \quad \text{(G-6)}$$

where

c = chip load, mm
d = cutter diameter, mm ($d = a$ for slotting cuts)
H = dynamic compliance, μm/N
n = spindle speed, rotations/min

The use of these formulas is illustrated in Chapter 9, Tables 9.4, 9.5, and 9.6, where the recommended test conditions are assembled for the individual classes of machining centers, together with typical dynamic characteristics and estimated test results.

G4 THE SPINDLE MODE AND THE TOOL MODE

In the analysis of the dynamics of the tool-spindle system, it is common to speak about a "spindle bending mode" or else a "tool mode." Characteristically, for smaller diameter tools the latter is more flexible and for larger diameter tools the former is more flexible. It is then necessary to coordinate properly the size of the tool with the size of the spindle.

For illustration, a particular spindle of a machine type D with a tool in the S type holder is shown in Fig. G5, together with the main mode shapes. For each, the modal stiffness is given in N/μm. The tool is $d = 19$ mm, $l = 75$ mm. The tool mode at 2 144 Hz is the most flexible, with a modal stiffness $k = 9.42$ N/μm. This mode consists mostly of vibration of the tool only, with the rest of the spindle immobile. No changes in the spindle design could increase the modal stiffness of this mode. The spindle bending mode with significant motions in the front bearings at 1015 Hz has $k = 62.7$ N/μm, and it is therefore 6.6 times stiffer. All of the other modes are even stiffer. The performance of this system is clearly dictated by the compliance of the tool.

The same spindle and holder, but with a $d = 38$ mm, $l = 75$ mm tool, is shown in Fig. G6. Now, the spindle mode at 839 Hz has $k = 59$ N/μm, whereas the tool modes at 2429 and 3193 Hz have $k = 234$ and 247 N/μm, four times higher. Obviously, this is the right choice of tool size for this spindle.

For all the machine classes, similar analyses as well as measurements have been compiled and used for test tool size choices.

G5 USE OF SENSORS TO DETECT CHATTER

Using an accelerometer or a microphone helps to improve the confidence in the test results by matching them with the measured transfer function and assurance that results are not faulty. Chatter is recognized by the development of a spectral line that is not a multiple of the tooth frequency; it is actually close to the natural frequency of the system. So, it helps if the expected chatter frequency is known in advance. An example of this distinction is shown in Fig. G7. In this figure, the spectrum of a stable case (top) is compared to the spectrum of an unstable (chattering) case to the bottom. The diagrams on the right show the spectra of the vibrations obtained from simulation. The ones on the left show an actual microphone signal spectrum as measured during the cut. The spectral lines in the stable case are due to the runout and tooth frequencies and, in the case of the microphone, also the background noise. Both methods show the chatter frequency at 800 Hz. Note how much

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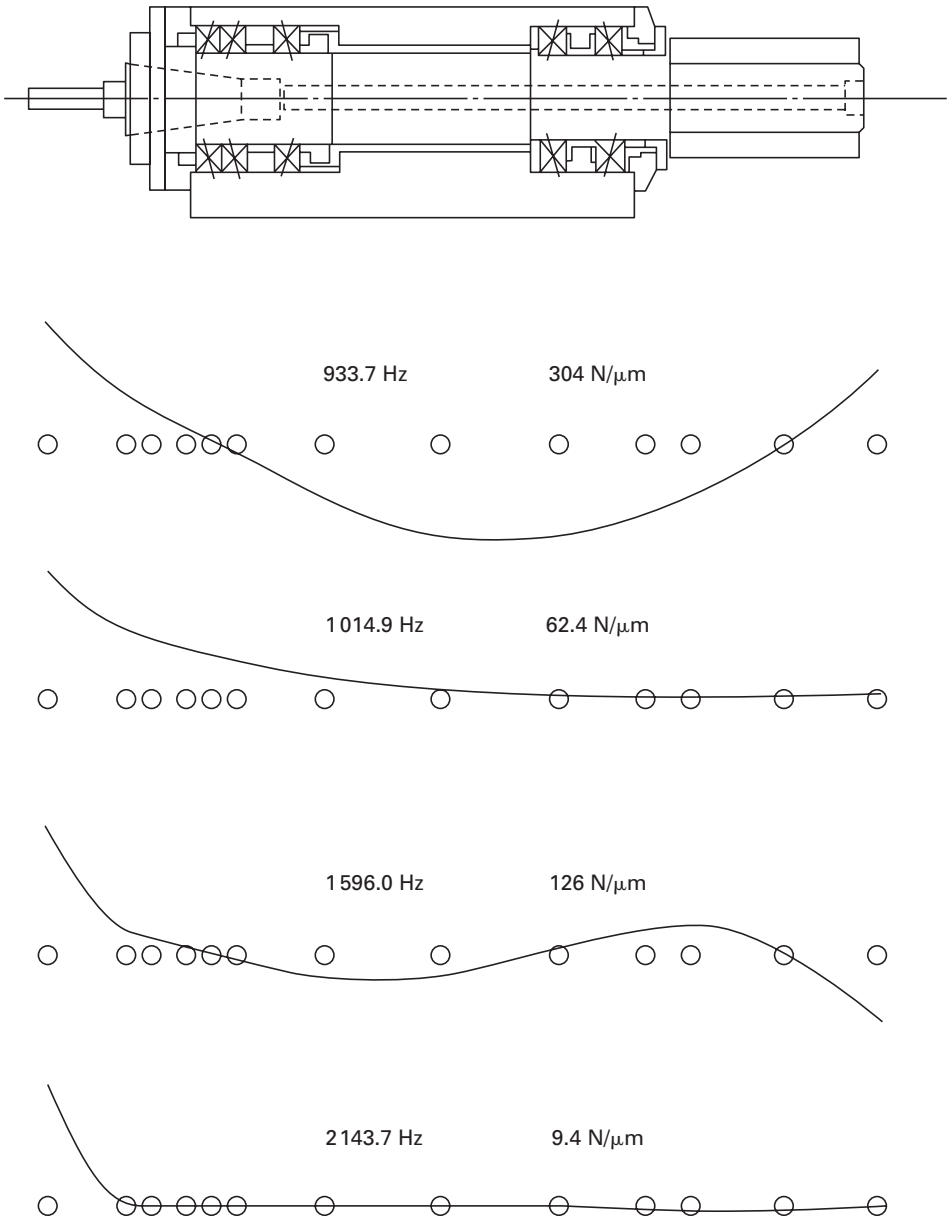


Fig. G5 Mode Shapes for a Spindle With a Compliant Tool

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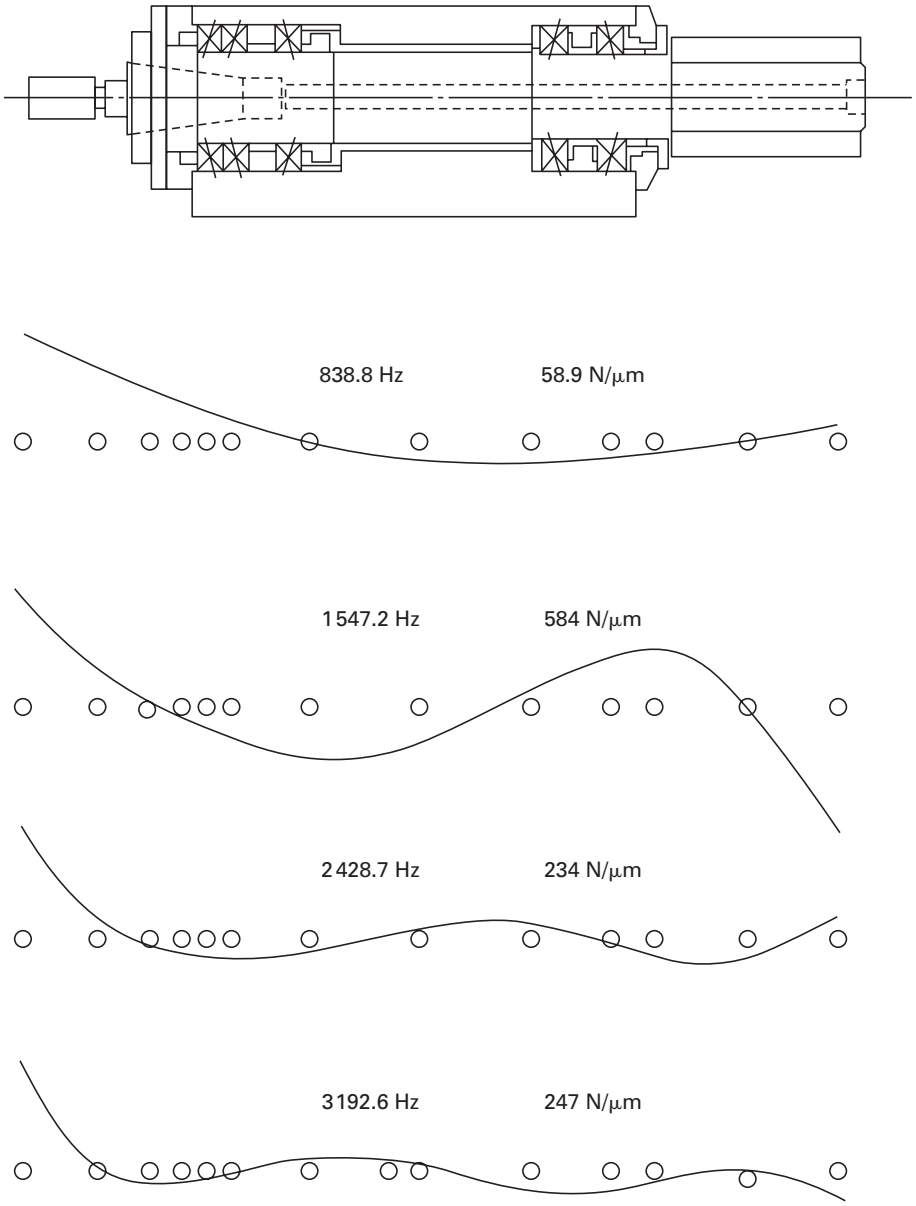


Fig. G6 Mode Shapes for the Spindle Mode With a Stiffer, Less Compliant Tool

the vertical scales increase in the chattering case. Moreover, the microphone signal can be used for automating the test in which the chatter recognition system determines the limits of the operation. Equipment for this kind of test is commercially available.

G6 BASIC PARAMETERS OF THE MACHINE TOOL OF A MILLING PASS

For the purpose of selecting tools, workpiece materials, and spindle speeds, machining centers have been classified in Table 9.2 of this Standard into several ranges according to speed and torque.

From the point of view of the drive, the torque, T (N-m), determines the size of the motor and the dimensions of the transmissions. The spindle drives generally possess characteristics of type (a) or (b) in Fig. G8. In (a), the power available on the tool increases in proportion to the spindle speed over the whole speed range. This means that over the whole speed range, the maximum available torque is constant. It is

$$P\ (\text{W}) = \frac{T\ (\text{N-m}) \times 2\pi n\ (\text{rpm})}{60} \qquad \text{(G-7)}$$

In most cases, however, the (a) type of characteristic extends only over the lower range of spindle speeds up

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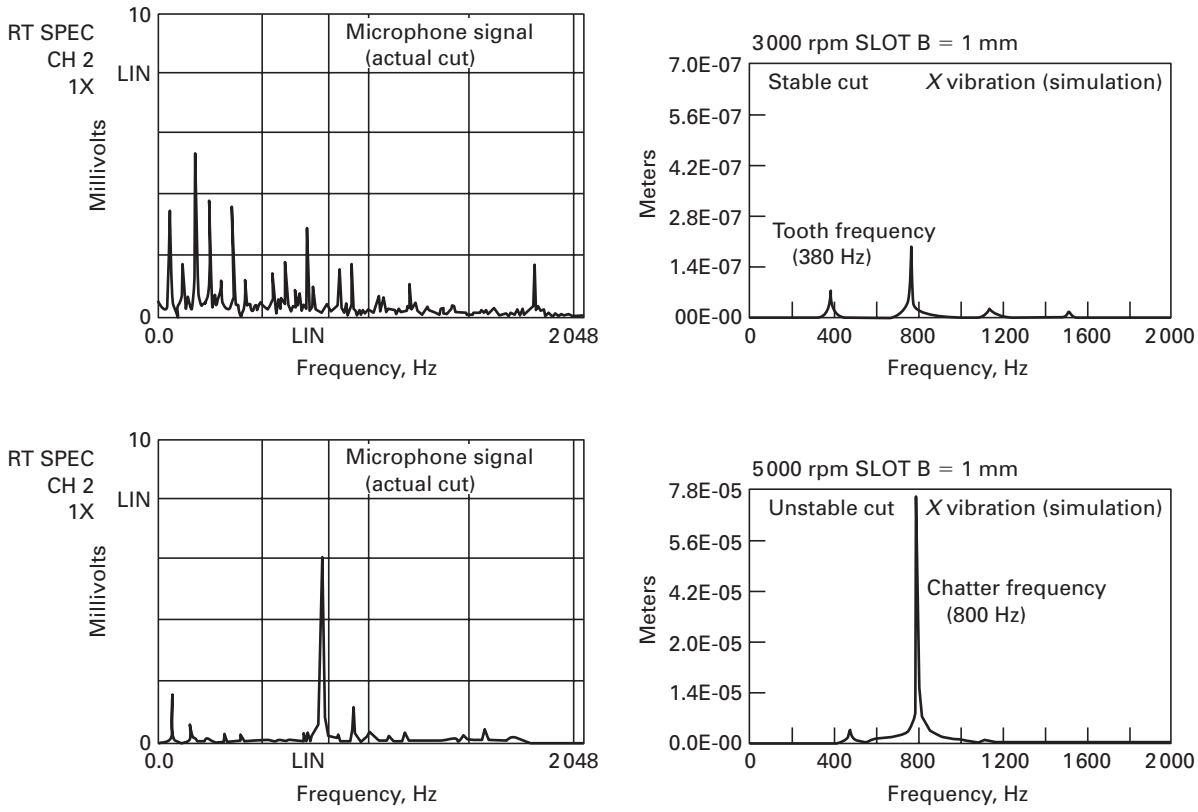


Fig. G7 Vibration Spectra of Stable (Top) and Unstable (Bottom) Milling

to the corner speed n_c. From there on, power remains constant and equal to $P_{\max}$ and the torque decreases hyperbolically:

$$T\ (\text{N-m}) = \frac{60P\ (\text{W})}{2\pi n\ (\text{rpm})} \qquad \text{(G-8)}$$

For face milling we are then usually again in the constant torque part of the range, whereas end milling often falls into the constant power range.

From the point of view of the milling operation, the necessary torque is obtained as

$$T\ (\text{N-m}) = \frac{K_s abmc}{1\,000(2\pi)} \qquad \text{(G-9)}$$

where

a = radial depth of cut, mm (see Fig. G9)
b = axial depth of cut, mm
c = chip load, or feed per tooth, mm
K_s = specific force for the given material {it is also the specific power, K_s [W/(cm^3/s)]}, N/mm^2
m = number of teeth on the cutter

In this way, torque signifies how "heavy" the cut is, irrespective of spindle speed, n (rpm), or cutting speed, v (m/min), as these are not involved in the formula [Eq. (G-9)]. Once the speed is chosen in addition to the torque, the needed power is obtained.

Here we will yet mention that, in general, chatter and accuracy depend on the same cutting parameters as the torque and their limits also depend on the dynamic stiffness between the tool and workpiece. In this way, it is proper to require more stiffness from machines with higher torques. These machines will have larger diameter spindles and generally heavier structures. These concepts were used to develop the machining center ranges (Table 9.3) used in this Standard.

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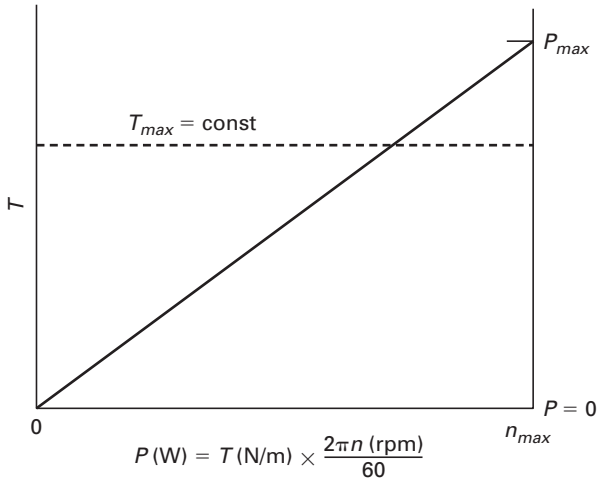
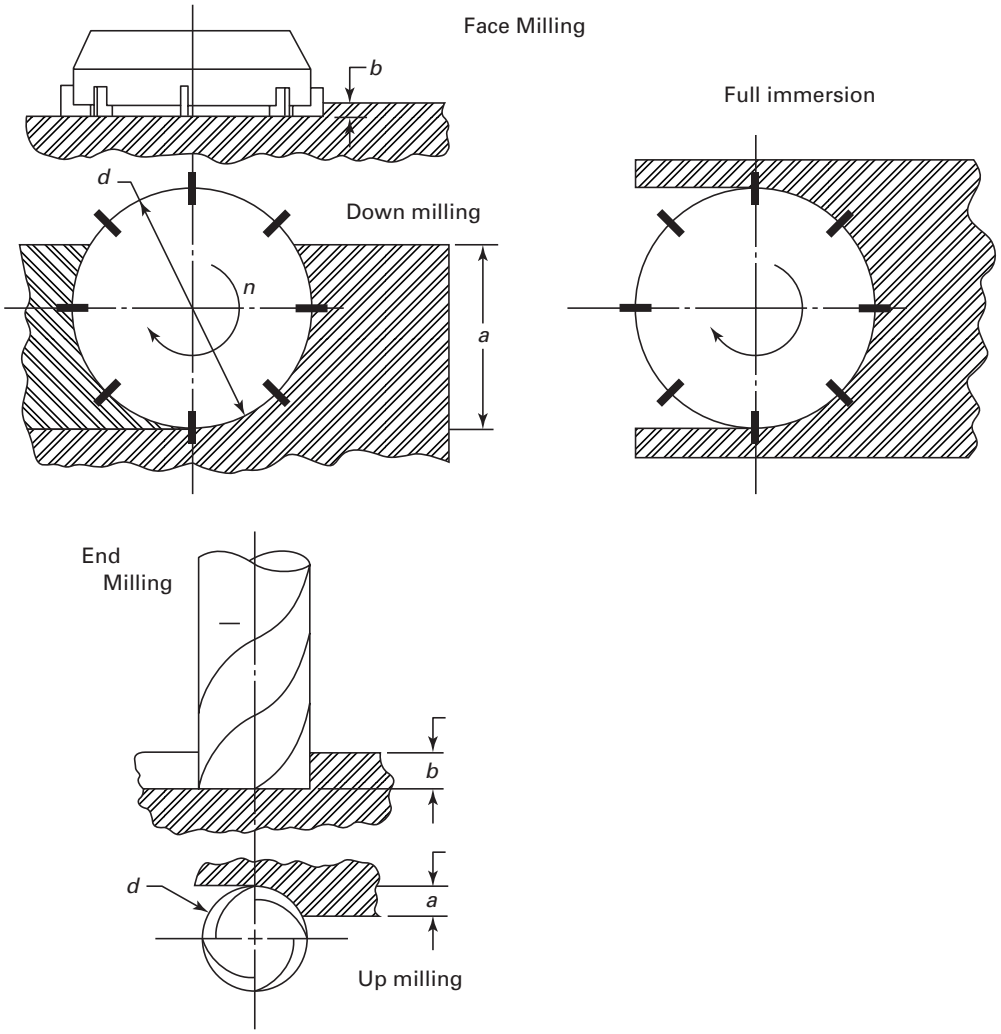


Fig. G8 Characteristics of Spindle Drives

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n = spindle speed, rpm
v = peripheral velocity cutting speed
c = chip load (feed/tooth)
i = rack radial immersion *(a/d)*

Fig. G9 Parameters Relevant in Milling

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NONMANDATORY APPENDIX H
LASER AND MACHINE SCALE CORRECTIONS

H1 LASER AND SCALE CORRECTIONS

If the laser interferometer used has environmental compensation features, the instrument manufacturer's recommendations regarding the use of these accessories shall be followed, with the material sensor placed on the appropriate machine scale or at some other position known to yield a measurement of the average scale temperature. Here the scale can be a lead screw, a ball screw, a linear scale, or an inductive scale (see Chapter 4). It is a requirement of this Standard that independent calibration of the temperature and pressure sensors of such compensation devices be performed on a regular basis (see Chapter 11).

If the corrections are to be performed manually, they shall be computed according to the following equation for a laser measurement system set to read correctly at 20°C (68°F), 760 mm Hg air pressure, and 10 mm Hg partial pressure of water vapor:[1,2]

$$CLR = LDR\left[\frac{1 + 7.86 \times 10^{-4} P_s}{(T_a + 273) - 1.5 \times 10^{-11} RH(T_a^2 + 160)}\right] \quad \text{(H-1)}$$

where

CLR = corrected laser reading
LDR = laser display reading
P_s = air pressure, kPa
RH = relative humidity of air, %
T_a = mean air temperature, °C

The preceding equation is a linearization of the modified Edlen equation and is accurate to approximately 0.1×10^{-6}. Other forms of this equation are equally accurate and for the purpose of this Standard are also suitable. To compare the corrected laser reading to the machine readings, the machine readings must also be corrected for temperature. The corrected machine readings are given by

$$CMR = MDR[1 + \alpha(T - 20)] \quad \text{(H-2)}$$

where

CMR = corrected machine reading
MDR = machine display reading
T = scale temperature during measurements, °C, in the case where the machine was set up at 20°C (68°F)
α = effective thermal expansion coefficient of machine scales

[1] This form of equation also assumes atmospheric air with the normal mixture of gases. Atmospheres that deviate significantly, particularly in regard to CO_2 and aromatic hydrocarbon concentration, have been observed and can lead to measurable errors. If this situation is suspected, appropriate corrections should be applied.

[2] The partial pressure of water vapor can be calculated from the relative humidity by multiplying the saturated vapor pressure at a particular temperature by the relative humidity expressed as a fraction. The saturated vapor pressure at 20°C (68°F) is 17.6 mm Hg. Thus, for example, 50% relative humidity at 20°C would yield a partial pressure of $0.5 \times 17.6 = 8.8$ mm Hg.

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NONMANDATORY APPENDIX I
DRIFT CHECKS FOR SENSORS, INCLUDING LASERS

I1 GENERAL

Many tests in this Standard involve the use of displacement sensors over long periods of time. These include the ETVE test (para. 6.2.1), spindle thermal stability test (para. 7.6.2), thermal distortion caused by moving linear axes (para. 7.6.3), and composite thermal error test (para. 7.6.4). Three of these tests require the use of short-range indicators, and one of these tests (thermal distortion caused by moving linear axes) requires the use of a laser interferometer. For the results of these tests to be most meaningful, it is advised that the User perform a stability test on the sensor before using it for the measurement. Such stability tests have traditionally been called cap tests. Two tests are described below.

I1.1 Drift Check for Short-Range Electronic or Short-Range Displacement Indicators

Aside from the usual calibration checks, short-range displacement indicators should be checked for possible sensitivity to a thermal environment in which the test is to be performed. A drift check should be conducted by blocking the transducer and recording the output for at least the same period of time as the test to be performed using the indicator. "Blocking" a transducer is used to make it effectively indicate on its own frame base or cartridge. Figure I1 shows a cartridge-type linear variable differential transformer (LVDT) blocked by means of a cap or capture device that holds the indicator armature in a fixed position relative to the cartridge. The figure also shows a similar clamp on a finger-type electronic indicator and on a capacitance gage.

During the electronics drift check, the entire displacement recording system should be located as nearly as possible to where it will be used during machine testing. Electronic drift tests have been useful in proving that in many cases where electronic indicators have been a suspected source of drift, the real cause was thermal drift.

I1.2 Drift Check for Laser Interferometer Optics

Some optical systems have excessive drift apparently caused by thermal instabilities in the optic mounts and mismatched glass paths. The exact cause of these effects is not known, but experiments have been made that show that, for precision applications, the drifts inherent in the laser interferometer optics should be measured. To perform this drift check, the two retroreflectors are rigidly mounted to the remote interferometer as shown in Fig. I2. The laser is then aligned with this interferometer and adjusted for maximum signal strength. The laser is zeroed, and the drift of the system is recorded over similar periods of time as used for the ETVE test (para. 6.2.1). If the drift is excessive for the application, then the laser interferometer Supplier should be contacted and the situation rectified.

I1.3 Drift Check for Laser Interferometer Systems

When used for displacement measurement, a laser interferometer can have several sources of drift. First there is drift in the laser frequency; second, thermal drifts in the interferometer optics and mounting; and finally, drifts caused by incorrect calibration of the laser system temperature and pressure sensors. In this Appendix, two simple tests are proposed to check the drift of most system components. In the first test, the laser is set up to read with a remote interferometer as shown in Fig. I3. The spacer between the interferometer and the retroreflector is made of steel, and the laser system temperature and pressure sensors are placed as

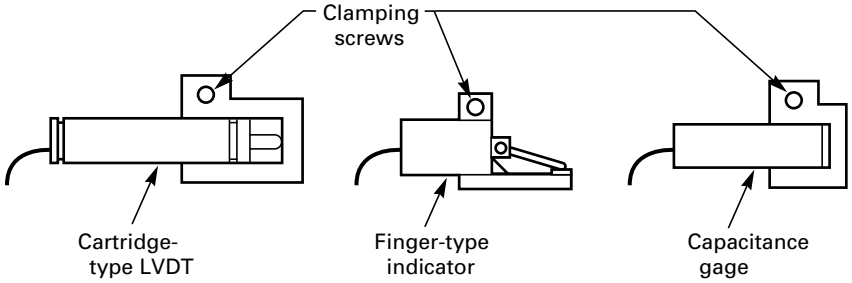


Fig. I1 Capture Devices for Several Displacement Indicator Types

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close as possible to the steel path. The steel spacer should contain holes to allow the free flow of ambient air and be at least 200 mm (approximately 8 in.) long. The temperature and pressure compensation of the laser is set, the part temperature sensor is attached to the steel spacer, and the laser interferometer is preset to the nominal length of the spacer. The appropriate expansion coefficient for the spacer shall be entered into the laser interferometer system.[1] The drift of the system is then measured over a period of time corresponding to the time of the proposed test (4 hr for the thermal distortion caused by moving linear axes test). The drift of the system should be less than ¼ of the repeatability for unidirectional positioning, linear axes. If the drift is larger, then the laser system and/or its supporting sensors should be repaired.

The second test is to be used for those laser systems where the interferometer is an inseparable part of the laser head. In these cases, the laser and the retroreflector or sensor assembly are set up on, and rigidly attached to, a steel plate. The steel plate should be at least 25 mm (approximately 1 in.) thick and mounted at three points. The face of the laser should be at least 200 mm (approximately 8 in.) from the retroreflector or sensor assembly. The environmental sensors should be placed as close as is possible to the laser beam path and the test conducted as described in the paragraph above. The drift of the system should be less than ¼ of the repeatability for unidirectional positioning, linear axes. If the drift is larger, then the laser system and/or its supporting sensors should be repaired.

[1] The Supplier of the steel spacer shall provide an accurate measurement of its nominal length and its thermal expansion coefficient.

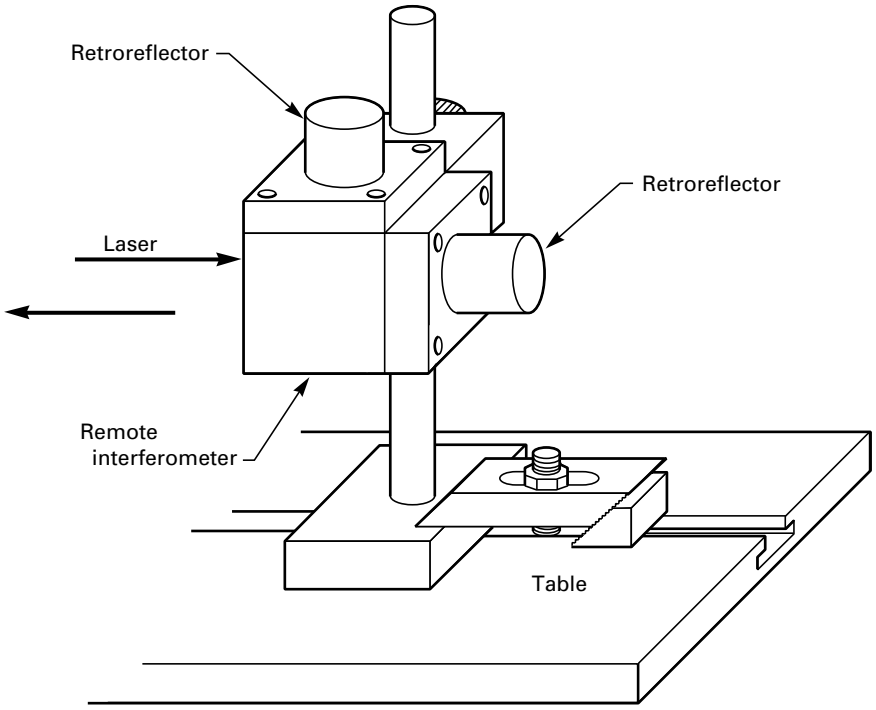


Fig. I2 Setup for Measuring the Drift of the Laser Interferometer Optics

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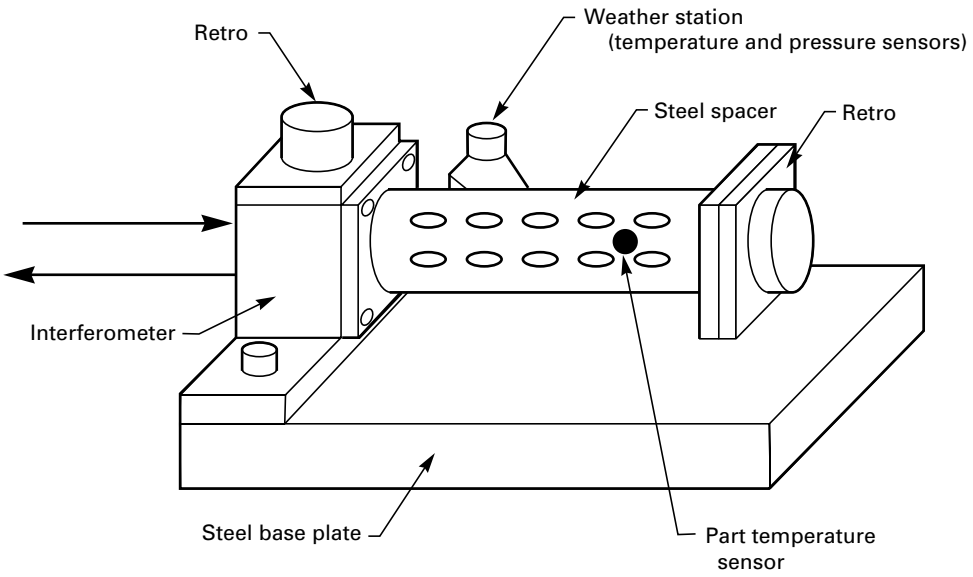


Fig. I3 Setup for Measuring Laser Measurement System Stability

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NONMANDATORY APPENDIX J
EXAMPLE BALL BAR PATTERNS FOR FOUR- AND FIVE-AXIS MACHINING CENTERS

J1 PURPOSE

Several telescoping ball bar patterns have been devised for four- and five-axis machining centers. These are illustrated in Figs. J1 through J7. In the current Standard, the ball bar is used only for verification of the contouring performance of the machine.

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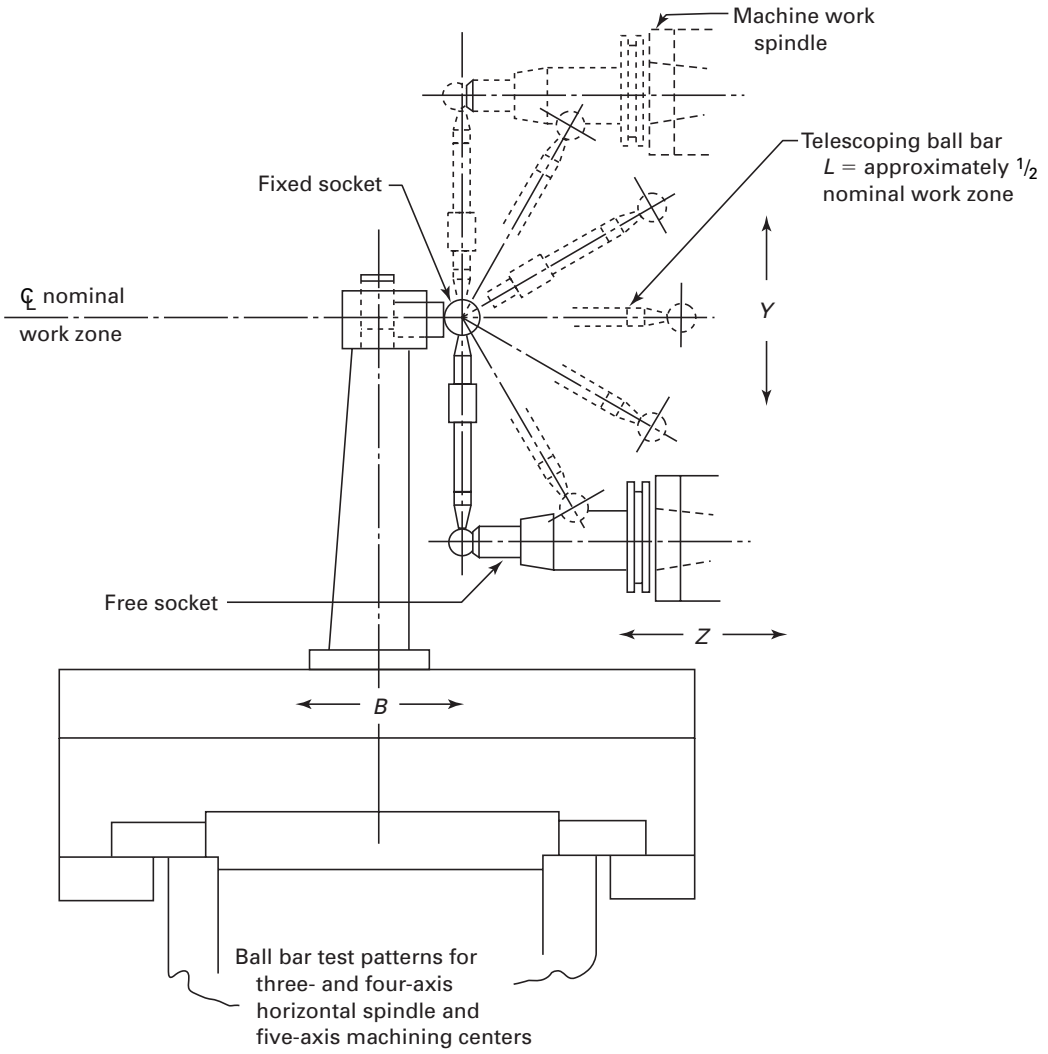


Fig. J1 *YZ* Plane Positioning Check

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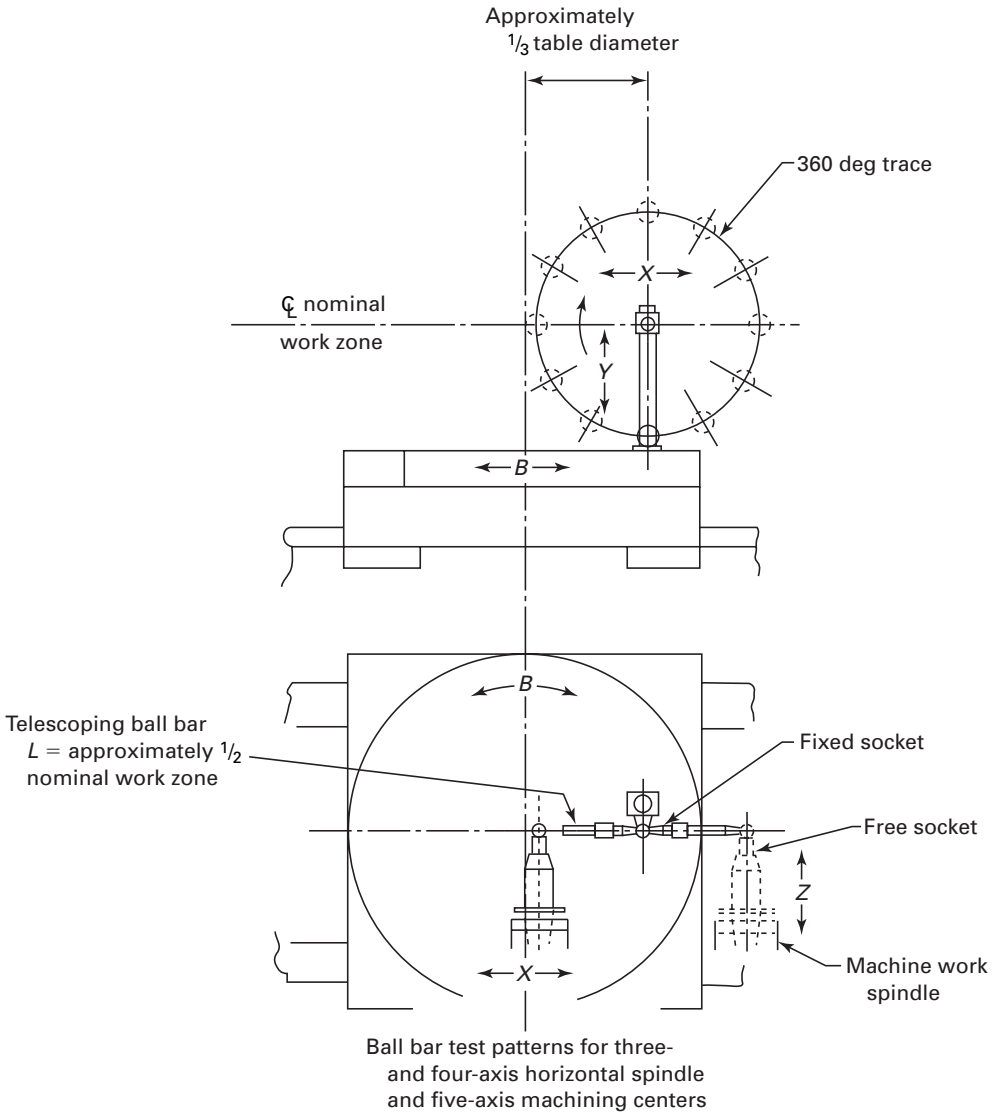


Fig. J2 *XY* Plane Positioning Check

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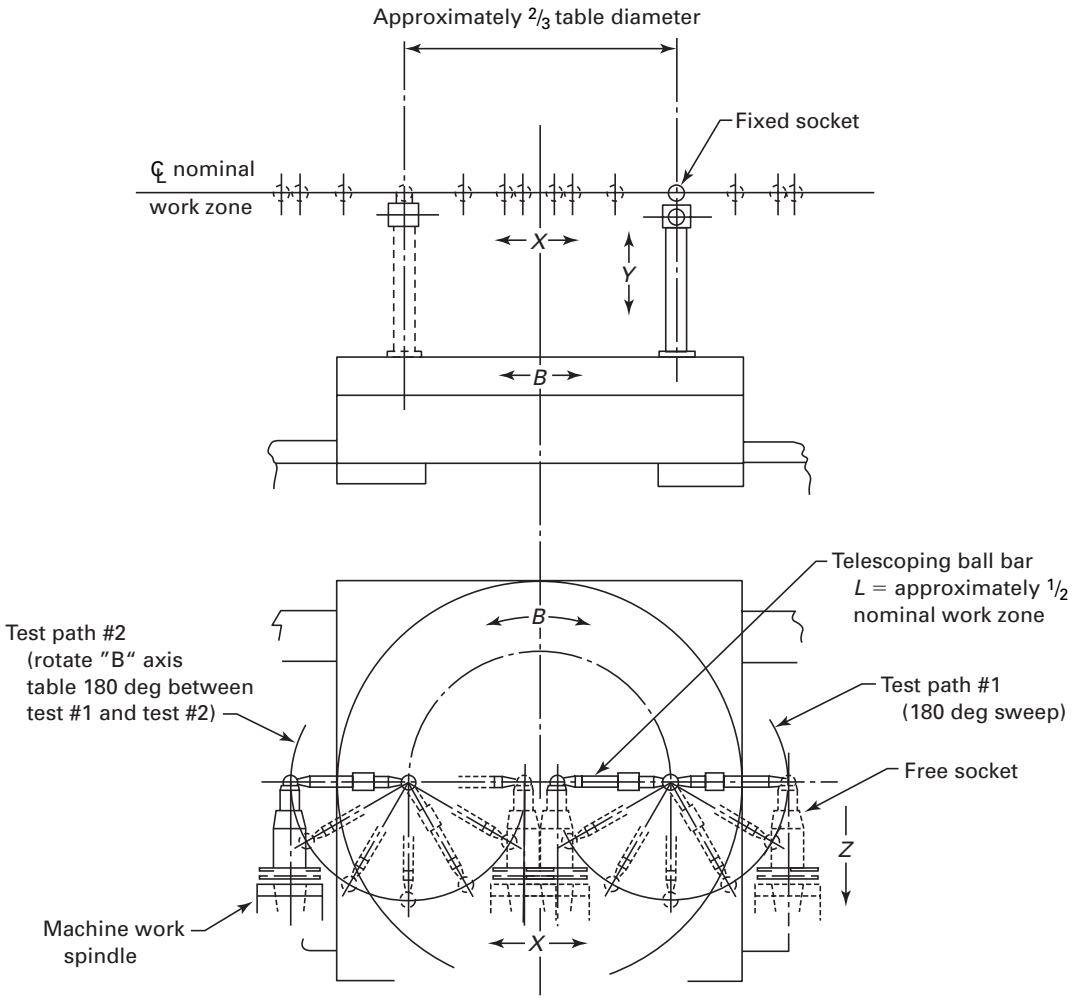


Fig. J3 *XZ* Plane Positioning Check

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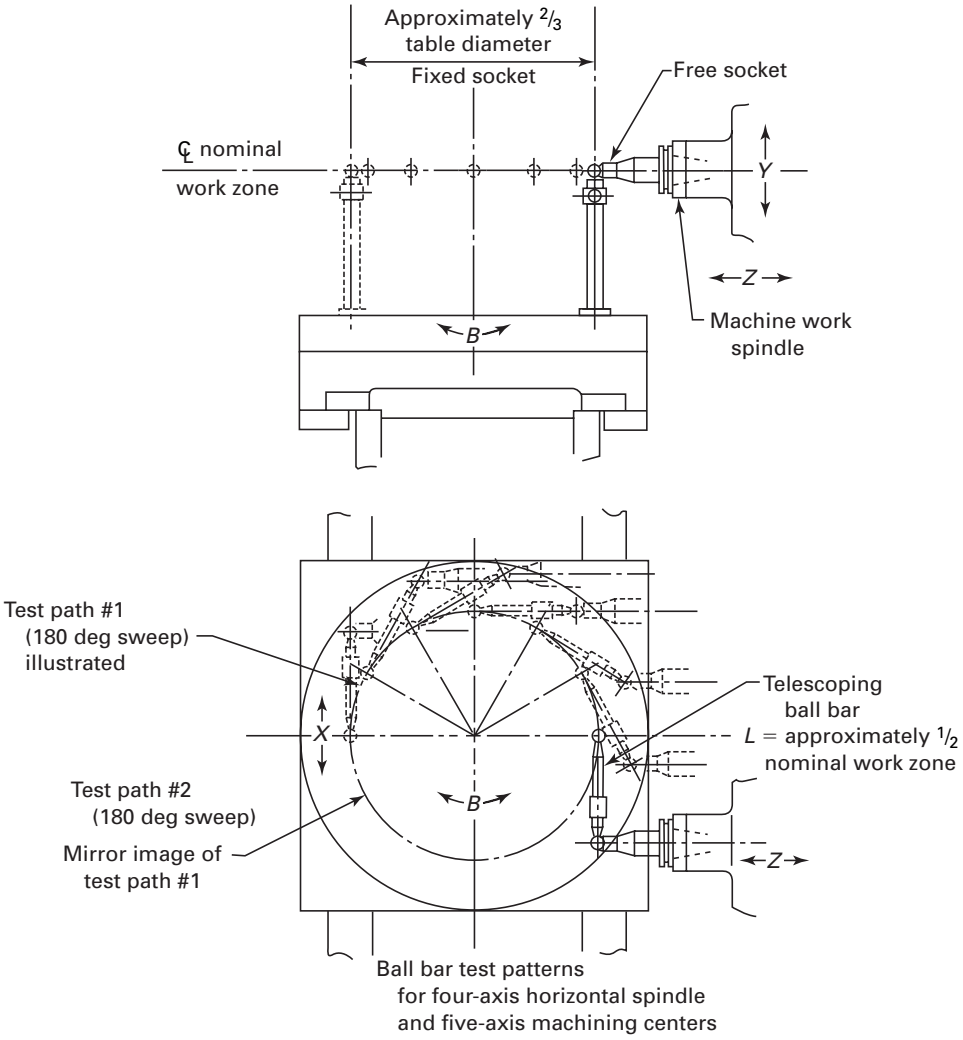
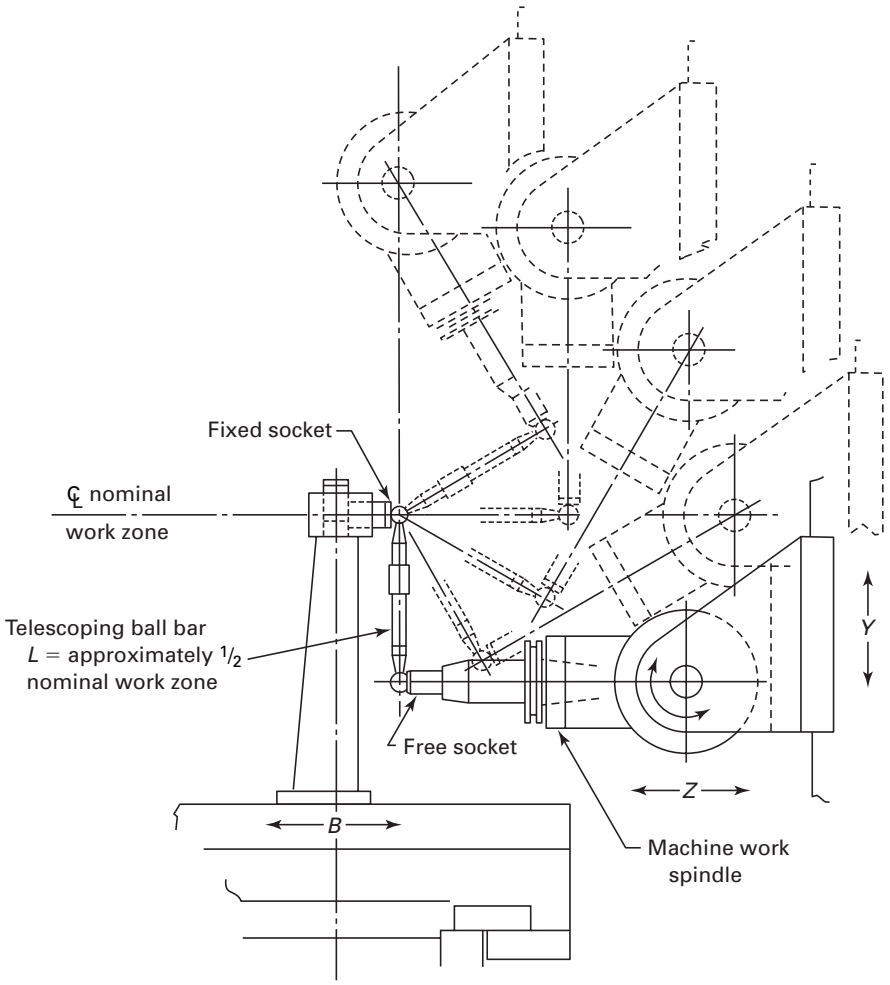


Fig. J4 *B*-Axis Rotary Positioning Check

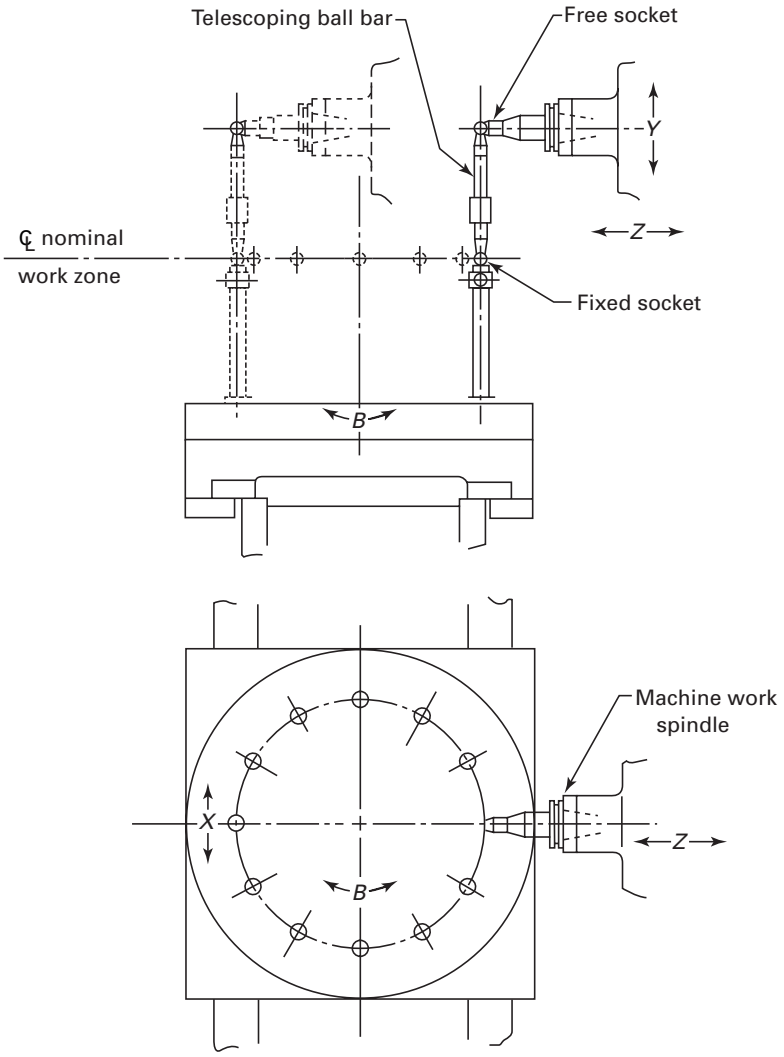
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Ball bar test patterns for five-axis machining centers

Fig. J5 *A*-Axis Rotary Positioning Check

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Ball bar test patterns for four-axis horizontal spindle and five-axis machining centers

Fig. J6 *B*-Axis Plane of Rotation Parallel to *XZ* Plane

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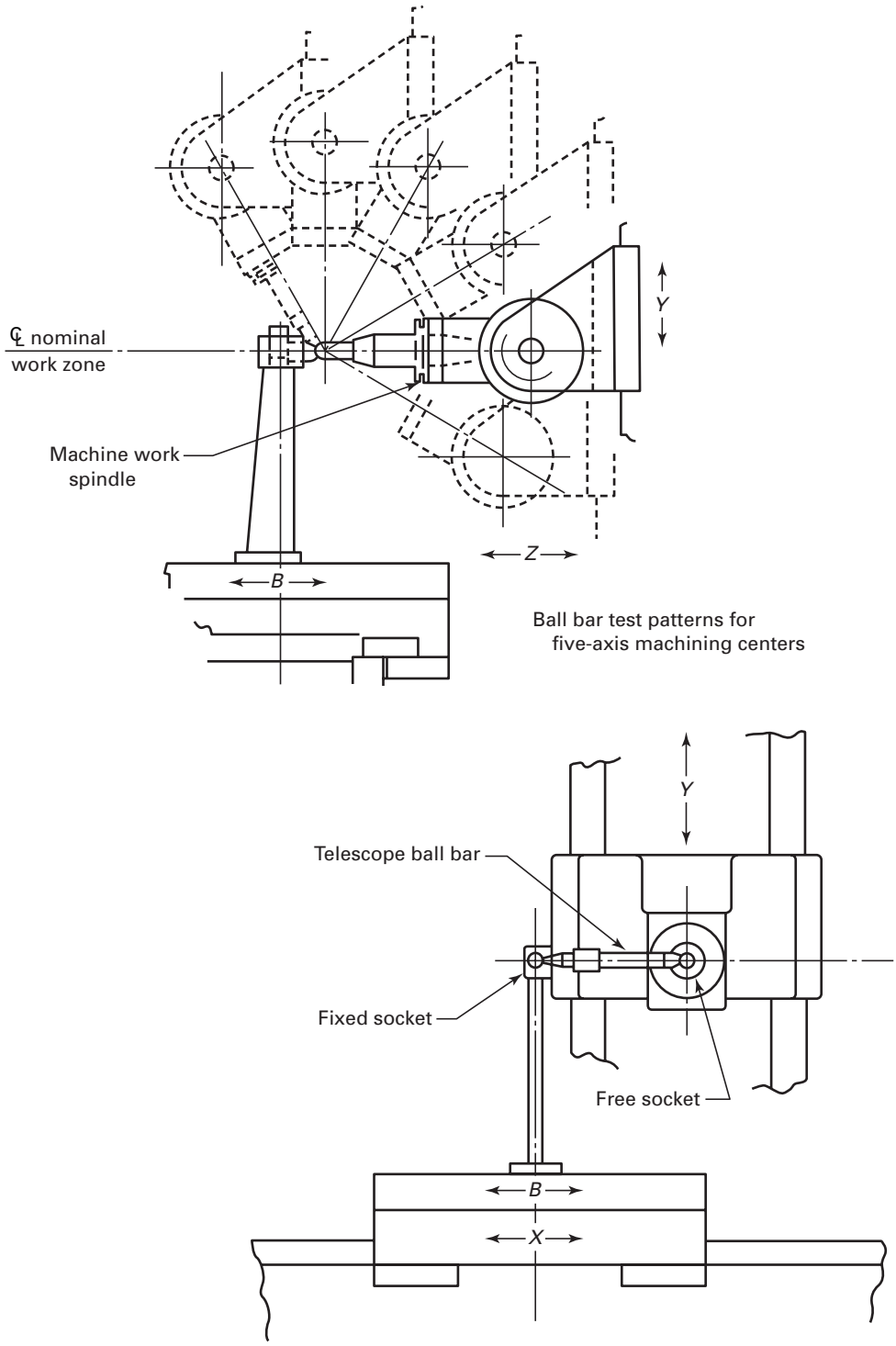


Fig. J7 *A*-Axis Plane of Rotation Parallel to *YZ* Plane

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NONMANDATORY APPENDIX K
DISCUSSION OF THE UNDE AND THERMAL UNCERTAINTY

K1 GENERAL

When calibration or measurement is performed at temperatures other than 20°C, nominal differential expansion (NDE) corrections must be made if the object to be calibrated or measured and the standard have different coefficients of thermal expansion

$$NDE = \alpha L(T - 20) - \alpha_s L_s(T_s - 20) \quad \text{(K-1)}$$

where variables are defined in para. 6.2.3.3.

The first term applies to the object being calibrated or measured. The second term applies to the standard. For laser calibration of a machine axis, the first term applies to the machine scale, while the second term applies to the laser. For on-machine part measurement using a probe, the first term applies to the part and the machine scale is the standard.

To estimate the uncertainty in making NDE correction, the *ISO Guide to the Expression of Uncertainty in Measurement* (1993) is used. The uncertainty depends on the uncertainty in each of the variables of Eq. (K-1). It also depends on the sensitivity of the NDE result to variation in each variable. For the purposes of this Appendix, it is assumed that no correlation exists between variations in individual variables. Therefore, four terms come directly from the uncertainty analysis.

$L(T - 20)u(\alpha)$ = uncertainty of nominal expansion of the object being calibrated or measured (K-2)

$L_s(T_s - 20)u(\alpha_s)$ = uncertainty of nominal expansion of the standard (K-3)

$L\alpha u(T)_{eff}$ = length uncertainty due to uncertainty in temperature of the object being calibrated or measured (K-4)

$L_s\alpha_s u(T_s)_{eff}$ = length uncertainty due to uncertainty in temperature of the standard (K-5)

The subscript *eff* is used to indicate that this term contains not only the uncertainty in temperature measurement, but also the range of temperatures that probably occurred during a test or measurement. One component of this uncertainty is related to the accuracy of temperature measurement. This is the length uncertainty due to temperature measurement (see Chapter 4).

The second component is related to the effective scale temperature due to time and positioning-varying temperature gradients and their effect on the machine geometry and scales. For the purposes of this Appendix, this second component is represented as a rectangular distribution with bounds $\pm(ETVE/2)/L_a$ for machine calibration, or $\pm(ETVE/2)/(L_s\alpha_s)$ when the machine is used as the measurement standard. Therefore, for the calibration of the machine axis,

$$u^2(T)_{eff} = \left[\frac{ETVE/2}{L\alpha\sqrt{3}}\right]^2 + u^2(T) \quad \text{(K-6)}$$

and

$$u^2(T_s)_{eff} = u^2(T_s) \quad \text{(K-7)}$$

For use of the machine as the measurement standard,

$$u^2(T)_{eff} = u^2(T) \quad \text{(K-8)}$$

and

$$u^2(T_s)_{eff} = \left[\frac{ETVE/2}{L_s\alpha_s\sqrt{3}}\right]^2 + u^2(T_s) \quad \text{(K-9)}$$

In either case, the combined standard thermal uncertainty is written as

$$u_{cT}^2(L) = L^2(T - 20)^2u^2(\alpha) + L_s^2(T_s - 20)^2u^2(\alpha_s) + L^2\alpha^2u^2(T) + L_s^2\alpha_s^2u^2(T_s) + u_{ETVE}^2 \quad \text{(K-10)}$$

where $u_{ETVE}^2 = ETVE^2/12$ arises from either Eq. (K-4) or (K-5).

The combined standard thermal uncertainty is used to derate performance specifications (Chapter 6) or to calculate a thermal error index (TEI) for any situation where NDE correction applies. The following examples demonstrate the calculation procedure.

K2 CALCULATION OF EXPANDED THERMAL UNCERTAINTY FOR PURPOSES OF DERATING PERFORMANCE SPECIFICATIONS

The following calculations are meant to be representative of a measurement of positioning accuracy and repeatability, linear axes (para. 7.3). The specification zone is for the bidirectional accuracy of positioning, *A*.

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Performance Parameter	Bidirectional Accuracy of Positioning
Specified accuracy	33 μm/m (FIR)
Axis length	1 016 mm
Measurement devices	Laser interferometer (displacement) Thermocouples (temperature of air and material)
Mean temperature	26°C
ETVE	33 μm
Coefficient of thermal expansion of the machine scale, α	11.7×10^{-6}/°C
Coefficient of thermal expansion of the laser, α_s	0.93×10^{-6}/°C
Specification zone	SZ = 33 μm/m (1.016 m) = 33.5 μm

Standard uncertainty due to ETVE (para. 6.2.3.3.1):

$$u^2_{ETVE} = ETVE^2/12 = 90.75\ \mu m^2 \quad \text{(K-11)}$$

Uncertainty of nominal expansion of the machine scale [para. 6.2.3.3.2, Option (c)]:

$$u(a) = 0.1a\sqrt{1/3} = 6.75 \times 10^{-7}/°C \quad \text{(K-12)}$$

$$u^2(\alpha) = 4.56 \times 10^{-13}/°C^2 \quad \text{(K-13)}$$

$$\begin{aligned}(UNE)^2 &= L^2(T - 20)^2u^2(\alpha)\\ &= (1\ 016\ mm)^2(26°C - 20°C)^2\\ &\quad \times (4.56 \times 10^{-13}/°C^2)(10^3\ \mu m/mm)^2\end{aligned} \quad \text{(K-14)}$$

Uncertainty of nominal expansion of the standard (para. 6.2.3.3.2; i.e., laser):

$$u(\alpha_s) = 0 \quad \text{(K-15)}$$

$$(UNE_s)^2 = L_s^2(T_s - 20)^2u^2(\alpha_s) = 0 \quad \text{(K-16)}$$

Length uncertainty due to temperature measurement (para. 6.2.3.3.3):

$$\begin{aligned}u^2(T) &= [1 - (-1)]^2/12°C^2\\ &= 1/3°C^2\end{aligned} \quad \text{(K-17)}$$

$$\begin{aligned}u^2(T_s) &= [1 - (-1)]^2/12°C^2\\ &= 1/3°C^2\end{aligned} \quad \text{(K-18)}$$

$$\begin{aligned}(LUTM)^2 &= L^2\alpha^2u^2(T) + L_s^2\alpha_s^2u^2(T_s)\\ &= (1\ 016\ mm)^2\left(\frac{11.7 \times 10^{-6}}{°C}\right)^2 1/3°C^2(10^3\ \mu m/mm)^2\\ &\quad + (1\ 016\ mm)^2\left(\frac{0.93 \times 10^{-6}}{°C}\right)^2 1/3°C^2(10^3\ \mu m/mm)^2\\ &= 47.1\ \mu m^2 + 0.30\ \mu m^2\\ &= 47.4\ \mu m^2\end{aligned} \quad \text{(K-19)}$$

Combined standard thermal uncertainty (para. 6.2.3.3):

$$\begin{aligned}u^2_{cT}(L) &= u^2_{ETVE} + (UNE)^2 + (UNE_s)^2 + (LUTM)^2\\ &= 90.8\ \mu m^2 + 16.9\ \mu m^2 + 0.00 + 47.4\ \mu m^2\\ &= 155\ \mu m^2\end{aligned} \quad \text{(K-20)}$$

$$u_{cT}(L) = 12.5\ \mu m \quad \text{(K-21)}$$

Expanded thermal uncertainty (para. 6.2.3.2):

$$\pm U_T(L) = \pm 2u_{cT}(L) = \pm 24.9\ \mu m \quad \text{(K-22)}$$

$$U_T(L) = 2u_{cT}(L) = 24.9\ \mu m \quad \text{(K-23)}$$

Derating of specified parameter (para. 6.2.3.2):

$$U_T(L)/SZ = 24.9\ \mu m/33.5\ \mu m > 0.25 \quad \text{(K-24)}$$

Because this ratio is greater than 0.25, a new acceptable limit must be specified.

$$SZ^* = U_T(L)/0.25 \quad \text{(K-25)}$$

$$SZ^* = 100\ \mu m\ (FIR) \quad \text{(K-26)}$$

$$SZ^* = 100\ \mu m/1.016\ m = 98\ \mu m/m \quad \text{(K-27)}$$

K3 EXAMPLE CALCULATIONS WHEN A MACHINE IS BEING USED FOR PART MEASUREMENT

Two examples that apply to the use of a machine tool for measurement of parts are given below. The first is in metric units and the second in English units, for those who prefer that system. While many other errors may affect the measurement results, the TEI is calculated to estimate the expected measurement error due to thermal effects alone. In both these cases, a part tolerance (TOL) is substituted for the specification zone (SZ).

K3.1 Example Calculation With NDE Correction

In this example, an aluminum part is measured on a machine with steel scales. The measurement conditions are summarized in Table K1.

Standard uncertainty due to ETVE (para. 6.2.3.3.1):

$$u^2_{ETVE} = ETVE^2/12 = (3.8 \times 10^{-5}\ m)^2/12 \quad \text{(K-28)}$$

$$u^2_{ETVE} = 1.20 \times 10^{-10}\ m^2 \quad \text{(K-29)}$$

Uncertainty of nominal expansion of the part [para. 6.2.3.3.2, Option (b)]:

$$u(a) = 0.05a\sqrt{1/3} \quad \text{(K-30)}$$

$$u^2(\alpha) = (0.05)^2(24.3 \times 10^{-6}/°C)^2(1/3) \quad \text{(K-31)}$$

$$\begin{aligned}(UNE)^2 &= L^2(T - 20)^2u^2(\alpha)\\ &= (4\ m)^2(22°C - 20°C)^2(0.05)^2\left(\frac{24.3 \times 10^{-6}}{°C}\right)^2(1/3)\\ &= 3.15 \times 10^{-11}\ m^2\end{aligned} \quad \text{(K-32)}$$

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Table K1 Calculation of TEI for the Case When NDE Correction Is Made

Dimension = 4.0 m	NDE correction: standard and part temperatures both measured as 22°C	T_{min} = 21.1°C
TOL = 0.25 mm	Material: aluminum 6061	T_{max} = 23.3°C
α = 24.3 μm/m°C [Note (1)]	Temperature measurement accuracy = ±1°F	T_m = 22°C
α_s = 11.7 μm/m°C [Note (1)]	. . .	*ETVE* = 38 μm

NOTE:
(1) These values are obtained from published data and may be in error by ±5%.

Uncertainty of nominal expansion of the standard [para. 6.2.3.3.2, Option (b); i.e., machine]:

$$u(a) = 0.05\, a_s \sqrt{1/3} \quad \text{(K-33)}$$

$$u^2(\alpha_s) = (0.05)^2(11.7 \times 10^{-6}/°C)^2(1/3) \quad \text{(K-34)}$$

$$\begin{aligned}(UNE_s)^2 &= L_s^2(T_s - 20)^2u^2(\alpha_s)\\ &= (4\text{ m})^2(22°C - 20°C)^2(0.05)^2\left(\frac{11.7 \times 10^{-6}}{°C}\right)^2(1/3)\\ &= 7.30 \times 10^{-12}\text{ m}^2\end{aligned} \quad \text{(K-35)}$$

Note that the mean air temperature is used for both T and T_s in the equations used to calculate uncertainty of nominal expansion of part and machine scale, respectively.

Length uncertainty due to temperature measurement (para. 6.2.3.3.3):

$$\begin{aligned}u^2(T) &= [1 - (-1)]^2/12°C^2\\ &= 1/3°C^2\end{aligned} \quad \text{(K-36)}$$

$$\begin{aligned}u^2(T_s) &= [1 - (-1)]^2/12°C^2\\ &= 1/3°C^2\end{aligned} \quad \text{(K-37)}$$

$$\begin{aligned}(LUTM)^2 &= L^2\alpha^2u^2(T) + L_s^2\alpha_s^2u^2(T_s)\\ &= (4\text{ m})^2(24.3 \times 10^{-6}/°C)^2\,1/3°C^2\\ &\quad + (4\text{ m})^2(11.7 \times 10^{-6}/°C)^2\,1/3°C^2\\ &= 3.87 \times 10^{-9}\text{ m}^2\end{aligned} \quad \text{(K-38)}$$

Combined standard thermal uncertainty (para. 6.2.3.3):

$$u_{cT}^2(L) = u_{ETVE}^2 + (UNE)^2 + (UNE_s)^2 + (LUTM)^2 \quad \text{(K-39)}$$

$$\begin{aligned}u_{cT}(L) &= \sqrt{1.20 \times 10^{-10}\text{ m}^2 + 3.15 \times 10^{-11}\text{ m}^2 + 7.30 \times 10^{-12}\text{ m}^2 + 3.87 \times 10^{-9}\text{ m}^2}\\ &= 0.063\text{ mm}\end{aligned} \quad \text{(K-40)}$$

Expanded thermal uncertainty (para. 6.2.3.2):

$$\pm U_T(L) = \pm 2u_{cT}(L) = \pm 0.126\text{ mm} \quad \text{(K-41)}$$

$$U_T(L) = 2u_{cT}(L) = 0.127\text{ mm} \quad \text{(K-42)}$$

For the purposes of calculating the TEI, NDE is taken as zero when NDE corrections are made. There is no contribution to the estimated thermal error.

$$NDE = 0.00 \quad \text{(K-43)}$$

Thermal error index

$$\begin{aligned}TEI &= \{[|NDE| + U_T(L)]/TOL\}(100\%)\\ &= (0.00 + 0.127\text{ mm})/(0.25\text{ mm})(100\%) = 51\%\end{aligned} \quad \text{(K-44)}$$

K3.2 Calculation Without NDE Correction

The second example of part measurement deals with measurement of a titanium part on a machine with steel scales, where the nominal differential expansion correction is not made. Measurement conditions are summarized in Table K2. English units are used throughout.

Standard uncertainty due to ETVE (para. 6.2.3.3.1):

$$\begin{aligned}u_{ETVE}^2 &= ETVE^2/12 = (0.0003\text{ in.})^2/12\\ &= 7.50 \times 10^{-9}\text{ in.}^2\end{aligned} \quad \text{(K-45)}$$

Uncertainty of nominal expansion of the part [para. 6.2.3.3.2, Option (b)]:

$$u(a) = 0.05a\sqrt{1/3} \quad \text{(K-46)}$$

$$u^2(\alpha) = (0.05)^2(4.8 \times 10^{-6}\text{ in./in. °F})^2(1/3) \quad \text{(K-47)}$$

$$\begin{aligned}(UNE)^2 &= L^2(T - 68)^2u^2(\alpha)\\ &= (20\text{ in.})^2(74°F - 68°F)^2(0.05)^2\\ &\quad \times (4.8 \times 10^{-6}\text{ in./in. °F})^2(1/3)\\ &= 2.76 \times 10^{-10}\text{ in.}^2\end{aligned} \quad \text{(K-48)}$$

Uncertainty of nominal expansion of the standard (para. 6.2.3.3.2, method b; i.e., machine):

$$u(a) = 0.05a_s\sqrt{1/3} \quad \text{(K-49)}$$

$$u^2(\alpha_s) = (0.05)^2(6.5 \times 10^{-6}\text{ in./in. °F})^2(1/3) \quad \text{(K-50)}$$

$$\begin{aligned}(UNE_s)^2 &= L_s^2(T_s - 68)^2u^2(\alpha_s)\\ &= (20\text{ in.})^2(74°F - 68°F)^2(0.05)^2\\ &\quad \times (6.5 \times 10^{-6}\text{ in./in. °F})^2(1/3)\\ &= 5.07 \times 10^{-10}\text{ in.}^2\end{aligned} \quad \text{(K-51)}$$

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Table K2 Calculation of TEI for the Case When NDE Correction Is Not Made

Dimension = 20 in.	No NDE correction	T_{min} = 70°F (measured)
Tolerance = 0.002 in.	Material: Ti 6-4	T_{max} = 78°F (measured)
α = 4.8 μin./in.°F [Note (1)]	Temperature measurement accuracy = ±1°F	T_m = 74°F (measured)
α_s = 6.5 μin./in.°F [Note (1)]	. . .	*ETVE* = 0.0003 in.

NOTE:
(1) These values are obtained from published data and may be in error by ±5%.

Length uncertainty due to temperature measurement (para. 6.2.3.3.3): LUTM cannot be calculated directly (see below).

When NDE correction is not made, the uncertainty related to temperature in Eq. (K-1) depends on variations in the air temperature. Temperature measurement accuracies of part and machine are not relevant, because these measurements are not made. The uncertainty of environmental temperature is introduced as

$$u(T_e) = (1/2)(T_{max} - T_{min} + 2a)\sqrt{1/3} \quad \text{(K-52)}$$

where it is assumed that the machine and part temperatures at any time can be expected to have rectangular probability distributions with bounds $(T_{max} - T_{min} + 2a)$. Variables are defined as

T_{max} = maximum air temperature measured over specified period of time
T_{min} = minimum air temperature measured over specified period of time
a = air temperature measurement accuracy

The variations in temperatures, T and T_s, are expected to be correlated under these assumptions, leading to the equation for LUTM, which includes the difference between scale and part expansion coefficients:

$$\begin{aligned}(LUTM)^2 &= (1/12)(T_{max} - T_{min} + 2\alpha)^2(L)^2(\alpha_s - \alpha)^2 \\ &= (1/12)(78 - 70 + 2)^2(°F)^2(20\text{ in.})^2 \\ &\quad \times (4.8 - 6.5)^2(\mu\text{in./in. °F})^2 \\ &= 9.63 \times 10^{-9}\text{ in.}^2 \end{aligned} \quad \text{(K-53)}$$

Combined standard thermal uncertainty (para. 6.2.3.3):

$$u_{cT}^2(L) = u_{ETVE}^2 + (UNE)^2 + (UNE_s)^2 + (LUTM)^2 \quad \text{(K-54)}$$

$$\begin{aligned}u_{cT}(L) &= \sqrt{7.50 \times 10^{-9}\text{ in.}^2 + 2.76 \times 10^{-10}\text{ in.}^2 + 5.07 \times 10^{-10}\text{ in.}^2 + 9.63 \times 10^{-9}\text{ in.}^2} \\ &= 0.00013\text{ in.} \end{aligned} \quad \text{(K-55)}$$

Expanded thermal uncertainty (para. 6.2.3.2):

$$\pm U_T(L) = \pm 2u_{cT}(L) = \pm 2(0.00013\text{ in.}) \quad \text{(K-56)}$$

$$\begin{aligned}U_T(L) &= 2u_{cT}(L) = 2(0.00013\text{ in.}) \\ &= 0.00026\text{ in.} \end{aligned} \quad \text{(K-57)}$$

Nominal differential expansion:

$$\begin{aligned}NDE &= \left|4.8 \times 10^{-6}\text{ in./in. °F} - 6.5 \times 10^{-6}\text{ in./in. °F}\right|(20\text{ in.})\left|74 - 68\right|°F \\ &= 0.00020\text{ in.} \end{aligned} \quad \text{(K-58)}$$

Thermal error index:

$$\begin{aligned}TEI &= \{[|NDE| + U_T(L)]/TOL\}(100\%) \\ &= [(0.00020\text{ in.} + 0.00026\text{ in.})/(0.002\text{ in.})](100\%) \\ &= 23.5\% \end{aligned} \quad \text{(K-59)}$$

K3.3 Summary

The different cases that can occur for temperature measurement are summarized in Table K3.

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Table K3 Summary of Equations for Thermal Uncertainty Calculations

Symbol	Definition	Equation
TEI	Thermal error index	$\{[\text{NDE} + U_T(L)] / TOL\}100\%$
NDE	Nominal differential expansion:	
	standard and object same material	0
	NDE correction	0
	no NDE correction	$NE - NE_s$
NE	Nominal expansion of the object	$L\alpha(T_m - 20)$
L	Length of dimension	. . .
α	Coefficient of thermal expansion of object	Specified
T_m	Mean environmental temperature	Measured
NE_s	Nominal expansion of the standard	$L\alpha(T_m - 20)$
α_s	Coefficient of thermal expansion of standard	Specified
$U_T(L)$	Expanded thermal uncertainty	$2u_{cT}(L)$
$u_{cT}(L)$	Combined standard thermal uncertainty	$\sqrt{(UNE)^2 + (UNE_s)^2 + (LUTM)^2 + u_{ETVE}^2}$
UNE	Uncertainty of nominal expansion of object	$u(\alpha)L(T_m - 20)$
$u(\alpha)$	Uncertainty of object thermal expansion coefficient [for method of para. 6.2.3.3.2(c)]	$\sqrt{1/3}\,(0.1)\,\alpha$
UNE_s	Uncertainty of nominal expansion of standard	$u(\alpha_s)L(T_m - 20)$
$u(\alpha)_s$	Uncertainty of standard thermal expansion coefficient [for method of para. 6.2.3.3.2(c)]	$\sqrt{1/3}\,(0.01)\,\alpha_s$
$LUTM$	Length uncertainty due to temperature measurement:	
	for NDE correction	$\sqrt{\alpha^2L^2u^2(T) + \alpha_s^2L_s^2u^2(T_s)}$
	for no NDE correction	$u(T_e)\,L\,(\alpha - \alpha_s)$
$u(T)$	Uncertainty of object temperature measurement	$\frac{a^+ - a^-}{2}\sqrt{1/3}$
$u(T_s)$	Uncertainty of standard temperature measurement	$\frac{a^+ - a^-}{2}\sqrt{1/3}$
$u(T_e)$	Uncertainty of environment temperature	$(1/2)(T_{\max} - T_{\min} + 2a)\sqrt{1/3}$
a	Accuracy of temperature measurement ($\pm a$)	Specified
$T_{\max}$	Maximum air temperature	Measured over specified time
$T_{\min}$	Minimum air temperature	Measured over specified time
u_{ETVE}	Standard uncertainty due to the environmental temperature variation error	$(1/2)ETVE\sqrt{1/3}$
$ETVE$	Environmental temperature variation error	Measured over specified time
TOL	Tolerance	For ±0.003 in., $TOL = 0.003$

GENERAL NOTE: The object being calibrated or measured is simply the "object" in this table. The calibrator or measuring device is the "standard."

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NONMANDATORY APPENDIX L
STRAIGHTEDGE REVERSAL TECHNIQUE

L1 GENERAL

Straightedges are often provided with a calibration chart to correct measurements for the straightness values of the straightedge. But correction using a calibration chart is not always necessary, since the straightedge reversal technique may provide an in-situ calibration. However, the straightedge reversal technique does not work when measuring the vertical straightness of a horizontal axis when the sag of the straightedge due to gravity is important. Therefore, an appropriate calibration of a straightedge in this position is required.[1]

L2 PROCEDURE

The straightedge reversal is performed by rotating the straightedge 180 deg about its long axis, as shown in Fig. L1, and measuring along the same line on the straightedge. Two sets of readings are suitably averaged to cancel out the straightness errors in the straightedge. The Y straightness of an X-axis is measured as an example. The machine straightness is defined as $M(X)$ and the straightedge straightness as $S(X)$. The sign convention adopted for these mathematical functions is as follows:

$M(X)$: plus for motion of the machine carriage in the $+Y$ direction, minus otherwise

$S(X)$: plus for displacements out of the gaging surface, minus otherwise

Now define $N(X)$ as the straightness values obtained when measuring with the straightedge in the normal position [Fig. L1, illustration (a)] and $R(X)$ as the straightness values obtained when measuring with the straightedge reversed (rotated 180 deg about its long axis) [Fig. L1, illustration (b)]. With the sign convention mentioned above, the resulting equations are:

$$N(X) = M(X) + S(X) \tag{L-1}$$

$$R(X) = -M(X) + S(X) \tag{L-2}$$

These measurements are sufficient to determine both the machine horizontal straightness and the straightedge calibration, since, by adding and subtracting these two equations, the results are:

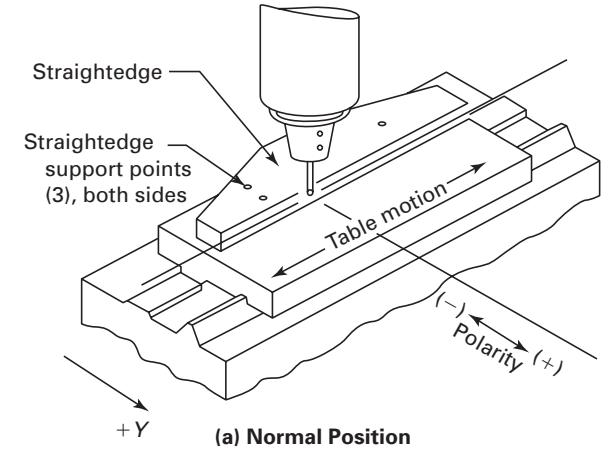
$$M(X) = \frac{N(X) - R(X)}{2} \tag{L-3}$$

$$S(X) = \frac{N(X) + R(X)}{2} \tag{L-4}$$

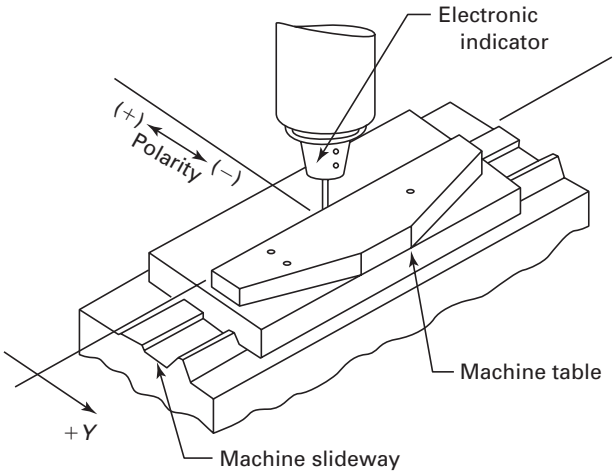
The above equations are written in continuous format; however, the operations may be performed point-wise. That is, for each measurement point on the straightedge, the operations above may be carried out.

[1] For more information, refer to Estler, W.T., "Calibration and use of optical straightedges in the metrology of precision machines," *Optical Engineering*, Vol. 24, No. 3, May/June 1985.

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(a) Normal Position



(b) Reversed Position

Fig. L1 Setup for Measuring Straightness Using an Electronic Indicator and a Mechanical Straightedge

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NONMANDATORY APPENDIX M
CALCULATION OF UNCERTAINTIES

M1 GENERAL

In many of the tests in this Standard, uncertainties have been assigned to the results of a measurement following widely accepted procedures.[1] In a subtle deviation from these procedures, the uncertainties are being assigned to the machine tool, rather than the measurement system. That is, it is assumed that the measurand (for example, linear positioning) is uncertain when measured with a perfect measurement system because of inherent lack of repeatability in the machine itself. Since machine tools, at the current level of accuracy, obey the laws of classical physics, this assumption is probably incorrect. Machine tools are, in fact, much more repeatable than is commonly believed, as has been demonstrated on numerous occasions. In the case of machine tool measurements, the major uncertainties arise from a combination of the following:

(a) incomplete definition of the measurand

(b) imperfect realization of the definition of the measurand

(c) nonrepresentative sampling (the sample measured may not represent the defined measurand)

(d) inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions.[1]

The fact is that the model normally used for the machine tool does not include all of the variables that are present when testing a machine. The "observed dispersion of the measurement results" implies a calculated standard deviation, which by definition is a Type A. Because of the current accuracy level of the instrumentation (see Chapter 11), this dispersion is correctly assigned to the machine tool, rather than the instrument system.

In the body of this Standard, uncertainties have not been computed for a number of tests due to one of the following three reasons:

(a) The test may be considered a functional test and thus an assignment of uncertainty is not called for.

(b) The test was already in the process of standardization, or standardized, by the International Organization for Standardization (ISO) and uncertainties were not computed there.

(c) The test duration was such that making enough repeated measurements to have statistical significance is impractical.

[1] *ISO Guide to the Expression of Uncertainty in Measurement,* 1993(E).

It is the purpose of this Appendix to explain the reasoning behind the decisions and, for Users who so desire, provide the methodology for the assessment of uncertainties in cases where it is practical to do so. Again, we emphasize that the intention is that these uncertainties be assigned to the machine tool system (including the testing environment) and not to the measurement instrument. This can only be correct if the measurement instrument conforms to the requirements of Chapter 11.

M2 UNCERTAINTY CALCULATIONS CURRENTLY IN B5.54

In this Standard there are many tests where the uncertainties are calculated. Some of these tests, in fact, are designed primarily to estimate the uncertainties caused by various factors. In general, these types of tests are called *repeatability tests.* The repeatability tests include the ETVE test (para. 6.2), relative vibration test (para. 6.3), structural motion test (para. 7.5.2), and subsystems repeatability tests (para. 7.8), such as tool changing repeatability, pallet changing repeatability, and toolsetting repeatability.

Besides these general tests for repeatability, other tests where the uncertainty is estimated according to the standard methodology are positioning accuracy and repeatability of linear axes (para. 7.3.2.1), angular error motions of linear axes (para. 7.4), positioning accuracy and repeatability of rotary axes (para. 7.3.2.2), machine performance as a measuring tool (para. 7.9), and geometric accuracy tests (para. 7.4). These tests will not be discussed further in this Appendix.

M3 FUNCTIONAL TESTS

After careful discussion, it was the opinion of the Committee that the following tests may be considered functional tests where it is not required to assign an uncertainty: setup hysteresis (para. 7.1.4), periodic linear and angular positioning (para. 7.3.5), cutting performance (Chapter 9), multifunction cycle test (Chapter 10), CNC performance test (para. 7.10), and machining test parts (Chapter 8). Uncertainties could, of course, be assigned to the final functional test, machining test parts, by machining a large number of parts and applying the procedures of statistical process control. Users desiring to do this should follow appropriate standardized methods.

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M4 UNCERTAINTY COMPUTATIONS NOT PRESENTLY IN B5.54

Several of the tests present in the current Standard do not provide the User with the methodology for computing an appropriate uncertainty. These tests are:

(a) spindle axes of rotation (para. 7.5)

(b) machine thermal test (para. 7.6)

(c) contouring performance using circular tests (para. 7.7.4)

These are discussed, in turn, below. In all cases, following previously established procedures, the repeatability for a given test should be reported as four times the standard uncertainty.

M4.1 Uncertainty Calculation, Spindle Axes of Rotation

In the opinion of the authors of this Appendix, following the procedure below will constitute unwarranted expense, as the information gained would not be particularly relevant to machine performance.

For spindle error motions, the Standard calls for performing the measurements at three spindle speeds. At each speed, the error motions are measured for a minimum of 20 revolutions and averaged to obtain the average error motion value. The maximum range of deviations from the average error motion value is reported as the asynchronous error motion and not as an uncertainty in the error motion. This is because it has been demonstrated that asynchronous error motion, although it may appear to be random, is actually highly systematic, at least for the case of ball-bearing and roller-bearing spindles, which constitute a very large percentage of the spindles on machining centers. The systematic nature of the asynchronous motion is less well documented for aerostatic and hydrostatic spindles. Because of the very large number of revolutions required for assessing uncertainty on ball- and roller-bearing spindles, no procedure is recommended here.

If it is desired to obtain an uncertainty from spindle measurements, it is the recommendation of this technical committee that the complete test (20 revolutions) for each error motion be repeated ten times. For each of these repetitions, an average error motion and an asynchronous error motion should be computed. The estimate of the standard uncertainty for these quantities should then be calculated according to the following expression:

$$u_q = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(q_j - \bar{q})^2} \qquad \text{(M-1)}$$

where

q = mean obtained from the ten repeated trials
q_j = outputs of the measurement procedure for each complete test (average or asynchronous error motion)

M4.2 Machine Thermal Tests

All of the machine thermal tests, the spindle thermal stability test (para. 7.6.2), thermal distortion caused by moving linear axes (para. 7.6.3), and composite thermal error (para. 7.6.4) require a measurement to be performed over a long period of time. If the User should decide that it is necessary to obtain an uncertainty, then the tests should be performed many times (say, a minimum of five times) and standard uncertainties in the reported parameters computed as described in para. M4.1. It is the recommendation of this Appendix that this would constitute unwarranted expense.

M4.3 Contouring Performance Using Circular Tests

For the contouring performance, it is required to report the circular deviations for clockwise, $G\uparrow$, and counterclockwise, $G\downarrow$, contouring, and the radial deviations, F_{max} and F_{min}, for clockwise ($\uparrow$) and counterclockwise ($\downarrow$) contouring, shall be reported, as well as the measured feed rates in the clockwise and counterclockwise directions (see paras. 7.11.2 and 7.11.3). The circular deviation is the minimum radial separation of two concentric circles that will envelop the actual path. Finally, the radial deviations are the maximum and minimum deviations from the circle radius, corrected to 20°C. To compute the standard uncertainties of these quantities, it is recommended that the circular test be conducted ten times in both the clockwise and counterclockwise directions. For each set of ten measurements, the artifact (ball bar, disk, or grid encoder) temperature is measured at the beginning and the end of the ten measurements and the mean value of the temperature recorded. In the following discussion, it is assumed that data are acquired at n intervals over the measured arc. After least-squares fitting to remove residual eccentricity, the data are analyzed as follows. At each interval, i, compute the standard uncertainty in the circular deviation following the normal procedure. That is,

$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(d_{ij}\uparrow - \overline{d}_i\uparrow)^2} \qquad \text{(M-2)}$$

$$s_i\downarrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(d_{ij}\downarrow - \overline{d}_i\downarrow)^2} \qquad \text{(M-3)}$$

where

$\overline{d}_i$ = mean circular deviation at the ith angular position
d_{ij} = jth circular deviation at the ith angular position
n = 10
s_i = estimate of the standard uncertainty of the circular deviations
$\uparrow$ = clockwise rotation
$\downarrow$ = counterclockwise rotation

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M4.3.1 Circular Deviation. For determining the uncertainty in circular deviation, both the clockwise and counterclockwise data are treated the same. Only the clockwise case will be given below. The procedure is to note the angles at which the maximum and minimum deviations in the mean circular deviation plot occurred for the appropriate rotation direction. Then the uncertainty is given by

$$u_C^2\uparrow = s_k^2\uparrow + s_m^2\uparrow \quad \text{(M-4)}$$

where

k = angular position where the maximum circular deviation occurred
m = angular position where the minimum circular deviation occurred

M4.3.2 Radial Deviation. As with the circular deviation, the clockwise and counterclockwise data analysis is the same. Only the clockwise case will be given below. The procedure is to locate the angular position where the maximum radial deviation between the calibrated radius and the mean measured radius occurred. This comparison is performed after the ball bar length has been corrected to 20°C, using its mean temperature measured as described in para. M4.3 above. The square of the standard uncertainty (variance) is then computed as follows (where $\uparrow$ and $\downarrow$ have been eliminated for simplicity):

$$u_F^2 = s_k^2 + L_s^2(T_s - 20)^2u^2(\alpha_s) + L^2(T - 20)^2u^2(\alpha) + L_s^2\alpha_s^2u^2(T_s) + L^2\alpha^2u^2(T) \quad \text{(M-5)}$$

where

k = angular position where the maximum radial deviation occurred
L = effective machine scale length, equal to the ball bar length
L_s = calibrated ball bar length
s_k = estimate of standard uncertainty of the circular deviation at the angular position k
T = temperature of the machine scales that should be assumed to be equal to T_s
T_s = mean temperature of the ball bar
$u(q)$ = standard uncertainty in the quantity, q
$u^2(q)$ = variance in the quantity, q
u_F = standard uncertainty of the radial deviation
α = thermal expansion coefficient of the machine scales
α_s = thermal expansion coefficient of the ball bar

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NONMANDATORY APPENDIX N
SIGN CONVENTIONS FOR ERROR VALUES

N1 GENERAL

This Standard does not require that the User use specific signs for the error values. However, it is customary to define errors as the actual (measured) response of the machine tool, minus the nominal or anticipated response (commanded). Errors are reported using the nominal workpiece coordinate system. This method is consistent with the method used in EIA-267-C-1990. Positive values of displacement errors (e.g., positioning and straightness errors) indicate error motion in the positive direction of the nominal workpiece coordinate axes. Thus, a positive positioning error of an axis indicates that the tool moved farther along that axis than commanded. Positive angular errors (e.g., angular positioning, roll, pitch, and yaw) indicate positive angular motions about a coordinate axis. These are customarily defined to be positive counterclockwise for rotation about an axis, using the right-hand rule.

N2 RELATIVE MEASUREMENTS

The sign of an error is affected by the reference relative to which the error motion is defined and measured. If a single axis is tested whose function is to carry the workpiece, measurements are made with respect to a tool position. The EIA standard describes the positive motion of this axis with a prime (+Z'), which is opposite to the positive motion of a corresponding axis that carries the tool (+Z). A positive axial error motion of the spindle indicates movement of the spindle axis away from the workpiece in the +Z direction. For the positioning accuracy test of an axis that moves the table, a positive error indicates an error in the +Z' direction of the table (relative to the tool). Thus, +Z axial error of the spindle and +Z' error of the table motion both increase the distance between the tool and the table.

N3 CRITICAL ALIGNMENTS

For critical alignments, the following sign convention is used. The squareness error between two axes should be reported as positive if the angle between the respective positive coordinate axes exceeds 90 deg. The parallelism error of axis $X2$ to $X1$ should be reported as positive if the actual angle of axis $X2$ relative to axis $X1$ exceeds the respective nominal angle. A positive angle corresponds to positive angular motion around the machine coordinate axis, orthogonal to the plane of the parallelism measurement. The offset of axis $X2$ to $X1$ should be reported as positive if axis $X2$ is displaced in a positive coordinate direction relative to axis $X1$.

NOTE: The sign convention used in the compensation tables of the machine tool controller does not necessarily comply with the convention outlined in this Appendix.

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NONMANDATORY APPENDIX O
STATIC ERROR MOTION MEASUREMENT

O1 PURPOSE

The purpose of this test is to separate spindle bearing errors from spindle error motion caused by dynamic effects of the spindle drive system. The previous edition of this Standard called for measurement of structural error motion with the spindle running to identify the spindle bearing errors. Static error motion measurement accomplishes the same goal without the cost of making special brackets and setups. See Chapter 4 for the definition of static error motion measurement.

It is important to isolate the errors caused by spindle bearings. They are often blamed for problems caused by the spindle drive system. Structural error motion of the spindle stator with respect to the tool can be as high as 95% and typically 50% of the spindle error motion. A static error motion measurement is strongly recommended before a decision is made to change spindle bearings.

O2 SETUP AND PROCEDURE

The test setup is the same as for each of the axis motion tests described in para. 7.5.3. Two capacitance indicators, mounted at 90 deg to each other, are set up in a nest supported from the table to read against a test ball mounted on the spindle rotor in general accordance with Figs. 7.32 and 7.33. It is important to note that the spindle error motion tests show the combined functional effect of bearing error motion and structural error motion on the workpiece. After the spindle error motion tests at 10%, 50%, and 100% of full speed are completed, the static error motion measurement procedure should be performed to determine the contribution of the bearings. The detailed procedure is as follows:

(a) Put the spindle drive into neutral. If the spindle has a nondisengageable belt drive, the belt tension should be removed so the spindle is free of all external forces.

(b) Rotate the spindle, by hand, a minimum of two revolutions, stopping at a minimum of eight points per revolution.

(c) Release all hand forces and record the average indicator reading at each point. Averaging the readings eliminates the effect of structural motion with the spindle stopped. Play or loss of preload in the bearings can easily be identified by applying opposing forces to the spindle.

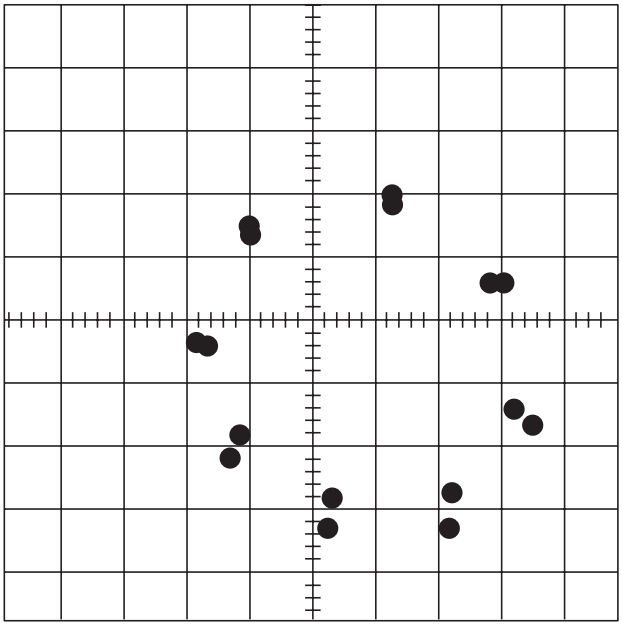


Fig. O1 Typical Data From a Static Error Motion Measurement on a Rolling Element Bearing Spindle

O3 DATA ANALYSIS

The data is analyzed for average and asynchronous radial, tilt, and axial motion using the methods described in para. 7.5. If an oscilloscope is used, as shown in Fig. 7.33, the recording can be done by photographing the oscilloscope screen at each rotational position. Figure O1 is an example of data from this test.

If a spindle error analyzer is used, the recording can be done by manual activation of the spindle error analyzer data recording system.

O4 DISCUSSION

The static error motion measurement concept assumes that bearings, which have acceptable performance at zero speed, will continue to have acceptable performance at operational speeds. Experience with rolling element bearing analyzers has shown that this assumption is generally true. The small differences that are observed when changing speed can be assigned to the effect of

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centrifugal forces that cause small changes in the line of contact of the balls or rollers with the races. The concept works for hydrostatic and aerostatic bearings, as well as rolling element bearings. However, it does not work for hydrodynamic bearings, which depend on rotational velocity for their load carrying and centering ability.

If there is doubt about the validity of the static error motion measurement, a structural error motion measurement, with the spindle running, can be performed as a cross-check. This measurement requires a special setup and careful attention to the design of the bracket that holds the indicator.

A significant increase in the value of spindle error motion with an increase in speed indicates a problem with the drive system. Worn belts and couplings, and unbalance and misalignment of drive motors, pulleys, and gears, are typical drive system problems. The measurement of static error motion is strongly recommended before a decision is made to change spindle bearings.

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