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ASME B5.57-1998

METHODS FOR PERFORMANCE EVALUATION OF COMPUTER NUMERICALLY CONTROLLED LATHES AND TURNING 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) lathes and turning 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 Standard does not address issues of machine safety. This Standard was approved by ANSI on July 16, 1998.

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METHODS FOR PERFORMANCE EVALUATION OF COMPUTER NUMERICALLY CONTROLLED LATHES AND TURNING CENTERS

1 SCOPE

This Standard establishes requirements and methods for specifying and testing the performance of CNC lathes and turning centers. In addition to clarifying the performance evaluation of lathes and turning centers, this Standard seeks to facilitate performance comparisons between machines by unifying terminology, general machine classification, and the treatment of environmental effects. The Standard defines testing methods capable of yielding adequate performance results for the majority of turning centers and is not intended to replace more complete tests. It is not the intent of this Standard to place limits on, or to enforce 100 percent testing of, any individual machine tool in accordance with this Standard. This shall be the subject of contractual agreement between the supplier and the user.

Sections 2 and 3 of this Standard reference documents that are used herein and provide a listing of symbolism. The first part of Section 4 is a glossary covering technical terms used throughout the Standard which might require explanation. The second part of Section 4 defines common machine classifications and provides guidance for developing other classifications.

The actual specification for CNC lathes and turning centers[1] is divided into six logical areas:

- General definitions and machine classifications
- Machine environmental specifications and responses
- Machine accuracy performance as a machine tool
- Machine cutting performance and short-term reliability
- Optional machine performance
- Machining test parts

General definitions and machine classifications include definitions of common terms, machine types, machining ranges, position resolutions, and other general specifications, as required.

[1] Throughout this Standard the terms "lathe" and "turning center" are used interchangeably.

Environmental specifications and responses include thermal, electrical, and vibration specifications and tests, as well as requirements on utility air and other externally-supplied services.

Machine accuracy performance as a machine tool includes positioning accuracy and repeatability for linear and rotary axes, angular error motion (yaw) of linear axes, spindle axis of rotation analysis, machine thermal tests, critical alignments, and contouring performance using circular tests.

Machine cutting performance and short-term reliability includes tests of spindle idle run losses and maximum metal-removal capability. Additionally, the machine is run for approximately 24 hours to determine short-term reliability.

Optional performance sections are provided for axis of rotation alignment, tail stock alignment, subsystems repeatability, tool-setting performance, CNC performance, and machine performance as a measuring tool.

Also optionally, this Standard provides for the machining of test parts for a particular manufacturing application. These test parts are to be fully specified as part of the original purchasing agreement between user and supplier. Such specification shall include, but not be limited to, material, tooling, machining sequence, and inspection procedure.

This Standard does not address issues of machine safety.

This Standard is rather comprehensive. A guide for using it is given in Appendix A. Further, for smaller, less expensive machines, a shorter series of tests for conformance to specification is given in Appendix L.

1.1 Specification Forms

Any specification described as complying with this Standard shall include at least those items specified in Forms 1, 2, 3, and 4. Optionally, special tests, as required in Form 5, shall be included.

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FORM 1 TURNING CENTERS SPECIFICATION FORM

GENERAL MACHINE SPECIFICATIONS

Machine Classification (Section 4.2): A figure with axis designation and direction of positive linear motion and clockwise rotary motion shall be supplied, as well as the appropriate machine classification.

_____

Linear Axis Full Travel:

X _____ mm _____ (in.)
Z _____ mm _____ (in.)
Other _____ mm _____ (in.)

Linear Axis Resolution Increment (least count):

X _____ mm _____ (in.)
Z _____ mm _____ (in.)
Other _____ mm _____ (in.)

Linear Axis Minimum Programming Increment:

X _____ mm _____ (in.)
Z _____ mm _____ (in.)
Other _____ mm _____ (in.)

Linear Axis Jog Increment:

X _____ mm _____ (in.)
Z _____ mm _____ (in.)
Other _____ mm _____ (in.)

Rotary Axis Full Travel

A _____ deg[2]
Other _____ deg

Rotary Axis Resolution Increment:

A _____ (deg)[3]
C _____ arc sec, deg
Other _____ (deg)

Rotary Axis Minimum Programming Increment:

A _____ arc sec (deg)
C _____ arc sec (deg)
Other _____ arc sec (deg)

[2] The ISO angular unit is the radian. The radian (ratio) is used by machine users primarily for small angles.

[3] This Standard will use decimal degrees, arc seconds, and radians, depending upon common usage.

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FORM 1 TURNING CENTERS SPECIFICATION FORM (CONT'D)

GENERAL MACHINE SPECIFICATIONS (CONT'D)

Rotary Axis Jog Increment:

A _____ arc sec (deg)
C _____ arc sec (deg)
Other _____ arc sec (deg)

Principal Spindle Parameters (for each spindle):

Workpiece or tool spindle: _____ headstock _____ tool
Spindle power — continuous duty: _____ kW _____ (hp)
Spindle power max. — intermittent duty: _____ kW _____ (hp)
Duration: _____ min
Tool holder standard (where applicable): _____
Maximum spindle rotation speed: _____ RPM
Minimum spindle rotation speed: _____ RPM

Supplier shall furnish spindle drive power/torque curve(s) for each spindle and each spindle speed range.

OTHER

Maximum feed rate — all axes _____ (mm/s) _____ (in./min)
Rapid traverse speed — all axes _____ (mm/s) _____ (in./min)
Tool indexing time — all turrets
Tool change time (where applicable) _____ (s)
Pocket-to-pocket: _____ (s)
Longest time: _____ (s)
Tool-setting system measurement time (where applicable) _____ (s)
Pallet change time (where applicable) _____ (s)
Axis indexing time (where applicable) _____ (s)

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.

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FORM 2 TURNING CENTERS SPECIFICATION FORM: ENVIRONMENTAL

ENVIRONMENTAL SPECIFICATIONS

Significant Mean Temperature Change (SMTC): ____ °C ____ (°F)

Safe Operating Temperature Range (SOTR):
Min. ____ °C ____ (°F), Max. ____ °C ____ (°F)

Nominal Location for ETVE Test[4] (Machine Coordinates):

X	____ mm	____ (in.)	*A*	____	deg
Y	____ mm	____ (in.)	*B*	____	deg
Z	____ mm	____ (in.)	*C*	____	deg
Other	____ mm	____ (in.)	Other	____	deg

Nominal Effective Coefficient of Thermal Expansion of Linear Machine Scales:

X	____ × 10^{-6}/°C	____ × (10^{-6}/°F)
Z	____ × 10^{-6}/°C	____ × (10^{-6}/°F)
Other	____ × 10^{-6}/°C	____ × (10^{-6}/°F)

Electrical (equivalent specification required for each electrical supply):
Voltage ____ V Frequency ____ Hz
Current ____ A Surge/Sag ____ V
Allowable Transient Voltage (0.5 to 800 μs) Magnitude ____ Volts

Ambient Vibration Allowances:

Option 1: Response Function Data ____ (Detailed permissible vector vibration spectra shall be attached as part of this specification.)

Option 2: Broad Band Data ____
Peak-to-Peak Vibration Amplitude ____ mm ____ (in.)
Frequency Range ____ Hz

Utility Air (if applicable):
Pressure ____ ± ____ Mka or ____ (psi)
Flow Rate[5] ____ $(dm)^3_n$/sec or ____ (SCFM)
Dew Point ____ °C ____ (°F)

Particle Removal Requirements:
Particle Size ____ μm or ____ (μin.) ____ % removal

Other Services (if applicable):

Foundation/Installation Specifications (must be included by supplier)
Construction drawings ____ yes ____ no

[4] The supplier shall also specify a definition for the quiescent state of the machine to be used for the ETVE test. Options are described in the text.

[5] The units here are the metric counterpart for SCFM. The dm stands for decimeter, one-tenth of a meter. The subscript "n" denotes normal conditions of pressure and temperature. $(dm)^3$ equals one liter. Ref. ANSI/NFPA B93.114M-1987, Sec. 5.5.1.

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FORM 3 THERMAL ENVIRONMENTAL GUIDELINES

THERMAL ENVIRONMENTAL GUIDELINES[6]

Nominal Mean Room Temperature: _____ °C _____ (°F)
Daily Cycling Amplitude (24 hr): ± _____ °C _____ (°F)

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

Gradients
Vertical: _____ °C/m _____ (°F/ft)
Horizontal: _____ °C/m _____ (°F/ft)

Flow Parameters:
Mean air speed surrounding the machine.[7] _____ m/s _____ (ft/s)

Additional guidelines on machine component placement and special flow requirements are to be attached if appropriate.

[6] 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.

[7] Maximum air speed should not exceed 6 m/min (20 ft/min) at 20°C (68°F). See ANSI B89.6.6 for a full discussion of parameters affecting operator comfort.

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FORM 4 TURNING CENTERS SPECIFICATION FORM: PERFORMANCE

MACHINE PERFORMANCE[8]

From the data in the tests below, many parameters may be derived (see Section 7.2). For the purposes of this Standard, it is recommended that at least those given below be reported.

POSITIONING ACCURACY AND REPEATABILITY, LINEAR AXES (Section 7.2):

X Axis (Compensated: ____ yes ____ no)

Bi-directional repeatability, R_{ae}	_____ mm	_____ (in.)
Uni-directional repeatability, $R_{ae}\uparrow$	_____ mm	_____ (in.)
Uni-directional repeatability, $R_{ae}\downarrow$	_____ mm	_____ (in.)
Bi-directional systematic deviation of positioning, E_{ae}	_____ mm	_____ (in.)
Uni-directional systematic deviation of positioning, $E_{ae}\uparrow$	_____ mm	_____ (in.)
Uni-directional systematic deviation of positioning, $E_{ae}\downarrow$	_____ mm	_____ (in.)
Periodic error, P	_____ mm	_____ (in.)

Z Axis (Compensated: ____ yes ____ no)

Bi-directional repeatability, R_{ae}	_____ mm	_____ (in.)
Uni-directional repeatability, $R_{ae}\uparrow$	_____ mm	_____ (in.)
Uni-directional repeatability, $R_{ae}\downarrow$	_____ mm	_____ (in.)
Bi-directional systematic deviation of positioning, E_{ae}	_____ mm	_____ (in.)
Uni-directional systematic deviation of positioning, $E_{ae}\uparrow$	_____ mm	_____ (in.)
Uni-directional systematic deviation of positioning, $E_{ae}\downarrow$	_____ mm	_____ (in.)
Periodic error, P (if applicable)	_____ mm	_____ (in.)

Other axes (the parameters above are required for each linear axis)

From the data in the tests below, many parameters may be derived (see Section 7.3). For the purposes of this Standard, it is recommended that at least those given below be reported.

Angular Error (Usually Yaw) and Repeatability, Linear Axes (Section 7.3)

X Axis (Compensated: ____ yes ____ no)

Bi-directional repeatability, R_{ae}	_____ arc sec
Uni-directional repeatability, $R_{ae}\uparrow$	_____ arc sec
Uni-directional repeatability, $R_{ae}\downarrow$	_____ arc sec
Bi-directional systematic deviation of angular error, E_{ae}	_____ arc sec
Uni-directional systematic deviation of angular error, $E_{ae}\uparrow$	_____ arc sec
Uni-directional systematic deviation of angular error, $E_{ae}\downarrow$	_____ arc sec

Z Axis (Compensated: ____ yes ____ no)

Bi-directional repeatability, R_{ae}	_____ arc sec
Uni-directional repeatability, $R_{ae}\uparrow$	_____ arc sec
Uni-directional repeatability, $R_{ae}\downarrow$	_____ arc sec
Bi-directional systematic deviation of angular error, E_{ae}	_____ arc sec
Uni-directional systematic deviation of angular error, $E_{ae}\uparrow$	_____ arc sec
Uni-directional systematic deviation of angular error, $E_{ae}\downarrow$	_____ arc sec

Other axes (the parameters above are required for each linear axis)

[8] When preparing a machine specification, the values in this performance form are defined as the specification zones. If the machine is compensated, specification zones may be specified with the compensation on and off, if desired.

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FORM 4 TURNING CENTERS SPECIFICATION FORM: PERFORMANCE (CONT'D)

MACHINE PERFORMANCE (CONT'D)

From the data in the tests below, many parameters may be derived (see Section 7.3). For the purposes of this Standard, it is recommended that at least those given below be reported.

POSITIONING ACCURACY AND REPEATABILITY, ROTARY AXES (Section 7.4)

Turret axis (Compensated: _____ yes _____ no)

Bi-directional repeatability, R	_____ arc sec	_____ (deg)
Uni-directional repeatability, R↑	_____ arc sec	_____ (deg)
Uni-directional repeatability, R↓	_____ arc sec	_____ (deg)
Bi-directional systematic deviation of angular error, E	_____ arc sec	_____ (deg)
Uni-directional systematic deviation of angular error, E↑	_____ arc sec	_____ (deg)
Uni-directional systematic deviation of angular error, E↓	_____ arc sec	_____ (deg)
Periodic error, P (if applicable)	_____ arc sec	_____ (deg)

C Axis (Compensated: _____ yes _____ no)

Bi-directional repeatability, R	_____ arc sec	_____ (deg)
Uni-directional repeatability, R↑	_____ arc sec	_____ (deg)
Uni-directional repeatability, R↓	_____ arc sec	_____ (deg)
Bi-directional systematic deviation of angular error, E	_____ arc sec	_____ (deg)
Uni-directional systematic deviation of angular error, E↑	_____ arc sec	_____ (deg)
Uni-directional systematic deviation of angular error, E↓	_____ arc sec	_____ (deg)
Periodic error, P	_____ arc sec	_____ (deg)

Other axes (the parameters above are required for each rotary axis)

SPINDLE AXES OF ROTATION (Section 7.5)

Structural motion, drives off (derate if required, see Section 7.5.2)

X _____ mm _____ (in.)
Y _____ mm _____ (in.)

Structural motion, drives on, feed hold (derate if required, see Section 7.5.2)

X _____ mm _____ (in.)
Y _____ mm _____ (in.)

Structural motion, drives on, program controlled (derate if required, see Section 7.5.2)

X _____ mm _____ (in.)
Y _____ mm _____ (in.)

Work Spindle, Fixed Sensitive Direction (one form per spindle per RPM)

Spindle designation _____
RPM (10%, 50%, and 100% max. spindle RPM are recommended) _____

Radial error motion	_____ mm	_____ (in.)
Asynchronous radial error motion	_____ mm	_____ (in.)
Axial error motion	_____ mm	_____ (in.)
Asynchronous axial error motion	_____ mm	_____ (in.)
Tilt error motion	_____ μrad[9]	
Asynchronous tilt error motion	_____ μrad	

[9] A microradian (μrad) is a millionth of a radian. It is equivalent to a rise of one μm in a meter (10 millionths of an inch in 10 inches).

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FORM 4 TURNING CENTERS SPECIFICATION FORM: PERFORMANCE (CONT'D)

MACHINE PERFORMANCE (CONT'D)

TOOL SPINDLE, ROTATING SENSITIVE DIRECTION (one form per spindle per RPM)

Spindle designation _____

RPM (10%, 50%, and 100% max. spindle RPM are recommended) _____

Radial error motion	_____ mm	_____ (in.)
Asynchronous radial error motion	_____ mm	_____ (in.)
Axial error motion	_____ mm	_____ (in.)
Asynchronous radial error motion	_____ mm	_____ (in.)
Tilt error motion	_____ μrad	
Asynchronous tilt error motion	_____ μrad	

MACHINE THERMAL TESTS (Section 7.6)

Spindle Tests (both work spindles and tool spindles shall be tested)

Spindle Warm-up Test (para. 7.6.2.1) (Compensated: ____ yes ____ no)

X axis drift	_____ mm	_____ (in.)
Y axis drift (optional)	_____ mm	_____ (in.)
Z axis drift	_____ mm	_____ (in.)
Angular drift of axis average line, *XZ* plane	_____ μrad	
Angular drift of axis average line, *YZ* plane (optional)	_____ μrad	

Note: *X*-, *Y*-, and *Z*-axis positional drifts are reported as close to the spindle face, work-holding device, or tool-holding device as is practical.

Spindle transient shut-off test, optional (para. 7.6.2.2) (Compensated: ____ yes ____ no)

X axis drift	_____ mm	_____ (in.)
Y axis drift	_____ mm	_____ (in.)
Z axis drift	_____ mm	_____ (in.)
Angular drift, *XZ* plane	_____ μrad	
Angular drift, *YZ* plane	_____ μrad	

Thermal distortions caused by moving linear axes (para. 7.6.3) (Compensated: ____ yes ____ no)

X-axis thermal distortion

X position 1, forward drift, $e(x_1\uparrow)$	_____ mm	_____ (in.)
X position 1, reverse drift, $e(x_1\downarrow)$	_____ mm	_____ (in.)
X position 2, forward drift, $e(x_2\uparrow)$	_____ mm	_____ (in.)
X position 2, reverse drift, $e(x_2\downarrow)$	_____ mm	_____ (in.)

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FORM 4 TURNING CENTERS SPECIFICATION FORM: PERFORMANCE (CONT'D)

MACHINE PERFORMANCE (CONT'D)

Z-axis thermal distortion

Z position 1, forward drift, $e(z_1\uparrow)$	_____ mm	_____ (in.)
Z position 1, reverse drift, $e(z_1\downarrow)$	_____ mm	_____ (in.)
Z position 2, forward drift, $e(z_2\uparrow)$	_____ mm	_____ (in.)
Z position 2, reverse drift, $e(z_2\downarrow)$	_____ mm	_____ (in.)

Other axes (the same parameters are reported for each servo-controlled linear axis)

Composite thermal error (para. 7.6.4): (Compensated: ____ yes ____ no)

Duration of total test, t _____ min.		
Distance between *X* indicator 1 and *X* indicator 2	_____ mm	_____ (in.)
X indicator 1 at 30 min, $C(X_1,30)$	_____ mm	_____ (in.)
X indicator 2 at 30 min, $C(X_2,30)$	_____ mm	_____ (in.)
Z indicator at 30 min, $C(Z,30)$	_____ mm	_____ (in.)
X indicator 1 at time *t*, $C(X_1,t)$	_____ mm	_____ (in.)
X indicator 2 at time *t*, $C(X_2,t)$	_____ mm	_____ (in.)
Z indicator at time *t*, $C(Z,t)$	_____ mm	_____ (in.)

CRITICAL ALIGNMENTS (Section 7.7)

Squareness of the cross slide (*X* axis) with the work spindle axis (often a *C* axis): (Compensated: ____ yes ____ no)

Select one: ____ Measurement using a mechanical straightedge (para. 7.7.2.1)

____ Measurement using a test part (para. 7.7.2.2)

Soak-out time _____ min
Machining time _____ min
Warm-up cycle must be specified

Squareness value _____ μrad

Parallelism of the longitudinal slide (*Z* axis) with the work spindle (often a *C* axis) in the *XZ* plane: (Compensated: ____ yes ____ no)

Select one: ____ Measurement using a mechanical straightedge (para. 7.7.3.1)

____ Measurement using a test part (para. 7.7.3.2)

Soak-out time _____ min
Machining time _____ min
Warm-up cycle must be specified

____ Laser measurement for long-travel axes (para. 7.7.4)

Parallelism value _____ μrad

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FORM 4 TURNING CENTERS SPECIFICATION FORM: PERFORMANCE (CONT'D)

MACHINE PERFORMANCE (CONT'D)

Critical Alignments (Section 7.7) (Cont'd)

Parallelism of the *Z* axis with other linear axes (one value for each auxiliary linear axis) (Compensated: ____ yes ____ no)

Parallelism value _____ μrad

Parallelism of the longitudinal slide (*Z* axis) with the work spindle (often a *C* axis) in the *YZ* plane: (Compensated: ____ yes ____ no)

Select one: ____ Measurement using a mechanical straightedge (para. 7.7.6)

____ Measurement using a test part (para. 7.7.6)

Soak-out time _____ min
Machining time _____ min
Warm-up cycle must be specified

____ Laser measurement for long-travel axes (para. 7.7.6)

Parallelism value _____ μrad

CONTOURING PERFORMANCE USING CIRCULAR TESTS (Section 7.8)
(Compensated: ____ yes ____ no)

Select one or as many as desired of the options below.

____ *XZ* plane 360 deg test (recommended, where possible)
____ *XZ* plane 190 deg test (recommended, where 360 deg test is not possible)
____ *XZ* plane 100 deg test (recommended, where 360 deg or 190 deg test is not possible)

Test results (one for each feed rate and angular range; feed rates[10] of approx. 10% and 80% of maximum feed rate are recommended for each angular range chosen):

Commanded feed rate	____ mm/min	____ (in./min)
Measured feed rate, clockwise	____ mm/min	____ (in./min)
Measured feed rate, counterclockwise	____ mm/min	____ (in./min)
Angular range	_____ deg	
Circular deviations, clockwise, $G\uparrow$	_____ mm	_____ (in.)
Circular deviations, counterclockwise, $G\downarrow$	_____ mm	_____ (in.)
Maximum radial deviation, clockwise, $F_{max}\uparrow$	_____ mm	_____ (in.)
Minimum radial deviation, clockwise, $F_{min}\uparrow$	_____ mm	_____ (in.)
Maximum radial deviation, counterclockwise, $F_{max}\downarrow$	_____ mm	_____ (in.)
Minimum radial deviation, counterclockwise, $F_{min}\downarrow$	_____ mm	_____ (in.)

[10] Feed rates should be checked using a stop watch, as some machine controllers will automatically slow down without operator warning.

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FORM 4 TURNING CENTERS SPECIFICATION FORM: PERFORMANCE (CONT'D)

MACHINE PERFORMANCE (CONT'D)

CUTTING PERFORMANCE TEST (Section 7.9)

Spindle idle run losses (report for each work and tool spindle) (para. 7.9.2)
Maximum spindle speed _____ RPM

% Max. Speed	Lost Power (kW)
20	
40	
60	
80	
100	

Chatter susceptibility and maximum torque test (para. 7.9.3)
Detailed specifications and procedures to be agreed between user and supplier and made part of the Machine Specification.

MULTI-FUNCTION CYCLE TEST (Section 7.10)

Test duration (24 hrs recommended) _____ hrs
Successful test completion time _____ hrs

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FORM 5 TURNING CENTERS SPECIFICATION FORM: PERFORMANCE (OPTIONAL)

MACHINE PERFORMANCE (OPTIONAL)

COAXIALITY OF AXES OF ROTATION (Section 8.2)

For each of the optional tests below, the user may specify the specification zones with machine compensation on or off, or both.

Select one: ____ Rim and face method (para. 8.2.1)
____ Reverse indicator method (para. 8.2.2)
____ Optical rotary axis alignment (para. 8.2.3)
____ Two-sphere axis alignment (para. 8.2.4)
____ Mechanical rotary axis alignment (para. 8.2.5.1)

Offset in the vertical direction, *VO*	_____ mm	_____ (in.)
Offset in the horizontal direction, *HO*	_____ mm	_____ (in.)
Parallelism, angularity in the vertical direction, *VA*	_____ μrad	
Parallelism, angularity in the horizontal direction, *HA*	_____ μrad	

Parallelism of the *Z* axis with other linear axes (*W*) (para. 8.2.5) (List all that apply)

ZW parallelism, *XZ* plane	_____ μrad
ZW parallelism, *YZ* plane	_____ μrad

Parallelism of the *Z* axis with the *C* axis, *YZ* plane (para. 8.2.6)

ZC parallelism, *YZ* plane	_____ μrad

SUBSYSTEM REPEATABILITY (Section 8.3)

Tool-change repeatability (para. 8.3.1)

Short tool length	_____ mm	_____ (in.)
Long tool length (100 mm recommended)	_____ mm	_____ (in.)
Short tool length repeatability, *X* direction	_____ mm	_____ (in.)
Short tool length repeatability, *Z* direction	_____ mm	_____ (in.)
Long tool length repeatability, *X* direction	_____ mm	_____ (in.)
Long tool length repeatability, *Z* direction	_____ mm	_____ (in.)

TURRET REPEATABILITY (para. 8.3.2)

Short tool length	_____ mm	_____ (in.)
Long tool length (100 mm recommended)	_____ mm	_____ (in.)
Short tool length repeatability, *X* direction	_____ mm	_____ (in.)
Short tool length repeatability, *Z* direction	_____ mm	_____ (in.)
Long tool length repeatability, *X* direction	_____ mm	_____ (in.)
Long tool length repeatability, *Z* direction	_____ mm	_____ (in.)

Repeatability location and drift of tool-setting systems (Section 8.4)

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FORM 5 TURNING CENTERS SPECIFICATION FORM: PERFORMANCE (CONT'D)

MACHINE PERFORMANCE (CONT'D)

Repeatability of tool-setting system (para. 8.4.1)

X repeatability	_____ mm	_____ (in.)
Z repeatability	_____ mm	_____ (in.)

Location of tool-setting system (para. 8.4.2)

X location	_____ mm	_____ (in.)
Z location	_____ mm	_____ (in.)

CNC PERFORMANCE TESTS (Section 8.5)

Desired increment length, INCR (para. 8.5.2) [Default value is 1 mm (approx. 0.04 in.)]	_____ mm	_____ (in.)
Maximum programmable feed rate, V_{max}[11]	_____ mm/min	_____ (in.)/min
Minimum block execution time, *MBET*	_____ sec	
Varying segment feed rate, *VSFR*	_____ mm/min	_____ (in.)/min

MACHINE PERFORMANCE AS A MEASURING TOOL (Section 8.6) (Specify option below)

_____ Software allows only 1*D* measurements (para. 8.6.2)
_____ Software allows 2*D* or 3*D* measurements (para. 8.6.3)

X measurement repeatability, *MR*(*X*)	_____ mm	_____ (in.)
Z measurement repeatability, *MR*(*Z*)	_____ mm	_____ (in.)
X feature-measuring accuracy, *FMA*(*X*)	_____ mm	_____ (in.)
Z feature-measuring accuracy, *FMA*(*Z*)	_____ mm	_____ (in.)
X linear measurement accuracy, *LMA*(*X*)	_____ mm	_____ (in.)
Z linear measurement accuracy, *LMA*(*Z*)	_____ mm	_____ (in.)
Volumetric measurement accuracy, *VMA*	_____ mm	_____ (in.)
Circular profile measurement accuracy, CPMA	_____ mm	_____ (in.)

[11] To be specified by machine supplier.

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1.2 Alternatives

Where specifications use definitions and procedures different than those in this Standard, the alternative items shall be identified and made part of the machine specification. Such procedures should follow the philosophy outlined in this Standard and be specified in equivalent detail.

This Standard allows parts of the environmental test section to be deferred or bypassed, and only the performance test to be carried out. This alternative is allowable only if it is acceptable to both the user and the supplier and if deferred according to the procedures outlined in Section 6.1.

2 REFERENCED DOCUMENTS

ANSI B5.54-1992, Methods for the Performance Evaluation of Computer Numerically Controlled Machining Centers

ANSI B89.6.2-1973, Temperature and Humidity Environment for Dimensional Measurement

ANSI B89.1.12M-1990 (R1997), Methods for the Performance Evaluation of Coordinate Measuring Machines

ANSI B89.3.4M-1985, Axes of Rotation

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

American National Standards Institute (ANSI), 11 West 42nd Street, New York, NY 10036

ISO TC3 WG15:1993 International Vocabulary of Basic and General Terms in Metrology

ISO 1:1975, Standard Reference Temperature for Industrial Length Measurements

ISO 554:1976, Standard Atmospheres for Conditioning and/or Testing Specifications

ISO 3205:1976, Preferred Test Temperatures

IEC 212 1971, Standard Conditions for Use Prior to and During Use of Solid Electrical Insulating Materials

ISO/TAG 4:1993, Guide to the Expression of Uncertainty in Measurement

ISO DIS 230-2:1998, Test Code for Machine Tools — Part 2: Determination of Accuracy and Repeatability of Positioning of Numerically Controlled Axes

ISO DIS 230-3:1997, Test Code for Machine Tools — Part 3: Determination of Thermal Effects

ISO 230-4:1996, Acceptance Code for Machine Tools — Part 4: Circular Tests for Numerically Controlled Machine Tools

ISO 841:1992, Industrial Automation Systems and Integration — Physical Device Control — Coordinate System and Motion Nomenclature

ISO 1940-1:1986, Mechanical Vibration-Balance Quality Requirements of Rigid Rotors — Part I: Determination of Permissible Residual Unbalance

ISO 10360-2:1994, Coordinate Metrology — Part 2: Performance Assessment of Coordinate Measuring Machines

International Organization for Standardization (ISO), 1 rue de Varembe, Case Postale 56, CH-1121, Geneve 20, Switzerland/Suisse

NAS 938 1959 (R1963), Machine Axis and Motion Nomenclature

JIS B 6202-1986, Test Code for Performance and Accuracy of Lathes

JIS B 6215-1977, Test Code for Performance and Accuracy of Turret Lathes

3 SYMBOLS

$1D$ = one-dimensional
$2D$ = two-dimensional
$3D$ = three-dimensional
a^+ = upper limit of a uniform distribution
a^- = lower limit of a uniform distribution
A = bi-directional accuracy of positioning of an axis
A = a computer-controlled rotary axis that rotates around the X axis[12]
A_{ae} = bi-directional total angular error
$A_{ae}\uparrow$ = uni-directional total angular error, forward direction
$A_{ae}\downarrow$ = uni-directional total angular error, reverse direction
$ANGF$ = angle measured in forward direction, straightedge reversal
$ANGR$ = angle measured in reverse direction, straightedge reversal
$A\uparrow$ = uni-directional accuracy of positioning of an axis, forward direction
$A\downarrow$ = uni-directional accuracy of positioning of an axis, reverse direction
α = coefficient of thermal expansion of object being measured or calibrated

[12] In this Standard, A is used to symbolize two different quantities. This is done in order to conform with existing ISO and ANSI Standards. The usage is so different it is expected that no confusion will arise.

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α_s = coefficient of thermal expansion of reference and/or working standard

B = maximum of absolute reversal values at all target positions along an axis

$\overline{B}$ = 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

$\beta(\theta)$ = tilt degree of freedom for a rotary axis in the sensitive direction

C = a programmable rotary axis or spindle that rotates around the Z axis

C_n = a programmable spindle axis on a machine with more than one spindle axis (n = 1, 2,...)

$CPMA$ = circular profile measurement accuracy

$\overline{CX}_n$ = mean X circle center at position n = 1, 2, two-sphere axis alignment

$c(X_n, 30)$ = X displacement at position n (n = 1, 2,...) after 30 minutes, composite thermal error test

$c(X_n, t)$ = X displacement at position n (n = 1, 2,...) after t minutes, composite thermal error test

$\overline{CY}_n$ = mean Y circle center at position n = 1, 2, two-sphere axis alignment

$c(Y_n, 30)$ = Y displacement at position n (n = 1, 2,...) after 30 minutes, composite thermal error test

$c(Y_n, t)$ = Y displacement at position n (n = 1, 2,...) after t minutes, composite thermal error test

$c(Z, 30)$ = Z displacement after 30 minutes, composite thermal error test

$c(Z, t)$ = Z displacement after t minutes, composite thermal error test

D_c = diameter of a test cylinder

$\Delta_X(\theta)$ = output of the X axis gage in spindle testing

$\Delta_Y(\theta)$ = output of the Y axis gage in spindle testing

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} = tilt of the spindle axis average line caused by thermal effects, XZ plane

D_y = spindle thermal drift, Y direction

D_{yz} = tilt of the spindle axis average line caused by thermal effects, YZ plane

D_z = spindle thermal drift, Z direction

DIA = diameter of a circle or part

E = bi-directional systematic deviation of positioning of an axis

$E\uparrow$ = uni-directional systematic deviation of position of an axis, forward direction

$E\downarrow$ = uni-directional systematic deviation of position of an axis, reverse direction

E_{ae} = bi-directional systematic angular error

$E_{ae}\uparrow$ = uni-directional systematic angular error, forward direction

$E_{ae}\downarrow$ = uni-directional systematic angular error, reverse direction

$ETVE$ = environmental temperature variation error

$E(X)$ = bi-directional systematic deviation of positioning, X axis

$E(Z)$ = bi-directional systematic deviation of positioning, Z axis

$e(x_n\uparrow)$ = 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 = out-of-squareness angle between a straightedge and a spindle axis

$F_{max}\uparrow$ = radial deviation, maximum, clockwise direction, circular test

$F_{min}\uparrow$ = radial deviation, minimum, clockwise direction, circular test

$F_{max}\downarrow$ = radial deviation, maximum, counterclockwise direction, circular test

$F_{min}\downarrow$ = radial deviation, minimum, counterclockwise direction, circular test

$FM(X)$ = feature measurement accuracy, X direction

$FM(Z)$ = feature measurement accuracy, Z direction

$\overline{FRN}$ = mean face reading at N, N = 0, 3, 6, 9, rim and face test

$\overline{FR}_s$ = mean sag of face indicator, rim and face test

$G\uparrow$ = circular deviation, clockwise, circular test

$G\downarrow$ = circular deviation, counterclockwise, circular test

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$\gamma(\theta)$ = tilt degree of freedom for a rotary axis in the nonsensitive direction
κ = thermal conductivity of a material
H = circular hysteresis, circular test
HA = horizontal angle between two axes of rotation, coaxiality of axes of rotation
HO = horizontal offset between two axes of rotation, coaxiality of axes of rotation
HO_n = horizontal offset at position n, n = 1, 2, two-sphere axis alignment
i = index of target position
$INCR$ = increment length used to test block execution time
j = index for number of measurements
k = coverage factor
L = dimension of workpiece at 20°C
$L_{1,2}$ = distance between indicators 1 and 2 and spindle face, spindle thermal stability test
L_c = length of a test cylinder
L_{cte} = distance between the displacement indicators in the composite thermal error test
L_d = dimension between two gages used to calculate angle
$LMA(X)$ = linear measurement accuracy, X direction
$LMA(Z)$ = linear measurement accuracy, Z direction
L_s = dimension of reference and/or working standard at 20°C
LSC = least-squares circle center of polar profile
L_T = dimension of an object at temperature T ≠ 20°C
$LUTM$ = length uncertainty due to temperature measurement
L_X = traverse length of the X axis
L_Z = traverse length of the Z axis
m = number of positions along or around an axis
M = range of the mean bi-directional positional deviations of an axis
$Max[q]$ = maximum value of a quantity, q
$MBET$ = minimum block execution time
MCC = minimum circumscribed circle center of a polar profile
MIC = minimum inscribed circle center of a polar profile
$Min[q]$ = minimum value of a quantity, q
$\overline{MRN}$ = mean M gage reading at N = 0, 3, 6, 9, reverse indicator test
MRS = minimum radial separation center of a polar profile
$\overline{MR}_s$ = mean sag of the M gage, reverse indicator test
$MR(R)$ = measurement repeatability of a radius
$MR(X)$ = measurement repeatability, X direction
$MR(Z)$ = measurement repeatability, Z direction
μm = micrometer, unit of length
n = number of measurements of the same quantity
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
P = periodic error of a linear or rotary axis
P_i = target position in the positioning tests, i^{th} position
P_{ij} = measured position at the j^{th} approach to the target position P_i
$PL(R)$ = probe lobing
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 j^{th} measurement of a quantity, q
r_0 = radius of the eccentricity in rotating sensitive direction spindle testing
$r_n(\theta)$ = radial motion of a spindle measured by gage n (n = 1, 2,...)
$r(\theta)$ = radial error motion of a spindle
R = bi-directional repeatability of a measurement
$R\uparrow$ = uni-directional repeatability for an axis, forward direction (maximum value)
$R\downarrow$ = uni-directional repeatability for an axis, reverse direction (maximum value)
R_A = radius of an artifact
R_{ae} = bi-directional repeatability of angular error
$R_{ae}\uparrow$ = uni-directional repeatability of angular error, forward direction
$R_{ae}\downarrow$ = uni-directional repeatability of angular error, reverse direction
R_i = bi-directional repeatability of positioning at position, i
$R_i\uparrow$ = uni-directional repeatability of positioning in the forward direction at position, i
$R_i\downarrow$ = uni-directional repeatability of positioning in the reverse direction at position, i

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R_{Mi} = measured radius of a part, i = 1, 2, machine performance as a measuring tool

R_{pi} = radius of a part, i = 0, 1, 2, 180, machine performance as a measuring tool

$\overline{R}_{pi}$ = average measured radius of a part, i = 0, 1, 2, 180, machine performance as a measuring tool

rpm = revolutions per minute

$\overline{RRN}$ = mean rim reading at position N, N = 0, 3, 6, 9, rim and face test

$\overline{RR}_s$ = mean sag of rim indicator, rim and face test

R_{sphere} = radius of a sphere

R_{xts} = tool change repeatability, X direction

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

$SMTC$ = significant mean temperature change

$SOTR$ = safe operating temperature range

$\overline{SRN}$ = mean S gage reading at N = 0, 3, 6, 9, reverse indicator test

$\overline{SR}_s$ = mean sag of the S gage, reverse indicator test

SZ = specification zone for a quantity specified in this Standard

t = time

τ = time constant of a physical quantity

θ = angular position of a rotary axis (spindle axes included) or the angle between two lines

T = temperature of workpiece

TEI = thermal error index

T_s = temperature of 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

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

u_{ETVE} = standard uncertainty due to the environmental temperature variation

$UNDE$ = uncertainty of nominal differential expansion

$UNDE$ = uncertainty of nominal thermal expansion

UNE_s = uncertainty of nominal thermal expansion of a standard

u_q = standard uncertainty of a quantity, q

u_{sub} = standard uncertainty of a measurement, denoted by the subscript, sub

$u(T)$ = uncertainty of temperature of the object being measured or calibrated

$U_T(L)$ = expanded thermal uncertainty

$u(T_s)$ = uncertainty of temperature of reference and/or working standard

u_x = estimate of the standard uncertainty, X direction, tool change repeatability

VA = vertical angle between two axes of rotation, coaxiality of axes of rotation

VMA = volumetric measurement accuracy

V_{max} = maximum feed rate observed, minimum block execution time test

VO = vertical offset between two axes of rotation, coaxiality of axes of rotation

VO_n = vertical offset at position n = 1, 2, two-sphere axis alignment

$VSFR$ = varying segment feed rate

W = out-of-squareness angle

X = a linear axis direction, usually the cross slide

X_n = a linear machine axis on a machine with more than one X axis (n = 1, 2,...)

$\bar{x}_i$ = bi-directional deviation of axis positioning at position, i

$\bar{x}_i\uparrow$ = mean deviation of an axis positioning in the forward direction at the i^{th} position

$\bar{x}_i\downarrow$ = mean deviation of an axis positioning in the reverse direction at the i^{th} position

x_{ij} = positional deviation for the j^{th} measurement at the i^{th} position

$x_{ij}\uparrow$ = j^{th} positional deviation at the i^{th} position along an axis, forward direction

$x_{ij}\downarrow$ = j^{th} positional deviation at the i^{th} position along an axis, reverse direction

x_{ti} = i^{th} X reading, tool change repeatability

$\bar{x}_t$ = average X reading, tool change repeatability

Y = a linear direction on a lathe, usually the nonsensitive direction

Z = a linear axis direction, usually parallel to the main spindle axis

Z_{MO} = measured step height, machine performance as a measuring tool

Z_n = a linear machine axis on a machine with more than one Z axis (n = 1, 2,...)

Z_{pO} = step height, machine performance as a measuring tool

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$\bar{Z}_{pO}$ = average measured step height, machine performance as a measuring tool

4 DEFINITIONS

4.1 Glossary

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

Abbe offset: the 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: the 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.[13]

actual path: the 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 j^{th} approach to the i^{th} target position.

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

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

angular error: undesired angular motion of a linear axis in motion (see *pitch, roll, yaw*).

artifact: a 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: for a turning center, defined as the ratio of the travel of the longest linear axis to the shortest linear axis. A long aspect ratio machine is defined as having an aspect ratio greater than three (3).

autocollimator: an optical instrument which 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: the average value of a series of measurements. Used synonymously with mean.

axial error motion: error motion collinear with the Z reference axis of an axis of rotation [see Fig. 1, (d)].

axis average line: the average axis of rotation for 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: the direction of any line parallel to the motion direction of a linearly moving component. Due to straightness errors, 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: the direction of rotation of a rotary axis. Such rotation shall be either clockwise or counterclockwise when facing into the axis. For example, the direction of axis rotation shown in Fig. 1(g) is clockwise.

axis of rotation: a 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.

ball bar: a gage consisting of two high-precision spherical tooling balls of the same diameter connected by a rigid bar.

[13] 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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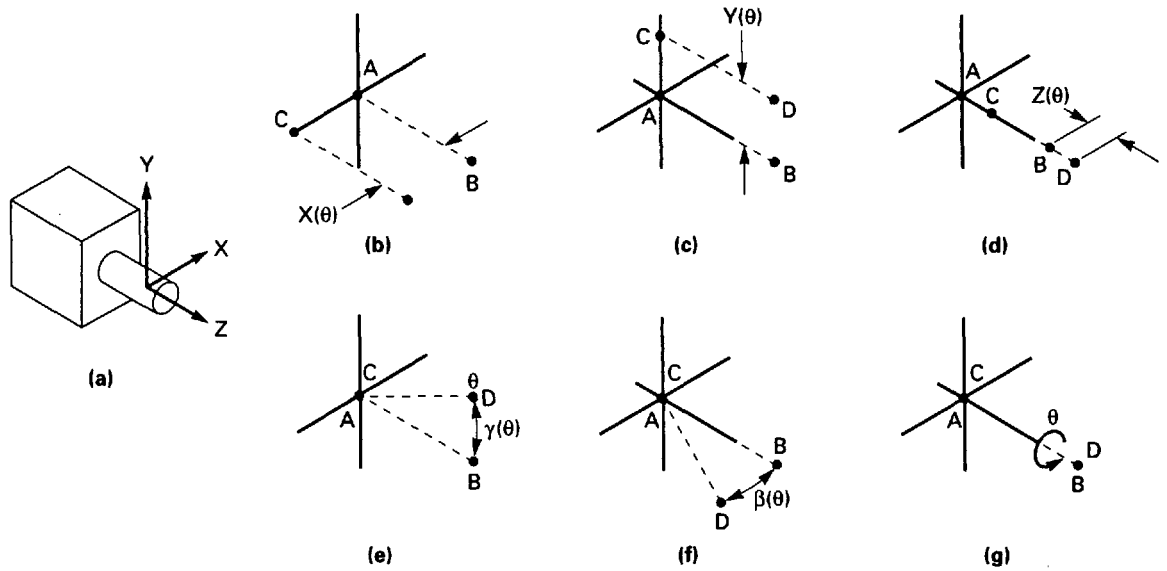


FIG. 1 SCHEMATIC DIAGRAMS OF THE SIX BASIC DEGREES OF FREEDOM OF AN AXIS OF ROTATION

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.

ball bar (socketed): a ball bar held by a socket which allows repeatable relocation at one or both ends.

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

bi-directional: 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 the axis.

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

$$A = \max\left[\bar{x}_i\uparrow + 2s_i\uparrow;\ \bar{x}_i\downarrow + 2s_i\downarrow\right] - \min\left[\bar{x}_i\uparrow - 2s_i\uparrow;\ \bar{x}_i\downarrow - 2s_i\downarrow\right]$$

bi-directional repeatability of angular error, R_{ae}: the maximum value of the bi-directional repeatability of angular error for an axis.

bi-directional repeatability for an axis, R: the maximum value of the bi-directional repeatability positioning for an axis; that is, $R = \max(R_i)$.

bi-directional repeatability of positioning at a position, R_i: the maximum range representing the expanded uncertainty of bi-directional 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,

$$R_i = \max\left[2s_i\uparrow + 2s_i\downarrow;\ +|B_i|;\ R_i\uparrow;\ R_i\downarrow\right]$$

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

bi-directional systematic angular error, E_{ae}: the difference between the algebraic maximum and minimum of the mean uni-directional angular motions for both directions of approach in any position along or around a linear axis being measured using the procedure and under the conditions specified in this Standard. Computed the same as bi-directional systematic deviation of positioning of an axis, E.

bi-directional systematic deviation of positioning of an axis, E: the difference between the algebraically

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maximum and minimum of the mean uni-directional 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 determined using the procedure and under the conditions specified in this Standard.

$$E = \max\left[\bar{x}_i\uparrow; \bar{x}_i\downarrow\right] - \min\left[\bar{x}_i\uparrow; \bar{x}_i\downarrow\right]$$

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

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

broad-band vibration amplitude: the amplitude (size) of vibration allowed over a specified frequency band, usually specified as the maximum vibration from a low-frequency, say 1 Hz, to an upper frequency of several thousand Hz.

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: a 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. Also called a drift check or drift test.

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

catenary: the 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 which may damage the cutting tool, the machine, or the part in roughing cuts and degrade the surface finish in finishing cuts.

circular deviation: defined as the minimum radial separation of two concentric circles enveloping the actual path (minimum zone circles) in the circular test. It is equivalent to the total error motion value (see *error motion value*). Values are denoted $G\uparrow$ for clockwise rotations and $G\downarrow$ for counterclockwise rotations.

circular hysteresis (not reported in this Standard): in the circular tests, denoted H, the maximum radial difference between two actual paths at any given angle, where one path is generated by clockwise machine motion and the other by counterclockwise machine motion.

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.

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

cold machine: a machine in a thermal state operating temperature where during the last two-hour period (1) the hydraulic systems and servos have been on, (2) the spindle has not been rotated above 10% of the maximum rpm, and (3) the axes motions have been restricted to only those necessary to set up measurement equipment. A secondary definition is a machine that has been allowed to thermally stabilize for a supplier-specified or user-specified soak-out time.

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

$$u_{cT}(L) = \left[u_{ETVE}^2 + L_s^2 (T_s - 20)^2 u^2(\alpha_s) + L^2 (T - 20)^2 u^2(\alpha) + L_s^2 \alpha_s^2 u^2(T_s) + L_s^2 \alpha^2 u^2(T)\right]^{1/2}$$

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

command mode: a 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 pre-recorded error tables and in-process sensing of variables such as temperature for correcting the position of a CNC machine using the CNC controller.

compliance: the 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 degrees to the reference axis.

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

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

(d) face compliance: applicable when the force and displacement are parallel to the Z 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): a numerical control system in which the data handling sequence, the control functions, and the response to data input are determined primarily by a control program executed by a computer.

constant surface speed: in turning application, the condition achieved by varying the speed of rotation of the workpiece relative to the tool inversely proportional to the distance of the tool from the center of rotation.

contouring control system: a system of control in which two or more controlled motions move in relation to each other so that the desired angular path or contour is generated.

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

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

NOTE: The control program may come in the form of a source program, an object program, or a special format as specified by the supplier.

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

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

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

NOTE: Typically used on contouring control systems.

cutter diameter (radius) offset: a displacement normal to the cutter path which is along a machine axis, to adjust for the difference between actual and programmed cutter radius or diameter.

cycle time: the period of time from starting one machine operation 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 average difference between an actual value and the desired value, unless otherwise specified.

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

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$$x_{ij} = P_{ij} - P_i$$

diagonal displacement: the 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: the 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.

differential response: the amplitude of the relative length variation between any two objects per unit sinusoidal environment temperature oscillation as a function of frequency of temperature oscillation.

dimensional response: the amplitude of absolute length variation of an object per unit of sinusoidal environmental temperature oscillation as a function of the frequency of temperature oscillation.

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. See Section 9 for further discussion.

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. 7.1.3).

drift test: an experiment conducted to determine the actual drift inherent in a measurement system under normal operating conditions. Since the usual method of monitoring the environment involves the correlation of one or more temperature recordings with drift, the test will usually consist of simultaneous recordings of drift and environmental temperatures. The recommended procedure for the conduct of a drift test is given in Section 6.2 for the measurement of environmental temperature variation error.

drift test (thermal): a type of test used to measure temperature variation error [see *temperature variation error (ETVE)*] on a machine. One form of this test consists of continuously recording the output of displacement sensors placed in the position of a tool on the machine and reading against a test artifact mounted in the machine main spindle over a period of time. Detailed procedures for conducting a drift test are given in Section 6.2.

environmental temperature variation error, ETVE: an estimate of the maximum possible measurement uncertainty induced solely by deviation of the environment from average conditions. The ETVE is determined from the results of two drift tests, one of the master and comparator and the other of the part and the comparator. Several American Standards define drift tests for particular instruments. For coordinate measuring machines, see ANSI B89.1.12M-1990 (R1996). For machine tools, see ANSI B5.54-1992. For the purposes of this Standard, it is assumed that the errors in measurement due to temperature variation are uniformly distributed with a total range equal to the measured ETVE, following either the drift test specified in this Standard or the drift test specified for specific instruments in the other previously-referenced Standards. Since the ETVE is a total range, it must be converted to a standard uncertainty as is discussed in para. 6.2.1.

error: the 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 (also see *deviation*).

error motion: change in position relative to the reference coordinate axes, of the surface of a perfect workpiece with its center line coincident with the axis of rotation. Error motions are specified as to location and direction as shown in Fig. 1, and do not include motions due to thermal drift.

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

error motion polar plot: a polar plot 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 which can be divided into

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

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

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

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

error motion value: the maximum scaled width of the error motion polar plot, after the average error motion has been subtracted from the error motion polar plot.

(a) asynchronous error motion value: the maximum value of the error motion obtained during a spindle error motion measurement, after the average error motion has been subtracted from the error motion polar plot.

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

(c) average error motion value: the scale 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 uni-directional standard uncertainty of positioning at a position, $s_i\uparrow$ or $s_i\downarrow$: the estimator of the standard uncertainty of the positional deviations obtained by a series of n uni-directional approaches at a position P_i

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

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

expanded thermal uncertainty: in the case where the effective number of the degrees of freedom for each of the uncertainties in the combined standard thermal uncertainties (see *standard thermal uncertainty*) is known, the expanded uncertainty should be computed following the example given in the ISO Guidelines, paragraph 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

$$\pm U_T(L) = \pm k u_{cT}(L) = \pm 2u_{cT}(L)$$

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

face runout: the runout of the face plate of a lathe as measured with an indicator in the tool position at some X distance off the axis of rotation.

feed function: a command defining a feed rate.

feed hold: the 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: the rate of motion of the tool relative to the workpiece.

fixed cycle: a preset series of operations which direct the machine axis movement and/or causes spindle operation to perform a complex function, e.g., boring, drilling, tapping, probing, facing, and a combination thereof.

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

NOTE: Typically 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: the 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, an 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.

gauge: see *gage*.

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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 8,000 rpm.

hysteresis: a component of bi-directional 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: the hysteresis of the various elements in a test setup, normally due to loose mechanical connections; and

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

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

indicator: a 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."

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

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

NOTE: Typically used for start-up.

initialization: a 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 percent operation, continuous duty.

laser interferometer: a fringe counting interferometer for displacement measurement which 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 in order 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

$$LUTM = \sqrt{\alpha^2 L^2 u(T)^2 + \alpha_s^2 L_s^2 u(T_s)^2}$$

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 0.93×10^{-6} per °C.

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

live tooling: a generic term used to refer to tooling on a turning center where the tool is rotated around a secondary axis of rotation for the purposes of milling, drilling, etc.

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

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

machine coordinate system: the coordinate system which 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 RS-267). (The machine may also include rotary axes usually designated A, B, and C.)

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

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machine home: a 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): the 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: a 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.

main spindle: on a turning machine, the largest spindle equipped for the fixturing of parts with the purpose of turning such parts to provide surface speed for metal removal. In the case where there are two spindles capable of fixturing the same size of part, the main spindle shall be that spindle that is used more often or that is closest to the operator's left hand when the operator faces the machine.

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

mastering: the action of nulling or setting a comparator with a master.

mastering cycle time:: the time between successive masterings of the process.

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

$$\bar{x}_i = \frac{\bar{x}_i\uparrow + \bar{x}_i\downarrow}{2}$$

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

mean gage temperature: the 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, $\bar{B}$: arithmetic mean of the reversal values, B_i, at all target positions along or around the axis,

$$\bar{B} = \frac{1}{m}\sum_{i=1}^{m} B_i$$

mean uni-directional 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 uni-directional approaches to a position P_i,

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

and

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

measurement cycle time: the time between measuring and the previous mastering.

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

measurement point: a point in the work zone of a machine at which machine coordinates are recorded as part of a measurement.

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measurement travel: part of the axis travel which is used for data capture. It is selected so that the first and last target positions may be approached bi-directionally (see Section 7).

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

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

nominal coefficient of thermal expansion: an 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. 7.2.4). Following ISO practice, this Standard does not differentiate between the expected value of quantity and its actual value. Therefore, the nominal coefficient of expansion, in this Standard, will be denoted α.

nominal differential expansion (NDE)[14]*:* the difference between the nominal expansion of the object to be calibrated and the standard:

$$NDE = (NE) - (NE)_s$$

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

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

$$NE = \alpha L (T - 20)$$

nominal path: a 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 of the work zone of the machine. Nominal paths for the circular tests may either be full circles or partial arcs.

nonsensitive direction: any direction perpendicular to any sensitive direction (see *sensitive direction*).

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

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

outlier: a measured value that is greater than plus twice the repeatability or less than minus twice 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. 7.2.7 of this Standard.

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

part probe: a probe mounted to the tooling axis of a CNC lathe or turning center that allows measurement of parts.

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 coordinate: the Cartesian (XYZ) coordinate system in which the part is defined and in which the tool coordinates are specified.

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

part trace test: consists of cutting a part and then replacing the cutting tool with a displacement indicator (usually an LVDT) and repeating the original tool path indicating against the part with the spindle off.

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

periodic error: an error in the linear or angular positioning of a machine that is periodic over an interval which normally coincides with the natural periodicity of the machine scales. For example, in a lead screw

[14] It is a requirement of this Standard that nominal differential expansion corrections always be made. See para. 7.2.4 for details.

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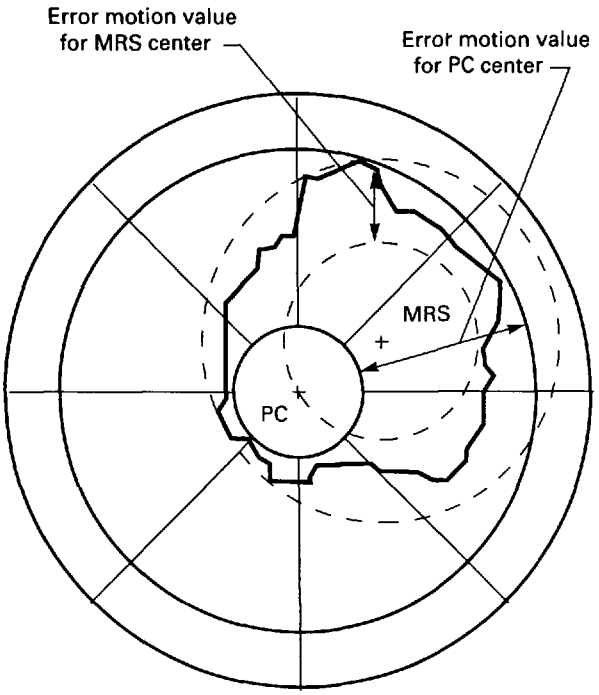


FIG. 2 ERROR MOTION POLAR PLOT SHOWING POLAR CHART (PC) CENTER, A MINIMUM RADIAL SEPARATION (MRS) CENTER, AND ERROR MOTION VALUES ABOUT THESE CENTERS

driven machine with rotary encoders, the periodicity is usually synchronous with the pitch of the lead or ball screw.

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

play: a 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: the center of the polar chart.

polar profile center: a 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: the center which minimizes the radial difference required to contain the error motion polar plot between two concentric circles (see Fig. 2).

(b) least square circle (LSC) center: the center of a circle which 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: the center of the largest circle that can be inscribed within the error motion plot.

(d) minimum circumscribed circle (MCC) center: the 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 instruction which 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: a mode of operation of a NC or CNC system that performs in accordance with the definition of a positioning control system.

probe: in this Standard a device which 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.

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

(b) proportional probe: a probe that gives a signal proportional to a displacement of the probe from its free position. Most commonly such probes use linear, variable differential transformers as displacement sensors and have electronic readout. Proportional probes are preferred; however, in lower accuracy applications a dial gage can be used.

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

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

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

probe cycle: a fixed cycle using a probe.

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

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

quadrant photodiode: a photodetector composed of four separate photodetectors arranged in a form that resembles the quadrants of a circle.

radial deviation: in the circular test, the radial deviations are the maximum and minimum deviations from the calibrated ball bar length, corrected to 20°C. They are denoted $F_{max}\uparrow$ and $F_{min}\uparrow$ for clockwise rotations and $F_{max}\downarrow$ and $F_{min}\downarrow$ for counterclockwise rotations.

radial error motion: error motion of a rotary axis normal to the Z reference axis and at a specified angular location (see Fig. 1).

radial runout: the maximum reading obtained from a displacement sensor when the displacement sensor is set to read in the radial direction against a part rotated in a spindle. Customarily the spindle rotation is at low speed.

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

range of the mean bi-directional positional deviation of an axis, M: the difference between the algebraically maximum and minimum of the mean bi-directional positional deviations $\bar{x}_i$ at any position along or around the axis determined using the procedure and under the conditions specified in this Standard.

$$M = \max[\bar{x}_i] - \min[\bar{x}_i]$$

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 non-zero frequency relative motion between the position of a nominal tool and a nominal workpiece.

repeatability: for the purposes of this Standard, 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. 7.2.7).

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

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

$$B = \max[|B_i|]$$

reversal value [error] at a position, B_i: value of the difference between the mean uni-directional deviations obtained from the two directions of approach,

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

roll: the 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 as follows.

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

(b) rotary positioning axis: a rotary axis which 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 material removal.

(c) spindle: see *spindle*.

runout: the total displacement measured by an instrument sensing against a moving surface or moved with respect to a fixed surface.

safe operating temperature range: the 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.).

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scale: part of a transducer system which 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, a 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 which comprises the portion of the scale which 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.

sense of contouring: the sense or direction of contouring (clockwise or counterclockwise contouring) as it applies to the circular test.

sensitive direction: the direction where relative motion between the tool and the workpiece causes one-for-one form errors to be cut into the workpieces. On lathes the error motion of the main spindle must be considered to be in the fixed sensitive direction. The error motions of tool spindles are in the rotating sensitive direction. 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.

COMMENTS: A lathe has a fixed sensitive direction; a jig borer has a rotating sensitive direction. With a fixed sensitive direction, the reference coordinate axis is fixed; with a rotating sensitive direction, the reference coordinate rotates with spindle.

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

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

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

significant mean temperature change: the 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 (Section 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. Soak out time is the time elapsed following a change in environment until the object is influenced only by the new environment. 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.

soak-out time: the time specified after machining, before measurements of critical alignments (Section 7.7) can be made, if the test part options are chosen.

socket: a socket that allows the accurate repositioning of one end of a telescoping ball bar.

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

specification zone (SZ): as defined in this Standard, the value specified in a machine specification for the result of a particular test.

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

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

spindle speed function: a 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.

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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 Section 6. In order 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

$$u_{ETVE} = \sqrt{\frac{ETVE^2}{12}}$$

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

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

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

static error motion measurement: a special case of spindle error motion measurement in which the error motion is sampled at a series of rotational positions with the spindle being moved slowly to each position and held at rest during the error motion measurements.

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

step gage: a 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.

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 which is stationary.

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

structural loop: an assembly of mechanical components which 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. 3).]

supplier: a 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 spindle testing.

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

temperature of a body:

(a) temperature at a point: when discussing a body which 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) the 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 which 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.)

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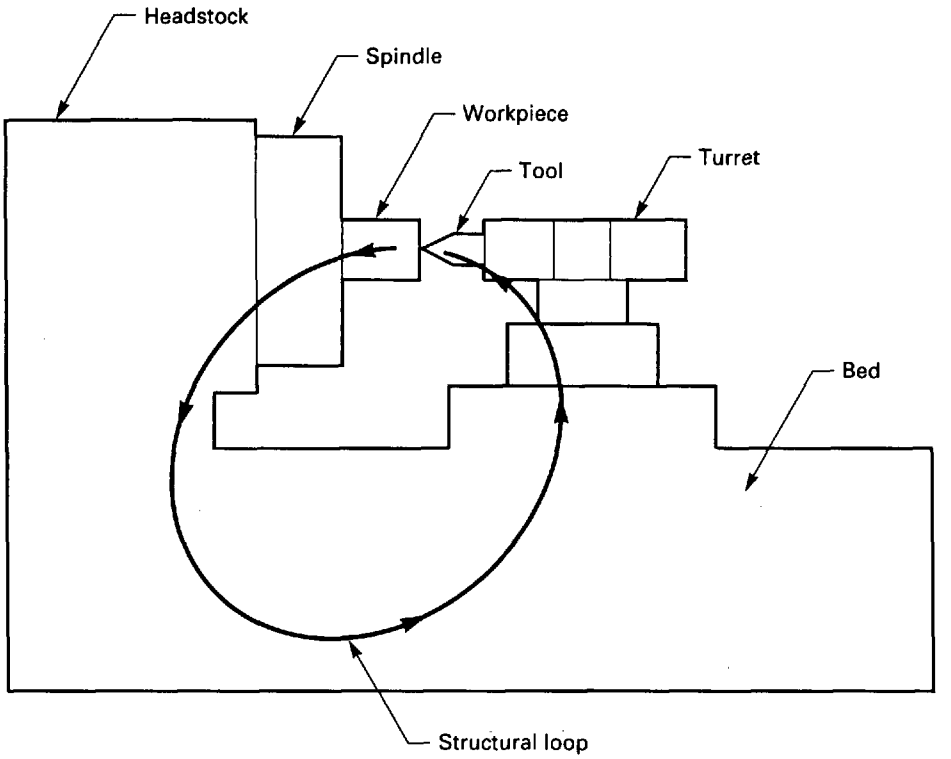


FIG. 3 AN EXAMPLE OF A STRUCTURAL LOOP SHOWING A PART, SPINDLE, MACHINE FRAME, AND TOOL

(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 conductivity: thermal conductivity is normally defined as the time rate of heat flow through unit area and unit thickness of a homogeneous material under steady conditions when a unit temperature gradient is maintained in the direction perpendicular to area. In this Standard it is designated by κ and has the units of watts/(m^2°C).

thermal error index (TEI): in some cases, particularly in factories, dimensional measurements are made at 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 which 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 which 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,

$$TEI = \left(\left[|NDE| + U_T(L)\right]/SZ\right)(100\%)$$

Here SZ is the desired specification zone (see *specification zone*) 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 the linear (or volumetric) thermal expansion of the body.

thermally induced drift: drift is defined as the differential movement of the part or the master and the comparator caused by the time variations in the thermal environment.

tilt error motions: error motion in the angular direction relative to the Z reference axis [see Fig. 1, (*e*) and (*f*)].

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tolerance: for the purposes of this Standard, 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: the 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 cause a displacement in that axis only in the direction determined by the sign of the offset value.

NOTE: For example, the tool offset are 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: a command identifying a tool.

NOTE: It may also be used to identify a tool offset.

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

NOTE: Typically used on milling and drilling machines.

tool-setting system: an instrument supplied with a CNC lathe or turning center that allows for the measurement of X and/or Z tool offsets as part of a computer-controlled cycle. Also sometimes called a tool-setter, a tool-gage, or a tool-setting probe(s).

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

tool spindle: a spindle whose purpose is to rotate a cutting tool for the purposes of removing material from a workpiece.

tow-along carriage: a 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 which 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: an 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, and so on. 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 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 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).

turning center: a computer numerically controlled lathe with at least one work-holding spindle (work spindle). Such a machine shall have a means of automatically introducing various tools to the workpiece by means of either an indexable turret or automatic tool-changer. In the most general case, such a turning center may also have "live" tooling.

type test: a machine performance test which, in the opinion of this Committee, 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. 6.2.4 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.

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$$UNDE = \sqrt{(UNE)^2 + (UNE)_s^2}$$

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

$$UNE = L(T - 20)\,u(\alpha)$$

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. 6.2.5 for further explanation.)

undulations per revolution (upr): a 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 ANSI B89.3.4M-1985 for a more detailed explanation).

uni-directional: 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 ↑ signifies a parameter derived from a measurement made after an approach in the positive direction, and ↓ one in the negative direction, e.g., $x_{ij}\uparrow$ or $x_{ij}\downarrow$.

uni-directional accuracy of positioning of an axis, $A\uparrow$ or $A\downarrow$: range derived from the combination of the uni-directional systematic deviations and the estimator of the standard uncertainty of uni-directional positioning using a coverage factor of two (2),

$$A\uparrow = \max[\bar{x}_i\uparrow + 2s_i\uparrow] - \min[\bar{x}_i\uparrow - 2s_i\uparrow]$$

and

$$A\downarrow = \max[\bar{x}_i\downarrow + 2s_i\downarrow] - \min[\bar{x}_i\downarrow - 2s_i\downarrow]$$

uni-directional 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 uni-directional repeatability of positioning.

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

$$R_i\uparrow = 4s_i\uparrow$$

and

$$R_i\downarrow = 4s_i\downarrow$$

uni-directional repeatability of positioning, $R\uparrow$ or $2R\downarrow$, of an axis: maximum value of the uni-directional repeatabilities of positioning at any position along or around an axis,

$$R\uparrow = \max[R_i\uparrow]$$

and

$$R\downarrow = \max[R_i\downarrow]$$

uni-directional systematic angular error, $E_{ae}\uparrow$ and $E_{ae}\downarrow$: the difference between the algebraic maximum and minimum of the mean uni-directional angular errors for both approach directions, at any position along a linear axis, determined using the procedures and under the conditions specified in this Standard. Computed similarly to uni-directional systematic deviation of positioning of an axis.

uni-directional systematic deviation of positioning of an axis, $E\uparrow$ or $E\downarrow$: the difference between the algebraically maximum and minimum of the mean uni-directional 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 determined using the procedure and under the conditions specified in this Standard.

$$E\uparrow = \max[\bar{x}_i\uparrow] - \min[\bar{x}_i\uparrow]$$

and

$$E\downarrow = \max[\bar{x}_i\downarrow] - \min[\bar{x}_i\downarrow]$$

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

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user: a 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, broad-band vibration amplitude is also used (see *broad-band vibration amplitude*).

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

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

work spindle: a spindle whose purpose is to rotate a workpiece in order to provide sufficient surface speed for the purposes of material removal by cutting.

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.

yaw: the 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 perpendicular to the XZ plane, 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 lathes and turning centers are provided for ease of machine specification. A position is provided in the machine specification form (Form 1) which should be used to designate the machine classification as described below. Figure 4 summarizes common machine tool configurations (spindles could also be vertical). They are further illustrated in Figs. 5 through 12. As part of this specification, the user should specify the machine sub-group as given in Fig. 4. Further, a drawing equivalent to those given in Figs. 6 through 12 shall be provided. Any of the machine configurations can have live tooling. An isometric drawing equivalent to that shown in Fig. 13 is highly desirable. If a machine does not conform to one of the described geometries, including machines with "tow-along" axes, a drawing similar in content to those shown in this classification section with axis designation and directions of positive travel shall be provided as part of the machine specification. Axis and motion nomenclature shall be consistent with ANSI/EIA RS 267 C-1990, ISO 841-1992, and ANSI/ASME B89.3.4M-1985.

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 Forms 2 and 3. The environment shall be considered acceptable if the requirements of this section and Section 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 Section 9, and support for equipment and tests, at a price to be negotiated between supplier and user.

5.2 Temperature

5.2.1 General. Temperature is a significant and often misunderstood influence on the accuracy of machining and measurement. The provisions of ANSI B89.6.2 form a part of this Standard, but interpretation is needed for application to machine tools. ANSI 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 be at exactly 20°C (68°F), is generally unobtainable. This Standard is primarily concerned with the second: that the expanded thermal uncertainty (see Section 6.2) 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 Form 3. 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

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Group	Subgroup	Z_1	Z_2	Z_3	Z_4	X_1	X_2	X_3	Y	C_1	C_2	A	(W)	No. of Control Axes
1	1-1	○				○							(○)	2(3)
	1-2	○				○								2
	1-3	○				○				○			(○)	3(4)
	1-4	○				○			○	○			(○)	4(5)
2	2-1	○	○			○	○						(○)	4(5)
	2-2	○	○			○	○			○			(○)	5(6)
	2-3	○	○			○	○		○	○			(○)	6(7)
3	3-1	○				○								2
	3-2	○	○			○								3
4	4-1	○	○			○	○							4
	4-2	○	○			○	○			○	○			6
	4-3	○	○	○		○	○			○	○			7
	4-4	○	○			○	○		○	○	○			7
	4-5	○	○	○		○	○		○	○	○			8
5	5-1	○	○	○	○	○	○	○	○	○				9
6	6-1	○	○			○	○		○	○		○	(○)	7(8)
	6-2	○	○	○		○	○	○		○	○			8

GENERAL NOTES:

(1) ○ is a controlled axis.
(2) W-axis for a programmable tailstock is optional.

FIG. 4 CLASSIFICATION OF CNC LATHES AND TURNING CENTERS

chooses not to conform to the guidelines supplied, the tests of environmental sensitivity (see Section 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.

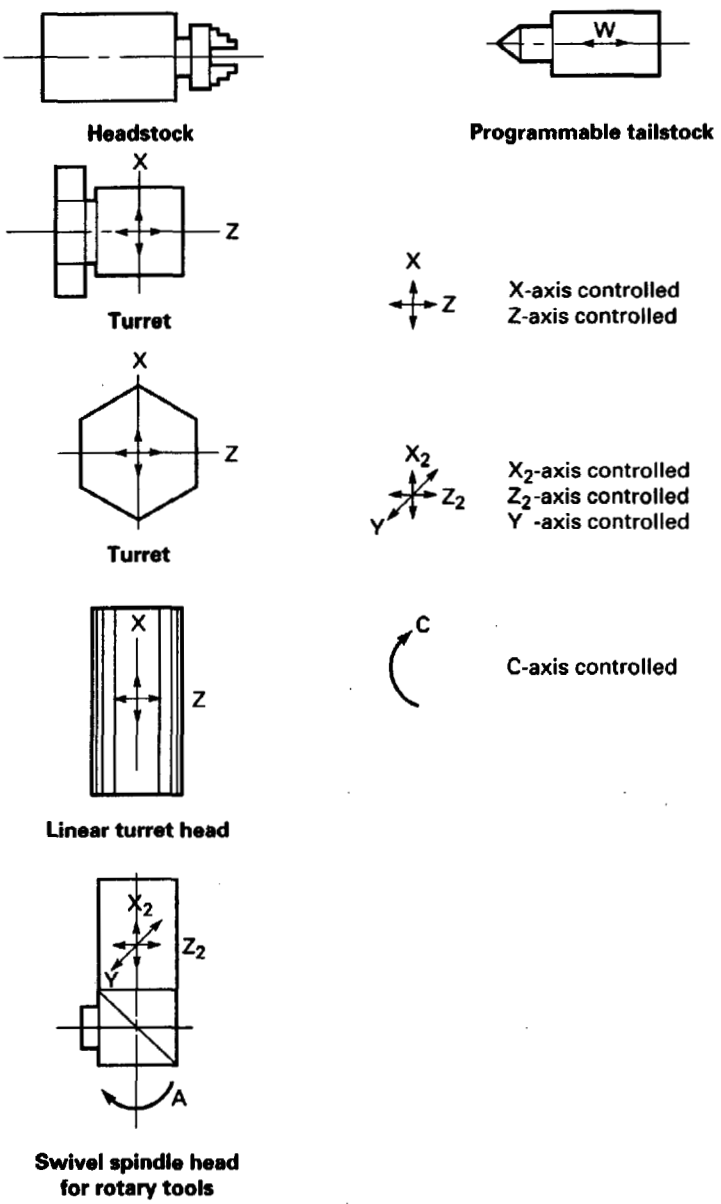
5.2.2.1 Time Variations. Particular attention should be given to time variations of temperature, although this Standard does not offer specific guidelines in this area. Machine tools are composed of numerous elements, each with different thermal behavior. For example, the ram of a machine may have a short thermal time constant and the bed of the machine 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 further time constants due to 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 (such as fluorescent lighting, radiant heaters, high-intensity lamps, etc.) shall be as far from the machine as possible, in order 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 should be warned that lights in the machine enclosure supplied by the supplier may sometimes have unwanted thermal influence.

5.3 Inertial 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

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GENERAL NOTES:
(1) No guideways are illustrated in the figures to avoid complication.
(2) Suffixes 1, 2, and 3 are primary, secondary, and third axes, respectively.
(3) Lathes with vertical main spindles are included.

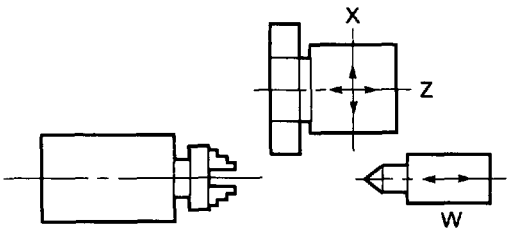
FIG. 5 SYMBOLS AND NOTES USED FOR MACHINE CONFIGURATION CLASSIFICATION

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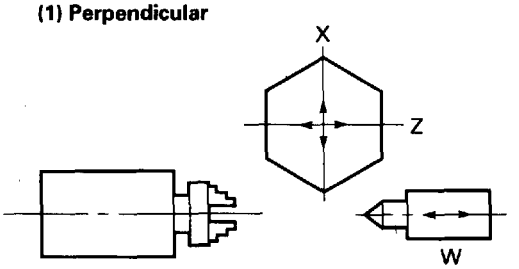
Group 1 (1 spindle and 1 turret)

Group 1-1

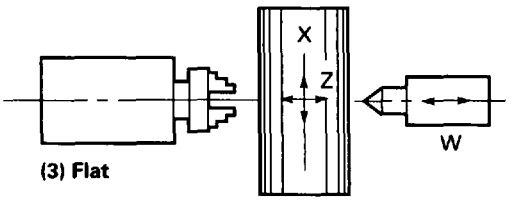
(Fixed headstock)
[Programmable tailstock (optional)]



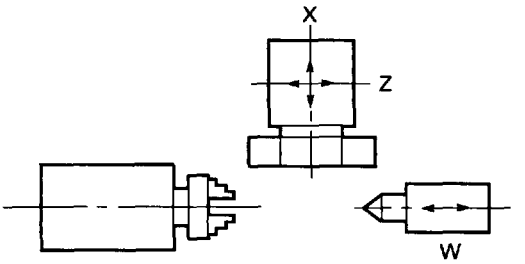
(1) Perpendicular



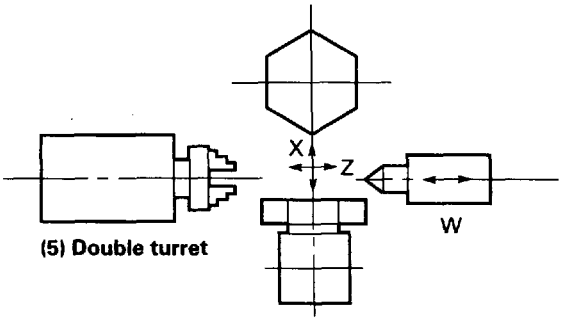
(2) Horizontal



(3) Flat



(4) Parallel



(5) Double turret

Group 1-2

Movable headstock

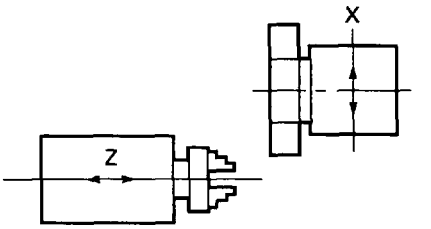
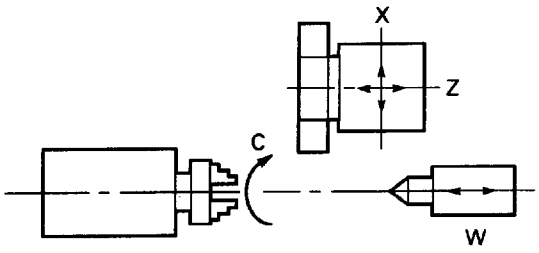


FIG. 6 GROUPS 1-1 AND 1-2: SINGLE-SPINDLE MACHINES WITH TWO PROGRAMMABLE AXES

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Group 1-3

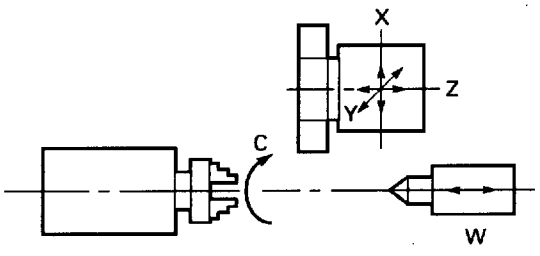
(Fixed headstock)
(C-axis controlled)
Programmable tailstock (optional)



Perpendicular

Group 1-4

(Fixed headstock)
(C-axis controlled)
(Y-axis controlled)
Programmable tailstock (optional)



Perpendicular

FIG. 7 GROUPS 1-3 AND 1-4: SINGLE-SPINDLE MACHINES WITH A PROGRAMMABLE SPINDLE AXIS AND A PROGRAMMABLE TAILSTOCK

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 relative motions between 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. Recently several major American corporations have developed extensive standards for vibration analysis on machine tools. These Standards have been conceived for 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 Section 6.3.

5.3.3 Inertial 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 specification form, Form 1, 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 highly 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 large or very heavy machines. It is expected that the number of such occurrences will be very small. 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 a strong effect on its ability to perform accurate and repeatable machining operations.

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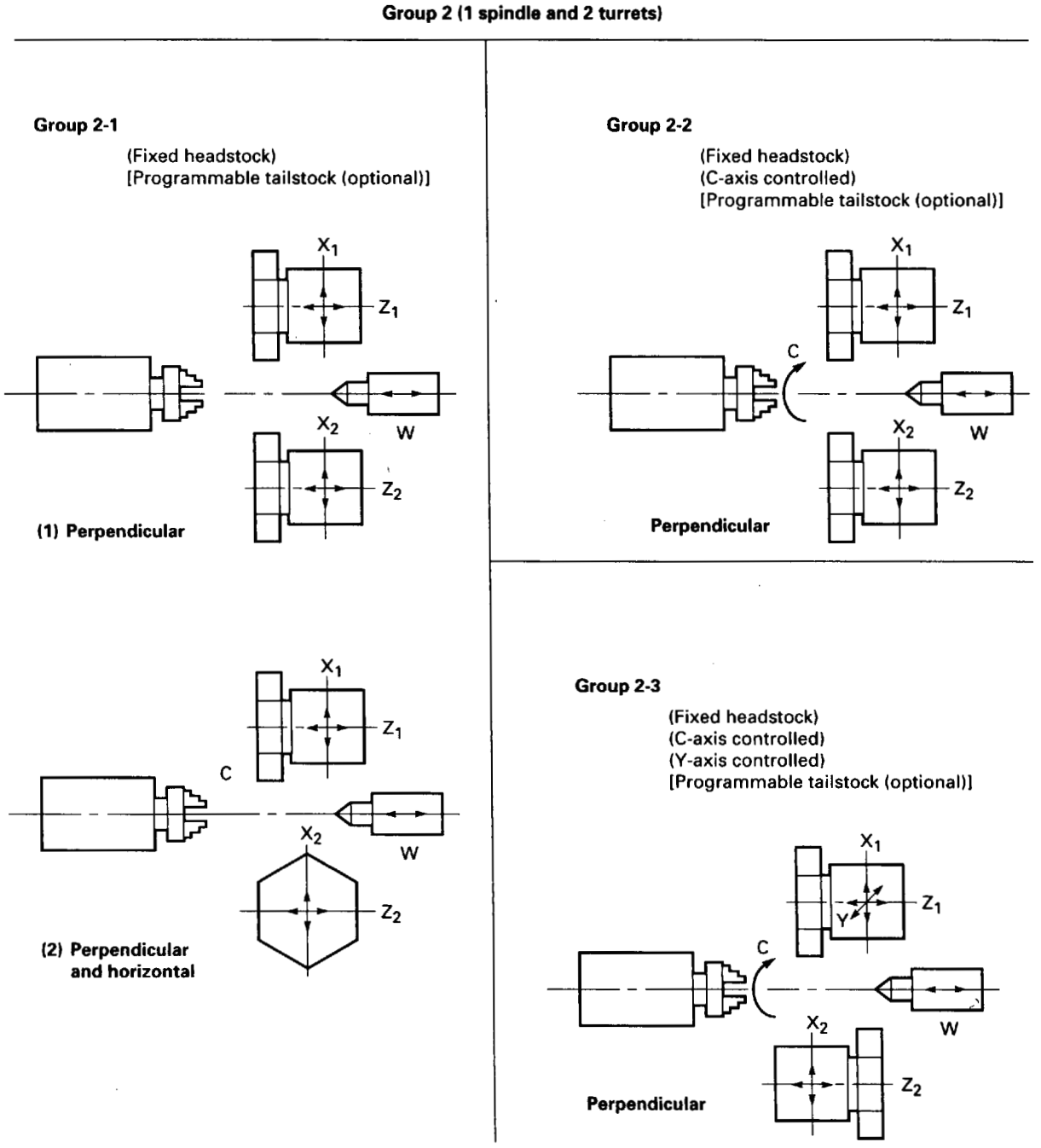


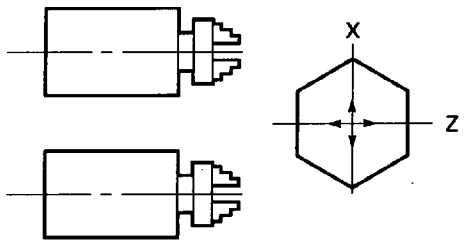
FIG. 8 GROUP 2: SINGLE-SPINDLE MACHINES WITH TWO TURRETS

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Group 3 (2 spindles and 1 turret)

Group 3-1

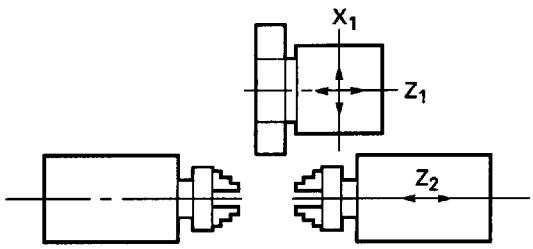
(Fixed primary and secondary headstock)



Parallel twin spindle and a horizontal turret

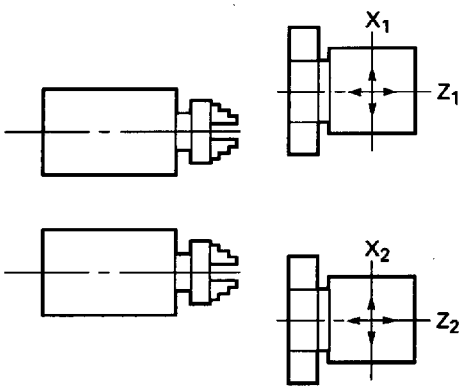
Group 3-2

(Fixed primary headstock)

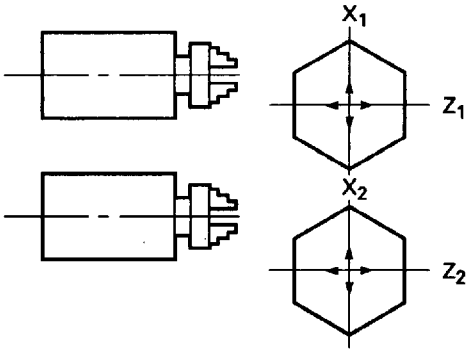


Perpendicular

Group 4 (2 spindles and 2 turrets)

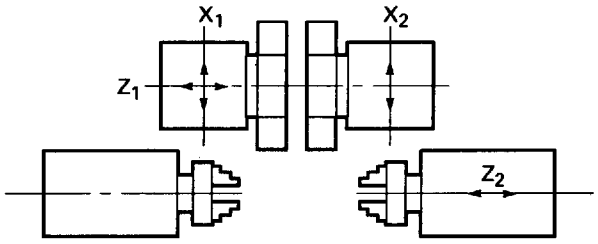


(1) Parallel twin spindle and turret

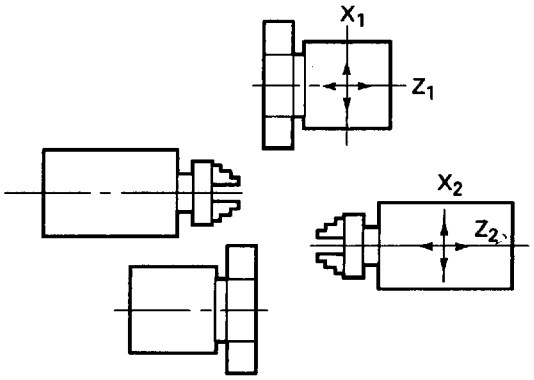


(2) Parallel twin spindle and horizontal turrets

Group 4-1
(Fixed primary headstock)



(3) Perpendicular



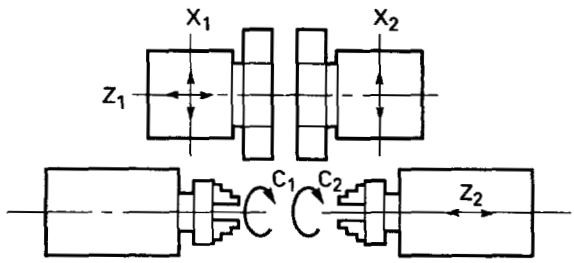
(4) Perpendicular

FIG. 9 GROUP 3: DUAL-SPINDLE MACHINES WITH ONE TURRET; AND GROUP 4: DUAL-SPINDLE MACHINES WITH TWO TURRETS

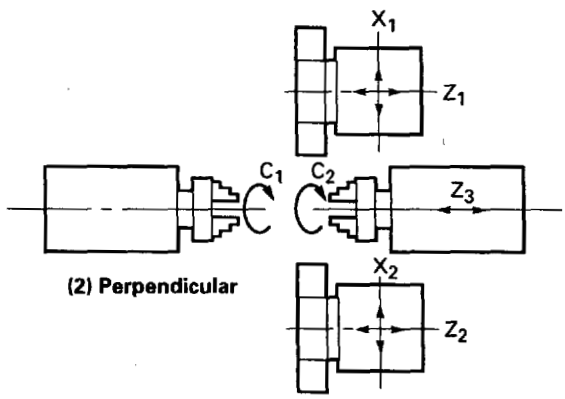
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Group 4-2

(Fixed primary headstock)
(C-axis controlled)



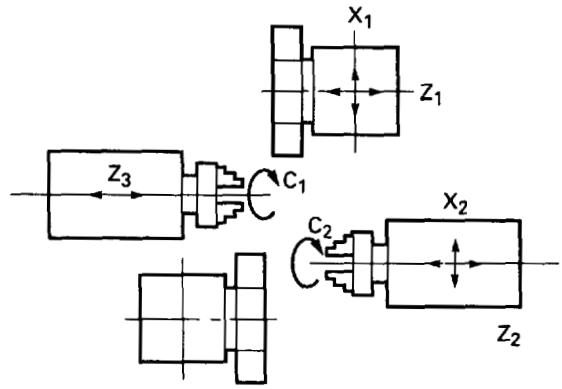
(1) Perpendicular



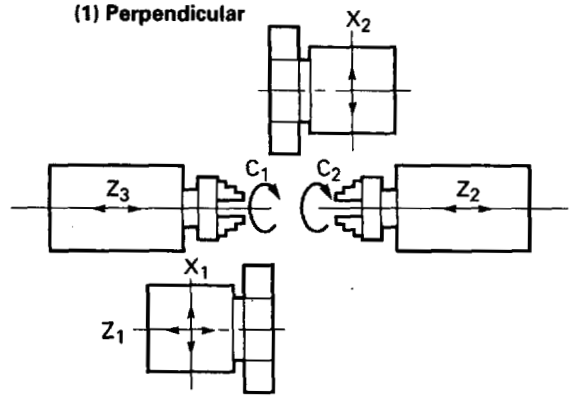
(2) Perpendicular

Group 4-3

(Movable primary headstock)
(C-axis controlled)



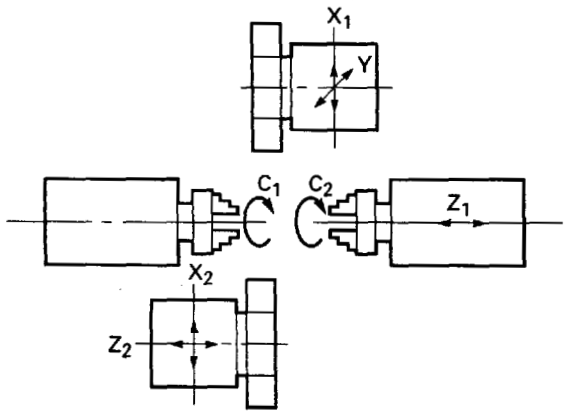
(1) Perpendicular



(2) Perpendicular

Group 4-4

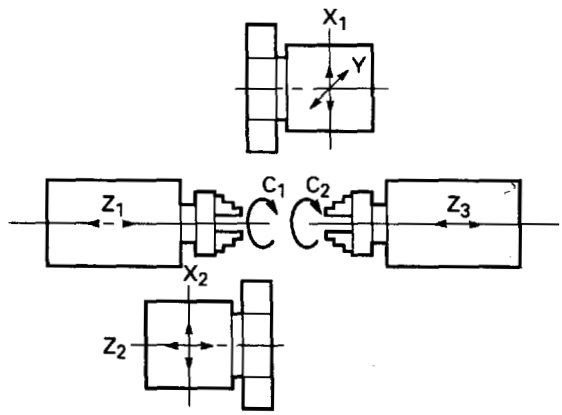
(Fixed primary headstock)
(C-axis controlled)
(Y-axis controlled)



Perpendicular

Group 4-5

(Movable primary headstock)
(C-axis controlled)
(Y-axis controlled)



Perpendicular

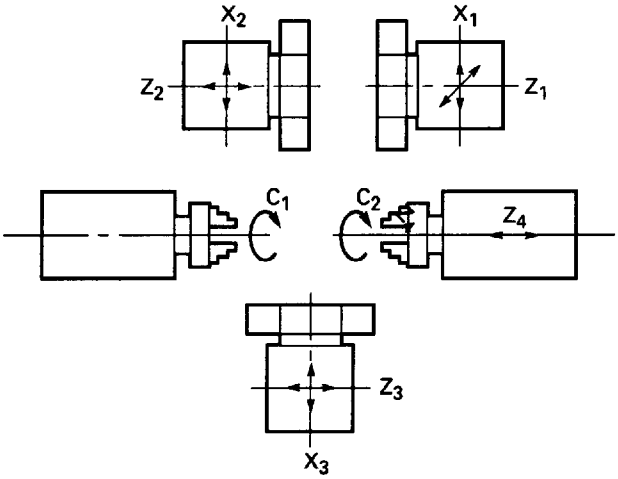
FIG. 10 GROUP 4 (CONT'D): DUAL-SPINDLE MACHINES WITH TWO TURRETS

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Group 5 (2 spindles and 3 turrets)

Group 5-1

(Fixed primary headstock)
(C-axis controlled)
(X-axis controlled)



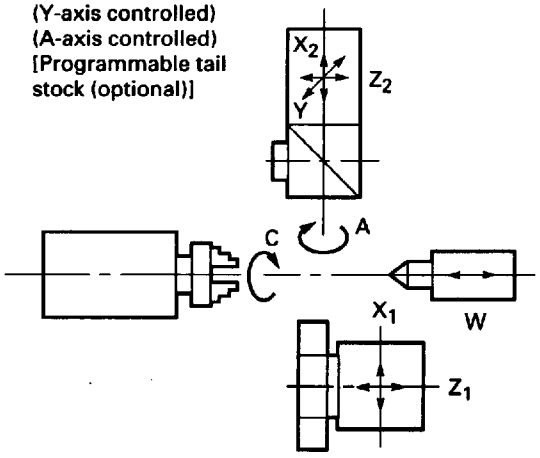
Perpendicular and parallel

FIG. 11 GROUP 5: DUAL-SPINDLE MACHINES WITH THREE TURRETS AND A CONTROLLED SPINDLE AXIS

Group 6 (1 spindle and 1 milling spindle head)

Group 6-1

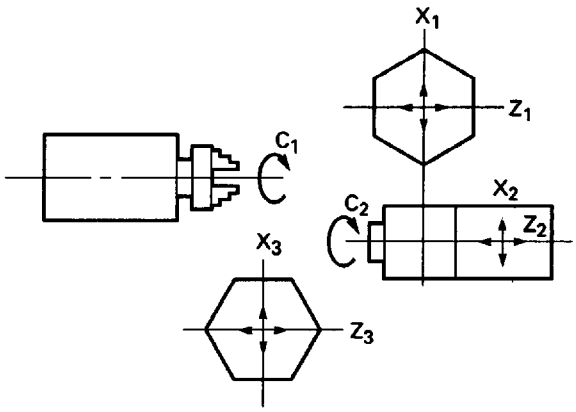
(Fixed headstock)
(C-axis controlled)
(Y-axis controlled)
(A-axis controlled)
[Programmable tail stock (optional)]



A perpendicular turret and a swivel head for rotary tools

Group 6-2

(Fixed headstock)
(C_1-axis controlled)
(C_2-axis controlled)



Two horizontal turrets and a milling head

FIG. 12 GROUP 6: MACHINES HAVING "LIVE" TOOLS FOR MILLING

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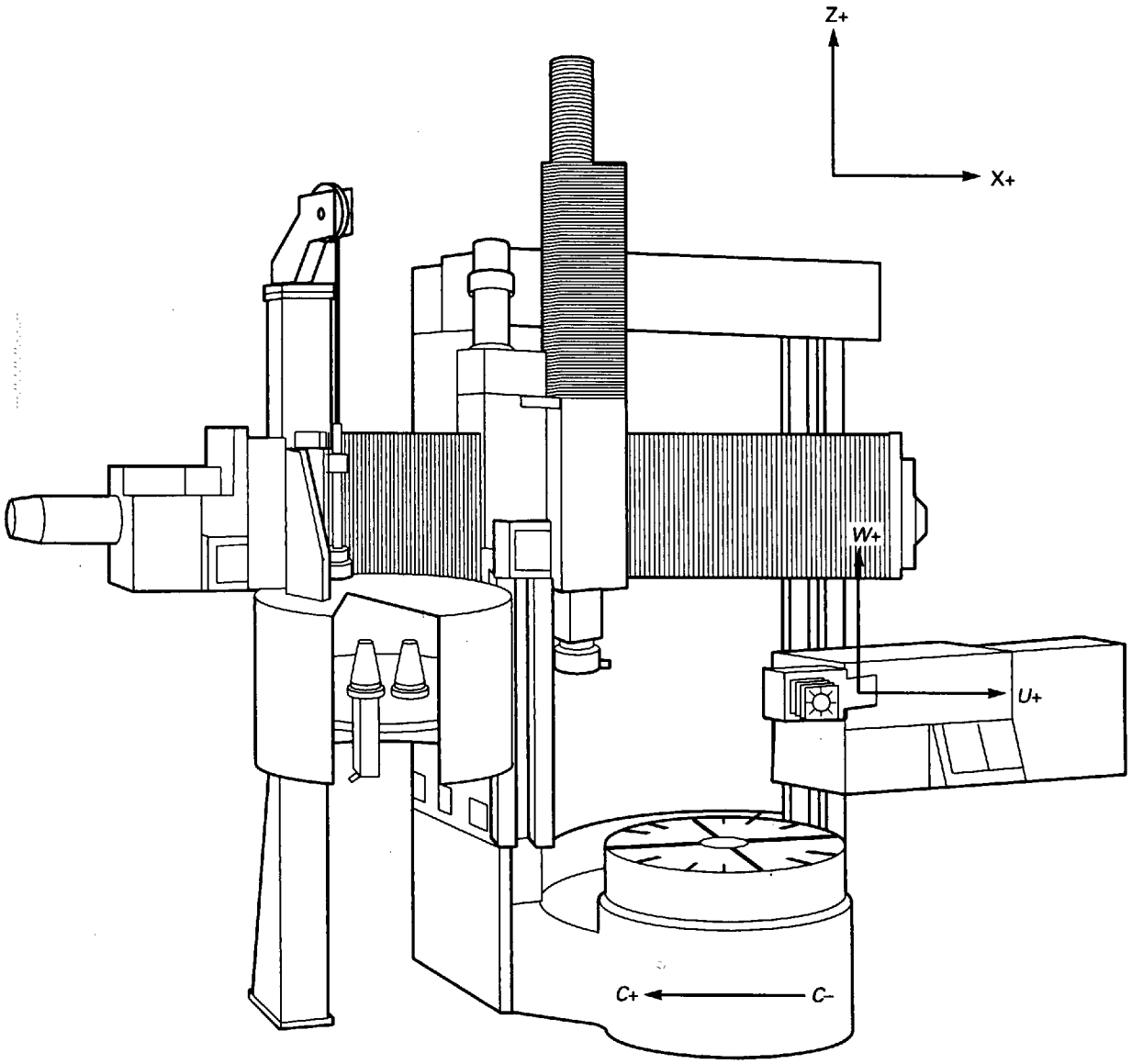


FIG. 13 AN ISOMETRIC VIEW OF A VERTICAL TURNING MACHINE

This is particularly true when a machine uses some form of computer for any control or readout function.

5.4.2 Responsibilities. It shall be the responsibility of the user to provide electrical power meeting requirements specified by the supplier.

5.4.3 Electrical Parameters. The supplier shall provide as part of the machine specification, a statement of the steady state voltage(s) requirements of the machine, allowable deviations from this voltage(s), frequency requirements, and amperage requirements. These parameters are listed in the sample specification form, Form 1.

5.5 Utility Air

5.5.1 General. Air supplies to machines can significantly degrade 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.

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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 be specified. These parameters are listed in the environmental specification form, Form 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 significantly degrade 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.

5.6.1.1 Foundations. 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 to 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.

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.

6 ENVIRONMENTAL TESTS

6.1 General

As stated previously, it is the philosophy of this Standard that the environment is the responsibility of the machine user. However, if the user follows the guidelines supplied by the machine supplier, that responsibility reverts to the machine supplier. The following tests are designed to reflect that philosophy, but if because of economic or other considerations the machine user chooses not to conform to the supplier's environmental specifications, this Standard provides a derating procedure on the machine performance. This is particularly true in the case of nonconformance of the thermal environment. In general, these environmental tests will be performed before the performance tests in order to verify the suitability of the environment for machine testing. However, for machines with large specification zones, the effects of the environment may be deemed acceptable by the supplier without the testing specified below. In these cases, specific environmental tests may be deferred. If measurements on the machine are within the specified specification zones in the performance tests, the deferred tests may be eliminated. If the performance fails, the environmental tests may be performed as part of the diagnostic process. The thermal computations, para. 6.2.2, may not be deferred or eliminated.

6.2 Environmental Thermal Test and Computations

The thermal test shall be performed under conditions equivalent to those pertaining during machine performance tests (Section 7).

6.2.1 Environmental Temperature Variation Error (ETVE). Environmental temperature variation error (ETVE) shall be determined by a drift test using the following procedure. If the supplier elects to defer the ETVE test, the value of ETVE shall be set to zero for the thermal computations (para. 6.2.2). If the ETVE test is performed later, then the measured value shall be used. It should be noted that on some specialized

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machines, such as diamond turning machines, variations in the mean value of the supplied air pressure can cause changes in machine squareness and positional drifts, which can be misinterpreted as ETVE. During this test, care should be taken to ensure proper air pressure regulation on machines of this type.

6.2.1.1 ETVE Test, Two Sensors. This test is designed to measure the response of a machine to its ambient environment, and not the response of a machine to its internal heat sources. (This test shall therefore be run with the machine in a start-up, cold, condition, unless some other quiescent state is specified by the supplier such as on oil shower machines. Further tests to determine the effects of machine-induced thermal behavior are described in Section 7.6 of this Standard.) Immediately prior to initiating this test, the machine shall be parked in a position as far as mechanically possible from the position selected by the machine supplier for the ETVE test for a period equal to the duration of time of the ETVE test (if the supplier does not specifically choose an ETVE test location, the location shall be at a distance of less than 100 mm in Z and X from the chuck face and center line, respectively). When the machine is parked the electrical power to the machine should be left on and the drives put in the feed-hold condition. A test artifact, such as an appropriate fixture with a sphere, or a mandrel, shall be mounted in the main machine spindle at the location specified for the ETVE test and appropriate displacement indicators set up measuring against the artifact with the displacement indicators attached to the position where the machine cutting tool would normally be fixtured. For the purposes of this test an appropriate displacement indicator would be a capacitance gage, an inductance gage, an LVDT, or other gage that meets the sensitivity and stability requirements of Section 9 (for example, on machines of low-accuracy, a dial displacement indicator (dial gage) may be considered as a proportional probe). This setup is illustrated in Fig. 14, where two probes are shown. After the period of parking the machine is complete, the machine shall be moved to the ETVE position, returned to the "feed-hold" condition, and measurement of changes of the test artifact position shall be made for each of the machine axes using the fixtured displacement indicators. The test shall be conducted for a time period at least as long as the longest performance test specified in later sections, and normal activities shall be continued around the machine during the total test period. While measuring the ETVE, the mean ambient temperature and the temperature of the spindle nose should also be monitored using thermometers that meet the requirements of Section 9.[15] The test period shall be divided into intervals of approximately one minute. The mean value[16] of readings from the radial gage and the axial gage during each one-minute sampling interval shall be determined throughout the test period. The range of variation of readings for each gage shall be the ETVE for that axis. The standard uncertainty due to the environmental temperature variation error is given by

$$u_{ETVE} = \sqrt{\frac{ETVE^2}{12}}$$

Data shall be analyzed as in Fig. 15. The ETVE used in the equation above shall be the largest of the ETVEs measured by either of the two gages for any spindle/turret combination and any axis direction on the machine. The choice of probe for this test is strongly dependent upon the machine thermal environment. For example, some machines use oil showers. In this case, noncontact inductance probes or LVDTs, meeting the requirements of Section 9, are preferred.[17] It is also possible, using such gages, to do this test with the machine coolant on. (Here the coolant used for cutting purposes is meant and not external oil used for machine thermal control.) Although the test with coolant on is not a requirement of this Standard, it can provide significant information regarding the effects of the machine coolant system on the machine performance.

6.2.1.2 ETVE Test, Five Sensors (Optional). It is also possible to measure the ETVE using a setup which has five sensors reading against an appropriate test artifact. This test is appropriate for rotating sensitive direction tool spindles and also can be useful for observing angular tilts of a work spindle. Such five-sensor systems are also used in this Standard for the measurement of spindle errors. A setup showing five sensors on the lathe is given in Fig. 16. Again, the sensors that indicate in the radial directions should be at least 100 mm (approx. 4 in.) apart in the axial direction. In this case, the procedure and analysis for the ETVE test, as described in para. 6.2.1.1, should be followed except that the largest value of the ETVEs

[15] The thermometer readings are not used in the thermal computations of para. 6.2.2. However, they provide valuable information that can be used for diagnostic purposes in cases where the ETVEs are unsatisfactory (see Appendices B and K).

[16] For this test the mean value shall be determined from at least three readings equally spaced in time during the one-minute interval.

[17] Capacitance gages can give erratic results when used on machines with oil showers.

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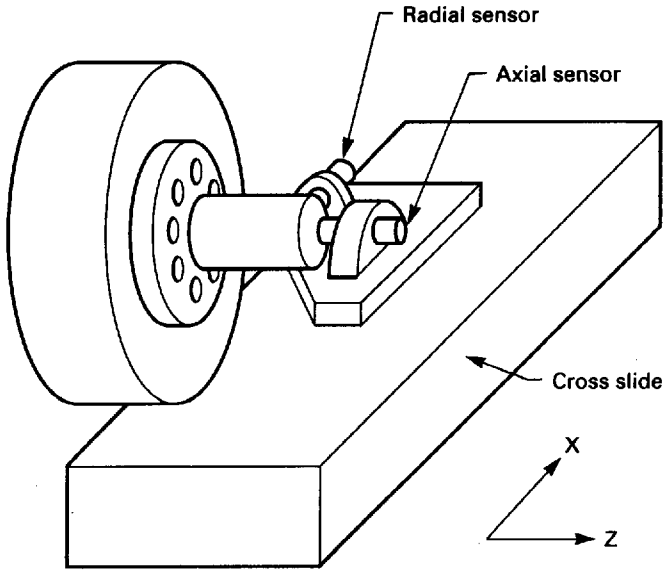


FIG. 14 SETUP SHOWING TWO PROBES TO MEASURE THE ENVIRONMENTAL TEMPERATURE VARIATION ERROR (ETVE) BETWEEN A NOMINAL TOOL LOCATION AND A WORK SPINDLE

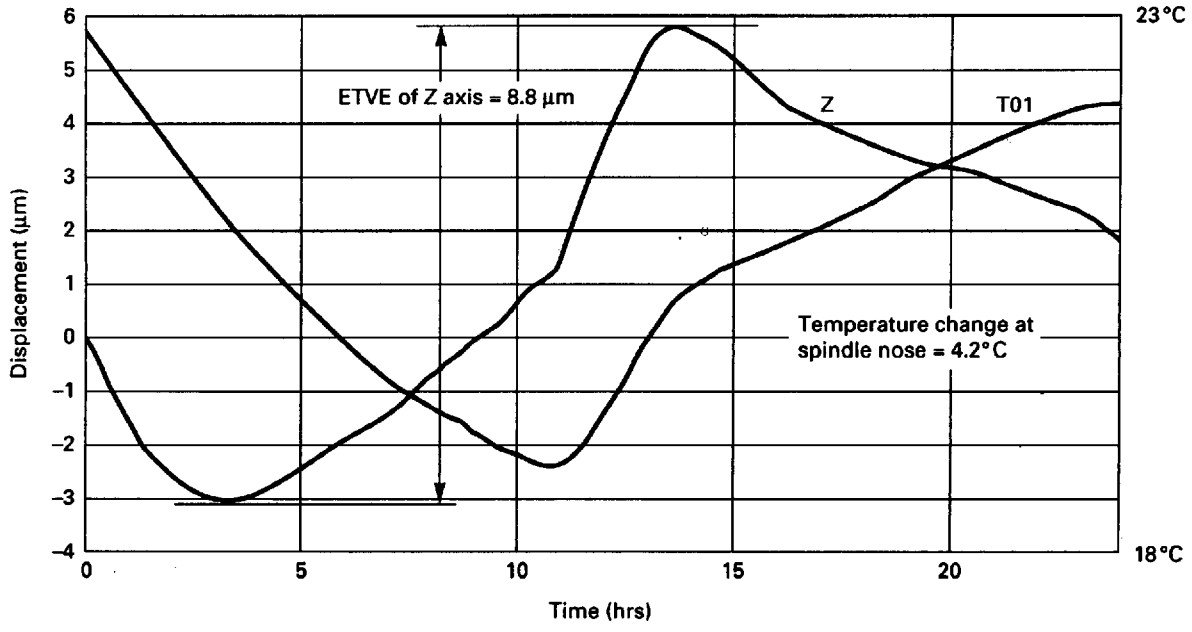


FIG. 15 GRAPH OF ENVIRONMENTAL TEMPERATURE VARIATION ERROR (ETVE) DATA. THE ETVE IS CLEARLY LABELED.

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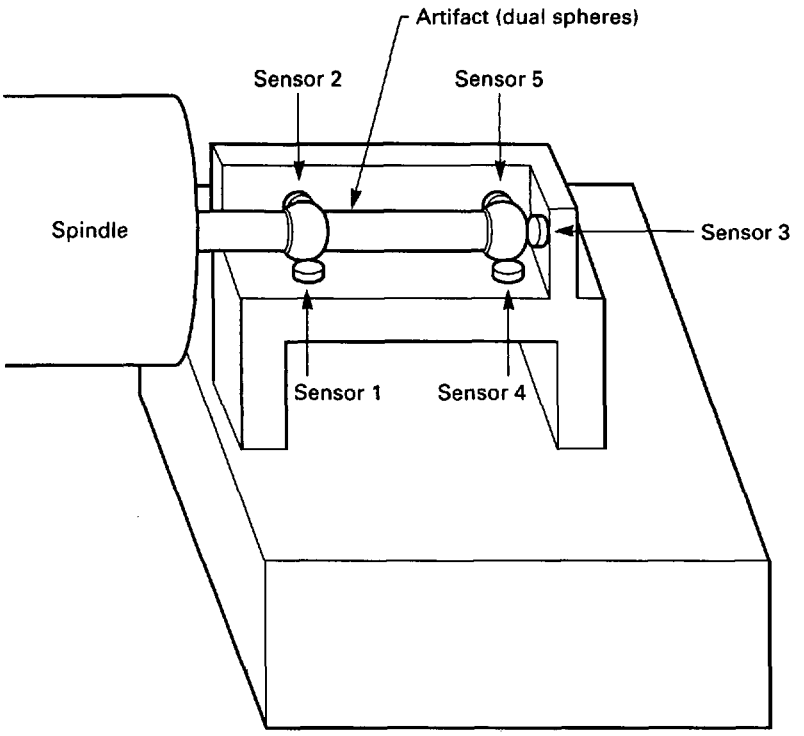


FIG. 16 SETUP SHOWING FIVE PROBES USED TO MEASURE ENVIRONMENTAL TEMPERATURE VARIATION ERROR (ETVE)

measured by any of the five gages for any spindle-turret combination and any axis direction shall be used for the ETVE in the thermal computations outlined in para. 6.2.2 through para. 6.2.5. While measuring the ETVE, the mean ambient temperature and the temperature of the spindle nose should also be monitored using thermometers that meet the requirements of Section 9.[18]

6.2.2 Thermal Computations. It is the requirement of this Standard that on all tests which measure machine accuracy, corrections shall be applied for the nominal differential expansion of machine scales, mechanical masters, and, if applicable, changes in the wavelength of the laser interferometer. These computations are described in the sections on the specific tests. Besides these corrections, it is a requirement of this Standard that the user also compute the expanded thermal uncertainty (with the ETVE equal to zero, if that test has been deferred). This expanded uncertainty shall be used to determine the suitability of the test environment. The test environment shall be considered acceptable if the expanded thermal uncertainty, as defined below, does not exceed 25% of the specification zone for any of the performance tests listed in Table 1. If the expanded thermal uncertainty exceeds 25% of the specification zone for a particular test in the table, 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 automatically increased by an amount such that the expanded thermal uncertainty is 25% of the new specification zone for the specified test. If the expanded thermal uncertainty exceeds 25% and the machine environment conforms to the supplier's guidelines, no derating of the permissible specification zones for the tests given in Table 1 is allowed. Methods for testing compliance of the thermal environment to the supplier's guidelines are given in Appendix B. The expanded thermal uncertainty shall be calculated for each performance test from the equation

$$\pm U_T(L) = \pm k u_{cT} = \pm 2u_{cT}(L)$$

where u_{cT} is the combined standard thermal uncertainty for a given measurement (see para. 6.2.3) and k is the coverage factor (which, for this computation, will be

[18] The thermometer readings are not used in the thermal computations of para. 6.2.2. However, they provide valuable information that can be used for diagnostic purposes in cases where the ETVEs are unsatisfactory (see Appendices B and K).

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TABLE 1 SPECIFICATION ZONES DERATED DUE TO AN EXCESSIVE EXPANDED THERMAL UNCERTAINTY (SEE APPENDIX K)

Parameter	Lengths Used for Uncertainty Calculation	Sec. No.
Linear Positioning (per axis)		7.2
Bi-directional Systematic Deviation of Positioning	$L = L_S$ = axis length	7.2.7.1
Bi-directional Accuracy of Positioning	$L = L_S$ = axis length	7.2.7.3
Uni-directional Systematic Deviations of Position	$L = L_S$ = axis length	7.2.7.2
Uni-directional Accuracies of Positioning	$L = L_S$ = axis length	7.2.7.4
Thermal Tests		7.6
Spindle Thermal Stability Test	$L = L_S = 0$	7.6.2
Thermal Distortion, Moving Linear Axes	$L = L_S$ = axis length	7.6.3
Composite Thermal Error	$L = L_S$ = ½ longest axis length	7.6.4
Circular Tests		7.8
Circular Deviations	ball bar length or circular contour radius	7.8.5
Tool-setting System Drift	$L = L_S = 0$	8.4
Linear Measurement Accuracy	$L = L_S$ = axis length	8.6.4

assumed to be 2). Values in the equation are absolute values and should be taken as positive.

6.2.3 Combined Standard Thermal Uncertainty (u_{cT}). The combined standard thermal uncertainty is defined in the glossary for the general case of a length measurement. For this Standard it requires interpretation. The general form is given by

$$u_{cT}(L) = [u_{ETVE}^2 + L_s^2 (T_s - 20)^2 u^2(\alpha_s) + L^2 (T - 20)^2 u^2(\alpha) + L_s^2 \alpha_s^2 u^2(T_s) + L_s^2 \alpha^2 u^2(T)]^{1/2}$$

where

u_{ETVE} = the standard uncertainty due to the environmental temperature variation error

L = the length being measured (usually, in machine tool applications, this is nominally the same as the length of the standard)

L_s = the length of the standard (calibrated gage or laser displacement)

$u(\alpha_s)$ = the uncertainty of the nominal coefficient of expansion of the master ($u(\alpha)$ = 0 for laser interferometers)

α_s = the thermal expansion coefficient of the standard ($\alpha_s = 0.93 \times 10^{-6}$/°C for lasers)

$u(T_s)$ = the uncertainty in the measurement of the temperature of the standard (air temperature in the case of the laser)

α = the thermal expansion coefficient of the machine scale

$u(T)$ = the uncertainty in the measurement of the temperature of the machine scale

T = temperature of machine scales, °C

T_s = temperature of the standard, °C

Note that in this Standard this equation is used in two forms. The simplest is that where a comparison is made between the length scales of the machine (ball screws, line scales, inductive scales, etc.) and the length of a calibrated ball bar or the diameter of a calibrated disk in the circular test. In that case the terms with the s subscripts refer to properties of the calibrated artifact and the un-subscripted terms refer to the properties of the machine scales. In the second case, that of comparison of the machine scales to a laser interferometer standard, the terms with the subscripts s refer to the laser, with T_s being the air temperature close to the laser beam path.

6.2.4 Uncertainty of Coefficients of Expansion [$u(\alpha)$]. 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. For example,

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

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

(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 then becomes

$$u(\alpha) = 0.1\,\alpha/\sqrt{3};\ u(\alpha_s) = 0.1\,\alpha_s/\sqrt{3}$$

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

Because the effects of inaccuracy of the estimate of the uncertainty are of second order, it is considered sufficient that good judgment be used. Clearly the concept of thermal expansion coefficient of the standard does not directly apply to lasers. However, the wavelength of a laser is dependent upon the refractive index of air, and that refractive index is a function of temperature as is the length of a material body. It can be shown that without loss of generality the coefficient used to correct laser readings or changes in ambient temperature (0.93×10^{-6}/°C) can be used in the place of the coefficient of expansion when using lasers. To the level of accuracy currently required for machine tool calibrations, it is assumed that the uncertainty in this value is equal to zero.

6.2.5 Uncertainty of Temperature Measurement. When the temperature of a body is measured and there is an uncertainty associated with this measurement, this uncertainty comes from the calibration of the thermometer, thermometer mounting procedures, and instrumental variations. This uncertainty can be estimated by various methods. For example,

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

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

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

where a^+ and a^- are the upper and lower ranges of the rectangular distribution, respectively. Note that when estimating the uncertainty in temperature measurement when using a laser as a standard, the uncertainty is in the measurement of air temperature. For the purposes of this Standard it can be obtained from any of the three options above. If option (c) is chosen, the estimated ranges of temperature uncertainties are the same.

6.2.6 Other Temperature Effects. 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 simple tests for these effects. It is therefore the recommendation in this Standard that if a machine is to be accepted at a mean temperature which is significantly different from that used during alignment and calibration, the positioning accuracy and repeatability, and the circular performance tests described in Section 7.8 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 with given specification zones. 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

The relative vibration tests shall be performed under conditions equivalent to those pertaining during the performance tests (Section 7). The test environment

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shall be considered acceptable if the vibration amplitude measured between the main spindle and the tool post is less than 25% of the machine specification zone for bi-directional repeatability for the appropriate axis. For the purposes of this Standard, this amplitude is to be assessed by the following simple functional tests. Care should be taken that such tests include both the steady state vibrations and any transients that might occur during normal use. In principle, such tests shall last for a complete daily cycle; however, for the sake of practicality, the minimum duration recommended is 10 minutes. These tests are specified with the full knowledge that they do not constitute a well-defined measurement of the forced vibration amplitude, but rather some complicated function which 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 the purposes of determining conformance to the supplier's specifications. Should the vibration amplitude as measured in this test exceed the requirements and the cause of the vibration be traced to sources that are the user's responsibility, and if the user does not desire to upgrade the machine interface, then the machine specification shall be derated, as specified in para. 6.3.1.

It should be emphasized that these vibration tests do not assess the classical dynamic performance of the machine tool when subjected to cutting conditions which lead to regenerative chatter.

6.3.1 Methodology for Functional Relative Vibration Tests. As with the ETVE test (para. 6.2.1), this test may be conducted a single axis at a time or for all axes simultaneously. In either event, a high-resolution, high-bandwidth, displacement indicator, conforming to the requirements of Section 9, shall be attached to the tool post of the machine and set to read against a test ball or other artifact mounted in the main spindle. (This test can also be performed in reverse with the displacement indicator in the spindle and the artifact in the tool post position.) The artifact used for the ETVE test is the recommended fixture since this test will be performed at the same time (see Fig. 14). In the absence of other guidance, the position used for the ETVE test shall be the default position for this functional vibration test. In the event that only two displacement indicators are used, they shall be aligned so that the direction of each displacement indicator is along a machine axis. The maximum spread of the displacement indicator(s) reading over a period of not longer than five seconds will be judged to be the machine vibration amplitude for that axis. The displacement indicators shall be read as rapidly as possible and therefore high-bandwidth capacitance gages, as described in Section 9, are most desirable. In the event that a single displacement indicator is used, the direction of displacement indication shall be aligned with each machine axis in succession and a similar analysis performed on the data. The purpose of this test is to assess vibration caused by the environment, and not vibration caused by the machine. The test is therefore carried out with the machine turned off; that is, the main machine power off. In some cases, high-precision machines are supplied with vibration isolation (pneumatic isolators, for example). In these cases, the isolation system shall be turned on or a separate agreement shall be made between supplier and user. In the case where the relative vibration amplitude, measured with the machine off, exceeds 25% of the specification zone of the machine for a particular test, the machine vibration environment does not conform to the supplier's guidelines, and the user chooses not to upgrade the environment, permissible specification zone limits for specific tests in this Standard, given in Table 2, shall be automatically increased such that the measured vibration amplitude is 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).

6.4 Electrical Tests

Well-defined procedures and highly-developed instruments exist which enable the measurement of the parameters characterizing the electrical power supplied to a machine. It is, however, the position in this Standard that such tests, in the general case, are not required and should be undertaken only in the event that the machines does not meet performance specifications and there is reason to suspect the electrical power. Failures due to electrical power usually show up 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 placed to the proper grounding of the machine in accordance with the supplier's guidelines, as this is one of the most common causes of improper electrical performance.

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TABLE 2 PERFORMANCE PARAMETERS DERATED DUE TO EXCESSIVE ENVIRONMENTAL VIBRATION

Parameter	Sec. No.
Linear Positioning (per axis)	7.2
Uni-directional Accuracies of Positioning	7.2.7.4
Bi-directional Accuracy of Positioning	7.2.7.3
Bi-directional Repeatability	7.2.7.5
Uni-directional Repeatabilities	7.2.7.6
Spindle Axis of Rotation (per spindle)	7.5
Asynchronous Radial Error Motion	7.5.3.1
Asynchronous Axial Error Motion	7.5.3.2
Circular Tests	7.8
Radial Deviations	7.8.5
Subsystems Repeatability	8.3
Tool Change Repeatability	8.3.1
Turret Repeatability	8.3.2
Repeatability, Location, and Drift of Tool-setting System(s)	8.4
Repeatability of Tool-setting System	8.4.1
Machine Performance as a Measuring Tool	8.6
Measurement Repeatability	8.6.1
Linear Measurement Accuracy	8.6.4

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 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.

7 MACHINE PERFORMANCE

7.1 General[19]

The supplier shall be responsible for providing a machine which meets all performance specifications agreed upon between the supplier and the user when installed according to the supplier's recommendations in any environment meeting the requirements of Section 5 with, if required, derating of the acceptable specification zones as described in Section 6. Note that the specification zone for any given test is the value given in Form 4 or Form 5. A machine meeting performance specifications and other conditions agreed upon between the supplier and user shall be accepted by the user.

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

[19] Users of this Standard should be aware that some test results will be reported with ±2 standard uncertainties as the confidence interval. This deviates from previous American practice of reporting ±3 standard uncertainties as the confidence interval.

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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 Section 4) 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 1 (see para. 6.2.2). The machine and, if relevant, the measuring instrument or artifact standard shall have been in the test environment long enough (preferably over night) to have reached a thermally-stable condition before testing. They shall be protected from drafts and external radiation such as sun light, 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 ANSI/ASME B89.6.2-1973 (R1993).]

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 alignment, and supplier functional checks shall be completed before starting performance testing. A minimal set of functional checks is given in Appendix E. All performance tests in Section 7 of this Standard, except the cutting performance test, shall be carried out with the machine in an unloaded condition, i.e., without a workpiece.

7.1.1.4 Compensation Systems. Some machines are now equipped with computer-controlled compensation systems for geometric and/or thermal errors. If the machine is so equipped, the following 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 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. In some cases users will be applying this Standard to machines that have been installed for some time. Before performing any measurements, it is advisable to re-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. If the machine is not correctly aligned and supported, poor performance test results are very likely. For a further discussion of these issues, see Appendix F.

7.1.3 Chucks and Other Part-Holding Devices. Several of the performance tests described in this Standard require using a chuck or other part-holding device to attach instrumentation to the machine. Unless otherwise agreed upon between supplier and user, the part-holding device to be used for these tests shall be that which is supplied with the machine and to be used during normal machine operation. If the machine has been supplied without such a part-holding device, then a part-holding device specified by the supplier shall be used for the purposes of performance testing.

7.1.4 Setup Hysteresis

7.1.4.1 General. Before beginning performance testing, it is essential to perform a hysteresis test on both a machine and any test setup in order to prevent wasted time and work. Excessive hysteresis is normally revealed as lack of repeatability in later testing. The test described in this section is for testing the hysteresis of any test setup, not the hysteresis of the machine. The machine hysteresis is measured, in this Standard, as part of the optional compliance and hysteresis check in Appendix G.

7.1.4.2 Setup Hysteresis Tests. Setup hysteresis should be measured on any test setup used for determining machine performance. All test setups normally involve two fixtures, one which establishes the datum point and the second which holds some type of displacement indicator which reads against the datum point or surface. The datum point could be the artifact, as in the ETVE test, or the retroreflector, as in the positioning accuracy and repeatability test. The displacement indicator could be a capacitance gage, an eddy current probe, a laser interferometer, an LVDT, or even a dial indicator (see Section 9). Setup hysteresis is measured by applying a suitable force on the fixture

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which holds the displacement indicator and on the fixture which holds the reference datum. This force is applied in the direction of the planned performance measurement. First this force is applied to the fixture holding the datum reference. After the force is applied, gradually decrease this force to zero. Read the displacement indicator. Next, apply the force to the fixture holding the displacement indicator and decrease this force gradually to zero. Read the displacement indicator. The sum of the differences in displacement indicator readings is the hysteresis of the test setup. (If the force is large, some machine hysteresis might be measured. Therefore, for these tests, forces of less than 40 N (approximately 10 lbs) or forces which caused full-scale indication on the displacement indicator, whichever comes first, are recommended.) If significant hysteresis[20] is measured, and this hysteresis is not altered by increasing the stiffness of the test setup or by altering its design, further testing shall be discontinued until this condition is corrected as the machine might be the cause. "A suitable force" is difficult to specify for a setup hysteresis test. The range of forces can range from between 20 N (approximately 5 lbs) and 220 N (approximately 50 lbs), depending upon the test setup and the resolution of the displacement indicator. It is clear that the forces applied should not threaten damage to the machine or the metrology setups. No attempt is made to measure these forces. They are applied by hand using judgment. The magnitude of the force may affect the result, but this is not usually so. The goal is to discover significant hysteresis which comes from loose bolts in test setups, insufficient structural strength in the brackets, etc., as soon as possible, before data are taken.

7.2 Positioning Accuracy and Repeatability, Linear Axes

7.2.1 General. The tests described in this section of this Standard are meant to represent a minimum requirement to ensure conformance to accuracy and repeatability specifications.[21] They are not comprehensive. These tests require the use of a laser interferometer conforming to the requirements of Section 9.

WARNING: These tests should not be performed until after the thermal test outlined in Section 6.2 as, if the thermal environment is inadequate, these tests will yield incorrect results and will have to be redone.

7.2.2 Lines of Measurement. The default line of measurement for laser interferometer tests shall be in the work zone parallel to each of the machine linear axis directions. For a simple Group 1 turning machine, the cross slide (X) should be measured close to the work spindle face, and the Z axis should be measured along the work spindle center line. Other options may be specified according to machine group, usage, and configuration. If so, such lines shall be made part of the original machine specification and described in equivalent detail. **Note that this Standard requires the measurement of angular error for each linear axis (see Section 7.3). For efficiency, these measurements can be made at the same time and in essentially the same locations as the positioning accuracy and repeatability, linear axes.**

7.2.3 Alignment. The laser interferometer shall be aligned as recommended by the laser interferometer supplier. Alignment should be such that cosine error is less than 1 percent of the specification zone of the axis under test. A typical laser setup for testing a cross slide is shown in Fig. 17. In the figure the interferometer is shown mounted in the spindle; however, on some machines the spindle can not be locked and thus the setup as shown would lead to instabilities. On machines where the spindle can not be locked a bracket should be made to position the interferometer (or retroreflector) near the point where a part would be, with the bracket attached to the spindle housing. **This is very important. An easy check is to set up the interferometer, lock the spindle, and try to rotate the spindle by hand, observing the interferometer readout. No change greater than one-tenth of the specification zone required for the test should be observable.**

7.2.4 Compensation for Environmental Conditions. This test requires that the interferometer be corrected for air temperature, air pressure, and air humidity and the machine scale be corrected for thermal expansion. The environmental compensation unit supplied with the laser interferometer must be used for this purpose. Further, the part temperature sensor must be placed in a position where the temperature corresponds, as closely as possible, to the temperature of the scale. The correct effective coefficient of expansion of the machine scales shall be used (see Form 2), and the instrument manufacturer's instructions for the compensation shall be followed. This Standard requires that the nominal differential expansion (NDE) correction

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

[21] Note that repeatabilities in this Standard are reported as ±2 standard uncertainties, not the more conventional ±3 standard uncertainties.

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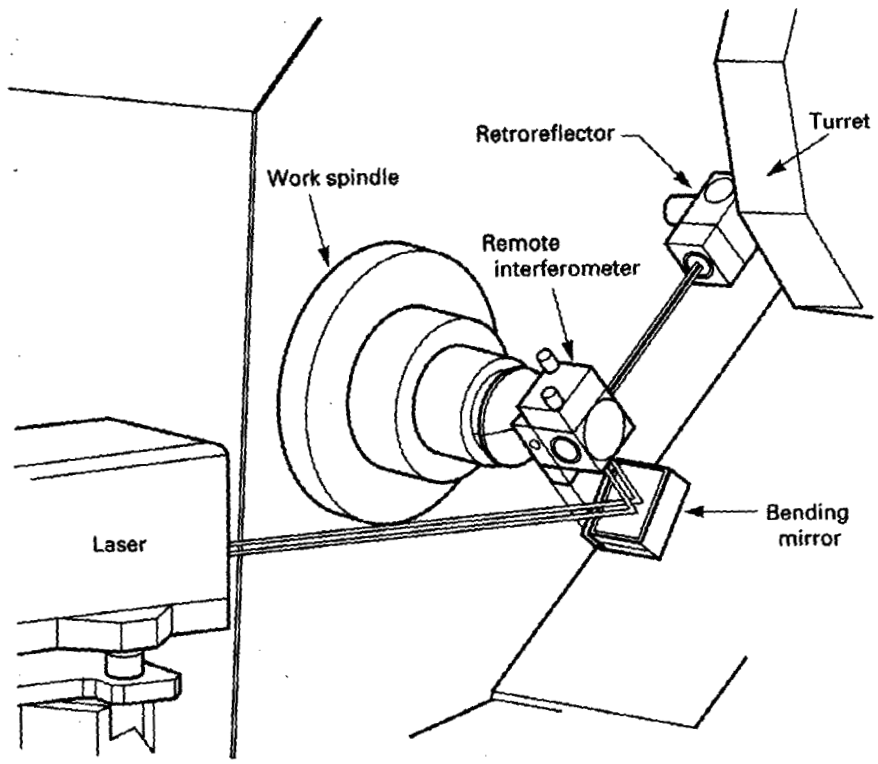


FIG. 17 TYPICAL SETUP FOR LASER INTERFEROMETER

be performed. If the laser system does not provide for environmental correction, both laser readings and scale readings shall be corrected manually. The procedure for making these corrections is given in Appendix H.

7.2.5 Measuring Intervals. Measuring intervals shall be no larger than 25 mm (1 in.) for axes of 250 mm (10 in.) length or less. For longer axes the interval shall be no more than $^1/_{10}$ of the axis length. It is recommended that the points chosen for measurement be points other than those used by the supplier to acquire data used for ball screw or lead screw compensation. Furthermore, it is highly desirable that these points be chosen at intervals that are not even fractions of the machine scale intervals. A simple way to accomplish this is to use metric intervals on a machine with inch scales and vice versa. Due to ease of measurement using laser systems, smaller intervals are strongly recommended. For machines that use ball or lead screws for displacement feedback, the user is strongly advised to make these closer-spaced measurements an integral part of the specification. The procedure for measuring periodic error is described in para. 7.2.8.

7.2.6 Measurements. Before commencing measurements, the machine shall be run through an exercise sequence of two complete back-and-forth cycles. These cycles shall be performed for each linear axis using the same NC program or manual time sequence that will be used during data acquisition. The default feed rate speed for these measurements shall be the machine's maximum programmable feed rate. Other feedrate speeds may be negotiated between user and supplier. Next, five sets of bidirectional measurements shall be taken for each axis sequentially along the line specified in para. 7.2.2 and at the points specified in para. 7.2.5, stopping the machine for a short duration, one to five seconds, at each of the data points. It is recommended that the laser readings be averaged for about 0.25 seconds and at least 120 points taken to compute this average. (On some large machines, longer settling times may be required. In this case the settling time should be negotiated between user and supplier.) These data shall be acquired without re-zeroing the laser system. A set of measurements shall consist of the machine axis readings and the corresponding laser readings. Note that for each point there will be ten measurements, five in each direction. These data shall be treated as described in the paragraph below.

7.2.7 Data Analysis and Reported Parameters. For each axis the data shall be plotted in a graph as illustrated in Fig. 18. Figure 18 shows the complete

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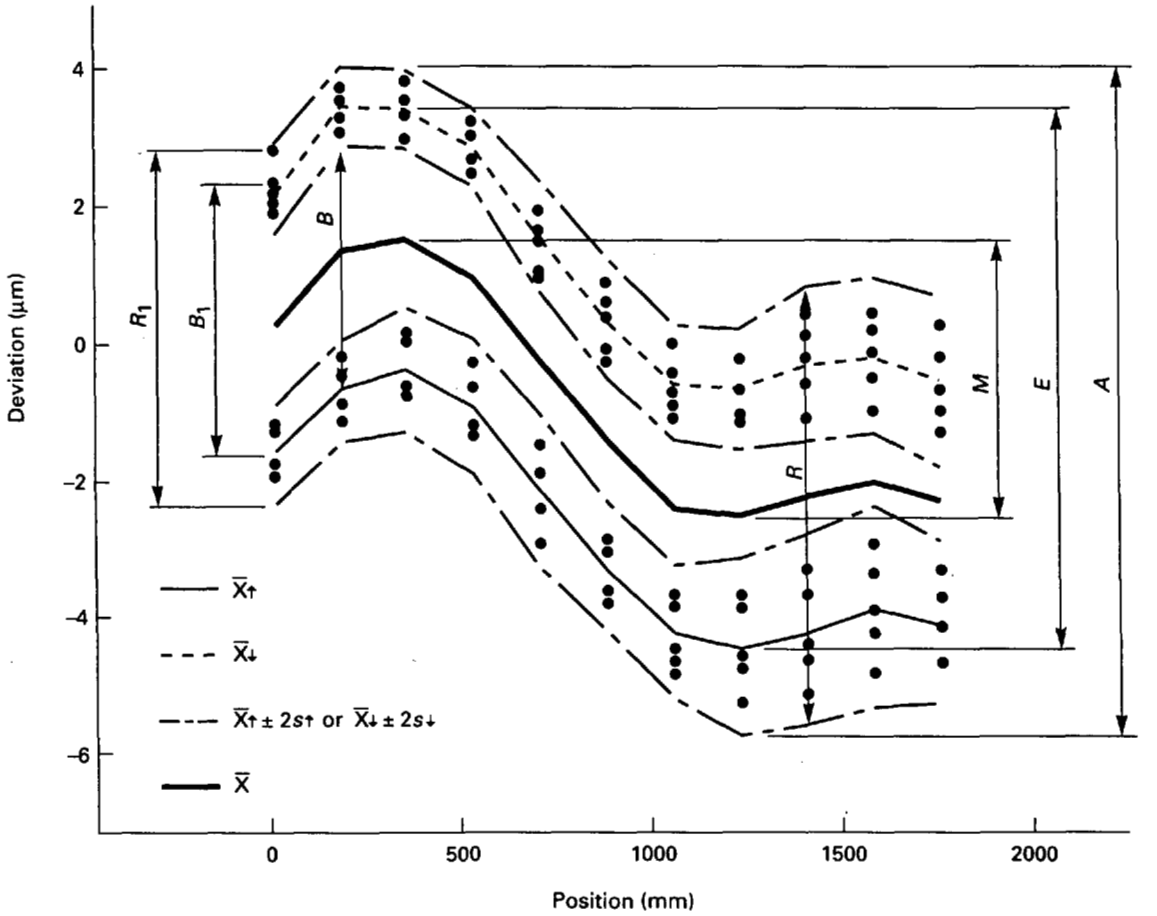


FIG. 18 THE FULL DATA SET FOR THE POSITIONING DEVIATIONS OF AN AXIS, BI-DIRECTIONAL

set of data. For clarity, the forward data are shown separately in Fig. 19. On both figures the data averages are clearly indicated with darker lines, either dashed or solid. From these data the following parameters shall be computed for each axis. For the purposes of this Standard, the following quantities which shall be compared to the appropriate specification zones shall be reported:

- the bi-directional systematic deviation of positioning, E
- the uni-directional systematic deviations of positioning, $E\uparrow$ and $E\downarrow$
- the bi-directional repeatability, R
- the uni-directional repeatabilities, $R\uparrow$ and $R\downarrow$.

The equations for computing these parameters are given in the paragraphs below. In order to do these computations a computer program is recommended. For those who wish to perform the computations graphically, an approximate method is given in para. 7.2.7.9. A report for a typical axis is summarized in Table 3.

Note: Table 3 shows more parameters than required by this Standard.

7.2.7.1 Bi-directional Systematic Deviation of Positioning of an Axis, E.[22] To determine the bi-directional systematic deviation of positioning first average the computed deviations from the target position in the forward and reverse directions. The difference between the algebraic maximum and minimum of the mean (average) uni-directional positional deviations for both approach directions (i.e., $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$) at any position, i, along or around the axis is the reported value. That is, the range of the average or mean values as shown in Fig. 18. The equation is

[22] The bi-directional systematic deviation of positioning of an axis is the preferred method for measuring positioning capability. It is the same as the linear displacement accuracy in the B5.54:1992 standard, "Methods for the Performance Evaluation of Computer Numerically Controlled Machining Centers."

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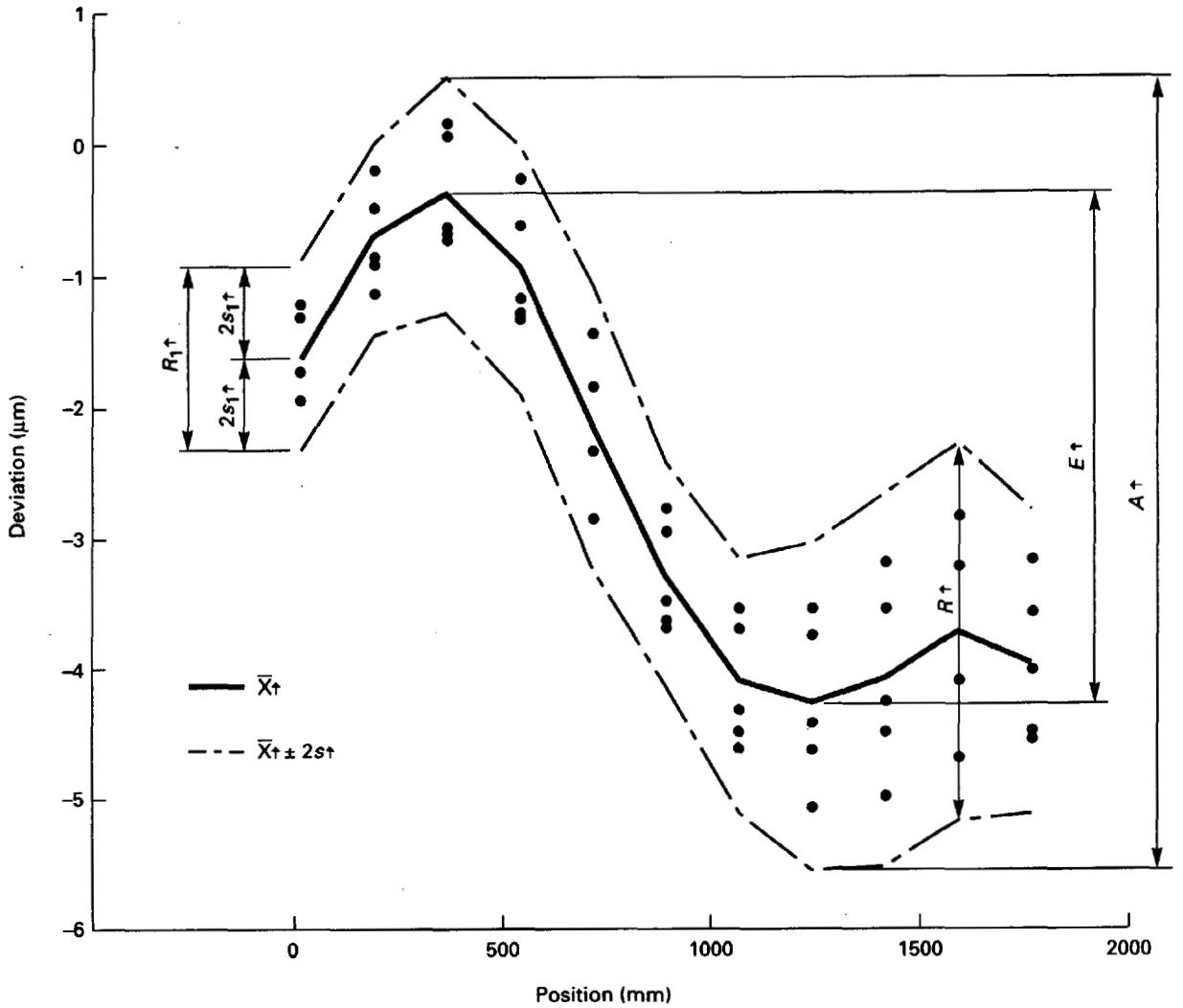


FIG. 19 POSITIONING DEVIATIONS OF AN AXIS, FORWARD DIRECTION ONLY

$$E = \max[\bar{x}_i\uparrow; \bar{x}_i\downarrow] - \min[\bar{x}_i\uparrow; \bar{x}_i\downarrow]$$

7.2.7.2 Uni-Directional Systematic Deviations of Positioning, E↑ and E↓. These are just the ranges of the average plots in the forward and reverse directions respectively. Mathematically they are the differences between the algebraic maximum and minimum of the mean uni-directional positional deviations for both approach directions (i.e., $x_i\uparrow$ or $x_i\downarrow$) at any position i along the axis. That is,

$$E\uparrow = \max[\bar{x}_i\uparrow] - \min[\bar{x}_i\uparrow]$$

and

$$E\downarrow = \max[\bar{x}_i\downarrow] - \min[\bar{x}_i\downarrow]$$

7.2.7.3 Bi-Directional Accuracy of Positioning of an Axis, A. The bi-directional accuracy of positioning is obtained from the same graph. It is the range derived from the combination of the bi-directional systematic deviations and the estimator of the standard uncertainty of bi-directional positioning obtained using a coverage factor k, of two (2). The estimates of the uncertainty are computed for each average value according to

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TABLE 3 TYPICAL TEST RESULTS (TEST FOR LINEAR AXES UP TO 2000 MM)

i	1		2		3		4		5		6		7		8		9		10		11	
Target position P_i mm	6.711		175.077		353.834		525.668		704.175		881.868		1,055.890		1,234.304		1,408.462		1,580.269		1,750.920	
Approach direction	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑
Positional deviations μm j=1	2.30	−1.20	3.64	−0.48	3.45	0.18	2.97	−0.61	1.66	−1.85	0.43	−2.95	−0.40	−3.70	−0.19	−3.74	−0.18	−3.54	0.29	−3.23	−0.11	−3.58
2	2.06	−1.72	3.51	−0.90	3.30	−0.63	2.67	−1.16	1.50	−2.32	0.20	−3.50	−0.68	−4.33	−0.64	−4.42	−0.15	−4.25	−0.05	−3.75	−0.61	−4.00
3	1.90	−1.93	3.06	−1.11	2.97	−0.69	2.44	−1.27	0.97	−2.85	−0.22	−3.65	−1.04	−4.61	−1.03	−5.07	−1.03	−4.97	−0.91	−4.69	−1.18	−4.47
4	2.78	−1.26	3.71	−0.18	3.80	0.09	3.17	−0.26	1.93	−1.42	0.87	−2.78	0.04	−3.55	−0.15	−3.55	0.47	−3.20	0.51	−2.84	0.36	−3.17
5	2.20	−1.94	3.17	−0.84	3.49	−0.72	2.63	−1.30	1.06	−2.34	−0.07	−3.69	−0.87	−4.49	−1.08	−4.63	−0.50	−4.48	−0.43	−4.10	−0.89	−4.52
Mean uni-directional positional deviation $\bar{x}_i$	2.25	−1.61	3.42	−0.70	3.40	−0.36	2.78	−0.92	1.42	−2.16	0.24	−3.31	−0.59	−4.14	−0.62	−4.28	−0.21	−4.09	−0.12	−3.72	−0.49	−3.95
Estimator of standard uncertainty s_i	0.33	0.36	0.29	0.37	0.30	0.45	0.29	0.46	0.41	0.54	0.43	0.42	0.42	0.48	0.44	0.63	0.59	0.72	0.57	0.72	0.62	0.58
$2s_i$	0.67	0.72	0.58	0.74	0.60	0.90	0.58	0.93	0.81	1.09	0.86	0.84	0.85	0.96	0.89	1.26	1.17	1.43	1.14	1.45	1.23	1.16
$\bar{x} - 2s_i$	1.58	−2.33	2.84	−1.44	2.80	−1.25	2.19	−1.85	0.61	−3.24	−0.62	−4.15	−1.44	−5.10	−1.50	−5.54	−1.38	−5.52	−1.25	−5.17	−1.72	−5.11
$\bar{x} + 2s_i$	2.91	−0.89	3.99	0.04	4.01	0.54	3.36	0.00	2.23	−1.07	1.10	−2.47	0.26	−3.18	0.27	−3.02	0.97	−2.66	1.02	−2.27	0.75	−2.79
Uni-directional repeatability $R_i = 4s_i$	1.33	1.43	1.15	1.48	1.21	1.79	1.16	1.85	1.62	2.17	1.72	1.68	1.70	1.92	1.77	2.52	2.34	2.86	2.27	2.90	2.46	2.32
Reversal value B_i	−3.86		−4.12		−3.76		−3.70		−3.58		−3.56		−3.55		−3.66		−3.88		−3.60		−3.46	
Bi-directional repeatability R_i	5.24		5.44		5.26		5.20		5.48		5.26		5.36		5.81		6.49		6.19		5.85	
Mean bi-directional positional deviation $\bar{X}_i$	0.32		1.36		1.52		0.93		−0.37		−1.54		−2.36		−2.45		−2.15		−1.92		−2.22	

Axis deviation	Uni-directional ↓		Uni-directional ↑		Bi-directional	
Reversal value B	Not applicable		Not applicable		4.12	(at $i=2$)
Mean reversal value $\bar{B}$	Not applicable		Not applicable		−3.70	
Range mean bi-directional positional deviation M	Not applicable		Not applicable		3.97	(1.52—2.45)
Systematic deviation of positioning E	4.04	(−3.42—0.62)	3.93	(−0.35—4.28)	7.70	(3.42—4.28)
Repeatability of positioning R	2.46	(at $i=11$)	2.90	(at $i=10$)	6.49	(at $i=9$)
Accuracy A	5.73	(4.01—1.72)	6.08	(0.54—5.54)	9.55	(4.01—5.54)

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

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

Then A is given by

$$A = \max\left[\bar{x}_i\uparrow + 2s_i\uparrow;\ \bar{x}_i\downarrow + 2s_i\downarrow\right] - \min\left[\bar{x}_i\uparrow - 2s_i\uparrow;\ \bar{x}_i\downarrow - 2s_i\downarrow\right]$$

7.2.7.4 Uni-Directional Accuracies of Positioning, $A\uparrow$ and $A\downarrow$. These are computed analogously to the computation of A, para. 7.2.7.3. They are the ranges representing the combination of the uni-directional systematic deviations and the estimator of the standard uncertainty of uni-directional positioning obtained using a coverage factor of two (2).

$$A\uparrow = \max\left[\bar{x}_i\uparrow + 2s_i\uparrow\right] - \min\left[\bar{x}_i\uparrow - 2s_i\uparrow\right]$$

and

$$A\downarrow = \max\left[\bar{x}_i\downarrow + 2s_i\downarrow\right] - \min\left[\bar{x}_i\downarrow - 2s_i\downarrow\right]$$

7.2.7.5 Bi-Directional Repeatability for an Axis, R. The maximum value of the bi-directional repeatability of positioning for an axis; that is, R = max $[R_i]$, where

$$R_i = \max\left[2s_i\uparrow + 2s_i\downarrow + |B_i|;\ R_i\uparrow;\ R_i\downarrow\right]$$

$$R_i\uparrow = 4s_i\uparrow$$

$$R_i\downarrow = 4s_i\downarrow$$

and

$$R = \max\left[R_i\right]$$

7.2.7.6 Uni-Directional Repeatabilities, R↑ and R↓. Uni-directional repeatabilities are defined as the maximum value of the repeatabilities at any position i. That is,

$$R\uparrow = \max\left[R_i\uparrow\right] = \max\left[4s_i\uparrow\right]$$

and

$$R\downarrow = \max\left[R_i\downarrow\right] = \max\left[4s_i\downarrow\right]$$

TABLE 4 CONVERSION FACTORS FOR ESTIMATING STANDARD UNCERTAINTY

Sample Size, n	Conversion Factor, d_2 (n)
5	2.33
6	2.53
7	2.70
8	2.85
9	2.97
10	3.08
12	3.26
15	3.47
20	3.74

7.2.7.7 The Reversal Deviation, B. Algebraically, maximum of the absolute mean reversal deviations $|B_i|$ at any position i along or around the axis determined using the procedure and under the conditions specified in this Standard,

$$B = \max\left[|B_i|\right]$$

7.2.7.8 The Mean Reversal Value, $\bar{B}$. The algebraic mean of the absolute reversal values, B_i, at all target positions along the axis,

$$\bar{B} = \frac{1}{m}\sum_{i=1}^{m} B_i$$

7.2.7.9 Approximate Calculations If a computer program is not available to calculate the standard uncertainties of the positioning data, then it is possible to estimate them from the range. The procedure is as follows. At each of the target points, measure the range graphically. Convert the range into a standard uncertainty using the factors shown in Table 4. For a given sample size n and range Rn_i the appropriate standard uncertainty s_i is estimated by

$$s_i = Rn_i / d_2\left(n\right)$$

The recommended number of repeated measurements for each target position is five. The table, however, may also be used for other sample sizes.

7.2.8 Periodic Error. Nearly all scales used on turning centers contain either classical periodic error (caused by pitch error in lead screws or ball screws, mismounted nuts, etc.) or some form of interpolation error which occurs during electronic interpolation between scale divisions on line scales, moiré scales,

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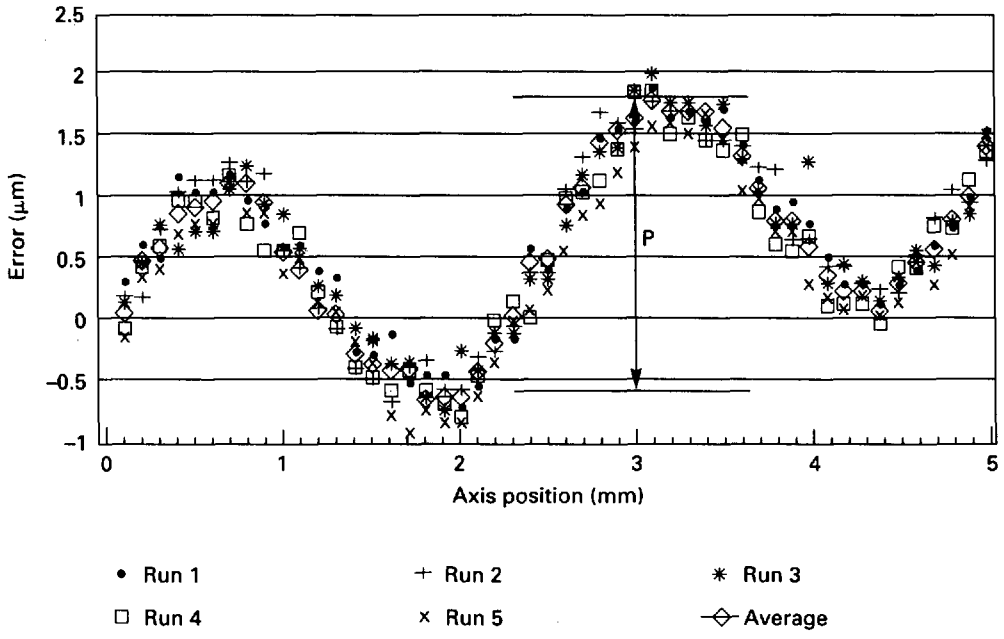


FIG. 20 PERIODIC ERROR (P) OF A LINEAR AXIS

inductive scales, and the like. Even laser interferometer scales have periodic error with a periodicity which is the wavelength of light or a fraction thereof, depending upon the exact optical configuration of the system (although periodic error in laser systems is generally small, it can be important on very high precision machines).[23] With a laser interferometer on all turning machines except those noted above, it is particularly easy to check for periodic error by measuring a large number of closely spaced displacements over an interval equal to the periodicity of the machine scale. For the purposes of this Standard, it is recommended to measure the positioning error for 20 points uni-directionally over two periods of the pitch of the expected periodic error. For a screw this would be the screw pitch, for a line scale the line spacing, for an inductive scale the coil spacing, etc. If the pitch of the scale is quite small, as on a line scale, fewer points can be taken. These measurements shall be repeated five times. These data shall be plotted as shown in Fig. 20. 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 $E\uparrow$, as described in para. 7.2.7.2; that is, $P = \max [\bar{x}_i\uparrow] - \min [\bar{x}_i\uparrow]$ for this test.

[23] Users of this Standard with machines whose bi-directional systematic deviation of positioning is expected to be less than 300 μm (approx. 12 μm) should consult with laser manufacturing regarding this effect.

7.3 Angular Error (Yaw) Motions, Linear Axes

7.3.1 General. Because of significant Abbe offsets when machining, errors in tool point location can occur due to angular errors in the machine linear slides. On a simple Group 1 machine these errors consist of small rotations about the Y axis and are called "yaw errors." This Standard requires that these angular error motions be measured for all linear machine axes. For machines where rotations about axes other than the Y axis are important, measurements of these angular error motions should be made part of the original machine specification. The lines of measurement shall be those lines used for the positioning accuracy and repeatability test for linear axes as specified in para. 7.2.2. A typical setup for making these measurements is shown in Fig. 21 for the cross slide of a Group 1 machine. The measuring intervals, averaging times and number of points, and measurement sequence, including the exercise cycle, shall be those used for the linear tests as specified in paras. 7.2.5 and 7.2.6.[24] The data shall be reported as given in para. 7.2.7 and in Form 4, except that the names of the parameters shall be different. They shall be computed for each axis as follows:

- the bi-directional systematic angular error, E_{ae}

[24] For larger machines, this Standard suggests that fewer number of runs might be negotiated between user and supplier.

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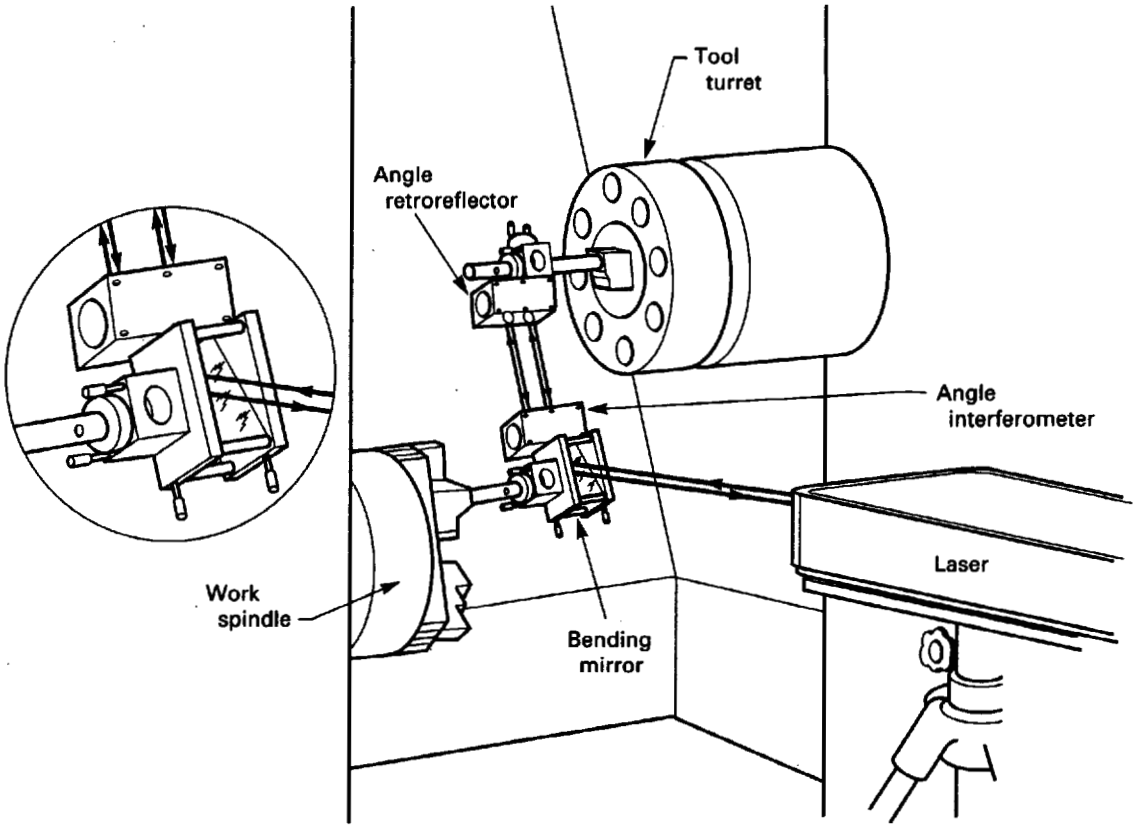


FIG. 21 TYPICAL SETUP FOR MEASURING THE ANGULAR ERROR MOTION (YAW) OF THE CROSS SLIDE ON A GROUP 1 MACHINE

- the bi-directional total angular error, A_{ac}
- the uni-directional systematic angular error, $E_{ac}\uparrow$ and $E_{ac}\downarrow$
- the uni-directional total(s) angular error, $A_{ac}\uparrow$ and $A_{ac}\downarrow$
- the bi-directional repeatability of angular error, R_{ac}
- the uni-directional repeatabilities of angular error, $R_{ac}\uparrow$ and $R_{ac}\downarrow$
- the reversal deviation of angular error, B_{ac}

7.3.2 Estimating the Effect of Angular Error. Angular error leads to positioning error for positions not on the lines measured in the linear positioning accuracy and repeatability test (Section 7.2). The magnitude of this error depends upon the perpendicular distance to the axis measurement lines and the point under consideration (the functional point). This perpendicular distance is called the "Abbe offset" (see Glossary). To obtain the estimated error at any point, the value of the angular error for that position, in radians, need to be multiplied by the Abbe offset.

7.4 Positioning Accuracy and Repeatability, Rotary Axes

7.4.1 General. As with the measurement of linear positioning, complete verification of a rotary axis designed for positioning can be a time-consuming task. In the following, a practical set of tests that represent a good compromise between the cost of testing and the cost of inaccuracy is defined. The tests are divided into two sections: the first is a test for full circle angular positioning; and the second a test for interpolation errors on a much finer scale. These tests are analogous to the tests performed for linear axes and the same parameters are reported, except in angular units. A similar exercise procedure should be followed, i.e., twice through the bi-directional test before acquiring data. The angular positioning test can be used for both continuously servoed rotary axes, servoed spindle axes, and indexing turrets. The angular positioning accuracy and repeatability are measured in a minimum of nine (9) positions for a servoed axis and at the number of

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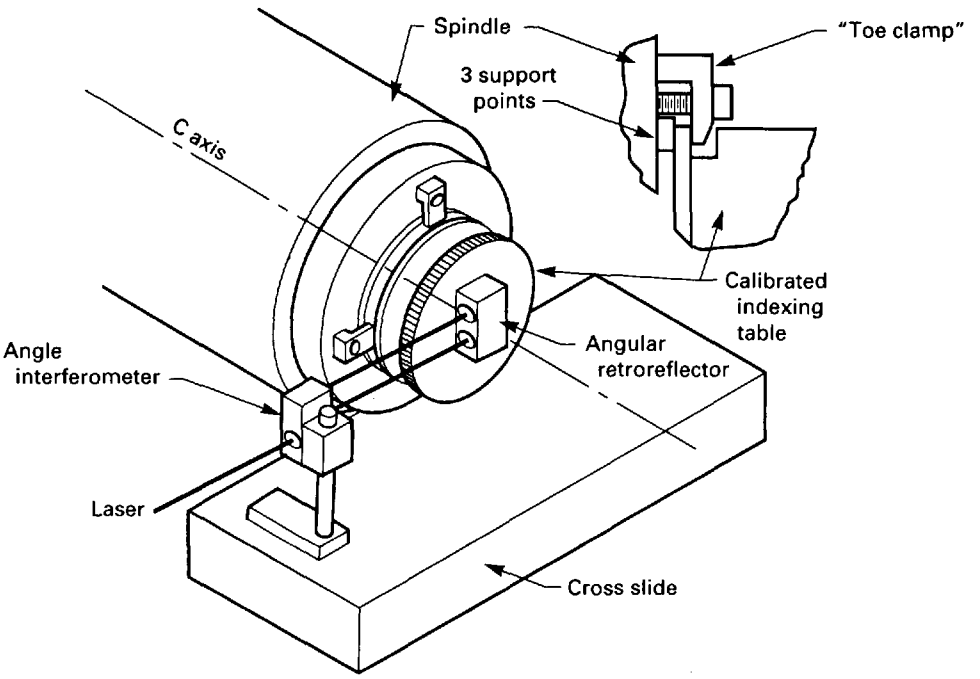


FIG. 22 SCHEMATIC FOR THE MEASUREMENT OF ANGULAR POSITIONING USING AN INDEXING TABLE AND A LASER INTERFEROMETER

positions equal to the number of turret positions for a turret axis. The periodic angular positioning test is only applicable to continuously-servoed rotary axes.

7.4.2 Angular Positioning Using an Indexing Table and an Interferometer. The preferred method for the testing of an angular axis consists of using a combination of an automatic indexing table and a laser angular interferometer. For such a system it is possible to obtain continuous angular displacements and to operate automatically. A calibrated indexing table is fixtured to the face of the rotary axis to be measured. The angular attachment to a commercial laser interferometer is attached to the table with a double retroreflector mounted on the indexing table center. A diagram for a typical setup for the spindle, C axis, of a lathe is given in Fig. 22. It should also be noted that laser-based, angular interferometers can have large errors if not properly aligned and need to be corrected for non-linearity if the measurement angle exceeds a few degrees. In such cases, the laser interferometer supplier's recommendations should be followed. Indexing tables must have their axis of rotation aligned parallel to the rotary axis being measured. In addition, the center line of the angle retroreflector must be square with the axis of the indexing table. Figure 23 illustrates the test for adjusting and/or verifying this alignment. An indicator is bracketed to the cross slide and adjusted so that the stylus contacts the outer edge of the double corner cube reflector. The indicator is zeroed at this point. The cross slide is moved so that the indicator is clear of the corner cube. The indexing table is lifted,[25] the spindle rotated 180 degrees, with the anti-rotation bar in place on the indexing table. The indexing table is then re-clamped and the cross slide returned to its original position. The procedure is repeated for a 90 degree and a 270 degree rotation. For each pair of rotations the reading of the indicator should be within 50 μm (approx. 0.002 in.) to ensure an error less than 1 part in 1000 of the measured angle.

Note: Such a procedure assumes that the side faces of the angular retroreflector assembly are parallel to the plane defined by the center line of the two cube corners to within 5 μm (approximately 0.0002 in.).

Before commencing measurements, the machine shall be run through an exercise cycle of two complete back-and-forth cycles. These cycles shall be performed for

[25] When measuring turrets, which also "rise" when indexed, the combination height change of indexing table and turret may cause loss of laser signal. In this case it is acceptable to index the turret and indexing table independently, provided the optics can accommodate the angular increment. If this cannot be accommodated, the autocollimator method (para. 7.3.3) or the polygon method (para. 7.3.4) may be substituted.

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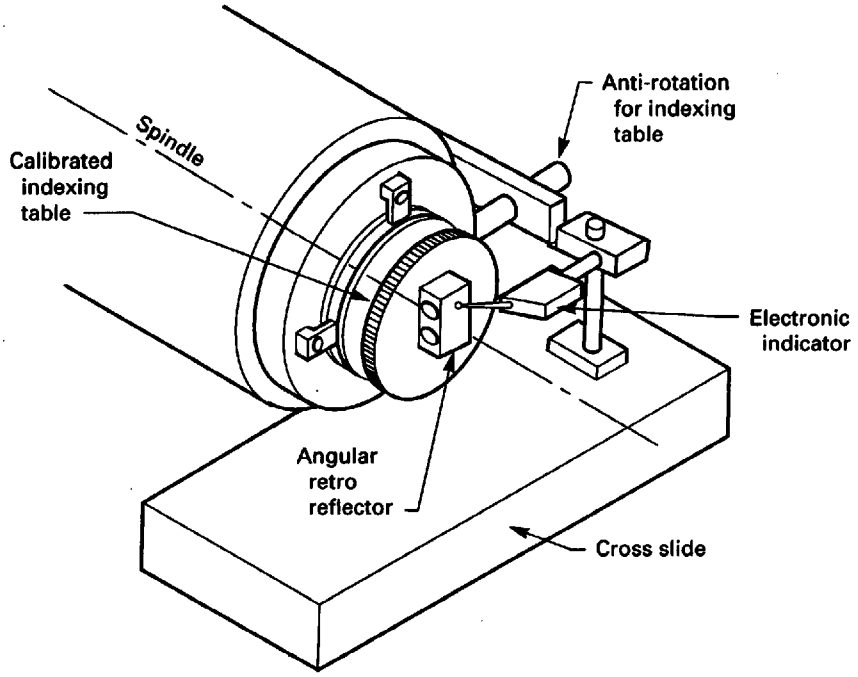


FIG. 23 SETUP FOR ADJUSTING THE ALIGNMENT OF AN INDEXING TABLE AND A LASER ANGLE INTERFEROMETER

each rotary axis, using the same program or manual time sequence that will be used during data acquisition. The procedure now is to command the machine under computer control to step known angular intervals and either manually or under computer control rotate the calibrated indexing table in the reverse direction to maintain a condition of perpendicularity between the retroreflectors and the interferometer. Data shall be taken and analyzed as described in para. 7.4.7.

7.4.3 Angular Positioning Using an Indexing Table and an Autocollimator. The procedure for testing angular positioning using an indexing table and autocollimator is conceptually similar to that described in para. 7.4.2 using an indexing table and an interferometer. As before, a calibrated indexing table is fixtured to the face of the rotary axis to be measured. Again, attention should be paid to fixture-induced stresses and table alignment which can alter the calibration accuracy. A flat mirror, with its face parallel to the axis of rotation, is mounted to the surface of the indexing table facing a manual or electronic autocollimator with the appropriate resolution and accuracy (see Section 9).

Note: The autocollimator has a smaller range than the laser interferometer and is therefore not preferred, except in the case when the combination of turret "rise" and indexing table "rise" is excessive for a laser interferometer.

The procedure is to first exercise the machine by running the calibration NC program twice (see para. 7.4.2) and then to command the machine under computer control to step known angular intervals and either manually or under computer control rotate the calibrated indexing table in the reverse direction to maintain a condition of near perpendicularity between the mirror surface and the autocollimator. After exercise, measurements shall be taken and data analyzed as described in para. 7.4.7.

7.4.4 Angular Positioning (Polygon Method). This test is performed using a calibrated optical polygon with a minimum of nine (9) faces for a positioning axis or with a number of faces equal to the number of turret positions for an indexing axis. The polygon is appropriately 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 which might distort the polygon mechanically and alter the calibration accuracy. Calibration shall be to at least the level required for the application; however, current state-of-the-art is approximately 0.2 arc sec. A manual or electronic autocollimator should then be placed so that an image is obtained from one of the polygon faces. A sample

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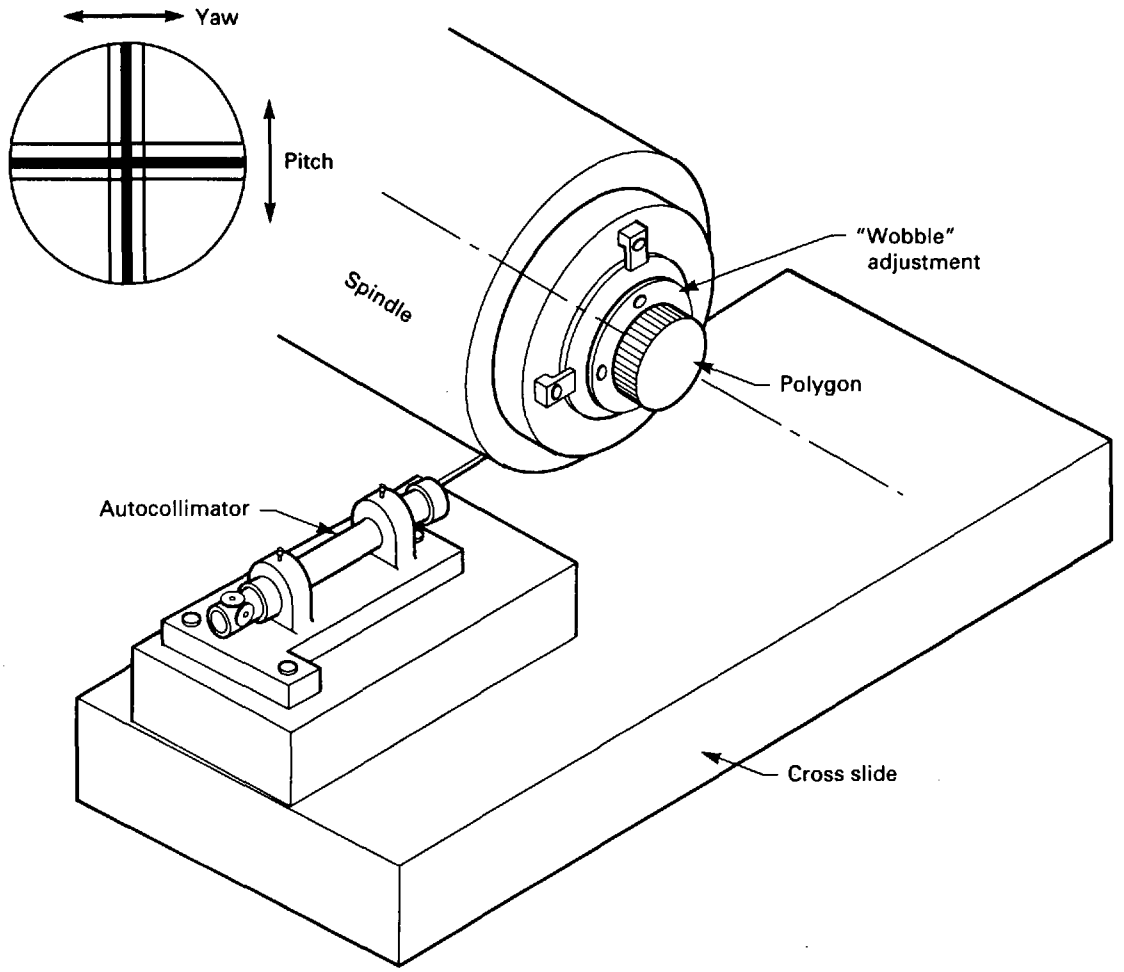


FIG. 24 A POLYGON MOUNTED TO A SPINDLE AXIS

setup is shown schematically in Fig. 24 for a servoed spindle axis. The autocollimator shall also have been calibrated to the required accuracy. Details on the polygon and autocollimator are given in Section 9.

After checking for on-scale behavior of the system by commanding the machine under computer control to step the appropriate faces of the polygon to a condition of perpendicularity with respect to the autocollimator, the axis should be exercised (two complete cycles, see para. 7.4.2) and a series of readings shall be taken in an incremental fashion on the angular position of each of the polygon faces.[26] After exercise (see para. 7.4.2), measurements shall be taken and data analyzed as described in para. 7.4.7.

7.4.5 Angular Positioning (Rotary Encoder Method). A third method for checking angular positioning, and perhaps periodic angular positioning, involves using a calibrated rotary encoder. Such devices are not currently as readily available as optical polygons, autocollimators, and indexing tables, and also come in different configurations. If such a system is used, the instrument manufacturer's recommendations for system mounting and alignment shall be followed, and the calibration of the device shall meet the minimum requirements as specified in Section 9. A typical setup

[26] Particular attention must be paid to obtain the correct sign (+ or −) for the autocollimator deviation when performing this calibration. On a machine with a servoed rotary axis, this sign may easily be obtained by jogging the machine in a direction of increasing angle and ensuring that the autocollimator reading also indicates an increasing angle. On an indexing machine, hand pressure on the rotary table, in the correct direction for a positive angle, is usually sufficient to create an autocollimator reading for obtaining the correct sign.

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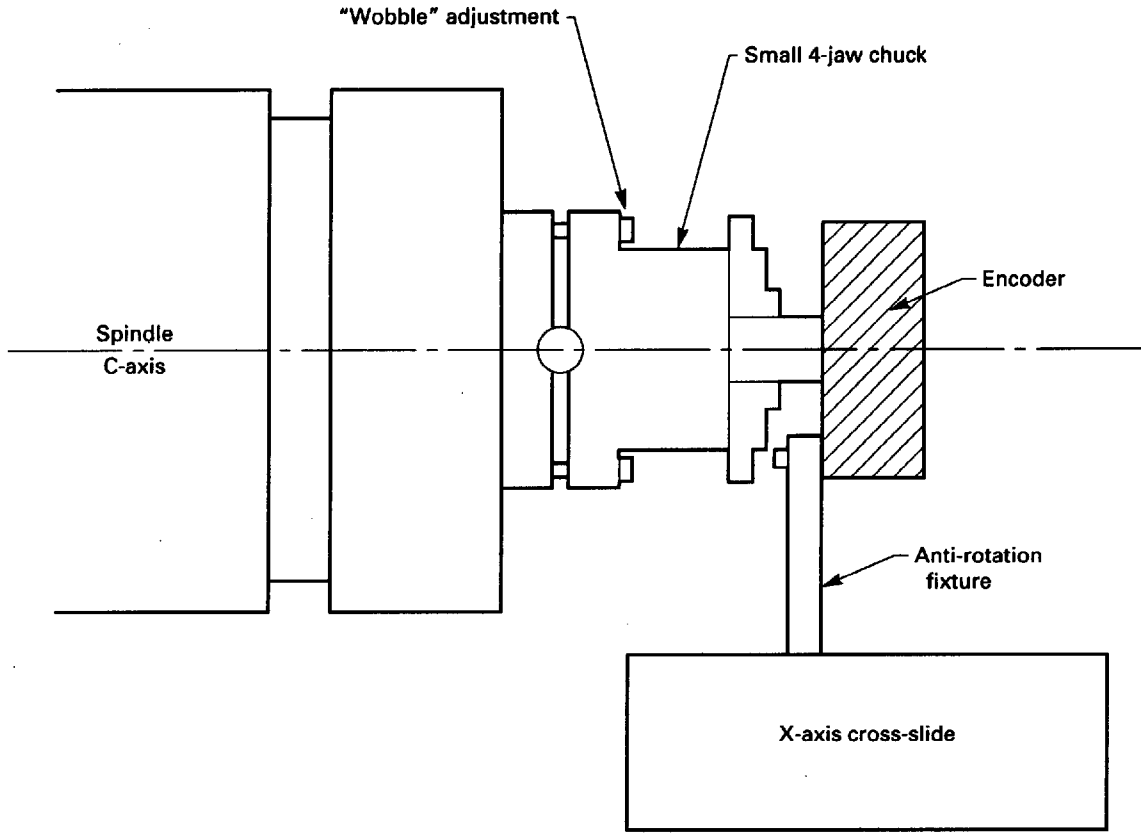


FIG. 25 TYPICAL SETUP FOR MEASURING THE ANGULAR POSITIONING ACCURACY OF A ROTARY AXIS USING AN ANGULAR ENCODER

is shown in Fig. 25. Following exercise, measurements shall be taken and data analyzed as described in para. 7.4.7.

7.4.6 Angular Positioning (Level Method). On some machines it is possible to measure the angular positioning of the turret or other rotary axis using an indexing table and an appropriate level as a small-angle indicator. In this case, the level is bracketed in a position equivalent to that shown for the laser angular retroreflector in Fig. 22, para. 7.4.2. If a level is used, the procedure outlined in para. 7.4.2 should be followed, including machine exercise cycle. Measurements shall be made and data analyzed as described in para. 7.4.7.

7.4.7 Angular Position Measurements and Data Analysis. Independent of the measurement instrumentation selected, a series of bi-directional measurements shall be taken in this fashion over the full circle angular position of the spindle, rotary axis, or turret at the predetermined number of locations, repeating this procedure five times as described in para. 7.4.1. Five sets of bi-directional measurements shall be taken. When using the laser interferometer, the readings at each location shall be averaged for 0.25 second, taking a minimum of 120 points. The angular deviation at each angular position shall be measured ten (10) times, five (5) times in one rotation direction and five times (5) in the reverse rotation direction. The data are plotted as shown in Fig. 18 and analyzed following the prescription for linear axes as given in para. 7.2.7, except that the units will be in arc seconds or decimal degrees and only nine (9) target angular positions are required. Although only nine (9) positions are required by this Standard, if the instrumentation allows, taking a larger number of points is highly recommended. It also should be noted that, in many cases, the periodic angular positioning (see para. 7.4.8) can be assessed simultaneously with performing this test.

The data obtained from the angular positioning tests are analyzed using the same procedures as are used to analyze a linear axis (see para. 7.2.7). The parameters reported are the same except that the units are to be in arc seconds or decimal degrees rather than millimeters.

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7.4.8 Periodic Angular Positioning. After obtaining the large angular positioning parameters it is necessary on a servoed angular axis to check the angular interpolation of the scale devices. Since many different types of angular scales are used, it is difficult to define, in general, an interval of small angle measurement that will be sufficient for all applications. This test is necessary because angular encoders are often built in such a fashion that the error between integral angles can be extremely small, but the error in interpolation between these angles can greatly exceed the error at integral angles. It is the recommendation of this Standard that the interval for periodic angular positioning measurement shall be chosen such that it encompasses at least the interpolation interval on an angular axis using optical encoders, moiré gratings, or inductive scales. 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 gear. Once the interval has been established, this Standard provides for three methods of measuring the periodic angle positioning. One uses the angular attachment to a commercial laser interferometer system, the second uses a mechanical setup consisting of an electronic or mechanical indicator and a micrometer, and the third uses a rotary encoder.

7.4.8.1 Periodic Angular Positioning Using a Laser Interferometer. The setup for this measurement is similar to that shown in Fig. 22, without the indexing table. Here the angular attachment to a commercial laser interferometer is used with the angle retroreflector mounted in the position of the polygon of para. 7.4.4. Note that this measurement may be made with the indexing table in place as part of the angular positioning test if the option in para. 7.4.2 is used. The servoed axis of the machine is then commanded to move in intervals $1/20$ of the interval derived in para. 7.4.8 and the laser angle reading recorded. This procedure shall be performed uni-directionally and repeated five times over the same range, without rezeroing the laser interferometer, to ensure consistency and assess instrumental and environmental drifts. The differences between the laser angle reading and the incremental angle command are plotted as shown in Fig. 20 for a linear axis (except the deviation units will be in arc seconds). The periodic angular positioning is the range of the average angular deviations as shown in the figure. The analysis is analogous to that for unidirectional systematic deviation of positioning (see para. 7.2.7.2). It should be noted that this procedure often shows up periodic components of interpolation which can be used for analysis purposes that are outside the scope of this specification. It should also be noted that laser-based angular interferometers can have large errors if not properly aligned and need to be corrected for non-linearity if the measured angle exceeds a few degrees. The interferometer manufacturer's recommendation shall be followed regarding the angle range of the angle interferometer.

7.4.8.2 Periodic Angular Positioning Using Displacement Measurements. Periodic angular positioning can also readily be measured using displacement-measurement apparatus. A mechanical setup using a micrometer and an appropriate electronic or mechanical indicator with a spherical stylus is shown in Fig. 26. A laser displacement-measuring interferometer, or other long-range displacement indicator, can also be substituted for the micrometer and indicator shown. The intervals of measurement are determined as described in para. 7.4.8. The machine is commanded to move in intervals of $1/20$ of the interval determined, and at each point the electronic or mechanical indicator is rezeroed using the micrometer. The angular motion, θ (in radians), is approximately the ratio of the measured displacement divided by the radius, as shown in the figure. With either the laser interferometer or the mechanical setup, this approximation is only valid for small angles, and corrections shall be applied if the measured angle exceeds a few degrees. Differences between the angle calculated from the displacement measurement and the incremental angle command are plotted as shown in Fig. 20 for a linear axis (except the units are angular), and the periodic angular positioning is computed as in para. 7.2.8. The angle may be calculated from the displacement measurements by dividing the displacement measurement by the measurement radius, MR (Fig. 26), and then converting the answer, which is in radians, to either arc seconds or decimal degrees.

7.4.8.3 Periodic Angular Positioning Using a Rotary Encoder. The periodic angular positioning may also be measured using an appropriate rotary encoder. The setup shall be performed as described in para. 7.4.5 and as shown in Fig. 25 and, in fact, the periodic angular positioning shall be assessed as part of the angular positioning if such instrumentation is available. The measurement intervals are described in para. 7.4.8 and the data reduction in para. 7.2.8. It should be noted that the rotary encoder often has periodic errors of the same magnitude of the rotary measurement device used in the table or spindle to be tested. This should be thoroughly assessed before using such a device for this measurement and in no case

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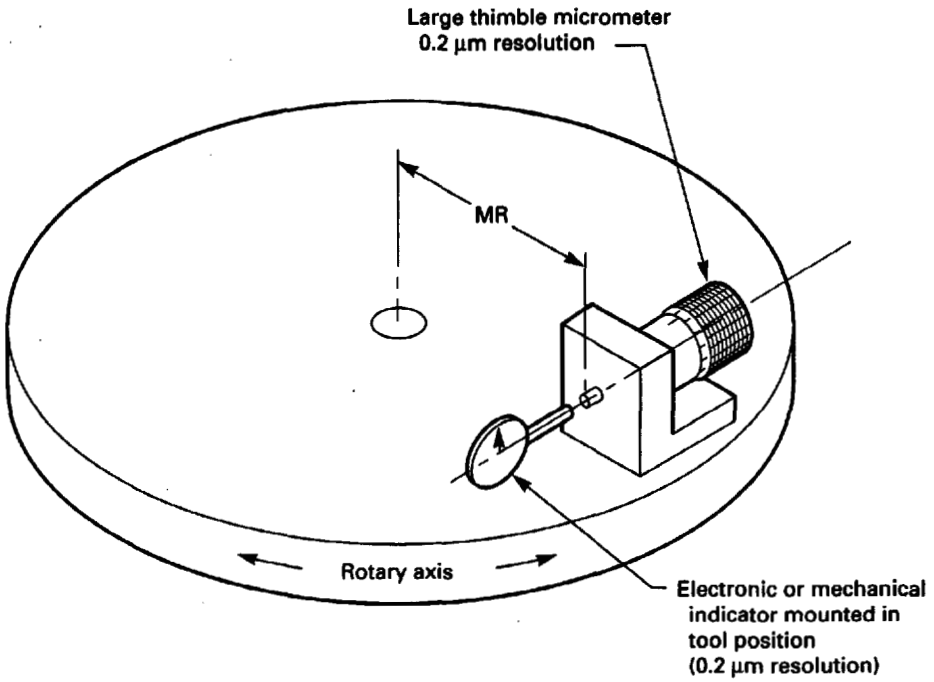


FIG. 26 TYPICAL SETUP FOR PERIODIC ANGULAR ERROR MEASUREMENT USING MECHANICAL MEANS

should a rotary encoder be used which has the same interpolation interval as the encoder used on the table or spindle to be tested.

7.5 Spindle Axis of Rotation

Traditionally, a simple lathe or turning machine is equipped with a spindle for fixturing a part (work spindle) and a cross slide, mounted on a saddle, for fixturing tools. Modern machines can be equipped with multiple spindles, multiple turrets, and even rotating ("live") tooling (tool spindles). It is impossible, in this Standard, to cover all conceivable configurations. For the purposes of this Standard, tests are defined for all work spindles and all part spindles that are supplied as part of a machine purchase. If spindles are to be excluded from these tests because they are "auxiliary" spindles (see Glossary), this exclusion shall be agreed upon between user and supplier as part of the original machine specification. Otherwise, such spindles shall be tested following the procedures described in Sections 7.5 and 7.6 of this Standard.

7.5.1 General. The general problem of the specifying and testing of axes of rotation is thoroughly treated in ANSI/ASME B89.3.4M-1985, "Axes of Rotation, Methods for Specifying and Testing." The details of that Standard will not be repeated here. Rather, minimum tests are defined that are necessary for ensuring spindle performance for the average user and others are referred to B89.3.4M for further background material. Both rotating sensitive direction and fixed sensitive direction measurements will be treated (see Glossary).

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 will not be evaluated in this Standard. For the purposes of this Standard, two types of sensitive direction are recognized. The first, fixed sensitive direction, occurs in turning, i.e., lathes, where the part is rotating in the spindle of interest and the tool is fixed. The second, called rotating sensitive direction, occurs where the tool is rotating and the workpiece fixed. In the case of turning centers, it is only applicable where such machines are equipped with "live" tooling. This Standard provides procedures for the evaluation of the ranges of some of the relevant spindle error parameters. The error parameters used in

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this Standard will be limited to subsets of average and uncertainty in radial, axial, and tilt motions. The axial measurement is optional for rotating sensitive direction. **All the measurements in this section require rotating a test ball, mandrel, or other artifact in a fixture at high speeds. Users are therefore warned to use appropriate cautions to ensure operator safety.**

7.5.2 Structural Motion, Spindle Off. Before commencing spindle error testing, assessing structural motions of the machine with the spindle off is required. These tests are similar in setup to those tests for relative vibration given in para. 6.3.1. They are, however, conducted in conditions designed to point out relative motion between the spindle and the tool, which is caused by the machine itself rather than the environment or actual spindle rotation. The tests shall be run three times for each axis: first with the machine's power and auxiliary systems on but with the machine drives off, that is, the emergency stop position; second with the machine's power and auxiliary systems, such as hydraulics, turned on, and with the machine drives on, that is, with the machine in the feed-hold mode; and third with the machine commanded under program control to position the test artifact mounted in the spindle at the position selected for the ETVE test. The setup is shown in Fig. 14. The values obtained from these tests should be compared to those obtained in the functional relative vibration tests (para. 6.3.1). If the vibration amplitude in any of these three conditions exceeds 25% of the specification zone for uni-directional repeatability and the user has met the supplier's guidelines regarding vibration and environment, the supplier shall be responsible for rectifying the situation. (See Appendix O for further information regarding structural motion measurements.)

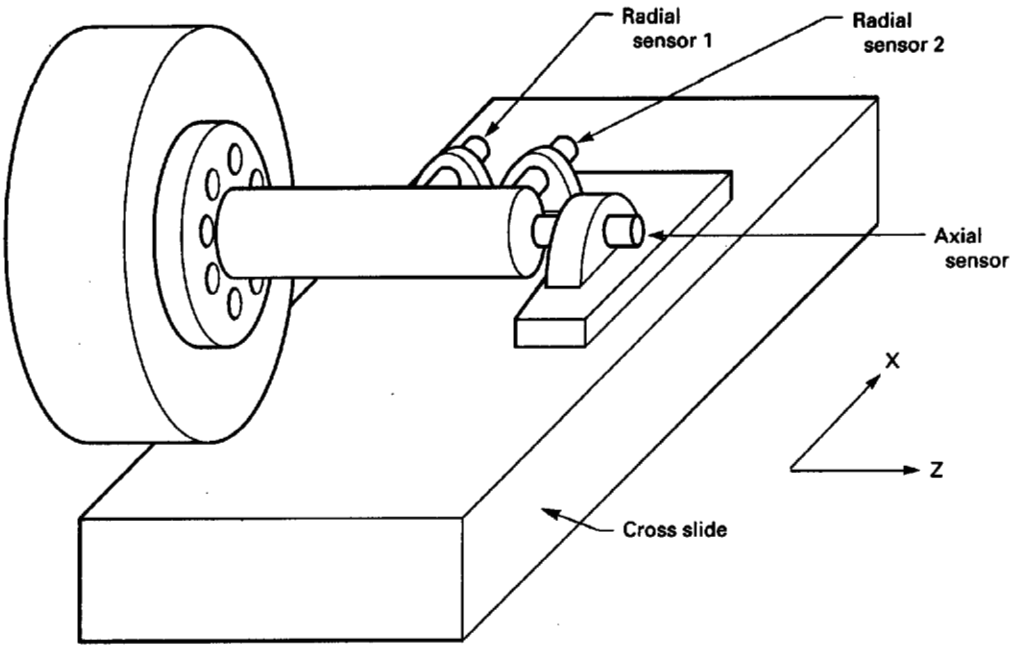
7.5.3 Spindle Tests, Fixed Sensitive Direction. Figure 27 schematically represents some test setups suitable for the measurement of the spindle error motions for the case of fixed sensitive direction, that is, for a work spindle. (In the following tests it is assumed that a signal, proportional to the angular orientation of the spindle, is generated so that polar plots of the error motion as a function of spindle angle can be generated either in a computer or on an oscilloscope.) A precision test ball system, or other suitable artifact, is mounted in the machine spindle and the displacement indicator is mounted to the tool post or to a fixture rigidly attached to the tool post. The ball system or artifact should be centered around the axis of rotation so as to minimize eccentricity. (It is assumed in the later text that the spindle analysis system is capable of removing small residual eccentricities.) The displacement indicator[27] and test artifact should meet the specifications outlined in Section 9. (In the case of ultra-high precision machines, such as diamond turning machines, residual errors due to artifact out-of-roundness should be removed; see Appendix B of B89.3.4M for this procedure).

7.5.3.1 Radial Error Motion, Fixed Sensitive Direction. The radial error motion shall be measured by positioning the displacement indicator in the radial direction, as shown in Fig. 27. Radial error motion measurements shall be made at three spindle rpms after the spindle has been allowed a warm-up period at half maximum rpm for a period of ten minutes. The spindle speeds chosen for this test shall be approximately 10%, 50%, and 100% of the machine's recommended maximum spindle speed. At each speed a polar plot of the spindle error motion shall be made for a minimum of 20 revolutions.[28] It is also recommended that the machine user simply observe the output of the error-indicating system while changing the spindle speed slowly throughout its total speed range. There may be speeds where excessive error motion results due to structural motion. If such speeds exist, they should be reported and avoided when machining. A typical plot for a single spindle speed is shown in Fig. 28. This plot should be evaluated as follows. First the data shall be least-squares fit to a circle and any residual eccentricity removed. Then the average (mean) values of the radial error motion and the asynchronous error motion values shall be computed for a minimum number of 16 angles uniformly distributed around the circle. (Many commercial spindle error analyzers sample at a much larger number of angles; 16 is the minimum, but a larger number is preferred.) The maximum range of these averages shall be called the "average radial error motion" (it is precisely analogous to the uni-directional systematic deviation, see para. 7.2.7.2). Similarly, the maximum value of the asynchronous motion shall be called the "asynchronous error motion." It must be emphasized that, although the plot (Fig. 28)

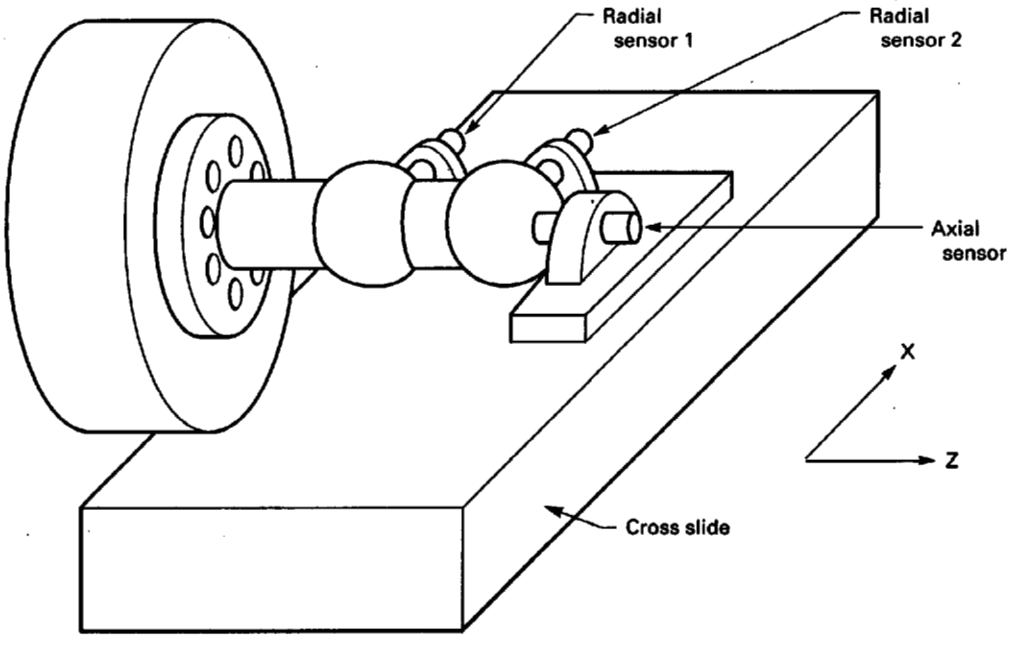
[27] At the time of the writing of this Standard, displacement indicators that work on eddy current principles are, in general, unsuited for spindle measurements. This is because they sense changes in the metallurgy of the test artifact, as well as its geometry, and can give incorrect results. For all spindle measurements, a high-bandwidth indicator which senses only the geometry of the artifact is required.

[28] For ball and roller bearing spindles a higher number of revolutions, up to several hundred, is recommended to properly assess error motions.

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(a)



(b)

FIG. 27 TEST SETUPS, (a) AND (b), USED FOR MEASUREMENT OF THE SPINDLE ERROR MOTION IN THE CASE OF FIXED SENSITIVE DIRECTION

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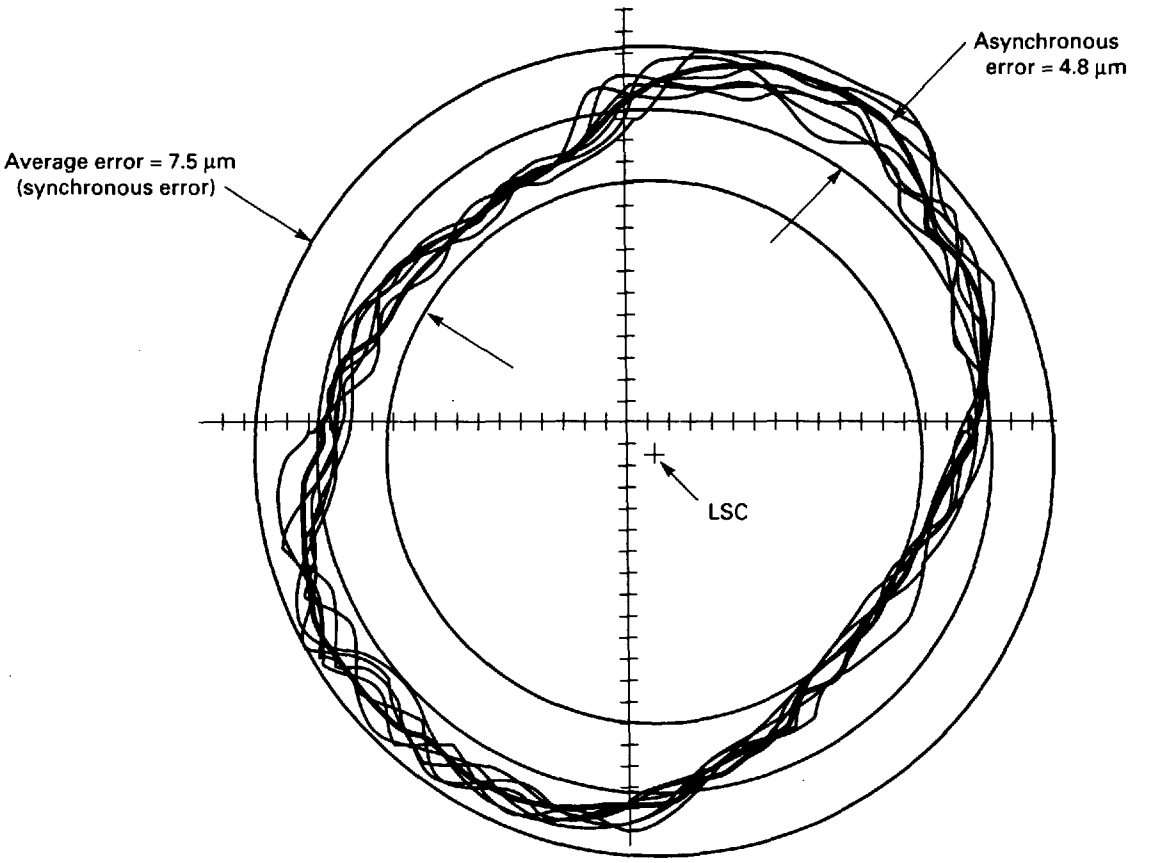


FIG. 28 TYPICAL PLOT OF SPINDLE ERROR MOTIONS AT A SINGLE SPINDLE SPEED. LSC = LEAST - SQUARES CENTER

looks the same for fixed sensitive direction and rotating sensitive direction, it is not. The plot represents the measure of a different quantity. **The rotating sensitive direction setup(s) should never be used for fixed sensitive direction measurements.**

7.5.3.2 Axial Error Motion, Fixed Sensitive Direction. The axial error motion shall be measured by positioning the displacement indicator in the axial direction, as shown in Fig. 27. Axial error motion shall be measured following the same procedure, including the warm-up cycle, and at the same spindle speeds as those specified for radial error motion as described in para. 7.5.3.1. The analysis of the error motion polar plot for axial error motion is also conceptually identical to that for radial error motion, except that fundamental error motion should not be removed analytically. The asynchronous axial error motion shall be the maximum value of the range at any angle on the error motion polar plot measured on a radial line through the polar chart center. The average axial error motion shall be the range of the average error motion values, defined with respect to the least-squares center.

7.5.3.3 Tilt Error Motion, Fixed Sensitive Direction — Option 1. Traditionally tilt error motion in the fixed sensitive direction has been measured by simultaneously sensing error motions at two spatially-separated points as is described below. For the purposes of this Standard, the following alternative is offered. First a test ball or other artifact and displacement indicators are fixtured as described in para. 7.5.2, and the average radial error motion and the asynchronous radial error motion are measured. Next the ball or other artifact and indicator are re-fixtured a distance of at least 50 mm (approximately 2 in.) from the previous position and a second set of measurements of these parameters performed. The difference in the radial error motion measurements divided by the distance between them (nominally 50 mm) is defined as the average tilt motion error. The difference in the asynchronous radial error motion divided by the length is defined as the

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asynchronous tilt motion error, in radians. The measurements of radial error motion may be used for the first set of measurements if the second set of measurements is taken shortly thereafter.

7.5.3.4 Tilt Error Motion, Fixed Sensitive Direction — Option 2. Accurate measurement of the tilt error motion requires simultaneous sensing of the radial error motion at two spatially-separated points, as shown in Fig. 27, using radial displacement indicators 1 and 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 commercial system) shall have a roundness such that any errors in their form are less than the value of error expected in the machine (see Section 9). Otherwise, procedures taken from B89.3.4M should be used to extract artifact out-of-roundness from the measurement. In either case, the analysis below assumes that the two displacement indicators are set upon the equators of the balls or along the test mandrel, at a distance L_d from one another. The two displacement indicators may be adjusted such that their sensitivity (output voltage/displacement) is the same and their outputs differenced before input into a spindle analyzer or their gains calibrated and the subtraction performed in software. In either event, the spindle shall be run for at least 20 revolutions at the three spindle speeds selected, as in para. 7.5.3.1, and the differences between the two readings (gage 1 and gage 2) plotted on a polar plot. The asynchronous tilt error motion value shall be the maximum range from the total error motion polar plot obtained from the difference between the two gage readings, measured along a radial line through the polar chart center and scaled by the length L_d between the two gages. That is,

$$\beta(\theta) = [r_2(\theta) - r_1(\theta)]/L_d$$

where

$\beta(\theta)$ = the tilt motion, in radians
$r_2(\theta)$ = the radial motion at gage 2
$r_1(\theta)$ = the radial motion at gage 1
L_d = the distance between the centers of the two gages
θ = the angular orientation of the spindle (angle on polar chart).

The average tilt error motion shall be the difference between the maximum and the minimum average error motion value, irrespective of radial direction, and defined with respect to the least-squares center, as in the equation above. For practicality, the computation of the averages and the asynchronous error motions at 16 positions shall be sufficient. For the purposes of this Standard, the maximum value of the asynchronous motion at the 16 positions shall be reported as the asynchronous tilt error motion. For the most accurate estimate, the average tilt motion must be removed from the data and the maximum range on the resulting plot used for the asynchronous motion analysis procedure.

7.5.4 Spindle Tests, Rotating Sensitive Direction. This test is only used on machines that have auxiliary spindles for milling, i.e., "live tooling." Figure 29 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 system or other artifact is mounted in the machine tool "live" spindle, which is the normal location for a tool. The test ball system or artifact can be the ball system or artifact used previously for the ETVE test, hysteresis test, and the like, and shall be of a precision greater than that desired for the spindle error motion test. (Various methods exist for removing the imprecision of the test ball system or artifact from the spindle error motion measurement. These techniques should be used in ultra-precision equipment and are outlined in B89.3.4M. For the "live tooling" on most turning centers, however, a test ball system or artifact of sufficient accuracy can be procured.) Displacement indicators are generally mounted to the work spindle of the machine in orthogonal orientations. The displacement indicators should be of the non-contacting type, such as capacitance, with a bandwidth sufficient to cover the rpm range specified. The bandwidth required depends upon the number of undulations per revolution which one desires to resolve and the rpm range of the spindle. For most turning centers with "live tooling," a bandwidth of 10 kHz is acceptable for rpms up to 6,000 and scaling of this value can be used for other spindle speeds. If capacitance gages were used for the ETVE and other tests and they have appropriate bandwidth, they can also be used for the spindle analysis tests. The figure (Fig. 29) shows one type of commercial error analyzer, but other models that meet similar specifications are perfectly suitable.

The ball system or artifact may be centered around the axis of tool rotation so as to minimize eccentricity and a signal proportional to the spindle rotation angle,

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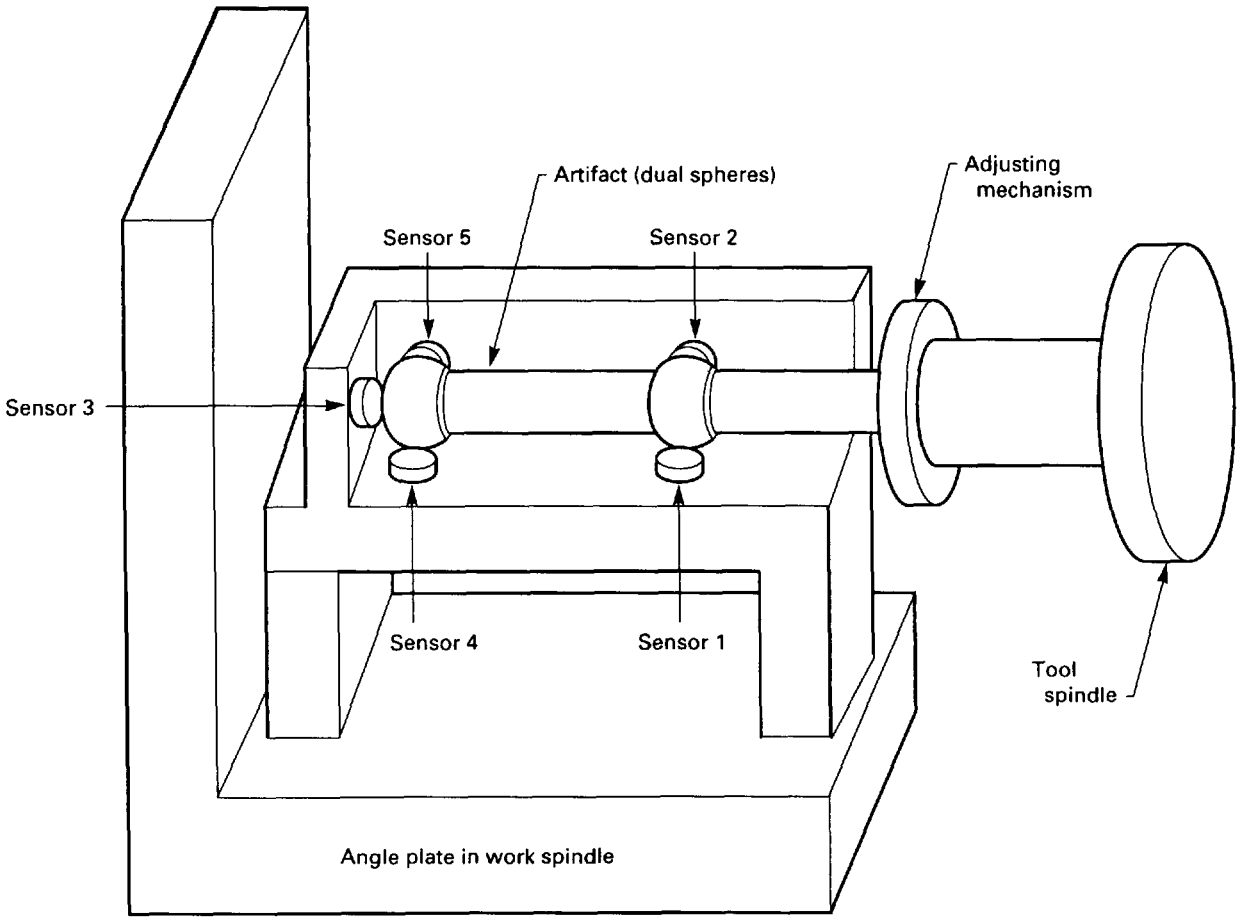


FIG. 29 TEST SETUP FOR THE MEASUREMENT OF SPINDLE ERROR MOTIONS IN THE CASE OF ROTATING SENSITIVE DIRECTION

generated by some subsidiary means or a ball or artifact may be mounted slightly eccentric and this eccentricity used to generate the signals necessary for a polar plot. The setup for this latter case is shown diagrammatically in Fig. 30, and both cases are described in detail in B89.3.4M. A third method, using a commercially-available spindle analyzer, is also acceptable.

7.5.4.1 Radial Error Motion, Rotating Sensitive Direction. The radial error motion shall be measured by computing and displaying the error motion polar plot according to the following formula:

$$r(\theta) = r_o + \Delta X(\theta) \cos \theta + \Delta Y(\theta) \sin \theta$$

where

θ = the angle of rotation of the spindle
$\Delta X(\theta)$ = the output of the gage oriented with the X axis
$\Delta Y(\theta)$ = the output of the gage oriented with Y axis and r_o as the value of the radii set by the alignment of the test ball or artifact

Radial error motion measurements shall be at three spindle rpms after the spindle has been allowed a warm-up period at half maximum rpm for a period of ten minutes. The spindle speeds chosen for this test shall be 10%, 50%, and 100% of the machine's recommended maximum spindle speed. At each speed a polar plot of the spindle error motion shall be made for a minimum of 20 revolutions.[29] A typical plot for a single spindle speed is shown in Fig. 28. It is also recommended that the machine user simply observe the output of the error-indicating system while changing the spindle speed slowly throughout its total speed range. Speeds may

[29] For maximum accuracy a higher number of revolutions may be required for ball and roller bearing spindles.

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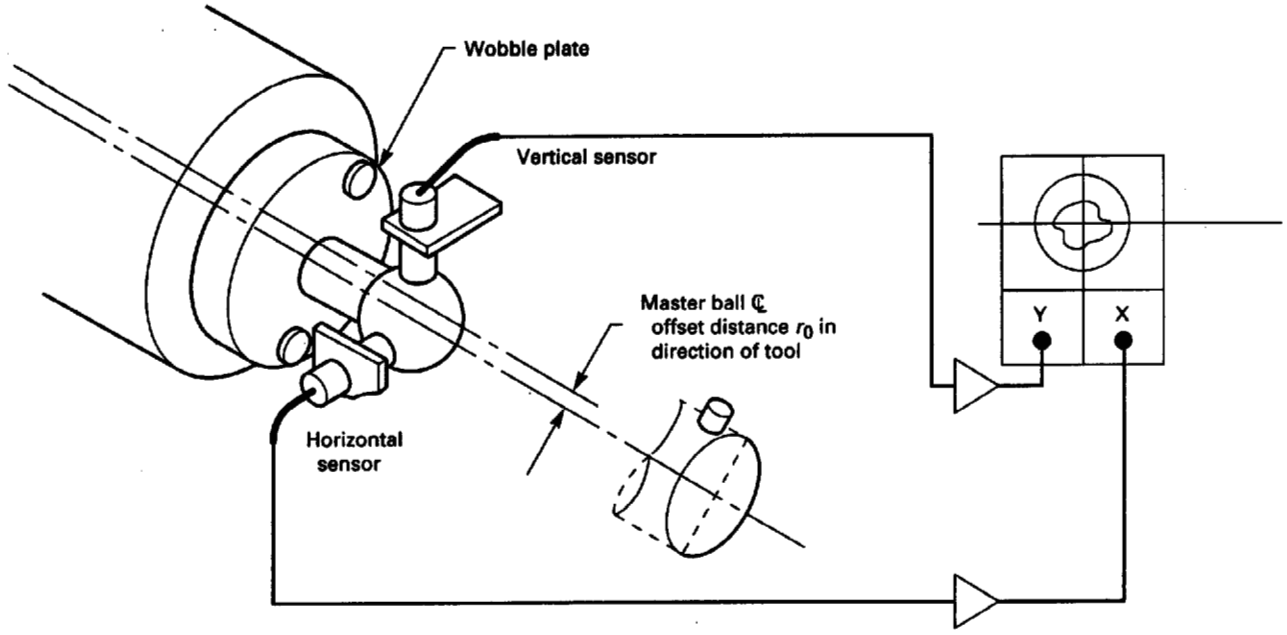


FIG. 30 SPINDLE TEST SETUP WITH AN ECCENTRIC BALL

be observed where excessive error motion results due to structural resonances. If such speeds exist, they should be avoided when machining. For the purposes of this Standard, only two error motion values will be computed from the error motion plot. The asynchronous radial error motion value (per spindle) shall be the maximum range in the radial error motion as computed from the total error motion polar plot (before averaging), measured along a radial line through the least-squares center, as shown in Fig. 28. Next, the average radial error motion polar plot shall be computed by averaging the radial 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 Fig. 28. The average radial error motion, for the purpose of this Standard, shall be the maximum value of the average (mean) radial error motion minus the minimum value of the average (mean) radial error motion, as measured with respect to the least-squares center of the polar plot.

7.5.4.2 Axial Error Motion, Rotating Sensitive Direction (Optional).[30] The axial error motion shall be measured by positioning the displacement indicator (such as a capacitance gage) in the axial direction, as shown in Fig. 29, or by using a commercial spindle analyzer system. For the measurement of axial motion with a rotating sensitive direction, synchronization to the spindle angular orientation and sophisticated data analysis are not required. Here the maximum range of the displacement over approximately 20 revolutions (see footnote 28) of the spindle shall be used as a measurement of axial error motion. The measurements can be done most simply with a commercially-available spindle analyzer, but an oscilloscope can also be used. 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 and fly cutting, however, it can contribute significantly to machining error and degradation of surface finish. For these applications it is recommended that these tests be performed.

7.5.4.3 Tilt Error Motion, Rotating Sensitive Direction (Optional). In the past, tilt motion has not been commonly measured for axes of rotation with a rotating sensitive direction. In order to measure this tilt motion, either a suitably-equipped commercial spindle error analysis system or four displacement indicators and electronics for differencing the data in a setup similar to that shown in Fig. 29 is required. In the first case, the spindle error analyzer is set up according to the supplier's recommendations and the tilt motion computed in the software. In the second case, data are taken and analyzed as in para. 7.5.4.1, except that the differences between the outputs of sensors 1 and 4 and

[30] This measurement is exactly the same as axial motion in the fixed sensitive direction, as axial motion is defined on the spindle axis (see para. 7.5.3.2).

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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 no. 3 is not required). The average tilt motion, in radians, is obtained by dividing the average differences by the distance between the sensors in the test setup. The maximum value is reported. The maximum value of the differences in the asynchronous error motions (total range on the polar plot), divided by the distance between the sensors, is reported as the asynchronous tilt motion value.

7.6 Machine Thermal Tests

7.6.1 General. For the thermal tests described in this section, the machine shall be powered up with auxiliary services operating and axes in the "feed-hold" position, with no spindle rotation, for a period sufficient to stabilize the effects of internal heat 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. Where the machine involves rotating both the workpiece and the tool on separate spindles, the tests shall be carried out for each spindle. 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 shall be recorded. All measuring instruments described in this section must conform to instrumentation and test equipment requirements given in Section 9 and also be drift tested according to the procedures outlined in Appendix I. The results of the drift test on the instrument should be no greater than one-tenth of the specification zone, otherwise the instrument should be modified or changed.

7.6.2 Spindle Thermal Stability Test. Movements of spindles caused by self-induced temperature changes yield significant errors in machining for both rotating and fixed sensitive direction. 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 hours.

7.6.2.1 Spindle Warm-Up Test. This test should be performed for all lathe, tool, and work spindles. For this test a test fixture, such as that used for the spindle error analysis tests (paras. 7.5.3 and 7.5.4), is fixtured in the machine spindle and set to read against a five-sensor "nest" as shown in Fig. 29 (for a tool spindle) and Fig. 16 (for a work spindle). The sensor "nest" should be fixtured to the tool post or to the cross slide in the location of the tool post when measuring work spindles.[31] The sensor "nest" should be fixtured to the work spindle when testing a tool spindle. The sensors should be of similar sensitivity to those used in the ETVE and spindle error tests and be of the non-contacting type (see Section 9). If desired, a test mandrel and a sensor-mounting bracket, made of a low-expansion alloy material, may be substituted for the test balls and fixturing used previously.[32] In either event, the mandrel or balls shall be adjusted to minimize radial runout and the sensors set to read positive for deflections of the balls or mandrels toward them. The spindle is then turned on to 75% of maximum rpm. Data from the five sensors are taken at intervals of a maximum of five minutes. During the first 30 minutes of the test the range of the data at all sensor locations shall be noted. The test shall proceed until the maximum change in any sensor reading over any 30-minute period, at all of the sensor locations, has reduced to 15% of the maximum of that sensor change over the first 30 minutes of the test, with a maximum test period of four hours, whichever is smaller. The data shall be plotted as shown in Fig. 31. The data during at least each five-minute interval should be averaged for at least five seconds to remove dynamic effects. (Shorter intervals than five minutes are acceptable. If a digital measurement system is used, a minimum of four samples per revolution for 20 revolutions, at any time during the five-minute period, is sufficient.) The zero for this figure is established by reading the sensors immediately after spindle rotation has commenced. In order to facilitate comparison between machines, this Standard requires reporting the offsets of the spindle axis average line, as close as possible to the chuck, part-holding device, or tool-holding device in the case of tool spindles (see para. 7.1.3). First compute the tilts of the spindle axis average line caused by thermal effects (refer to Fig. 29 for gage designations). The tilts are

$$D_{xz} = \frac{D_5 - D_2}{L_d}$$

and

[31] For work spindles, two sensors in a five-sensor nest will be in the non-sensitive direction and need not be used.

[32] If desired, the fixturing for the gage nest and for the test ball may also be made of low-expansion material. The concept here

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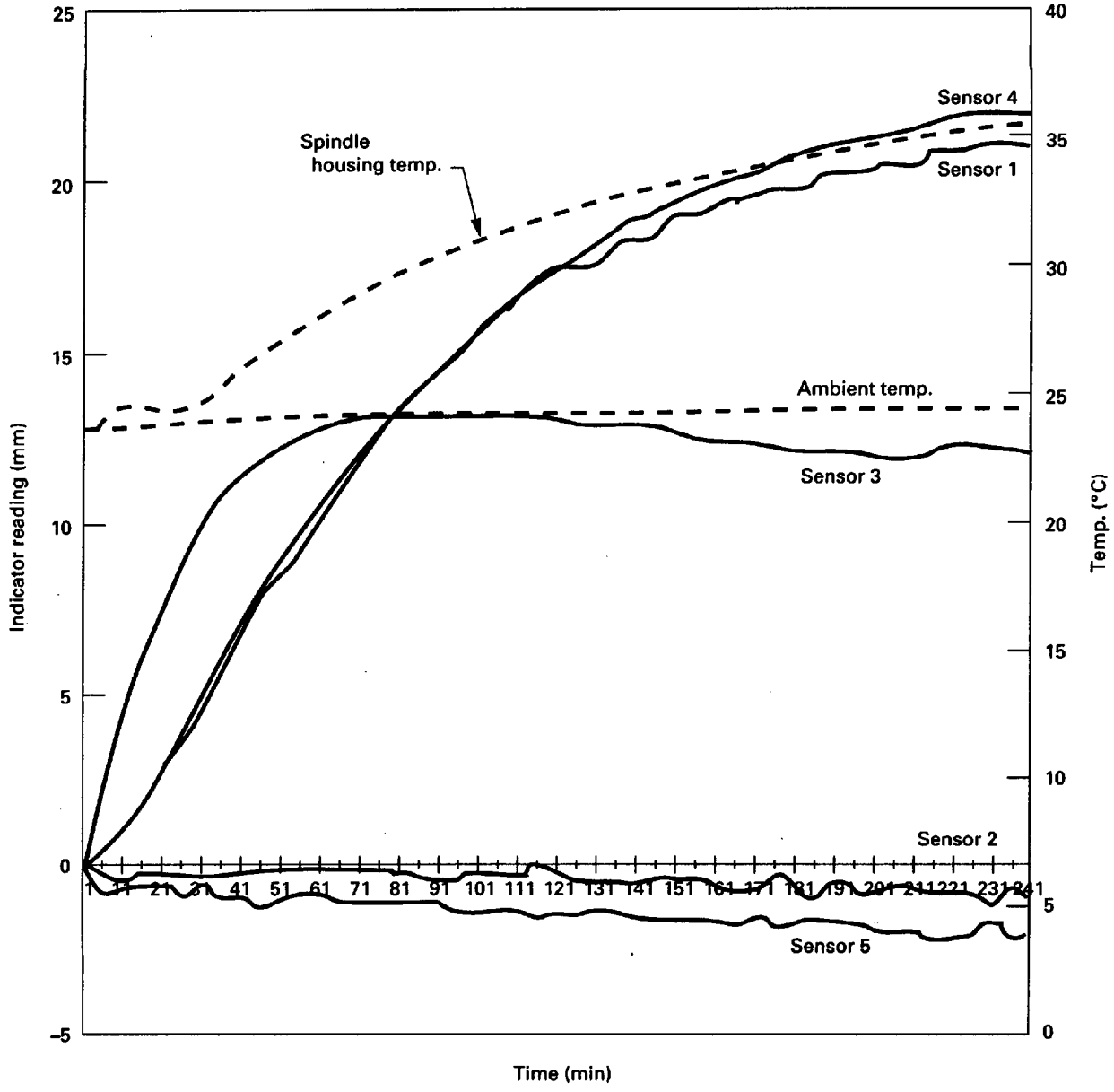


FIG. 31 SENSOR DATA FROM A TYPICAL SPINDLE THERMAL WARM-UP TEST

$$D_{yz} = \frac{D_4 - D_1}{L_d}$$

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, defined with respect to the gages and not to the machines axes.) Angular drifts of the axis average line are plotted in Fig. 32. To determine the offset drifts, measure the distance, $L_{1,2}$, between the center lines of sensors 1 or 2 and the face of the chuck, other part-holding device,

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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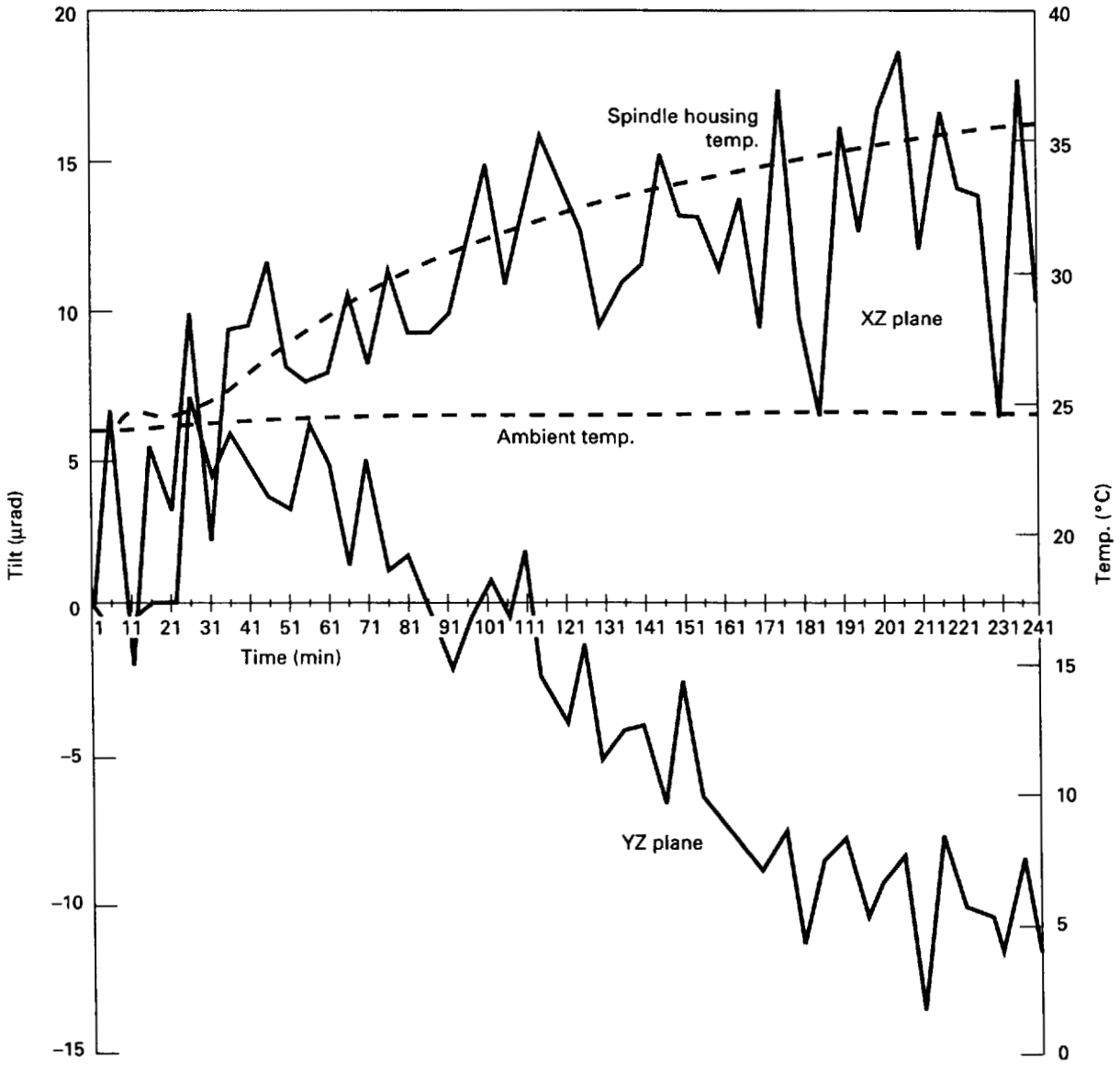


FIG. 32 TILTS OF THE AXIS AVERAGE LINE, SPINDLE WARM-UP TEST

or tool-holding device. The offsets of the axis average line at the face of the chuck, etc., are given by

$$D_x = D_2 - L_{1,2} \cdot D_{xz}$$

$$D_y = D_1 - L_{1,2} \cdot D_{yz}$$

$$D_z = D_3$$

where

D_x = the X offset in the selected plane
D_y = the Y offset in the selected plane
D_z = the Z offset
D_3 = the reading of gage 3

Like the angles, the offsets are positive in the direction of the gages and not necessarily in machine coordinates. For this test the numbers reported are to be a range of the average in precise analogy to the systematic deviations of positioning discussed in Section 7.2. As with the ETVE test, 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

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on and coolant off, where coolant here refers to the cutting lubricant.[33]

7.6.2.2 Transient Shut-Off Test (Optional). The behavior of a spindle during warm-up is often dramatically different than the behavior of a spindle during cool-down. This can lead to significant problems when using machines in intermittent duty cycles. It is therefore recommended that a transient shut-off thermal stability be measured. This is performed with either of the two setups, fixed sensitive direction or rotating sensitive direction, and for each of the machine's work or tool spindles. For the purpose of this Standard, this test should last for the length of time required for the preceding test on that spindle (para. 7.6.2.1) or four hours, whichever is shorter. For either rotating or fixed sensitive direction, this test is performed in the same way. At the end of the warm-up test, the spindle is turned off and the sensors read for a period equal to that of the warm-up test. The data are analyzed as described above. The transient shut-off thermal stability is defined as the total range of the linear (and angular) readings for a period of one hour after spindle shut-down. Again, the data are taken at maximum intervals of five minutes, with each data point being an average of all the readings obtained for a minimum of five seconds within the five-minute interval. For a more detailed discussion of the sampling required, see para. 7.6.2.1.

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 the elongation of machine scales 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 drift tested as specified in Appendix I. An example of a typical test setup is shown in Fig. 17. Note that the setup is the same as that used for the positioning accuracy and repeatability test. 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 bi-directional 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. A diagram showing this procedure is given as Fig. 33. 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 (Section 7.2). 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 bi-directionally at the two target positions. During the first 30 minutes of the test the range of the data for each axis shall be noted. The test shall proceed until the maximum change in any axis reading over any 30-minute period at both endpoints has reduced to 15% of the maximum of either endpoint change over the first 30 minutes of the test, with a maximum test period of four hours, 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.[34] It is recommended that the average value over 10-minute 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

[33] When tests are performed using cutting lubricant, capacitance sensors should not be used.

[34] 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 this position periodically recorded as the machine cools down.

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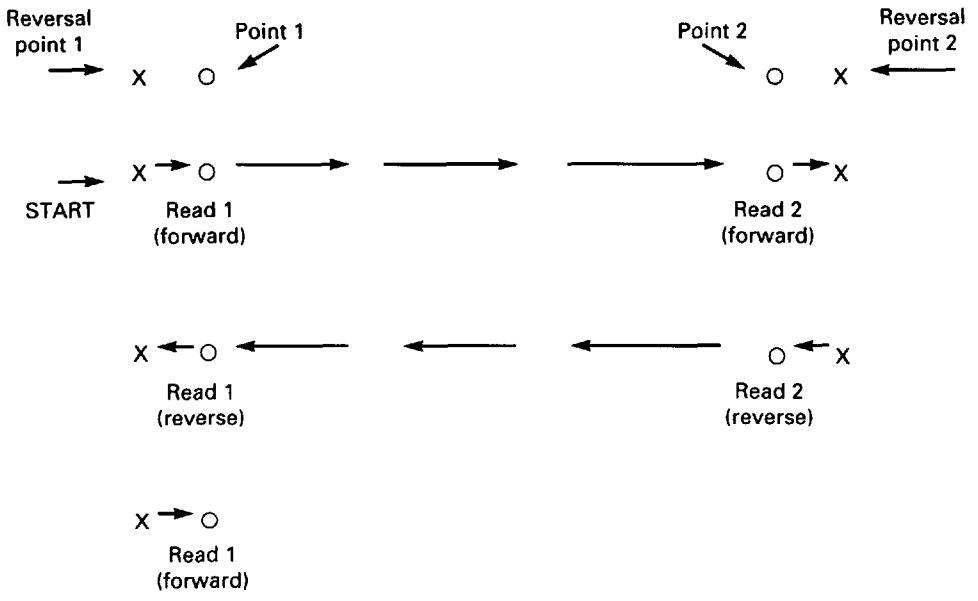


FIG. 33 PATH FOR MEASURING THERMAL DISTORTION CAUSED BY MOVING LINEAR AXES

assess the machine's thermal behavior but rather indicates thermal problems and can be effective for machine comparison.

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 temperature 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.

7.6.3.2 Interpretation of Results. At the end of the test period, the error at the two target positions for each direction shall be calculated at 10-minute 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. 34. 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 (↓). 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 27(b) shows a typical measurement setup for a lathe or a turning center with a single work spindle and a single tool position or turret. Three displacement indicators shall be rigidly mounted to the tool-holding zone of the machine, so as to be able to monitor the following:

(a) the relative displacements occurring between the structure that holds the tool and the structure that holds the workpiece along the two orthogonal axes parallel to the axes of travel of the machine; and

(b) tilt or rotation around one axis[35] normal to the spindle axis.

[35] If desired, this test may also be performed on a turning center with "live tooling" for each of the tool spindles. In that case, the test for each spindle should be specified in equivalent detail. Also, the five-gage nest (Fig. 31) may be used.

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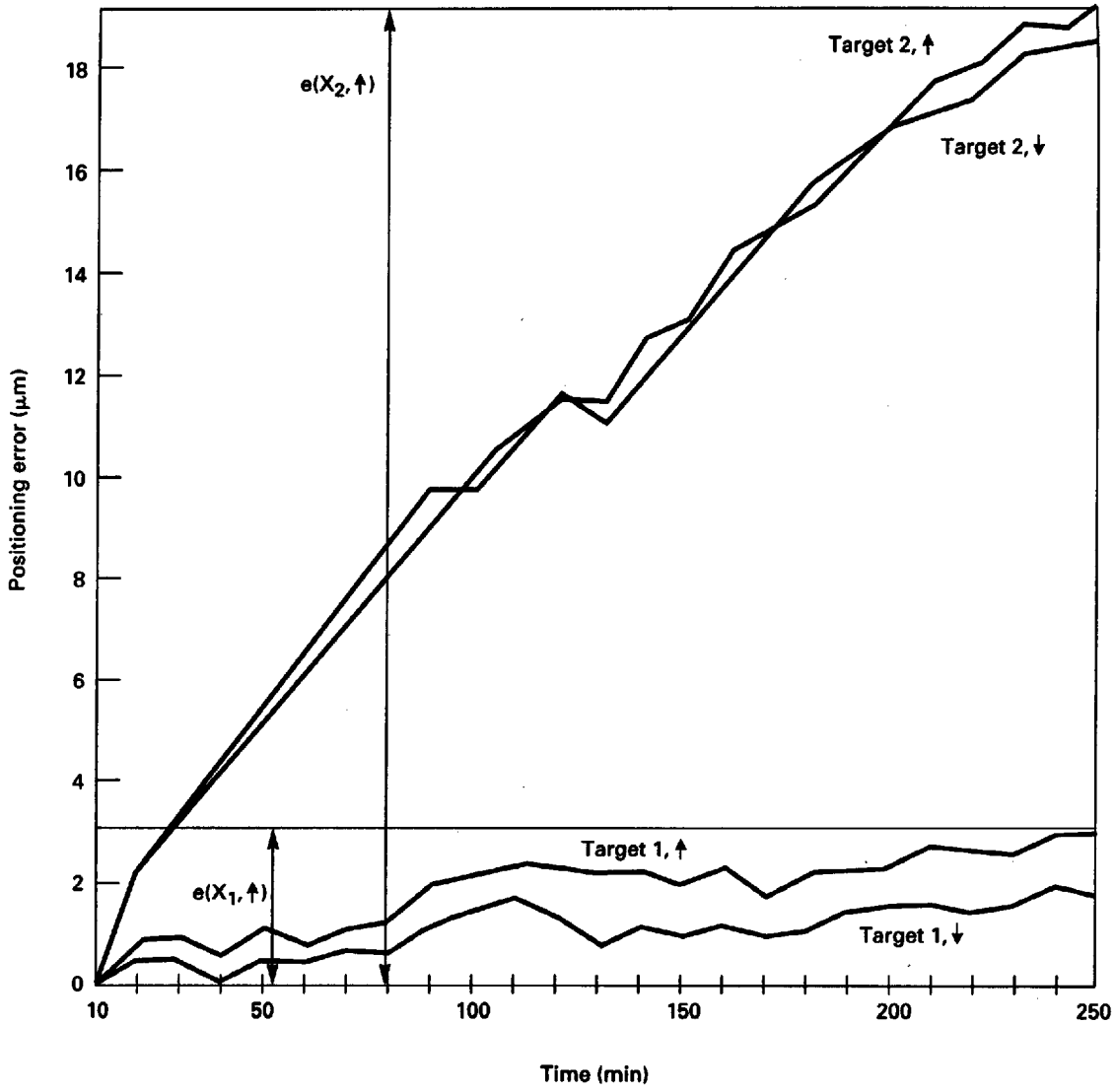


FIG. 34 POSITION ERROR VERSUS TIME FOR A TYPICAL TEST FOR THERMAL DISTORTION CAUSED BY A MOVING LINEAR AXIS

If the machine has more than one spindle or turret, the test(s) should be performed as follows. On multiple-turret, single-spindle machines (Groups 2-1 through 2-3), the sensor should be placed in the most commonly-used turret and the artifact in the spindle. Where possible, all axes should be exercised. On Group 3 machines (see Section 4.2), use one spindle with the gage and sensor "nest" and the turret, but exercise both spindles and the turret. On Group 4 and 5 machines, one commonly-used spindle and one commonly-used turret should be selected, but all spindles and all turrets should be exercised. For Group 6 machines the test should be performed twice: first with the sensor "nest" in a turret measuring with respect to a work spindle, and second with the sensor "nest" in a work spindle reading with respect to a turret. Wherever possible, all the other axes and spindles should be exercised during the test. If desired, the user may also select other combinations if these combinations are made part of the specification and described in equivalent detail. 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

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to the measured displacements, they are indications of the thermal changes on the machine structure. For the purposes of this Standard, the spindle(s) shall be run continuously at 0.5 times the maximum speed throughout the test. The axes shall be moved from the test position to the far end of travel and immediately returned to the test position where they should dwell for a sufficient time for the next reading to be recorded. A minimum of four samples per revolution for 20 revolutions shall be averaged. Axis movements shall be at 0.5 times the rapid traverse rate except for the final 5 mm approach to the test position which should be carried out at a low feed rate, and the dwell time shall be the settling time as specified in the positioning accuracy and repeatability test (Section 7.2).

Note: The sequence of axis and other movements, including turret indexing, should be such as to avoid collisions with the measuring equipment and to keep the direction of approach to the test position constant.

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-minute period, at all the measurement locations, has reduced to less than 15% of the maximum position change over the first 30 minutes of the test, with a maximum test time of four hours. The results should be plotted in graphs of displacement and temperature versus time, as shown in the example given in Fig. 35.

7.6.4.2 Interpretation of Results. 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 displacements versus time graphs. The results are influenced by the positional repeatability of the machine axis.

7.6.4.3 Presentation of Results. The range of displacements along each machine axis within the first 30 minutes [$c(X_1,30)$, $c(X_2,30)$, $c(Z,30)$] and during the total test period [$c(X_1,t)$, $c(X_2,t)$, $c(Z,t)$], where t is the time at the end of the spindle running period, shall be recorded along with the distance, L_{cte}, between the two X displacement indicators and the total time of the test, t. These values, as shown in Table 5, shall be presented with the displacement versus time graphs. The test procedure, traverse rate, dwell time, sequence of axes movements, location of target positions, and the location of the measurement setup, including the locations of the temperature sensors, should also be reported with the results of the tests.

7.7 Critical Alignments

7.7.1 General. In a lathe or turning center some alignments reflect themselves one-to-one into errors in the finished part. For a simple two-axis machine, these alignments are the parallelism of the Z slide with the spindle axis of rotation and the perpendicularity of the cross slide (X axis) to the spindle axis. These critical alignment parameters shall be measured using metrology instrumentation or by cutting test parts and performing part-trace tests for all XZ axis pairs. The procedure for performing a part-trace test is outlined in Appendix J. If the machine is equipped with on-machine probing, the probing system could possibly be used to perform these tests. In such cases, the supplier shall provide appropriate brackets and electrical connections. Both procedures are allowed in this Standard. It should be noted, however, that the measurements performed by cutting test parts contain information regarding the thermal variations of the machine due to spindle growth and thus will yield different results than the measurements performed using metrology instruments. The choice of test(s), either measurement with a straightedge or test part measurement, or both, shall be clearly stated as part of the original machine specification.[36]

Note: Those users desiring to assign an algebraic sign to squareness and parallelism measurements should follow the conventions given in Appendix N. Most of the figures in the following sections show negative squareness errors.

7.7.2 Squareness of the Cross Slide (X Axis) with the Work Spindle Axis (Often a C Axis)[37]

7.7.2.1 Measurement Using a Mechanical Straightedge. A typical setup for measuring the squareness of the cross slide to the spindle axis using a mechanical straightedge and a displacement indicator (or an optical straightedge substituting for a mechanical

[36] In the absence of specifications to the contrary, the general parameters of machine geometry are presumed to apply when the machine is "cold." The reason for this rule is that the "hot" conditions are too variable to have any meaning. If the squareness of X to C is measured when the machine is "cold" using the straightedge or log reversal, and then measured "hot" using the part trace past center, the thermal errors can be identified. The machine user is, of course, concerned with the "bottom line" accuracy. If the user is aware of the sources of each error, special procedures can often be developed to improve the bottom line accuracy. These are often called "procedural solutions."

[37] Note that many lathes use "diameter programming" and care should be taken when programming a machine with these setups to avoid possible damage to expensive instruments.

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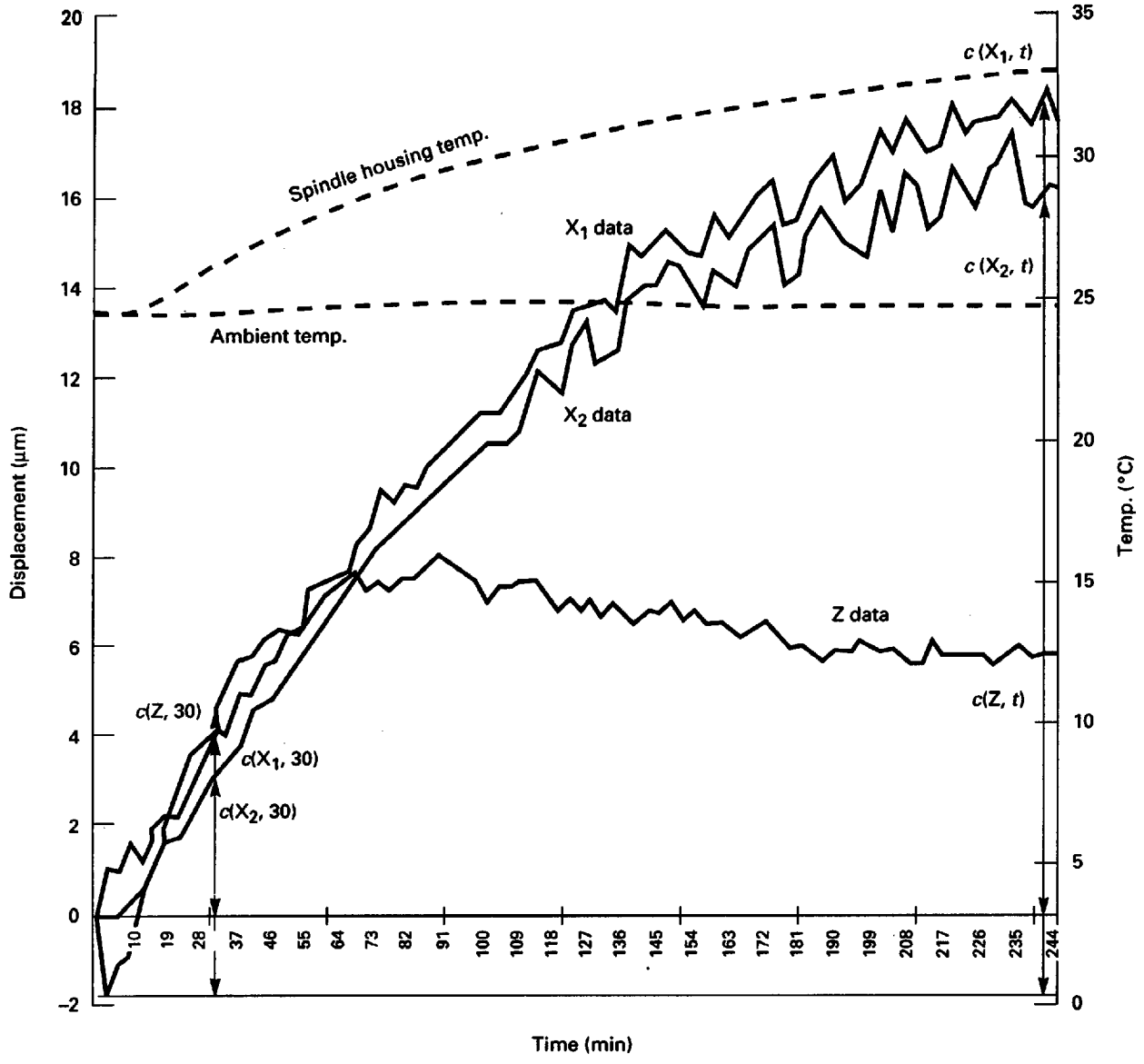


FIG. 35 TYPICAL RESULTS FROM A COMPOSITE THERMAL ERROR TEST

straightedge and a plane mirror interferometer as the indicator) is shown in Fig. 36, which shows a horizontal spindle turning center. (A straightedge can be manufactured rather than purchased; see para. 7.7.2.2.) With the spindle at position $\theta = 0$, the straightedge is mounted so as to straddle the rotary axis center and aligned using the indicator with the machine axis. The change in separation between the gaging surface of the straightedge and the appropriate machine axis, shown as 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, ANGF, between the X axis and the straightedge gaging surface. Next, the rotary axis is rotated to $\theta = 180$ degrees and a similar measurement performed yielding an angle ANGR. Note that the straightedge must be of the right length and properly clamped for this 180-degree reversal to be possible, without damaging the machine or the straightedge or both. The angles involved are shown in Fig. 37. In Fig. 37, an arbitrary "forward direction" with the angular axis at zero angle is depicted and the "reverse direction" with the angular axis rotated 180 degrees. The angle *F* in the figure is the squareness error between the straightedge and the spindle axis

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TABLE 5 TYPICAL PRESENTATION OF RESULTS FROM COMPOSITE THERMAL ERROR TESTS

	X_1	X_2	Y_1 [Note (1)]	Y_2	Z
After 30 minutes	$c(X_1, 30)$	$c(X_2, 30)$	n/a	n/a	$c(Z, 30)$
After end of spindle running period (t)	$c(X_1,t)$	$c(X_2,t)$	n/a	n/a	$c(Z,t)$
Time (t)					
Distance (L_{cte})					

NOTE:
(1) Values for Y_1 and Y_2 are obtained only when the optional five-gage nest is used. They are in the non-sensitive direction of the work spindle on lathes.

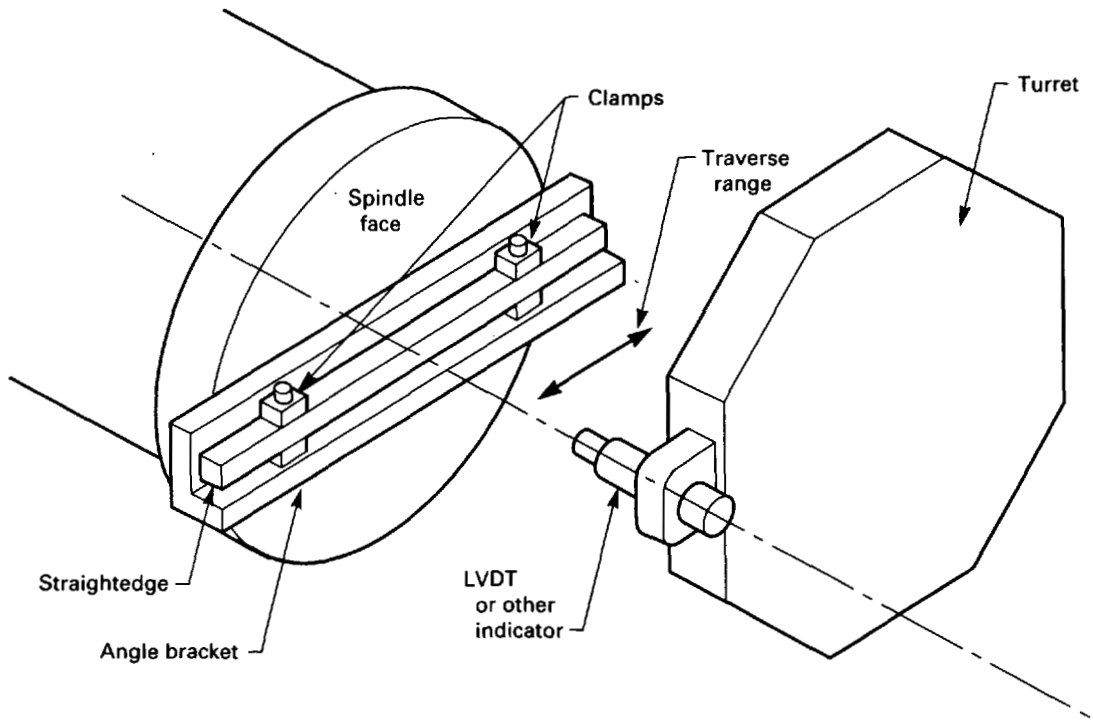
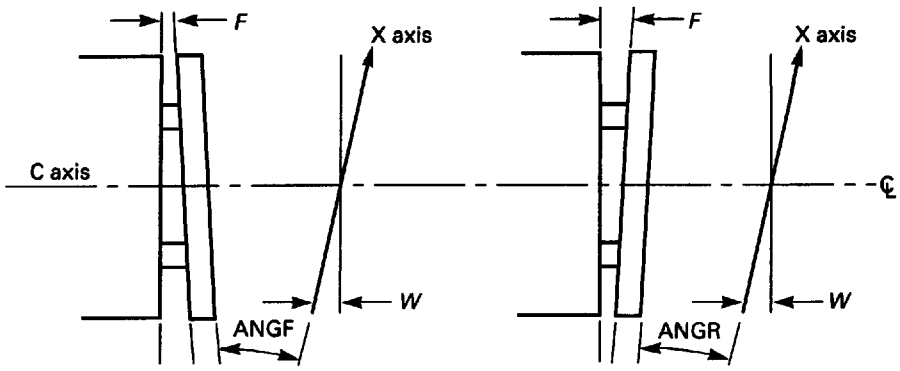


FIG. 36 SETUP FOR MEASURING SQUARENESS OF THE CROSS SLIDE TO THE WORK SPINDLE USING A MECHANICAL STRAIGHTEDGE

resulting from initial alignment, while the angle W is the desired squareness error. The measured angles and the respective orientations are denoted by ANGF and ANGR. The out-of-squareness is the bisector of these two angles, algebraically $W = 1/2 \times (\text{ANGF} + \text{ANGR})$. If the straightedge is supplied with a correction table, corrections should be made prior to the creation of the graph shown as Fig. 38.[38] In the cases of highest accuracy, the straightedge should be pre-calibrated using straightedge reversal (see ASME B5.54-1992 for the mathematics of this technique). If it is desired to

[38] The data shown in this figure contain a sinusoid straightness term which may not be typical of most machines.

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Forward, Theta = 0 deg. **Reverse, Theta = 180 deg.**

FIG. 37 SCHEMATIC SHOWING THE ANGLES INVOLVED WHEN MEASURING CROSS SLIDE SQUARENESS TO THE SPINDLE AXIS

measure the out-of-squareness of a Y axis, this can be done using the same procedure, but with the spindle at positions $\theta = 90$ degrees and $\theta = 270$ degrees.

7.7.2.2 Measurement by Part Tracing Past Center. Figures 39 and 40 illustrate this technique. The procedure consists of facing an aluminum cylinder to center with an appropriate tool.[39] Since this test is performed after the spindle has been on, the machine supplier shall recommend an appropriate warm-up cycle, machining time, and soak-out time. The size of the cylinder depends on the size of the machine. The diameter, D_c, should be somewhat less than the swing of the lathe but needs not be greater than 300 mm (approx. 12 in) for small machines. The cylinder may also be used, if the user selects, to measure the Z-axis parallelism; thus, its length, L_c, should be at least 300 mm (approx. 12 in.) or the maximum Z capacity of the lathe, whichever is smaller. Examination of Fig. 39(b) shows that the test cylinder is drilled and countersunk at six locations but is only mounted at three. Six holes are necessary only in the case that the cylinder is to be measured for roundness using the Donaldson Reversal Method (see ASME B89.3.4-1985, pg. 40). It is recommended that the part be "roughed" with one tool and then finished with a light cut using a new, sharp tool. After cutting, the spindle is stopped and the machine is allowed to soak out. A displacement indicator is then bracketed on the X slide in the tool position and indicated against the part over the range of X travel used to machine the face. The data obtained from this are shown in Fig. 38 as the "before center" data. (Ideally, the indicator should always read zero when traversed along the cutting path, but thermal changes may cause the machine spindle axis to move.) Next, the indicator is re-bracketed to the tool post, with the bracket that moves it the radius of the part in the X direction. This is illustrated in Fig. 40. This allows the indicator to travel beyond center. The data obtained from this measurement are shown in Fig. 38 as the "after center" data. The bisector of these two angles is the machine out-of-squareness, as is clearly indicated in Fig. 38. Calculations are equivalent to those given in para. 7.7.2.1.

Note: One-half the change in direction (angle) that is observed by the indicator as it travels across center is the "effective" non-squareness of the X axis (including spindle growth) at one particular interval of the spindle growth curve. The "effective" non-squareness will depend on which direction the facing cut is made as well as the interval on the spindle growth curve. This test can be used as an educational experiment to reveal the sensitivities to these variables. The effect of using the constant cutting velocity feature (variable spindle rpm) can also be measured. Since the test part is generated with the spindle running, this test will not, in general, give the same results as the test conducted with the mechanical straightedge.

Note: A diamond tool cutting aluminum is preferred because of its (1) minimum wear, (2) no built-up edge, and (3) sharpness. Elimination of the built-up edge means that there is minimum sensitivity to cutting velocity, rake angles, type of coolant, etc. Diamond tools have a sharpness which permits very light cuts [0.1 μm (approx. 4 μin.) or less] if the machine has that positioning capability. Cutting force deflection on light finishing cuts is usually negligible.

Note: Bracketing the indicator to a position different than the functional point of the tool is a violation of the Bryan Principle. This causes an error in the calculated squareness if the X axis has a yaw error. The error equals the change in yaw error per unit of X-axis motion times half the distance between the indicator positions.

[39] Depending upon the machine accuracy, this tool can be a single crystal diamond tool, or a polycrystalline diamond insert with a small nose radius (less than 0.75 mm), or another sharp tool of comparable nose radius.

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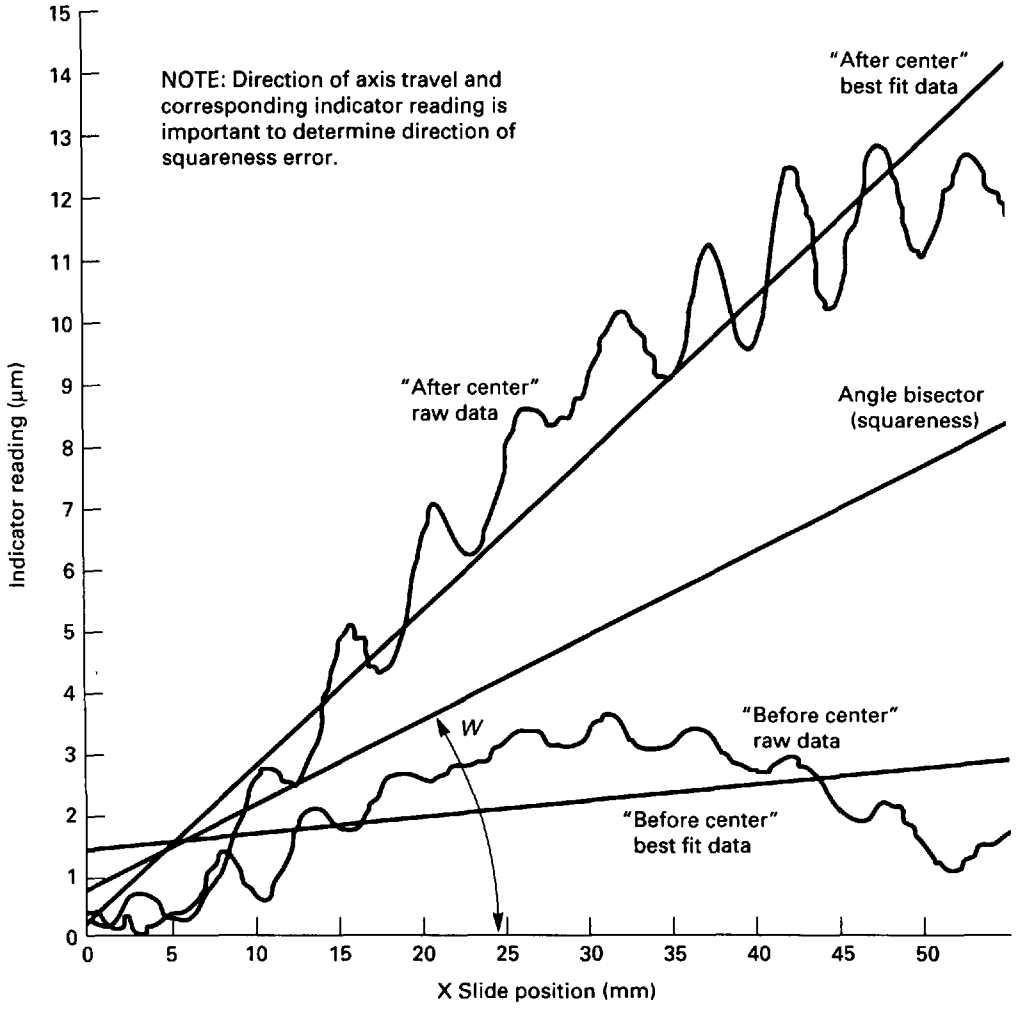
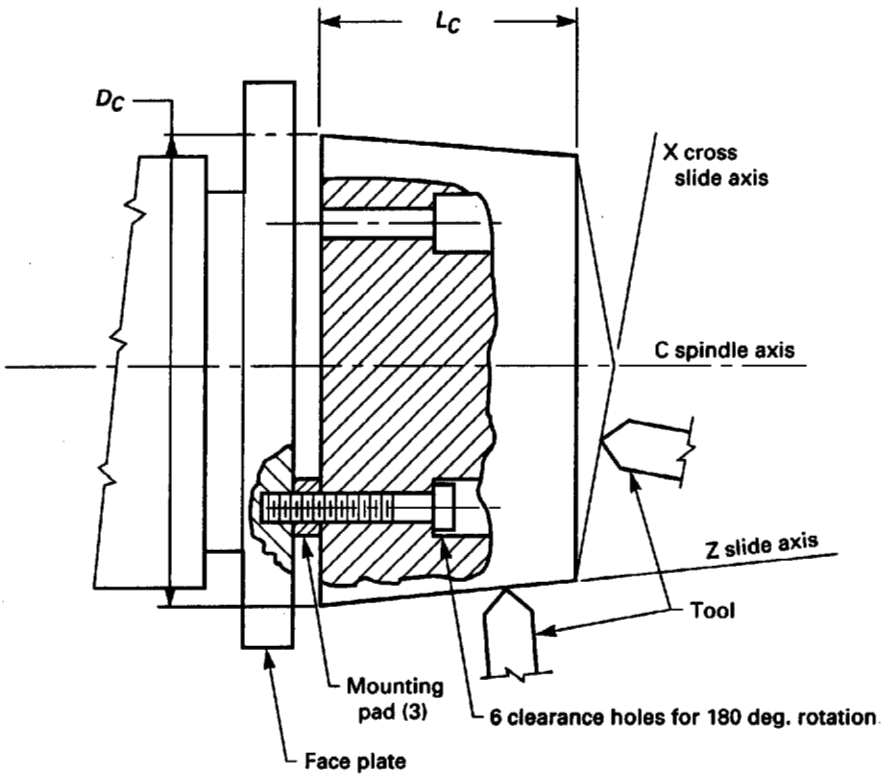


FIG. 38 TYPICAL DATA, CROSS SLIDE OUT-OF-SQUARENESS MEASUREMENT. WHEN USING A STRAIGHTEDGE, INTERPRET "BEFORE CENTER" AS THE FORWARD POSITION AND "AFTER CENTER" AS THE REVERSE POSITION

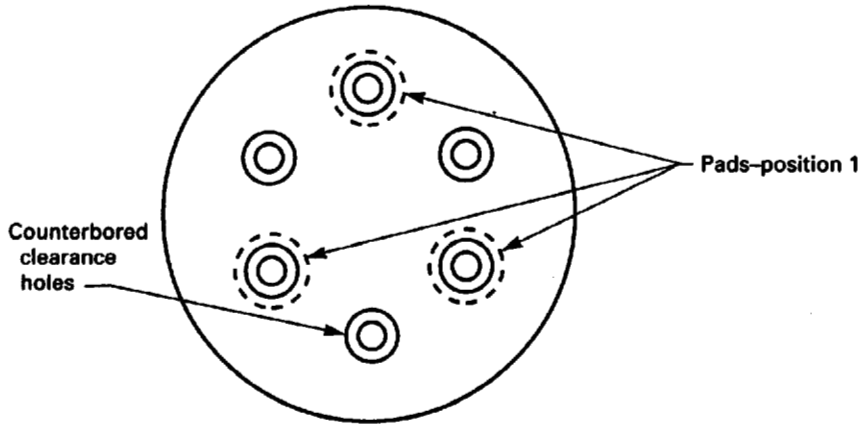
The yaw error per unit of axis motion can be estimated by plotting the measured yaw error as a function of the X-axis position. It equals the angle of the best fit line through the data points over the range of the X-axis positions used to measure the face of the cylinder.

7.7.2.3 End-for-End Cylinder Reversal. The same cylinder faced in para. 7.7.2.2 may also be used for a straightedge, as described in para. 7.7.2.1. First, the cylinder is machined using the machine Z axis to make a cylinder. While the turned cylinder is still in the machine, its straightness is measured using reversal principles, as described in ASME B5.54-1992. The diamond turned cylinder, which now has a known straightness profile as a result of the straightedge reversal procedure, is removed and remounted on a bracket on the spindle approximately parallel with the X axis in both horizontal and vertical planes. This is shown in Fig. 41. The cylinder now serves as the mechanical straightedge described in para. 7.7.2.1. A displacement indicator is mounted on the X axis at the functional point, tool location, and traversed in the X direction along the crest (diameter) of the cylinder until it reaches center. The spindle is then rotated 180 degrees and the trace repeated in the outward direction. The data are fit to straight lines as shown in Fig. 38. The bisector of the angle between the two best-fit straight lines to these data is the non-squareness of the X axis to the C axis in the cold condition. (Straightness of the X axis can also be assessed since the cylinder now has a known nonstraightness, but that is not a requirement of this Standard.)

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(a)



(b)

FIG. 39 TWO VIEWS OF THE CYLINDER USED FOR MEASURING MACHINE OUT-OF-SQUARENESS AND PARALLELISM. THE TAPER AND THE CONE ANGLE ON THE TEST CYLINDER ARE HIGHLY EXAGGERATED

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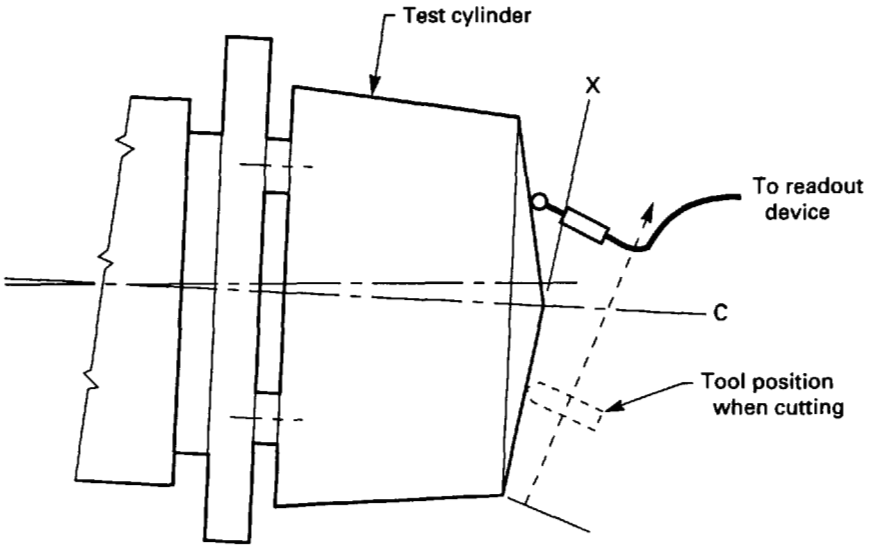


FIG. 40 PART TRACE TEST PAST CENTERS TO DETERMINE CROSS SLIDE SQUARENESS WITH THE SPINDLE AXIS

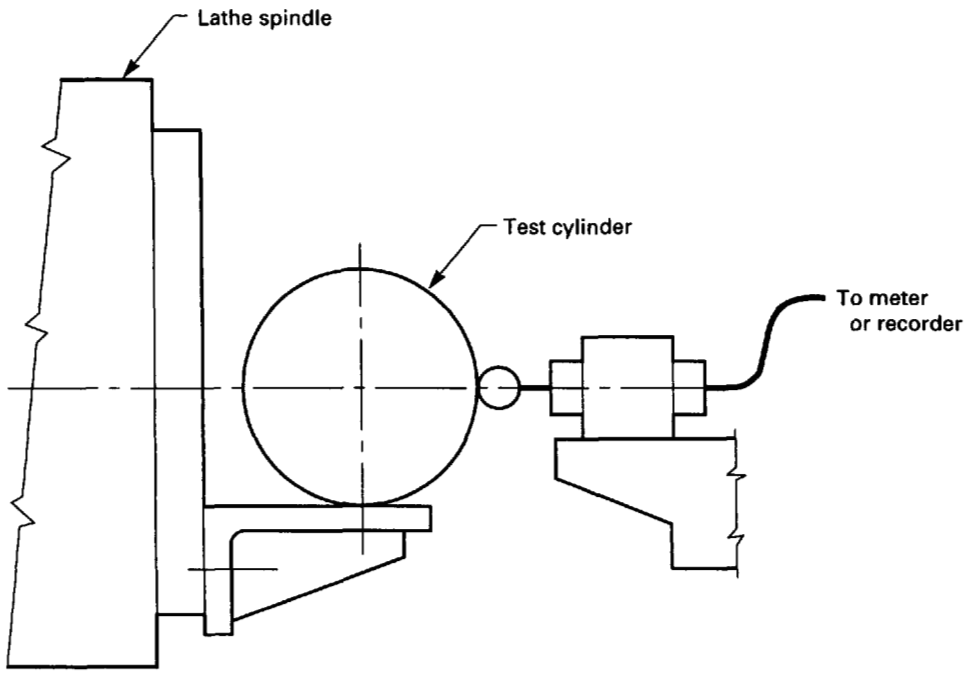


FIG. 41 CYLINDER REVERSAL FOR CROSS SLIDE SQUARENESS

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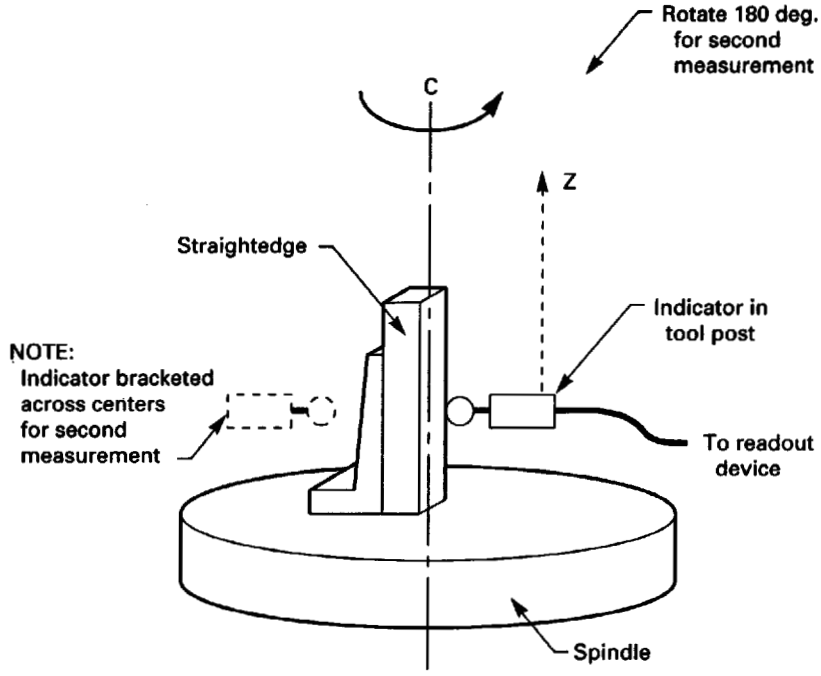


FIG. 42 SETUP FOR STRAIGHTEDGE ROTATION ON A VERTICAL SPINDLE LATHE FOR MEASURING Z-AXIS PARALLELISM TO THE C-AXIS

7.7.3 Parallelism of the Longitudinal Slide (Z Axis) with the Work Spindle (C Axis) in the XZ Plane[40]

7.7.3.1 Straightedge Rotation Method. This technique consists of mounting a straightedge (optical or mechanical), or precision mandrel, on the spindle and adjusting it approximately parallel to the Z axis. Figure 42 shows the setup on a vertical spindle lathe and Fig. 43 a horizontal spindle lathe. An indicator is bracketed in the tool position, facing in the X direction, and a trace is made along the front side of the straightedge. Data are plotted as shown in Fig. 38. The spindle is rotated 180 degrees, the indicator is re-bracketed using an extension from the tool post, and a second trace is made from the back side along the same line on the straightedge. For this measurement the sign of the indicator reading should be reversed. These data are also plotted. The angle that bisects the best-fit straight line to these two sets of data is the "cold" out-of-parallelism of the Z axis to the C axis. The calculations are identical to those given in para. 7.7.2.1. (Analysis of these two traces also gives the straightness of the straightedge and the straightness of the Z axis of the machine; see ASME B5.54 for a full discussion of straightedge reversal).

7.7.3.2 Part Traces on the Cylinder Method. Figure 44 illustrates this technique. It consists of turning an aluminum cylinder (see Fig. 39), using tooling as described in para. 7.7.2.2, on the "front" side (normal machining side) of center, letting the machine soak out, and then making two part traces with an appropriate displacement indicator (see Appendix J), one on the front side and the other on the back side of center. For the back side trace the sign of the indicator is reversed. If this option is selected, the supplier should specify a soak-out time, a machining time, and an appropriate warm-up cycle. Note that the second trace has to be made by re-bracketing the indicator and not moving the machine in the X direction. This is particularly true for vertical turret lathes, where the Z slide is stacked on the X slide. Data from these traces are plotted similarly to those shown in Fig. 38. As in the previous test, the out-of-parallelism of the Z axis to the C axis is the line which bisects the best-fit straight lines to these data. Note that the indicator, when it is bracketed across centers, should be at the same Z position, with respect to the turret, as was the cutting tool and, when the cylinder is traversed, the same range

[40] Some lathes are quite long. If either the mechanical straightedge or part-trace test option is chosen, the user should specify the length of the straightedge or cylinder as part of the original machine specification.

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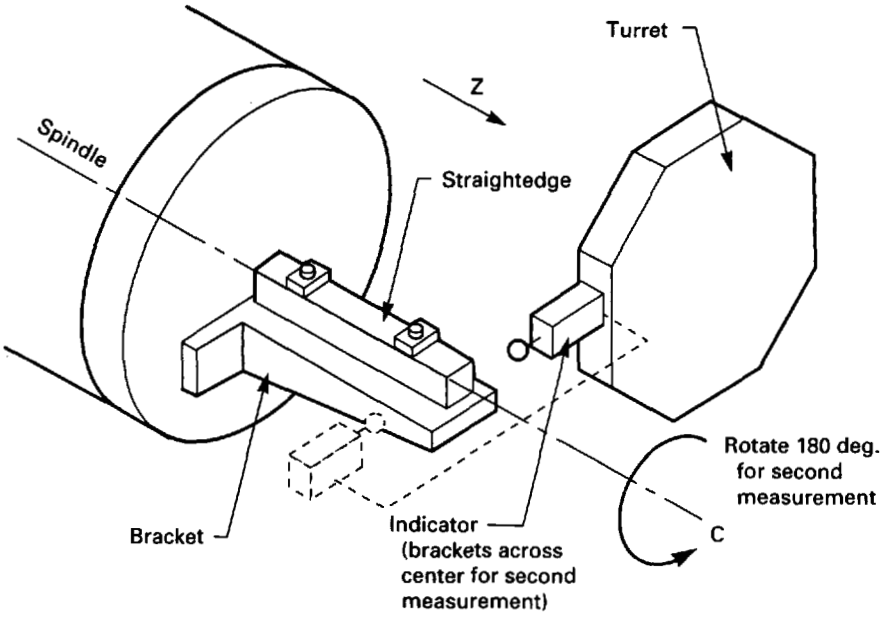


FIG. 43 SETUP FOR STRAIGHTEDGE ROTATING ON A HORIZONTAL SPINDLE LATHE FOR MEASURING Z-AXIS PARALLELISM TO THE C-AXIS

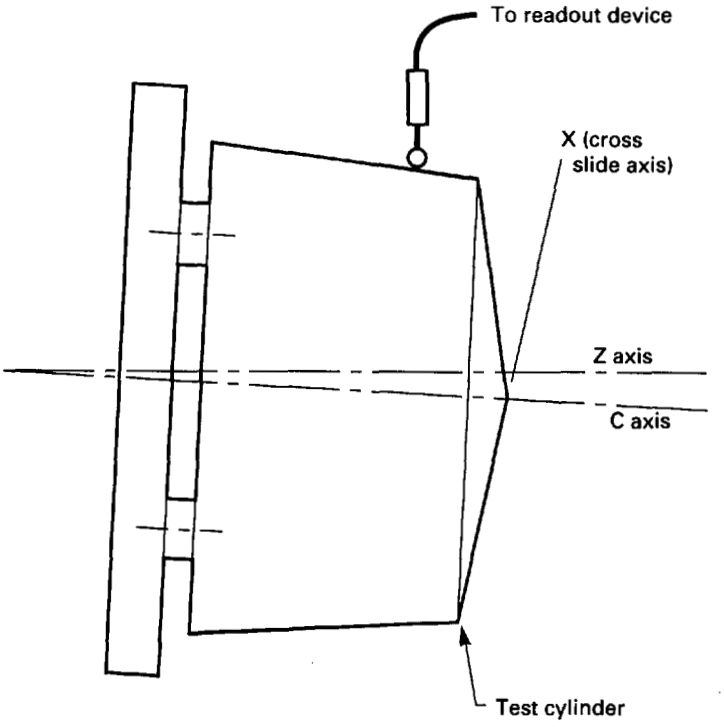


FIG. 44 Z SLIDE PARALLELISM SCHEMATIC SHOWING TEST CYLINDER

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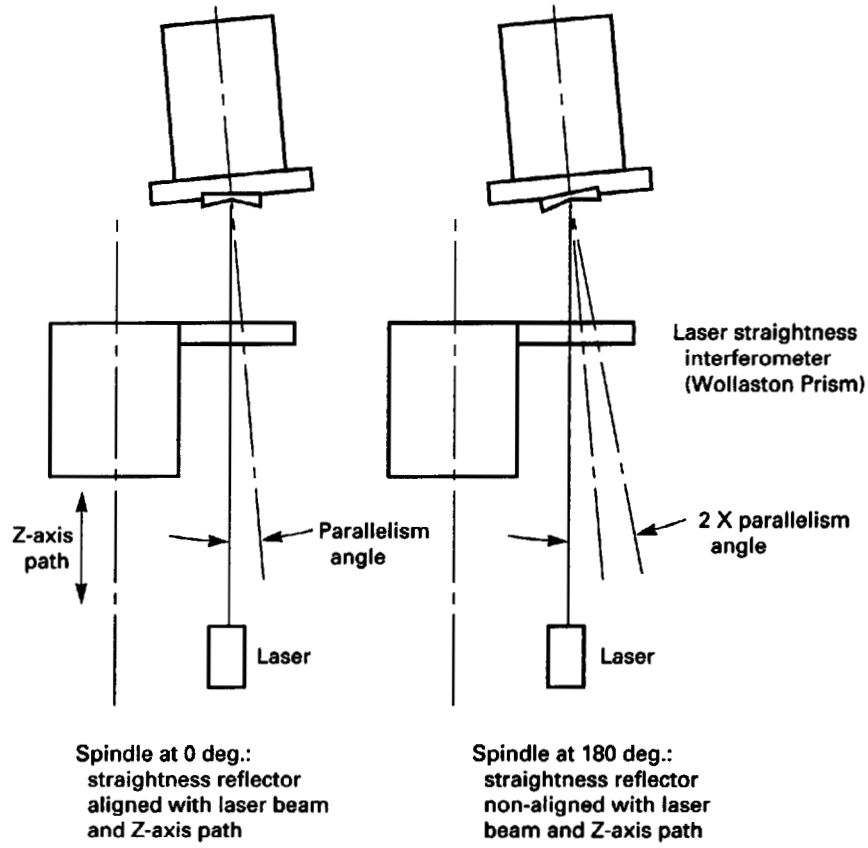


FIG. 45 DUAL STRAIGHTNESS MEASUREMENT FOR PARALLELISM

is traversed as when the part was machined but the sign of the indicator is reversed. (The straightness of the Z axis as well as its parallelism to the C axis in both the machine "hot" and "cold" condition can be determined from these traces.)

The part trace on the front side of center is conceptually zero since it has just been turned. It may, however, show a slope if the heat generated in the spindle during machining is not symmetrically distributed or the drive motor is located next to the spindle. These heat sources can rotate the headstock of the machine so the average axis line tilts with respect to the Z axis. The slope of the part trace on the front side of center represents this tilt.

7.7.4 Long-Range Parallelism of the Z Axis (Longitudinal Slide) with the C Axis (Work Spindle). When parallelism is required for the total length of a longitudinal axis, a dual straightness measurement can be made using the laser straightness interferometer and straightness reflector, as shown in Fig. 45. Conceptually, this is the same as cutting a cylinder and indicating the opposite side. Two straightness measurements are required. For the first measurement, the laser beam and path of the moving Wollaston prism (straightness interferometer) are aligned mechanically (i.e., no data fit is permitted). The spindle, with straightness reflector, is rotated 180 degrees and the second straightness measurement is recorded. The average straightness at each Z-axis position is plotted for each of the two measurements, as shown in Fig. 46. At each measurement point in both the forward and the reverse directions, the laser reading should be averaged for a minimum of five seconds time and taking a minimum of 2,000 data points. Neither data curve is corrected for alignment of the optics, slideway, and laser beam.[41]

The setup for a vertically traversing axis is more complicated. It is shown in Fig. 47. In this case, a retroreflector is used in the tool position and the laser

[41] In principle, the parallelism of the Z axis to the spindle axis can be obtained without mechanical alignment for the first measurement. However, error can be significant when measuring large straightness values.

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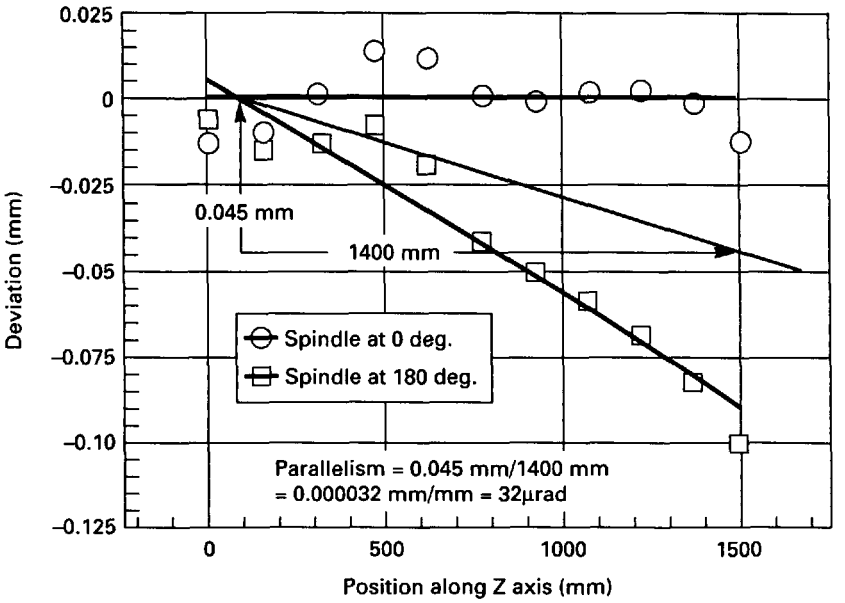


FIG. 46 PARALLELISM OF Z-AXIS TO SPINDLE AXIS OF ROTATION (THE BISECTOR IS THE PARALLELISM ANGLE)

and bending mirror must be moved between the setups. In no case should the straightness reflector, shown in the insets 1 and 2 of the figure, be moved.

In some cases, the parallelism of a rotary axis is more easily measured mechanically. For a description of this procedure, see para. 5.8.4.2 of ASME B5.54-1992.

7.8 Contouring Performance Using Circular Tests

7.8.1 General. Circular tests provide a rapid and efficient way of measuring a machine tool's contouring accuracy along a circular contour.[42] Circular contours provide one of the best checks for contouring performance in that as a machine is traversing with multiple axes along a circular trajectory each axis goes through sinusoidal acceleration, velocity, and position changes. In this Standard, circular tests using telescoping ball bars, grid plates, or precision disks are typically used. Here tests are specified for machines with only two axes. More complex tests, if desired, should be devised for other machines and agreed on between supplier and user as part of the machine purchase. Each test specified shall be run at two speeds. These two speeds are approximately 10% of maximum feed rate and 80% of maximum feed rate. 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 ball bar test and report the actual feed rate from the circle circumference and the time. Other feed rates may be specified by the user, if desired. The length of the telescoping ball bar recommended for this test is slightly less than one-half of the range of travel of the shortest axis under test or 250 mm (approx. 10 in.), whichever is smaller. For clarity of explanation, the tests described below are illustrated for a particular type of telescoping ball bar. 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. For these tests the spindle must be rigidly locked.[43] Other test conditions are given in Section 7.1.

[42] When used statically in a point-to-point positioning mode the ball bar can also provide valuable information about positioning performance and machine geometry.

[43] Machines which incorporate angular positioning capability, with spindle rotation, may exhibit angular "hunting" of the spindle, leading to unwanted errors when making measurements. Angular motion may be reduced by turning the spindle off and disengaging the drive (if possible). A frictional anti-rotation device, such as a magnetic base, should be placed between the fixed and rotating positions of the spindle. Under no circumstances should a rigid connection be made between the fixed and rotating portions of the spindle. The friction connection protects both the operator and the spindle from damage due to inadvertent starts.

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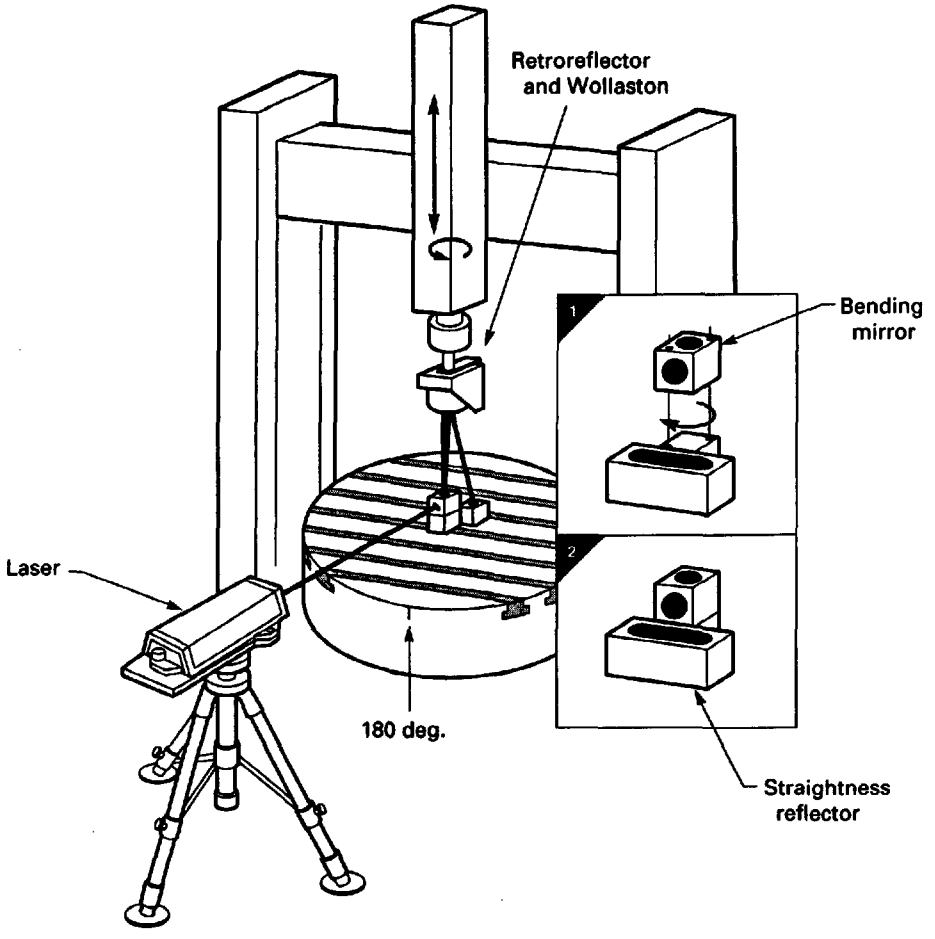


FIG. 47 SETUP FOR MEASURING LONG-RANGE PARALLELISM OF THE Z-AXIS IN THE CASE OF A VERTICALLY TRAVERSING AXIS

7.8.2 Telescoping Ball Bar Performance — XZ Plane, 360 Degree Trace.[44] On some machines there is enough axis travel in both X and Z to perform a 360 degree full-circle test. On such machines this test is required. A setup for such a test is shown in Fig. 48. Note that in this configuration the fixed socket is no longer on the center line of the spindle in the X direction. Before programming the machine it must be located using the procedure recommended by the ball bar manufacturer. After location of the fixed socket, the machine should be programmed to make a complete 360 deg trace in the XZ plane, both in the clockwise and counterclockwise directions. Typical results of such a test are shown in Fig. 49. The data for the test shall be analyzed and reported as described in para. 7.8.5.

[44] Many lathes are programmed in diameter, rather than radius. Users should take care not to damage the instrumentation.

7.8.3 Telescoping Ball Bar Performance — XZ Plane, 190 Degree Trace (Optional). Where possible, a 190 degree test should also be performed. A setup for this test is shown in Fig. 50. For this test the support arm may also be placed below the ball bar. The machine should be programmed to move along the arc shown in the figure, from 190 degree to 0 degree and back, at both of the pre-selected feed rates (see para. 7.8.1). Typical results of such tests are shown in Fig. 51. Data are analyzed and reported as described in para. 7.8.5.

7.8.4 Telescoping Ball Bar Performance — XZ Plane, 100 Degree (90) Test (Optional). This test should only be used on those machines where either the 360 degree or the 190 degree test cannot be performed due to limitations in axis positioning or available ball bar lengths. The telescoping ball bar

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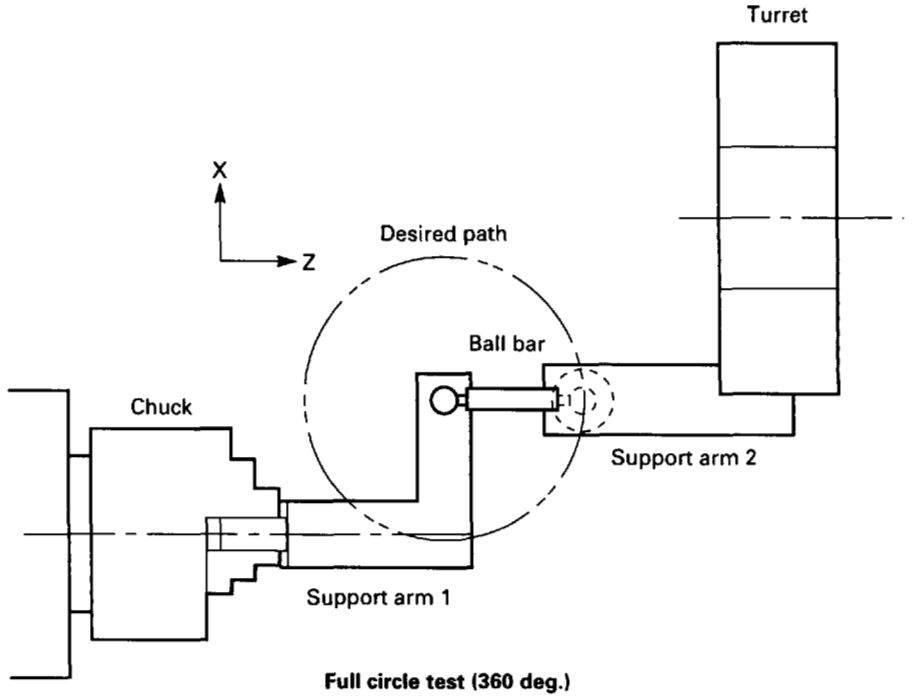


FIG. 48 TYPICAL SETUP FOR A 360 DEG BALL BAR TEST

conforming to the requirements of Section 9 is required for this test. One of the magnetic sockets, called the "fixed socket," is attached to the work spindle using a suitable fixture and the machine chuck. The other socket, called the "free socket," is attached at the nominal position of the tool in the turret. A schematic showing such a setup is given in Fig. 52. The machine is commanded to move along a radius from the position labeled 0 degrees to the position labeled 100 degree and back to position 0 degree at both of the preselected feed rates (para. 7.8.1). The results are presented in a polar plot such as that shown in Fig. 53. Data are analyzed and reported as in para. 7.8.5.

7.8.5 Telescoping Ball Bar Data Analysis. For each ball bar test, the 360 degree, the 190 degree, and/or the 100 degree, 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, corrected to 20°C, shall be reported, as well as the measured feed rates in the clockwise and counterclockwise directions. The circular deviation is the minimum radial separation of two concentric circles that will envelope the actual path. Finally, the radial deviations are the maximum and minimum deviations from the true ball bar length, corrected to 20°C. For the purposes of this Standard, the manufacturer of the ball bar shall supply an effective coefficient of thermal expansion for the ball bar and recommendations as to appropriate ball bar calibration procedures, where applicable. Table 6 shows typical results of a ball bar test.

Note: For the 100 degree test it is not advisable to remove the centering error by calculation; rather, it must be removed mechanically.

7.8.6 Contouring Performance Using Precision Disks or a Grid Encoder. This Standard allows the substitution of precision disks or grid encoders for the telescoping ball bars in the circular test. The circular test is a comparison of a circular path which is carried out by a machine tool to an accurate circle, a circular comparison standard. For disks, this comparison is carried out using a two-dimensional probe reading against a precision disk. When grid encoders are used, the pattern on a special grid encoder is sensed using photo-optical sensors. On the machine tool a circle is programmed, the diameter of the circle corresponding to the diameter of the circle comparison standard. The 2D probe or the photo sensor is moved on the circular path by the machine tool and either measures deviations of the program circle from the disk standard, or, in the case of the grid encoder, simply gives the

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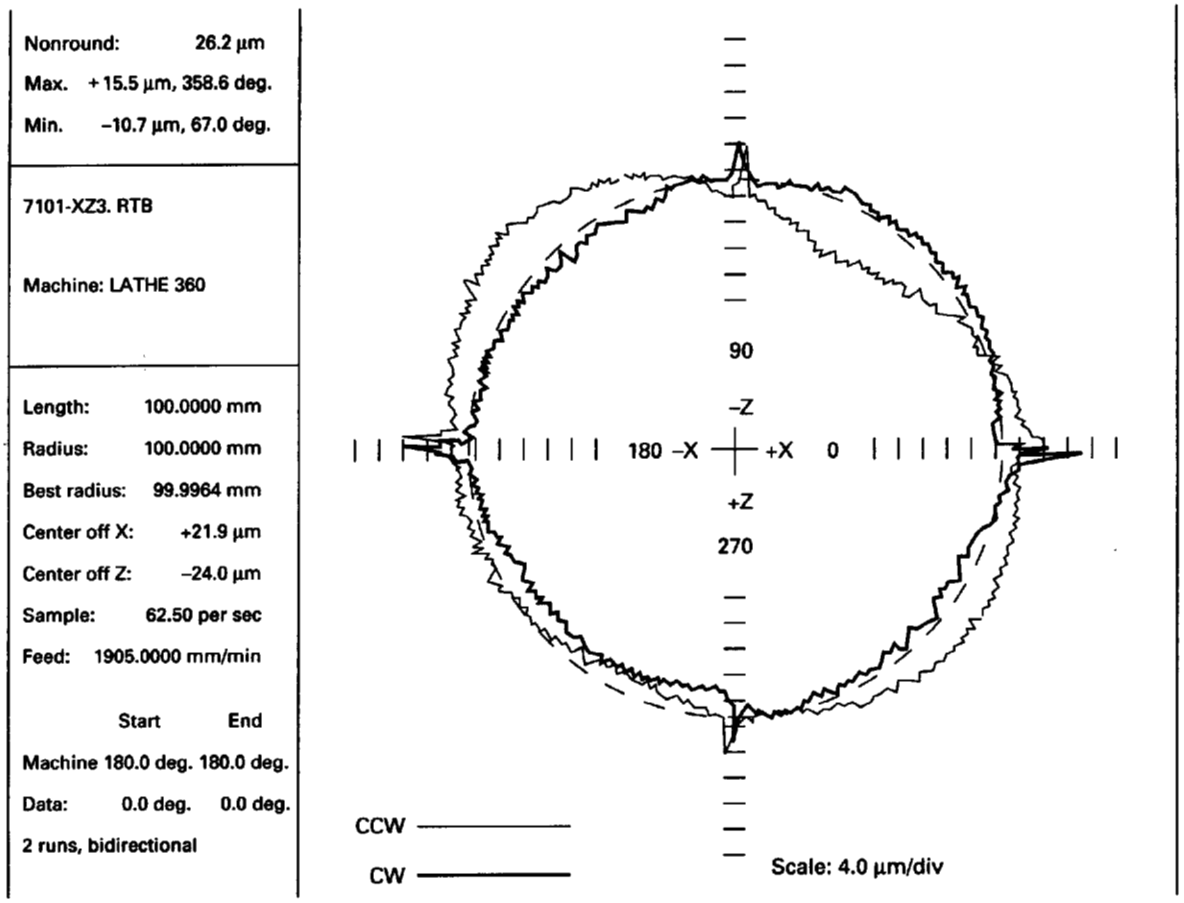


FIG. 49 TYPICAL RESULTS FROM A 360 DEG BALL BAR TEST

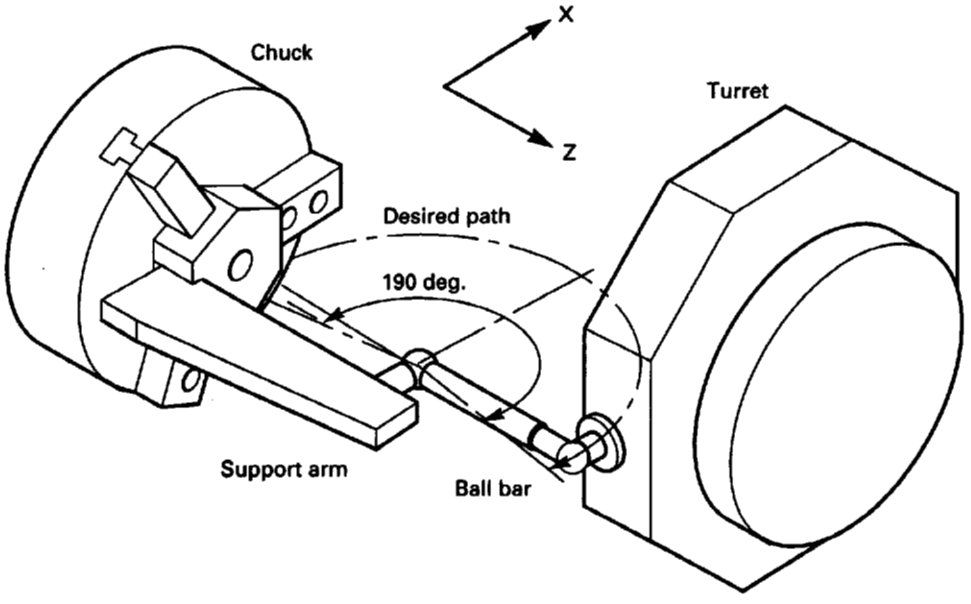


FIG. 50 SCHEMATIC SHOWING THE BALL BAR SETUP FOR THE 190 DEG TEST ON A LATHE

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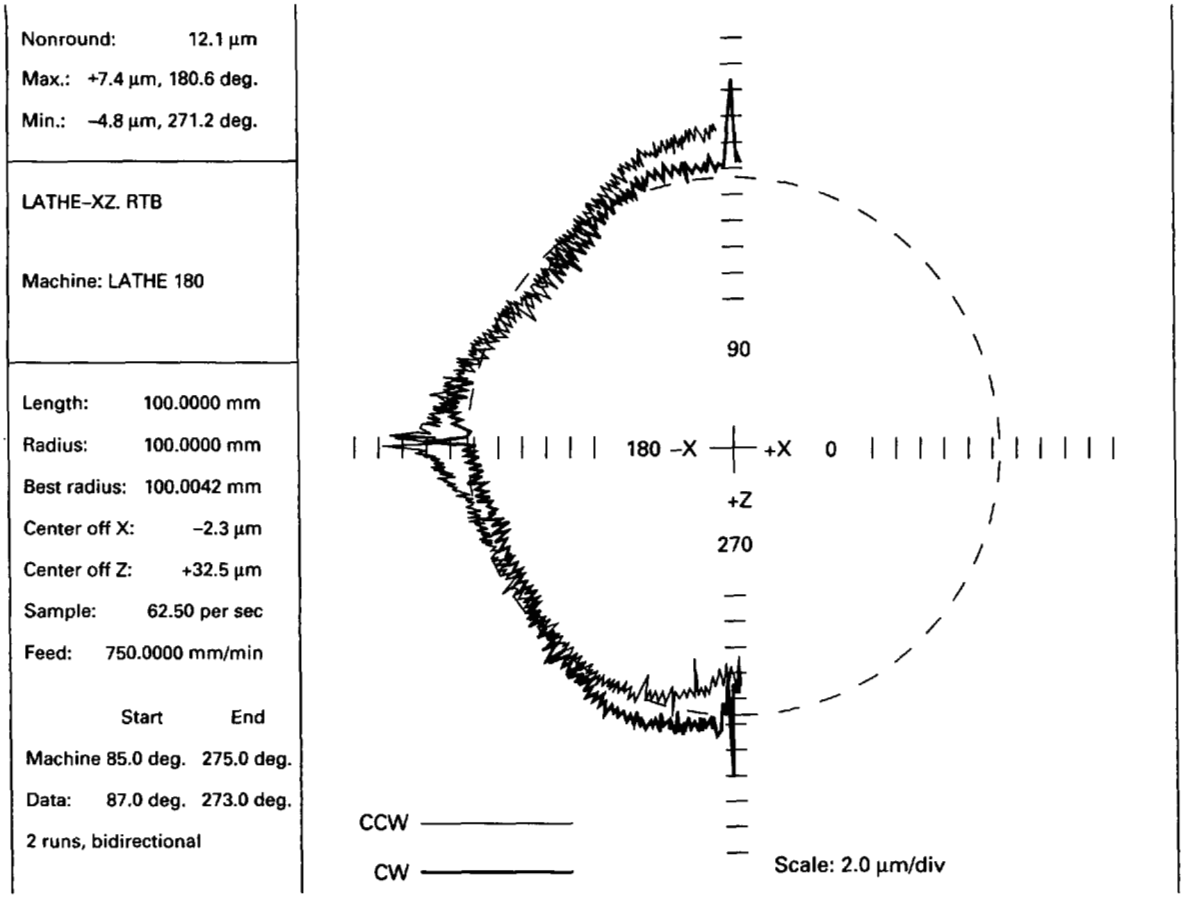


FIG. 51 TYPICAL RESULTS FROM 190 DEG TESTS ON A LATHE

XY coordinates of the programmed path. Commercial systems are available for both the precision disks and the grid encoders. The deviations from circularity so measured are analogous to those obtained with the circular test using the ball bar. The analysis must follow that discussed above for the circular test.

7.8.7 Other. At the time of the issuance of this Standard, several different ball bar designs or other instruments are in the process of development and testing. The use of any of these ball bars or other instruments is suitable, as long as the instrument system is able to perform the same task with the required accuracy (see Section 9).

7.9 Cutting Performance Tests

7.9.1 General. In the performance of a cutting operation the following conditions 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 utilize 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 to 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 we distinguish from tests by calling them simple checks. These are not discussed any further in this Standard.

For the purposes of this Standard, the limitations (a) and (b) shall be determined in well organized tests

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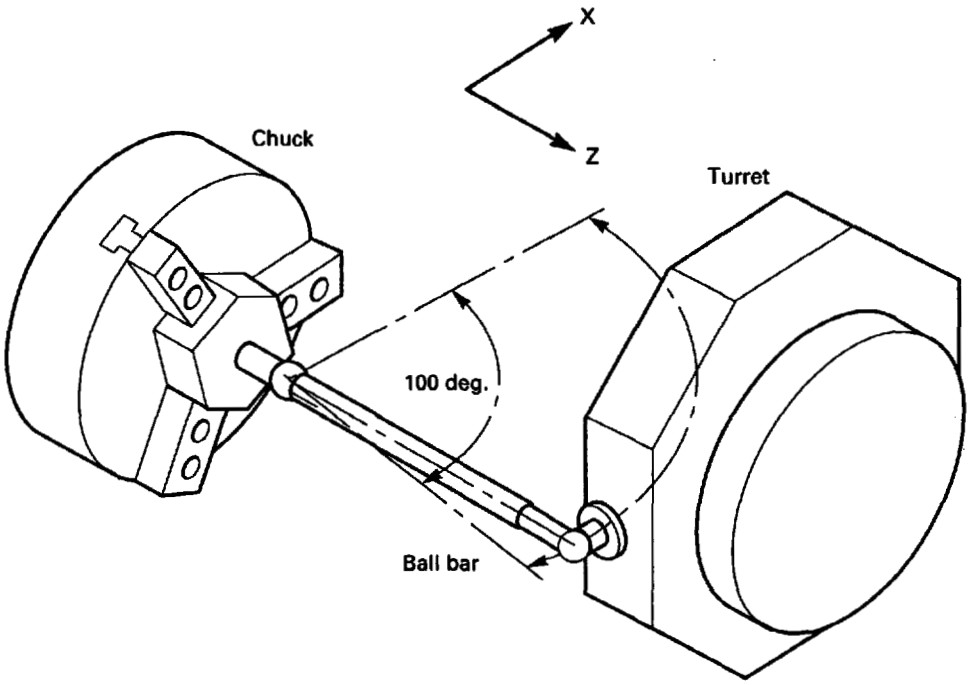


FIG. 52 SCHEMATIC SETUP OF A BALL BAR BEING USED FOR A 100 DEG TEST

performed under carefully specified conditions. For practical reasons the tests are organized in the following sequence:

1. Spindle idle run loss test. This test is carried out first in order to measure the power available for the cutting tests.

2. Chatter limits and full torque test. Measurements of these two limitations are combined in a user and supplier agreed-upon test(s) during which one or the other limitation prevails.

7.9.2 Spindle Idle Run Loss Test. This test 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. This test should be performed for each work spindle and each tool spindle. 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. 54 is produced. The wattmeter is connected to the power feed of the spindle drive. 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 (see Form 1).

7.9.3 The Chatter Limits Test and Full Torque Test. Because of the wide variety of turning centers currently available, it is the recommendation of this Standard that the user and supplier negotiate as part of the original specification a cutting performance test that will determine the capability of the machine to apply its full torque (horsepower) to a metal-removal operation, without the existence of chatter. Guidelines for such tests are available in other Standards (for example, see JIS B 6215-1977 and JIS B 6202-1986).

7.10 Multi-Function Cycle Test

7.10.1 General. The machine shall be cycled through all basic machine functions for a specified time period (usually 24 hours) to demonstrate its complexity, capability, and short-term reliability. Preceding this test, a subsidiary test should be performed to check the function of the machine limit switches, coolant cycling, etc.

7.10.2 Procedure. The machine and control shall cycle automatically under numerical control for a specified time period 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, tool changes, traverse and feed motions, contouring, G-code canned

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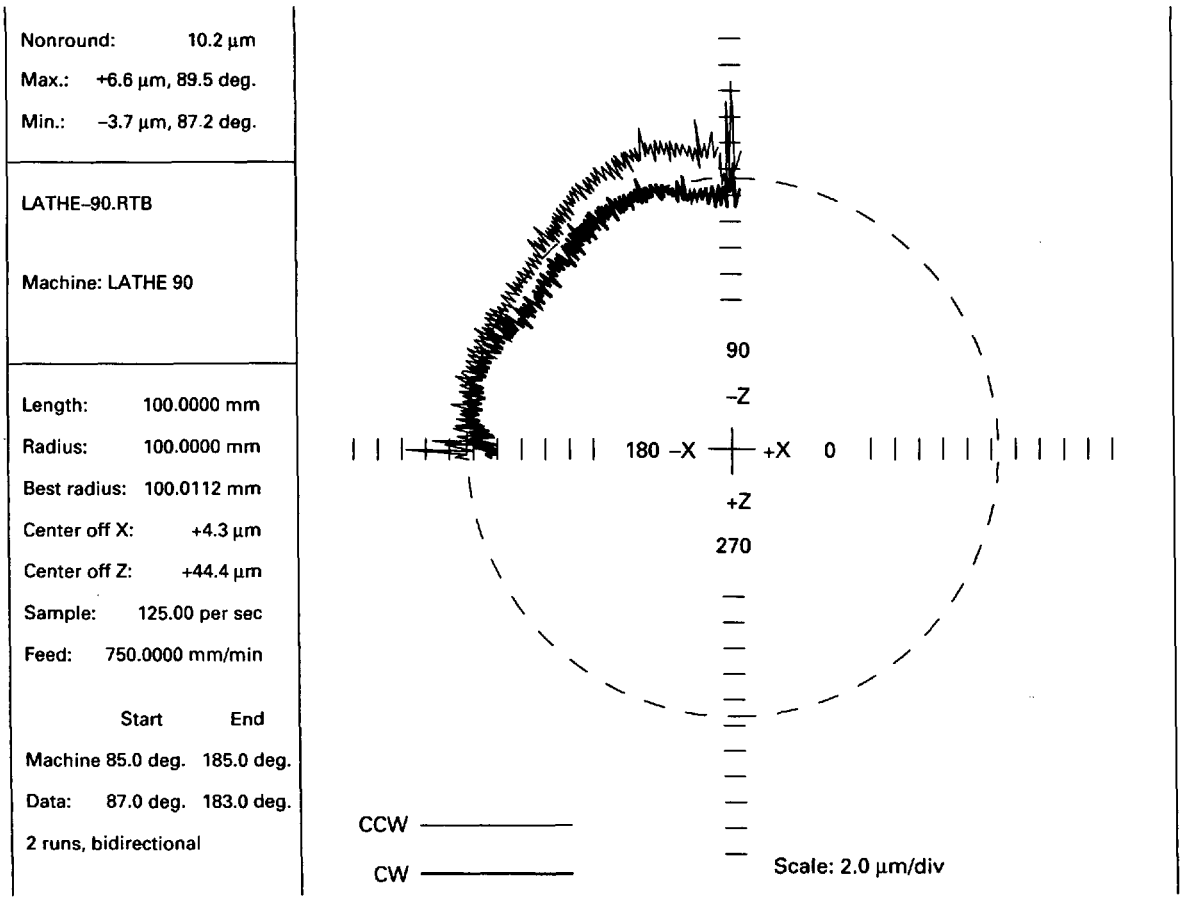


FIG. 53 RESULTS OF A 100 DEG BALL BAR TEST

TABLE 6 TYPICAL RESULTS OF A BALL BAR TEST

Machine: not applicable
Test angular range: 190 deg
Ball bar length: 77 mm
Angular measurement interval: manufacturer-supplied
Contour speed: 1335 mm/min

Parameter Name	Symbol	Value (μm)
Circular deviation, clockwise	G ↑	130
Circular deviation, counterclockwise	G ↓	127
Min. radial deviation, clockwise	F_{min} ↑	−70.0
Min. radial deviation, counterclockwise	F_{min} ↓	−59.0
Max. radial deviation, clockwise	F_{max} ↑	61.7
Max. radial deviation, counterclockwise	F_{max} ↓	73.2

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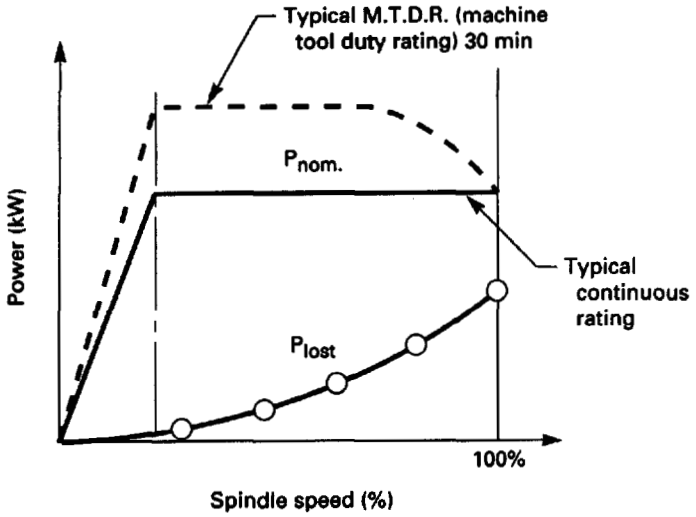


FIG. 54 A TYPICAL PLOT OF THE POWER LOSS IN THE SPINDLE IDLE RUN LOSS TEST

cycles, etc. The spindle shall operate through its entire speed range during the test. A complete program run (cycle) time shall not exceed 15 minutes, unless specifically negotiated between supplier and user. The supplier and user shall also negotiate and make part of the original specification the number of failures, if any, and the type of failures that are to be allowed during the specified time period.

8 MACHINE PERFORMANCE (OPTIONAL)

8.1 General

Many turning centers offer optional features. In the sections below an attempt has been made to include tests for those most commonly supplied. If a machine is to be purchased with options that are not covered in these sections, it is recommended that the user and supplier devise an appropriate functional test to be made part of the original machine specification.

8.2 Coaxiality of Axes of Rotation[45]

The alignment of axes of rotation is often necessary on many machines. This situation occurs when spindle axes need to be aligned and, of course, when a tail stock needs to be aligned to a spindle axis. This alignment is independent of the actual mechanical runout of the spindle nose(s) or tail stock itself. Such runout should be determined by traditional machine tool practices and corrected where excessive. Five methods of checking the alignment of axes of rotation are given below. The first two methods have been traditionally used for the alignment of rotating machinery. The third method is more modern and requires the use of a laser alignment system. The fourth method relates to methods used for establishing rotary table axis alignment on machining centers. Finally, the fifth method is one that is traditionally used for aligning tail stocks on normal production machines. The choice of the method used is left to the user; however, it should be made part of the original specification and should have an accuracy sufficient for the intended use of the machine.

Four parameters are required to specify the alignment of two axes of rotation.[46] Two of these parameters specify the angularity between the two axes, and the other two the offset between the two axes in some specified plane. Note that in the presence of any angularity the offset is a function of position. This situation is depicted in Fig. 55 in one plane. For historical reasons, as well as reasons relating to measurement procedures, angles are normally described with respect to vertical and horizontal planes, and offsets are defined similarly. Following this convention in this Standard and, for each of the proposed measurement methods, the plane where the offsets are to be reported will be clearly specified. If not specified, these offsets should

[45] These measurements are often used to make machine adjustments. It is the recommendation of this Standard that if the alignments are worse than the supplier's specifications then such adjustments should be made.

[46] The nomenclature in this section refers to horizontal spindle machines. Those using other configurations should specify the planes in which the offsets and angles are to be reported. Sag measurements should not be required for vertical spindle machines.

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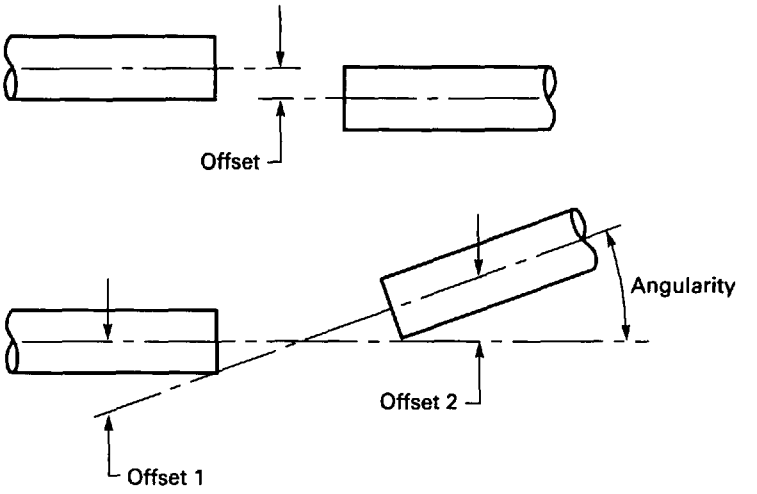


FIG. 55 ILLUSTRATION OF ANGULARITY AND OFFSET BETWEEN TWO AXES OF ROTATION

be reported in a plane nominally 50 mm (approx. 2 in.) from the face of the machine main spindle. For the purpose of this section the following nomenclature is defined:

VO = vertical offset in a specified plane
VA = vertical angle between two axes of rotation
HO = horizontal offset between two axes of rotation in a specified plane
HA = horizontal angle between two axes of rotation

Traditionally these measurements are performed with the machine cold, but the user is warned that the offsets and angles change with temperature. These changes are measured in Section 7.6, Machine Thermal Tests.

8.2.1 "Rim and Face" Method. This measurement method requires the use of two displacement indicators conforming to the requirements of Section 9. Depending upon machine accuracy levels, the displacement indicators could range from dial gages to air-bearing LVDTs. A typical setup, using dial gages attached with brackets to short stiff mandrels fixtured to the two axes of rotation, is shown in Fig. 56. The indicators are set for positive reading for motions toward the indicator dials in the figure. For simplicity of notation the rotary axis to the left in the figure will be called the "C" axis and the axis to the right the "M" axis. The bracket holding the indicators and the mandrels should be as short and as stiff as possible. Before commencing the test the sag (compliance) of the bracket shall be measured. This is done by attaching the bracket to a stiff mandrel supported between centers as shown in Fig. 57. For spans up to 200 mm (approximately 8 in.), a steel mandrel 50 mm (approx. 2 in.) in diameter is considered adequate. (For very high-accuracy machines, a calculation of the requisite mandrel diameter should be made or a correction applied for mandrel sag.) The indicators are zeroed at the top position (12:00 o'clock in the figure) and the mandrel rotated until the indicators are at the bottom position (6:00 o'clock in the figure). The readings of both indicators are recorded. RR_s is the sag of the rim indicator and FR_s is the sag of the face indicator. RR_s will generally be negative (pay attention to signs), while the sign of FR_s will depend on details of the setup. Perform this test three times and compute the mean of the readings. The indicators are now fixtured to the two axes of rotation (see Fig. 56) and the two axes rotated together reading the indicators at the 12:00, 3:00, 6:00, and 9:00 o'clock positions. These measurements should be repeated three times, with care to avoid thermal effects (gloved hands and a temperature shield may be required on high-accuracy machines). The alignment parameters of the two axes in the plane of the rim indicator are given by

$$\text{Vertical offset, } VO = \frac{\overline{RR0} - \overline{RR6} - \overline{RR_s}}{2}$$

$$\text{Vertical angle, } VA = \frac{\overline{FR6} - \overline{FR0} - \overline{FR_s}}{DIA}$$

$$\text{Horizontal offset, } HO = \frac{\overline{RR3} - \overline{RR9}}{2}$$

$$\text{Horizontal angle, } HA = \frac{\overline{FR9} - \overline{FR3}}{DIA}$$

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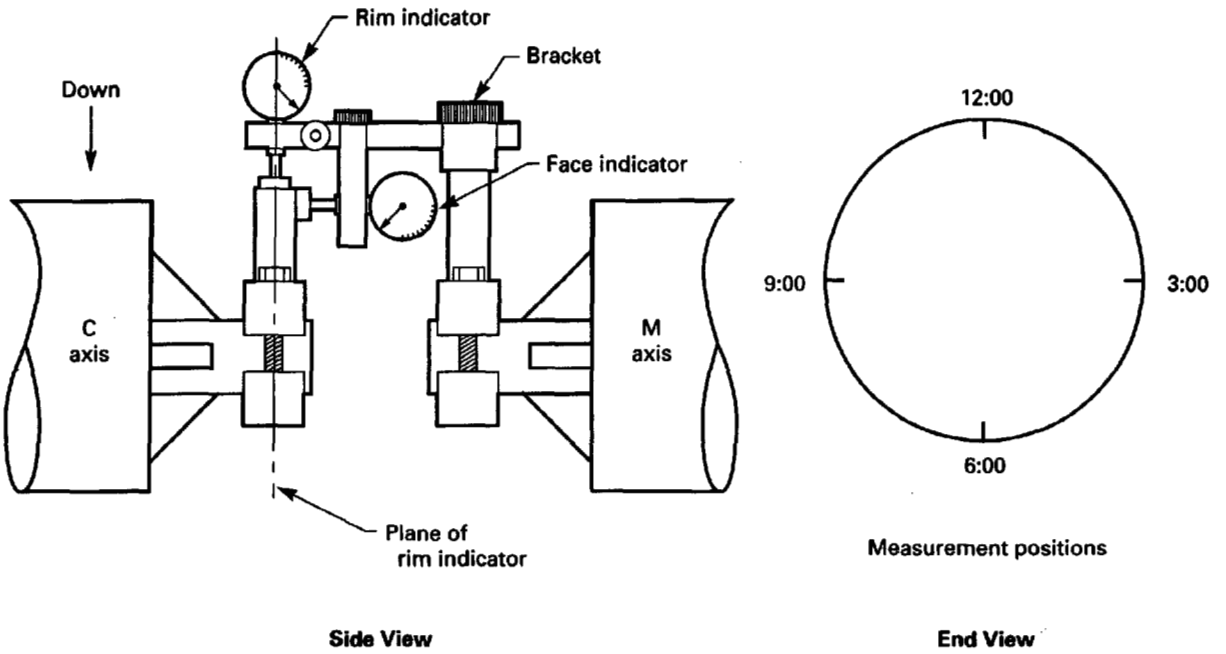


FIG. 56 TYPICAL SETUP FOR THE "RIM AND FACE" TEST

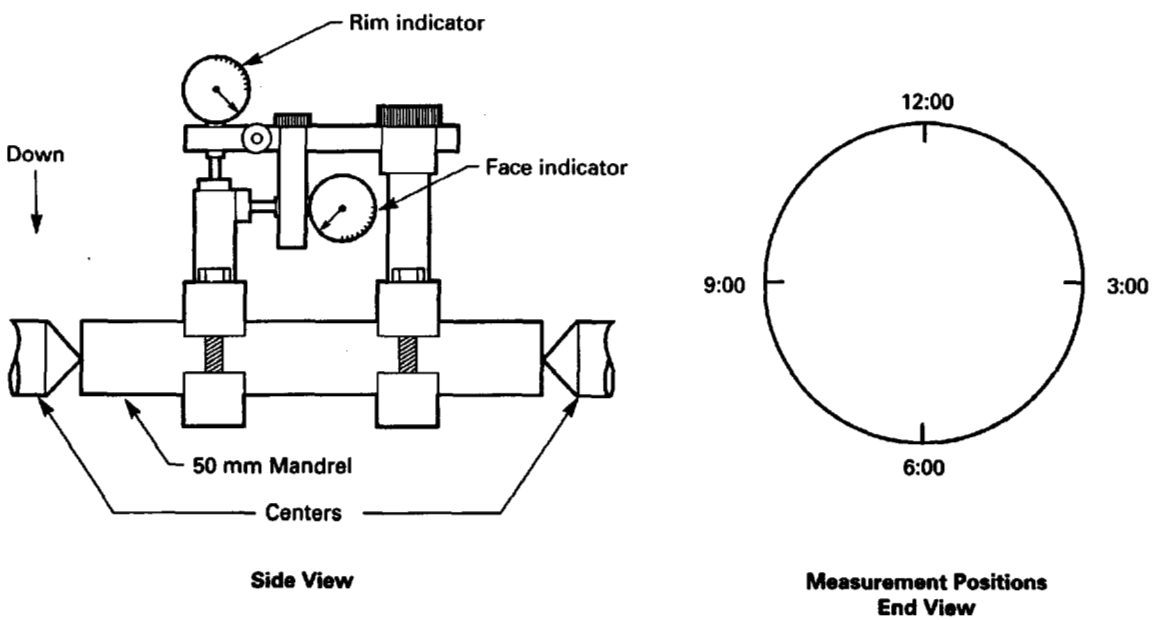


FIG. 57 SETUP FOR MEASURING THE SAG OF THE PAIR OF INDICATORS

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where

$\overline{RR0}$ = mean rim reading at 12:00
$\overline{RR3}$ = mean rim reading at 3:00
$\overline{RR6}$ = mean rim reading at 6:00
$\overline{RR9}$ = mean rim reading at 9:00
$\overline{FR0}$ = mean face reading at 12:00
$\overline{FR3}$ = mean face reading at 3:00
$\overline{FR6}$ = mean face reading at 6:00
$\overline{FR9}$ = mean face reading at 9:00
$\overline{DIA}$ = diameter of the circle traveled by the face indicator center line
$\overline{RR_s}$ = mean sag of rim indicator
$\overline{FR_s}$ = mean sag of face indicator

If desired, standard uncertainties in these quantities may be computed (see Appendix M).

8.2.2 Reverse Indicator Method. The setup for using this method is shown in Fig. 58. As in the rim and face method, two appropriate indicators are required, with the choice depending upon machine accuracy. The indicators are set to read positive for motions towards the dials as shown in the figure. Before commencing measurements, the "sag" of the indicator setup must be measured. The procedure is as outlined in para. 8.2.1 above, with the reverse indicator brackets (Fig. 58) being substituted for the rim and face brackets in Fig. 57. Zero the indicators at the 12:00 position, rotate the mandrel to the 6:00 position, and record the readings from the S and the M indicators. Perform this measurement three times and compute the mean sags. The indicators are now fixtured to the two axes of rotation, using mandrels as described in para. 8.2.1. Once mounted, the two axes are rotated and indicator readings are taken at the 12:00, 3:00, 6:00, and 9:00 o'clock positions. These measurements should be repeated three times and the means computed. The misalignment of the two axes in the plane of indicator S is given by

$$\text{Vertical offset, } VO = \frac{-(\overline{SR0} - \overline{SR6} - \overline{SR_s})}{2}$$

$$\text{Vertical angle, } VA = [-(\overline{SR0} - \overline{SR6} - \overline{SR_s} + \overline{MR0} - \overline{MR6} - \overline{MR_s})] / 2D_g$$

$$\text{Horizontal offset, } HO = \frac{-(\overline{SR3} - \overline{SR9})}{2}$$

$$\text{Horizontal angle, } HA = \frac{-(\overline{SR3} - \overline{SR9} + \overline{MR3} - \overline{MR9})}{2D_g}$$

where

$\overline{SR0}$ = the mean S gage reading at 12:00
$\overline{SR3}$ = the mean S gage reading at 3:00
$\overline{SR6}$ = the mean S gage reading at 6:00
$\overline{SR9}$ = the mean S gage reading at 9:00
$\overline{SR_s}$ = the mean sag of the S gage
$\overline{MR0}$ = the mean M gage reading at 12:00
$\overline{MR3}$ = the mean M gage reading at 3:00
$\overline{MR6}$ = the mean M gage reading at 6:00
$\overline{MR9}$ = the mean M gage reading at 9:00
$\overline{MR_s}$ = the mean sag of the M gage
D_g = the distance between the S and M gages

8.2.3 Optical Tailstock Alignment. Several alignment laser systems are available that may also be used for axes of rotation alignment. A basic system is shown in Fig. 59. In such a system, a laser is attached to either of the axes of rotation and a photodetector attached to the other of the two. Procedures vary. Some systems require rotating one axis, by hand, taking readings of the laser position, and then the other axis, by hand, again recording the results. Other systems require rotating the axes together as described in paras. 8.2.1 and 8.2.2 above. The out-of-alignment of the two axes of rotation is calculated by the system software. In all cases the supplier's recommendations for the laser instrument system usage should be followed. The measurements shall be repeated three times, and mean values for the four out-of-alignment parameters shall be calculated.

8.2.4 Two-Sphere Axis Alignment. To perform this test a set of test balls is fixtured to one spindle and adjusted to have minimum runout (each ball is separately adjusted). Such a situation is shown in Fig. 60(a) where the fixture is in the machine main spindle. Here the fixture used for the spindle error analysis may be readily used. Next, an indicator bracket is attached rigidly to the second rotary axis [shown as a tailstock in Fig. 60(a)]. The bracket should be stiff and light and needs only to be stable for the duration of the test. The bracket should also be checked for sag using a procedure similar to that described in paras. 8.2.1 and 8.2.2 above. If the sag is excessive a stiffer bracket should be used or the sag measured, as described in Section 8.2. The mean sag at gage 1 ($\bar{S}\bar{R}_1$) and the mean sag at gage 2 ($\bar{S}\bar{R}_2$) shall be recorded. Also, if a high thermal expansion material is chosen (such as aluminum), the user should be aware that thermal effects might bias the results. It therefore would be advisable to insulate the bracket. An indicator is positioned on the bracket to read against the artifact at position 1,

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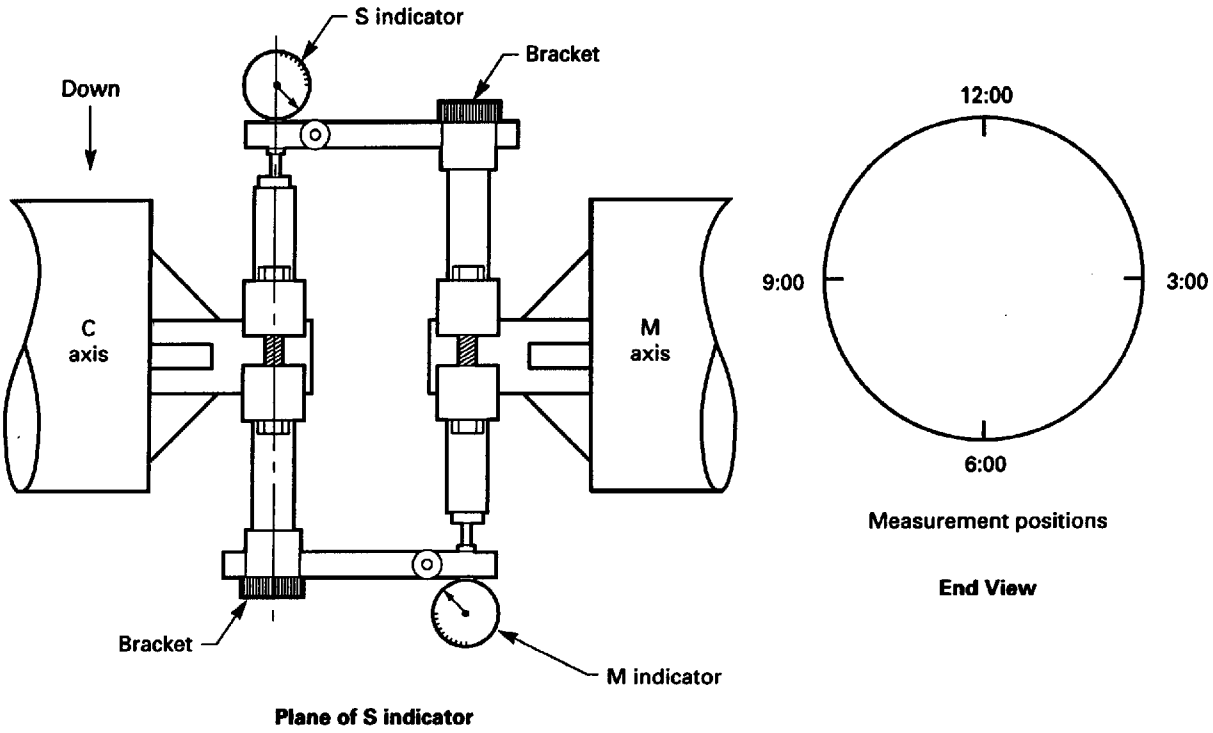


FIG. 58 TYPICAL SETUP SHOWING THE REVERSE INDICATOR METHOD

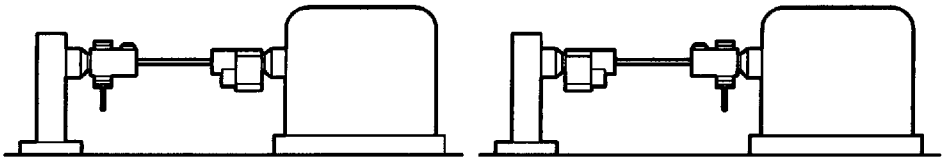


FIG. 59 ROTATION AXES ALIGNMENT USING AN OPTICAL ALIGNMENT LASER. A TAILSTOCK AND SPINDLE ARE SHOWN.

and three full-circle traces are taken as the tailstock is rotated. Data from these circle tests are least-squares fit to a circle and the mean circle center, CX_1,CY_1, determined. Next the indicator is re-bracketed to make three traces around the artifact at position 2. Again, the data are least-squared fit to a circle to obtain a CX_2,CY_2 center. (Two indicators can also be used at the same time, which requires less stability but introduces the problem of matching gage calibrations.) For the purposes of this Standard, the offsets are reported at position 1, which is nominally 50 mm (approx. 2 in.) from the main spindle face. The equations are

$$\text{Horizontal offset, } HO = HO_1 = \overline{CX}_1$$

$$\text{Vertical offset, } VO = VO_1 = \overline{CY}_1 - \frac{\overline{SR}_1}{2}$$

$$HO_2 = \overline{CX}_2$$

$$VO_2 = \overline{CY}_2 - \frac{\overline{SR}_2}{2}$$

$$\text{Horizontal angle, } HA = \frac{\overline{HO}_2 - \overline{HO}_1}{D_g}$$

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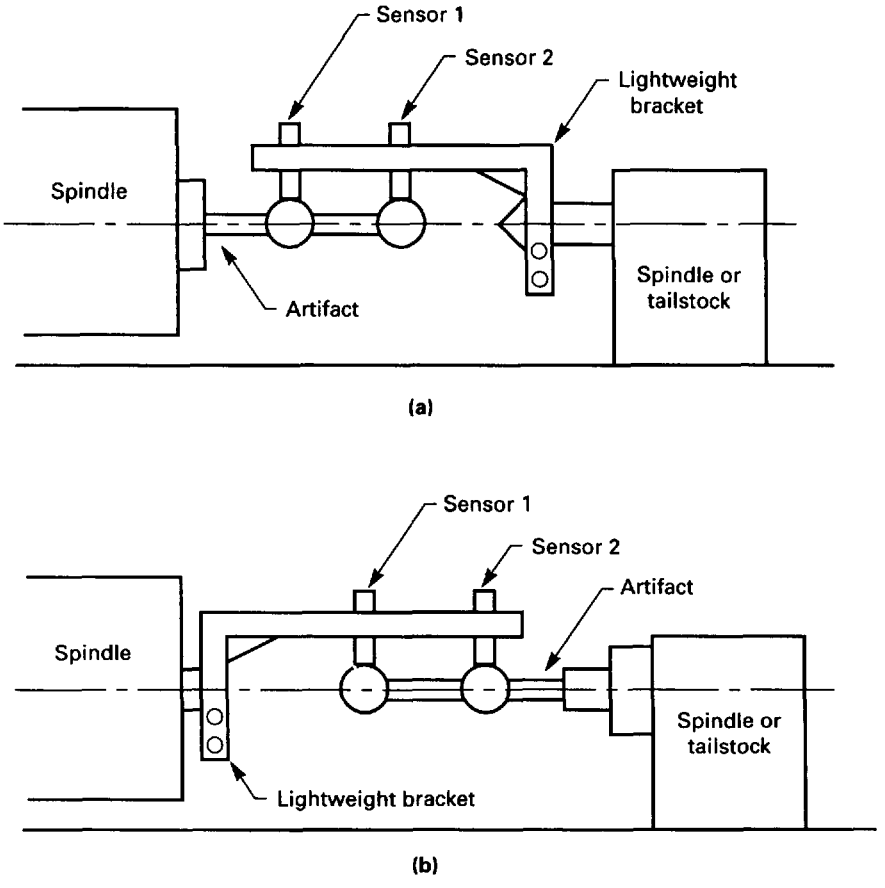


FIG. 60 TWO-SPHERE SETUP FOR THE ALIGNMENT OF TWO ROTATION AXES

$$\text{Vertical angle, } VA = \frac{\overline{VO}_2 - \overline{VO}_1}{D_g}$$

where

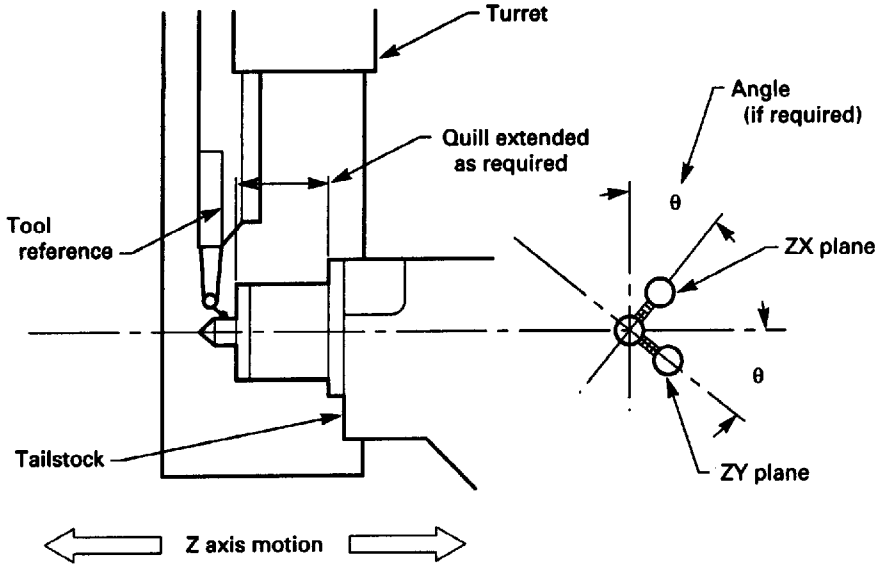
D_g = the distance between the two gages.

As shown in Fig. 60(b), the setup may be reversed and the measurement repeated. Similar procedures should be followed. Note that the gage numbering is the same in order to make the previous equations apply.

8.2.5 Parallelism of the Z Axis with Other Linear Axes (W). For machines equipped with auxiliary axes that move in the Z direction, such as a tailstock, it is important to measure the parallelism of the auxiliary axis motion with the machine Z axis. This situation is illustrated in Fig. 61 for a machine with a movable tailstock. The simplest method for measuring this parallelism is to indicate against the tailstock center using indicators in the XZ and YZ plane. At some initial position the indicators are zeroed. Then the tailstock is moved in increments. After each motion increment the indicators are again moved to read against the tailstock, at the same point on the tailstock, using the machine Z axis. The indicator data are plotted for both planes, and the slopes of the lines obtained by least-squares fitting are the out-of-alignment in the respective planes. At least 10 positions along the Z axis should be used for each plane and the standard uncertainty obtained from the least-squares fit to the slopes reported.

8.2.5.1 Mechanical Tailstock Alignment. Many machines are equipped with a tailstock. In these cases it is often sufficient to indicate the tailstock center line location with respect to the spindle center line,

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NOTE: Move tailstock in increments along entire stroke and clamp during measurement

FIG. 61 SCHEMATIC OF THE MEASUREMENT OF PARALLELISM OF THE Z-AXIS TO THE AXIS OF A MOVABLE TAILSTOCK

using the machine Z axis.[47] This situation is depicted in Figs. 62(a) and (b), where the two axes of rotation are called C_1 and C_2. First the parallelism of the C_1 axis to the Z axis is measured in both the X and Y planes, using the procedures described in para. 7.7.3.1. (Values obtained previously may be used.) Next the Z axis is traversed and the parallelism of C_2 measured by the same procedure. Note that this procedure does not require that the mandrels be precisely aligned to the spindle axis. The offset is measured using precision spheres. These precision spheres, of the same diameter (see Section 9), are mounted at a fixed distance from the face of the spindle and the face of the tailstock. The recommended distances are 50 mm (approx. 2 in.), as discussed previously, though other distances may be chosen. They are adjusted to minimize the run-out. First the X deviation of the surface of the sphere in spindle C_1 is measured, and the Z axis is then traversed to position 2, without re-zeroing the indicator, and the X deviation of the second sphere and C_2 determined. The measurement is performed similarly in the Y direction. Offsets and angles are then calculated.

8.2.6 Parallelism of the Z Axis (Longitudinal Slide) with the C Axis (Work Spindle) in the YZ Plane (Optional).[48] Parallelism of the Z axis to the C axis in the YZ (vertical) plane is important on some machines that require facing a workpiece to center without a defect, at different positions along the Z axis. Stated in a different way, if the tool is set to center-line height at one position of the Z axis, it will not be at center line in other positions unless the Z-axis motion is parallel to the C axis in this plane. This parallelism may be measured by one of the three methods mentioned previously for measuring the parallelism in the YZ plane. That is, it may be measured using a mechanical straightedge positioned in the correct direction (para. 7.7.3.1), by part traces on a machined cylinder (para. 7.7.3.2), or using a straightness interferometer as described in para. 7.7.4. When using the first two methods, care must be taken that appropriate attention is paid to gravitational sag on a horizontal spindle machine.

[47] Parallelism of the Z axis to the C axis in the X,Y (vertical) plane is important on some machines that require facing a workpiece to center without a defect ("blip") at different positions along the Z axis. Stated in a different way, if the tool is set to centerline height at one position of the Z axis it will not be at centerline at other positions.

[48] Note that the results of this procedure are biased by angular and straightness errors of the Z axis.

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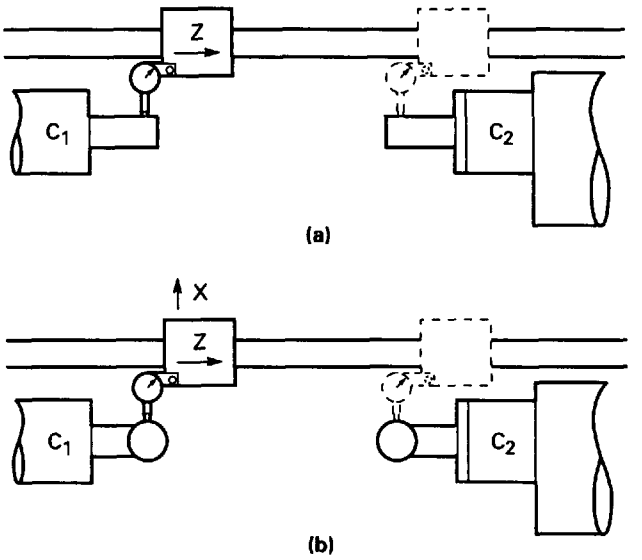


FIG. 62 SETUP FOR MEASURING TAILSTOCK ALIGNMENT TO THE Z-AXIS

8.3 Subsystems Repeatability (Optional)

Turning centers are complex systems and contain many subsystems which also contribute to the accuracy and performance of the machine. Subsystems that contribute to the accuracy are the tool change repeatability, turret repeatability, and tool-setting system repeatability, location, and drift. Tests for these important subsystems are addressed in the sections that follow.

8.3.1 Tool-Change Repeatability. For the purposes of this Standard, tool change repeatability is checked using two tool holders selected from a supplier's specified tooling package by the user. Precision test spheres are to be mounted in these tool holders in a manner similar to that shown in Fig. 63. One of the test spheres is to be at the minimum possible distance from the turret or tool holder, and the second test sphere is to be mounted on a rigid column at a distance of 100 mm (approx. 4 in.) from the first sphere. (These lengths are default options, and the user is free to select other lengths appropriate to his/her application, if required.) The tool holders with their test spheres are to be inserted in user-selectable positions in the tool magazine for the machine, and a displacement indicator nest, such as the sensor nest shown in Fig. 14, is to be rigidly attached to the machine chuck in the nominal position of the part.[49] The test then proceeds as follows. The first sphere is loaded into the turret and the machine jogged into position such that the two 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 turret and position it to its established null in the displacement indicator 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 10 times in rapid succession and the X and Z offsets of each ball are recorded for each trial. Four tool-change repeatabilities are defined: they are the difference between four standard uncertainties of the X and Z readings for the short setup, minus the machine uni-directional repeatability for the direction(s) of approach to the sensor nest (para. 7.2.7.6); and the difference in four times the standard uncertainty of the X and Z readings, minus the machine uni-directional repeatability for the direction of approach to the sensor nest for the long

[49] This test can, if required, be performed on an axis-by-axis basis using a single sensor.

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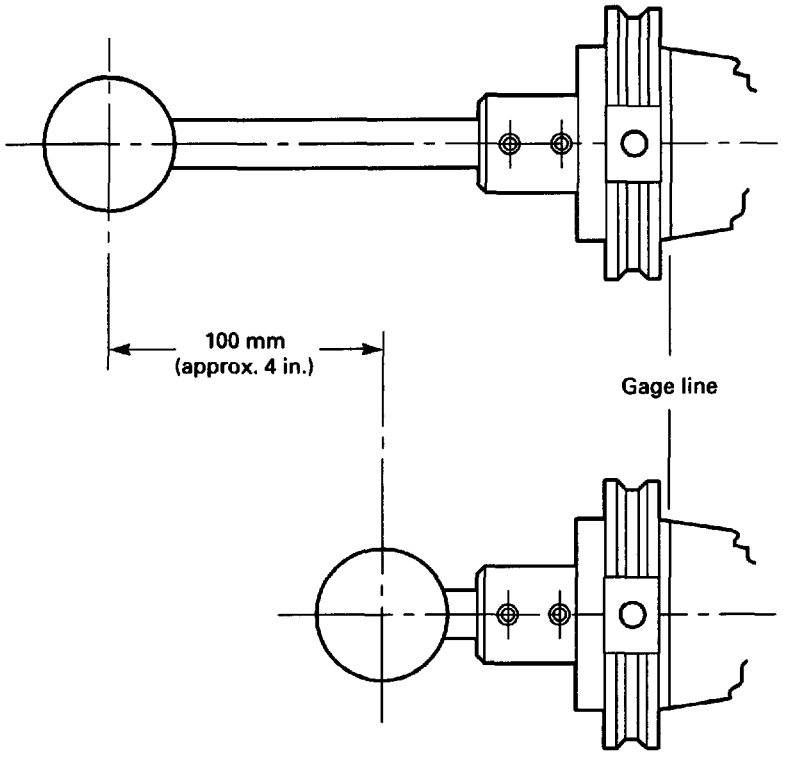


FIG. 63 TOOL HOLDERS USED FOR TOOL CHANGE REPEATABILITY

setup.[50] For example, the tool-change repeatability for one tool length in the X direction is given by

$$u_x^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_{ti} - \bar{x}_t)^2$$

$$R_{xts} = 4u_x - R\uparrow \text{ or } R_{xts} = 4u_x - R\downarrow$$

where

x_{ti} = the i[th] reading in the X direction
x_t = the average of the 10 readings in the X direction
u_x = the estimate of the standard uncertainty
$R\uparrow$ or $R\downarrow$ = the appropriate repeatability for the X axis
R_{xts} = the tool-change repeatability for that direction and tool length
n = 10 is the default value for this test

Note that this test includes changes in tool position caused by rotating the tool magazine and any thermal errors induced by traversing to and from the tool change location. The user is advised that to obtain the most realistic estimate of tool change effects, it is advisable to have the two spheres with their tool holders placed in magazine locations that require extensive motion of this mechanism.

8.3.2 Turret Repeatability. Turret repeatability is checked in a method analogous to that used in para. 8.3.1 for tool change repeatability. For this test the short and the long precision test spheres are mounted in two user-selectable turret positions. The tool holders should be those normally supplied with the machine. If the machine has straight-shank tooling, tool holders such as those shown in Fig. 64 are appropriate. As previously, a two-indicator sensor nest is rigidly attached to the machine chuck in the nominal position of the part. After establishing the null locations for both tools, an automatic cycle is established to place sphere 1 into the indicator nest, withdraw it, index the turret, and place sphere 2 into the indicator nest. This program is executed 10 times in rapid succession and the XZ deviations for both tool and turret positions are recorded. Four turret repeatabilities are defined. They are the difference between four times the standard uncertainty of the X and Z readings for the short setup, minus

[50] Note that on most lathes the Y is the non-sensitive direction; however, improper Y positioning will lead to a dimple at the center of a faced part and thus is included here as an important parameter.

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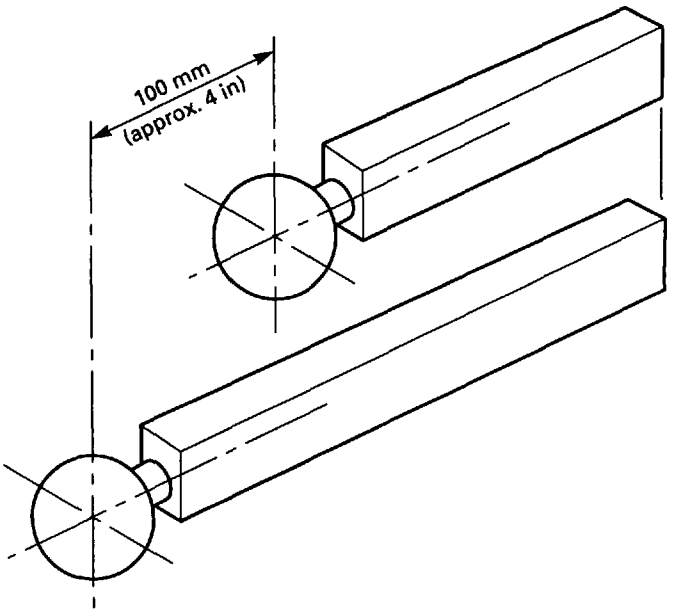


FIG. 64 EXAMPLE TOOL HOLDERS TO BE USED FOR TURRET REPEATABILITY

the machine uni-directional repeatability for the direction(s) of approach to the sensor nest (para. 7.2.7.6); and the difference in four times the standard uncertainty of the XZ readings, minus the machine uni-directional repeatability for the direction(s) of approach to the sensor nest for the long setup in the second turret position. The calculation and notation are identical to those outlined in para. 8.3.1.

8.3.3 Gage Line Repeatability. The purpose of this test is to determine the gage line repeatability for all of the pockets on a turret with tool-changing capabilities. For this purpose the short tool (see Fig. 63) is used. First the tool is put in one pocket and its XZ offsets measured three times using the tool-setting system. The tool is now inserted in all the other pockets, in turn, measuring its offsets three times for each pocket. The total range of the X offsets is reported as the X gage line repeatability, and the total range of the Z offsets is reported as the Z gage line repeatability. If desired, the standard uncertainty in the offsets may be calculated on a pocket-by-pocket basis (see Appendix M).

8.4 Repeatability, Location, and Drift of Tool-Setting System(s)

Turning centers are now supplied with tool-setting systems that allow for the automatic setting of tool offsets in the X and Z directions. (Other names, such as tool-setters, tool-gaging, and tool-setting probes, are also used.) On most turning machines, the Z direction location is set with respect to some feature on the machine part-holding device. The X direction, on the other hand, is set with respect to a more stable machine parameter, that is, the spindle axis of rotation. Tests here are designed with this in mind. If the machine has more than one work spindle and/or turret, tests should be performed for each possible spindle/turret combination. Further, if the tool-setting system is on a movable arm, the arm should be moved between each tool set when checking repeatability. Only one such combination will be discussed here, namely, the single spindle/single turret. If other options are desired, they should be negotiated between user and supplier and be made part of the original machine specification.

8.4.1 Repeatability of Tool-Setting System. Before establishing the position of the tool-setting system with respect to the spindle center line, it is necessary to check its repeatability. To do this it is recommended to use a new insert or a small precision ball mounted in the location of an insert in the tool holder. Whichever option is chosen, the tool holder should be short and as stiff as possible. Before proceeding, the machine should be exercised following an exercise procedure to be specified by the machine supplier. Next, the machine should be jogged to allow the tool or ball to contact the tool-setting system in both the X and Z

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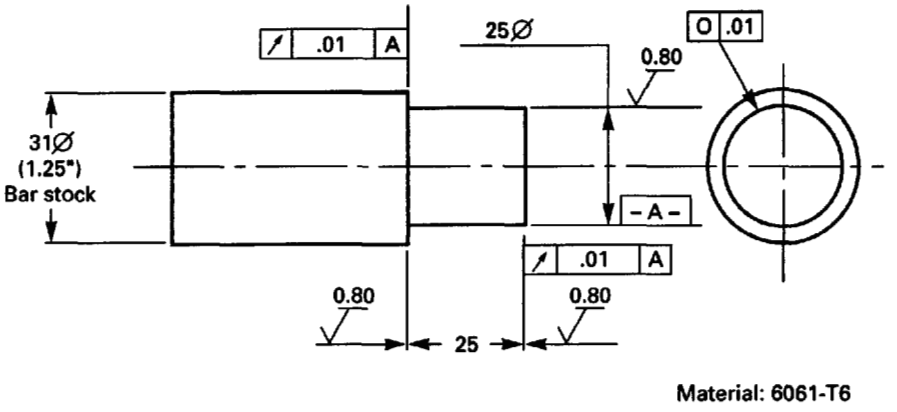


FIG. 65 TEST PART FOR DETERMINING THE LOCATION OF A TOOL-SETTING SYSTEM AND TOOL-SETTING SYSTEM DRIFT

(if applicable) directions and an original XZ position established. A cycle should be established, following the supplier's recommendations, to quickly reset the tool 10 times. This procedure should be representative of how the tools will be set during normal machine operation. If the machine is equipped with an arm that moves in and out of the work zone, that arm should be introduced during each cycle; that is, the tool-setting cycle should be that normally used to set tools when machining. For each of these 10 repeats, the X and Z locations of the tool (ball) should be recorded. From these numbers, a standard uncertainty is computed for each axis, following the procedures analogous to those outlined in para. 8.3.1. The repeatability is reported for both the X and Z (if applicable) directions as four times the standard uncertainty obtained from these measurements. For some specific purposes, it might be desirable to test the tool-setting sensor independent of the complete system performance. In that case, the procedures described above should be followed but the tool-setting arm left in position. The repeatability of the sensor in both the X and Z directions should be computed as above.

8.4.2 Original Location of Tool-Setting System. To initially establish the position of the tool-setting system, this Standard requires cutting a test part. This proposed test part is shown in Fig. 65. It consists of a small cylinder, the cut portion of which is 25 mm (approximately 1 in.) in diameter and 25 mm (approximately 1 in.) long. These dimensions do not need to be precise. The material for this test part is 6061-T6 aluminum like that used for the previous tests for machine critical alignments (see Section 7.7). A part program is established to face the part, turn the diameter, and face the shoulder near the spindle base. For the finish cut, a sharp single-crystal diamond tool, polycrystalline diamond tool, or other appropriate insert with a small nose radius of approximately 0.5 mm (approx. 0.020 in.) and low-tool-wear characteristics when machining aluminum shall be used. Before the finish cut is made, the tool position shall be sensed using the tool-setting system in both the X and the Z directions. The locations in machine coordinates of the tool as reported by the tool-setting system should be recorded. The final cut is then made on the part to a specified nominal diameter. Before the part is removed from the spindle, the Z offset between the step on the part and an appropriate feature on the chuck face, spindle nose, or spindle face plate should be measured in the Z direction. This distance should be compared to the Z reading of the tool-setting system to establish the correct offset.

The test part diameter should now be measured. Depending upon the application, this diameter may be measured on the machine with an appropriate micrometer or taken off the machine and measured using suitable metrology instrumentation of the requisite accuracy for the application. The difference between the actual diameter and the programmed diameter is then used to establish the correction to the X location of the tool-setting system. For high-accuracy applications, nominal differential expansion corrections should be made (see Glossary). This should be entered into the machine controller, taking care to get the appropriate sign (the sign of the correction can be checked by re-machining the same part to a smaller diameter and repeating the test).

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8.4.3 Combination Test for Tool-Setting System Drift.[51] The location of the tool-setting system with respect to the spindle center line and an appropriate spindle surface will vary with the machine's thermal state. Exhaustive tests could be conducted analogous to those given in Section 7.6. For the purposes of this Standard, a single test is defined which combines several of these effects. This test requires the machining of four test parts of 6061-T6 aluminum using two tools. A drawing of the test part is given in Fig. 65. The duration of the test shall be the duration established in previous spindle thermal stability tests (para. 7.6.2), or four hours, whichever is shorter. The tools used for this test are the same type as the tool that was used for the original location of the tool-setting system tests in para. 8.4.2 above. The test normally proceeds as follows.[52]

The first part is mounted following the procedure that will normally be used in machining. The spindle is then set to run at 50% of maximum rpm. The first part is faced. Then the tool is set following the normal procedures used when machining. Then the diameter and the shoulder of the part are cut to generate the nominal 25-mm step (the face of the part should not be re-cut). At the end of this machining cycle, the spindle is kept running at the same rpm and the X and Z axes of the machine are exercised over most of their travel (the part should not be contacted), at 80% of rapid traverse, for a period of one-fourth the duration of the test, or one hour, whichever is shorter. At the end of this period the spindle is stopped, a new blank mounted, and the process of facing, tool-setting, and part diameter and step cutting repeated. After the second part is cut, a new tool is inserted into the tool holder (or the turret indexed to a new tool) and the process repeated for two more parts. At the completion of this test, all four test parts are measured for both step height (Z direction) and diameters (X direction). The instrumentation chosen for the measurement is application- and machine-accuracy-dependent. For example, on many turning centers, micrometers and height gages might be sufficiently adequate. On diamond turning centers, other instrumentation is required.

The data are analyzed as follows. The differences between the programmed diameters and the measured diameters are computed. The step height data are computed similarly. The total range of the difference between the programmed and actual diameters is reported as the X-axis tool system drift, and the total range of the difference in programmed step heights versus actual step heights is reported as the Z-axis tool system drift. If desired, more than four test parts may be used in order to establish the statistical validity of the results. In this case, groups of parts should be machined in rapid succession at each of the time intervals previously defined and the average diameter step height and standard uncertainties computed for each interval.

8.5 CNC Performance Tests (Optional)[53]

8.5.1 General. The following tests are designed to check the function of the machine tool controller and the programming limitations of the system.

8.5.2 Test for Minimum Block Execution Time. A part program is prepared to run the machine tool in one axis only, using the maximum practical traverse length and linear interpolation. This is normally the Z axis on turning centers. The length of line segments will be set to a value one-fourth the "desired increment length," which should be the chordal length normally used when contour cutting. For example, if the machine will be used to make parts with a normal chordal length of 1 mm (approximately 0.04 in.), the test line segment length shall be 0.25 mm (approx. 0.01 in.). The programmed feed rate is set to the maximum contour feed rate available on the machine. The feed rate is measured by a time-recording device or a laser interferometer set in the velocity-measurement mode. Begin the test by running the program at a selected low feed rate. If the feed rate is constant over the axis travel, increase the feed rate setting. Continue to do this until the feed rate begins to vary over the axis travel distance. The maximum steady feed rate measured, V_{max} is then used to compute the minimum block execution time (MBET) using MBET = $INCR/V_{max}$

8.5.3 Test for Varying Segment Lengths. As in para. 8.5.2, this test moves one axis of the machine only. The part program is prepared to move along this axis. 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. 8.5.2 in a random pattern. The feed rate shall be the maximum feed rate observed in para.

[51] Note: this test may include spindle thermal stability (see para. 7.5.2).

[52] For machines that can not follow this procedure, a conceptually-equivalent procedure shall be agreed upon between user and supplier and made part of the original machine specification.

[53] Users of this Standard are requested to report results of this test to the Committee (B5/TC52) for possible future revisions.

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8.5.2 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 five percent during the total axis travel, the feed rate should be reduced by five-percent increments until the feed rate does not vary by more than five percent. This steady feed rate should be recorded as the varying segment feed rate (VSFR). Realistic line segments and feed rates shall be negotiated between user and supplier.

8.6 Machine Performance as a Measuring Tool (Optional)[54]

The following procedures have been designed to evaluate the performance of a turning center, 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. Although machines equipped for part scanning are not currently commercially available, this section could also be used on such machines, provided their data were acquired in the point-to-point measuring 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 which 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 which most closely represents the way in which the machine's measurement system will be used after acceptance. This section is in conceptual agreement with similar tests for coordinate measuring machines, as outlined in ASME B89.1.12M-1990(R1996), and machining centers, as outlined in ASME B5.54-1992. Prior to commencing these tests, the machine probe shall be calibrated according to the supplier's recommendations for normal operation of the machine when measuring parts, using an artifact of a different size than the part which will be machined and measured. 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 Section 7 of this Standard.

8.6.1 General. Unless otherwise specified by the user, the measurement repeatability and feature measurement accuracy tests shall be performed close to the spindle center line and in the center of the work zone. The probe orientation and configuration shall represent the configuration to be used after acceptance, with a default stylus length of 50 mm. It should be noted that the value for measurement repeatability and feature measurement accuracy is dependent on position, probe configuration, and stylus length; therefore, the user may specify other locations and configurations or several locations and configurations, if required as part of the original specification.

In these measurement repeatability and feature measurement accuracy 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 in the spindle near the center of the work zone. Ten determinations of the reference artifact's center shall be made as rapidly as practical in order to determine measurement repeatability. For each axis, four times the standard uncertainty of the artifact's center coordinates shall be reported as the measurement repeatability for that axis. Machine measurement repeatability will be reported on a per-axis basis. In order to determine the feature measurement accuracy the same data will be used; however, these data will be evaluated by the software in order to determine the size of the artifact being measured. In the event that a data point(s) obtained during this test appears to be an outlier (see Glossary), this point may not be simply discarded when either defining the standard uncertainty or the dimensions of the artifact. Rather, the complete test must be repeated and the data from a complete test evaluated.

For machines that have the option of operating in a radius mode or a diameter mode, all tests shall be performed and reported in the radius mode. For machines that only operate in a diameter mode, all results computed as diameters shall be divided by 2 and reported as radii.[55]

The user is cautioned that it is extremely important that the measuring stylus be on center in the Y direction for the measurement of diameters or radii. The error made when the stylus is off center measuring a diameter is given by

$$error = \frac{2\,(offset)}{DIA^2}$$

where

offset = the distance above or below center
DIA = the part diameter

[54] The tests described in this section do not cover the case when the machine is used as a comparator.

[55] Diametrical measurements are preferred; radial measurements are susceptible to thermal drift of the spindle center line with respect to the probe location.

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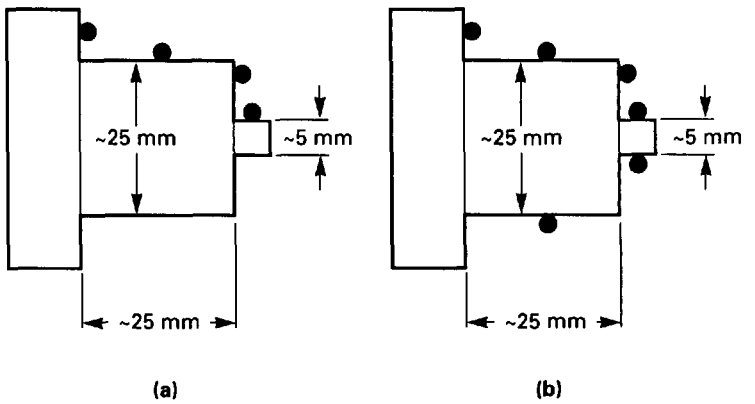


FIG. 66 APPROXIMATE LOCATION OF PROBED POINTS, DEPENDING ON PROBE CONFIGURATION WHEN MEASURING A MACHINED TEST PART:
(a) RADIUS MEASUREMENTS
(b) DIAMETER MEASUREMENTS

8.6.2 Measurement Accuracy Where Software Allows for only ID Measurements. For this test a test part shall be machined in the spindle. The part is user-selectable, with two diameters not greater than 80% and 40% of the maximum swing. The default size for the part is given in Fig. 66. The material is not specified but should be a dimensionally-stable metal that is capable of holding a good surface finish. A thermometer conforming to the requirements of Section 9 shall be appropriately thermally contacted with the test part 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. The two diameters of the test part shall be measured 10 times each using at least 10 points along each profile of the test part.[56] In the case of machines capable of measuring past the spindle center line, the diameters of the test part shall be measured 10 times each using at least five points along each profile of the test part. The step height of the test part, indicated in the figure, shall be measured 10 times using at least five points on each face. Contact points for each set shall be as widely spaced as possible. From these data, two average measured radii, $\bar{R}_{p1}$ and $\bar{R}_{p2}$, corrected for temperature, and the average step height, $\bar{Z}_{p0}$, corrected for temperature, shall be computed. The equations are as follows.

$$R_{p1} = R_{M1}\left(1 - \alpha_s\left(T_s - 20\right) + \alpha\left(T - 20\right)\right)$$

$$R_{p2} = R_{M2}\left(1 - \alpha_s\left(T_s - 20\right) + \alpha\left(T - 20\right)\right)$$

$$Z_{p0} = Z_{M0}\left(1 - \alpha_s\left(T_s - 20\right) + \alpha\left(T - 20\right)\right)$$

where

R_{Mi} = measured radii
α = nominal thermal expansion coefficient of the machine scales
T = average temperature of point selected as representative of the mean scale temperature
α_s = thermal expansion coefficient of the test part
T_s = average temperature of the test part during measurement
Z_{M0} = measured step height

The mean values and their standard uncertainties are computed following standard procedures (see Glossary). Measurement repeatability shall be computed as

- X measurement repeatability, MR(X): four times the largest standard uncertainty of either radius
- Z measurement repeatability, MR(Z): four times the standard uncertainty of the step height

The test part shall be measured using dimensional-measuring equipment at 20°C in a metrology lab. The measuring equipment should be suitable for the machine accuracy specification. The feature measurement accuracy shall be computed as follows.

The feature measurement accuracy in the X direction, FMX, shall be reported as the largest of the differences between either of the average radii measured on the machine, corrected for temperature, and the radii measured in the metrology lab. The feature measurement accuracy in the Z direction, FMZ, shall be reported as the difference between the average step measured on

[56] This test part will be measured in a metrology laboratory and thus serves as the calibration gage for checking machine accuracy.

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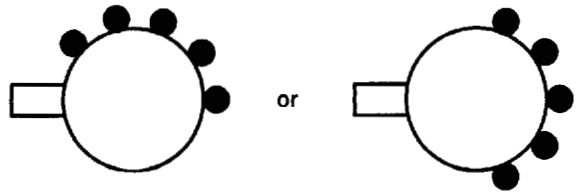


FIG. 67 APPROXIMATE LOCATION OF PROBED POINTS, DEPENDING ON PROBE CONFIGURATION WHEN MEASURING A TEST SPHERE

the machine, corrected for temperature, and the step height measured in the metrology lab. There is no test for probe lobing for a machine of this configuration.

8.6.3 Measurement Accuracy Where Software Allows for 2D or 3D Measurements. A 25-mm (approx. 1 in.) calibrated reference sphere, conforming to the requirements of Section 9, shall be mounted in the main spindle such that it is readily accessible for machine probing. A thermometer conforming to the requirements of Section 9 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. Ten sets of at least ten readings shall be made on the reference sphere. Contact points for each set shall be as widely spaced as possible. A schematic is shown in Fig. 67. X and Z coordinates of the center of the ball and the radius of the ball shall be computed for each set of readings, using the software supplied with the machine. From these computed results, an average measured radius, corrected for temperature, $\bar{R}_{p0}$, and the average X and Z center coordinates, $\bar{X}_{p0}$ and $\bar{Z}_{p0}$, and their standard uncertainties shall be computed.

Measurement repeatability shall be reported as:

- Measurement repeatability, MR(X): four times the standard uncertainty of the mean X coordinate
- Measurement repeatability, MR(Z): four times the standard uncertainty of the Z mean coordinate
- Measurement repeatability, MR(R): four times the standard uncertainty of the mean radius

Note that these repeatabilities are defined as the uncertainties obtained from the calculated values for 10 sets of readings.

The spindle shall be rotated approximately 180 degrees with the reference sphere remaining rigidly attached. Ten more sets of at least 10 readings shall be made on the opposite side of the reference sphere in a similar manner. X and Z coordinates of the center of the ball and the radius of the ball shall be computed for each set of readings. From these computed results, the average measured radius, corrected for temperature, $\bar{R}_{p180}$, and the average X and Z coordinates, $\bar{X}_{p180}$ and $\bar{Z}_{p180}$, and their standard uncertainties shall be computed.

The feature measurement accuracy shall be computed as

Feature measurement accuracy, *FMA* (X):

$$\max\{|R_{p0} - R_{\text{sphere}}|, |R_{p180} - R_{\text{sphere}}|\} + |X_{p0} - X_{p180}|;$$

Feature measurement accuracy, *FMA* (Z):

$$\max\{|R_{p0} - R_{\text{sphere}}|, |R_{p180} - R_{\text{sphere}}|\};$$

where

R_{sphere} = the calibrated radius of the gage at 20°C

For each reading in each of the 10 sets of data, a radius is calculated using the average computed center location. For each set of data, the minimum point radius is subtracted from the maximum point radius. The largest value among these is the specification zone for circular profile measurement accuracy, CPMA.[57]

8.6.4 Linear Measurement Accuracy. The procedure described in this section 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 bi-directional systematic deviation of positioning of an axis (para. 7.2.7.1) and the feature measurement accuracy (para. 8.6.2 or para. 8.6.3) have been previously measured, the values obtained for these measurements will be used in the computation of the linear measurement accuracy.

[57] Contributing to circular profile measurement accuracy are a number of error sources: probe lobing; thermal errors; geometric errors; and the CNC's ability to repeatably latch the probe's interrupt signal.

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The linear measurement accuracy for each linear axis [LMA(X), LMA(Z)] shall be reported. It is the sum of the measurement repeatability (MR) for an axis (paras. 8.6.2 or 8.6.3), the feature measurement accuracy (FMA) (paras. 8.6.2 or 8.6.3) for that axis, the spindle thermal stability (D_x or D_z) (para. 7.6.2), and the bi-directional systematic deviation of positioning of an axis (E) (para. 7.2.7.1) for an axis, minus the bi-directional systematic deviation of positioning of an axis multiplied by the radius (R_A) of the artifact used in the feature measurement accuracy test and divided by the axis length (L) of the axis of interest.[58] That is,

$$LMA(X) = MR(X) + FMA(X) + D_x + E(X) - E(X) \times (R_A / L_x)$$

$$LMA(Z) = MR(Z) + FMA(Z) + D_z + E(Z) - E(Z) \times (R_A / L_z)$$

8.7 Machining Test Parts (Optional)

8.7.1 General. Machining test parts have an important role in the acceptance of machine tools. However, using such test parts alone to determine machine accuracy and acceptance is not recommended. There are many variables that can affect the test part in machining tests that have no direct relation to the machine tool per se. Examples include material properties, tool wear, coolant flow and selection, temperature fluctuations in the workpiece, programming errors, fixture-induced distortions, etc. Thus, machine positioning accuracies and alignment are best tested by the procedures outlined in the preceding sections of this Standard. Two types of tests are discussed below.

8.7.2 Standard Test Parts. A large number of standard test parts has been generated as the result of decades of work by other Standards committees. In particular, test parts have been developed by BAS, NAS, JIS, and many other organizations. It is the recommendation of this Standard that if a test part is required an appropriate standard part be chosen and made part of the original machine specification. This part should contain tests for contouring accuracy, threading, and boring, as well as any other machining operations that are of importance to the machine user.

8.7.3 Production Parts. Where the machine is to be used in producing a single part or a family of parts, the best machine test to determine machine capability would be a run of production part or parts that are as close to the production part as possible. In this case the machine shall be started and allowed one hour for warm-up. The first part shall be cut and checked and any corrections to the tooling or programming made at that time. An additional 6 to 10 parts shall also be cut over a two-day period, allowing the machine to settle into thermal stability. The machine shall be kept running between the various test cuts, in a dry cycle, in order to increase thermal stability of the machine, without requiring an excessive amount of material to be cut and inspected. Further tests shall be negotiated between user and supplier and be part of the original machine specification.

8.8 Parametric Tests (Optional)

8.8.1 General. In order to obtain more complete information regarding the machine, some users may desire to perform complete parametric testing, measuring angular error terms other than yaw (Section 7.3), and also measuring straightness errors. If these error measurements are performed, it is recommended that the user follow the instrumentation guidelines for these tests given in ASME B5.54-1992. The measurement procedure and data analysis should, however, follow the procedure given for positioning accuracy and repeatability of linear axes (Section 7.2) as specified in this Standard.[59] This includes lines of measurement, measuring intervals, and measurement procedures including data analysis. The data should be reported with the correct titles, as has been done for the measurement of angular error motion (yaw) in Section 7.3. Note that for straightness measurements a straight line alignment term must be removed before data analysis, as is described in the B5.54 Standard referenced above.

9 INSTRUMENTATION

The instrumentation section of this Standard is still in the development stage. Recommendations from users and suppliers of test equipment are welcome and should be addressed to ASME (see Foreword).

[58] The number reported is highly approximate and is only intended to give a worst-case estimate.

[59] For larger machines, this Standard suggests that fewer runs might be negotiated between user and supplier.

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9.1 Temperature

The time constant of thermometers shall be no more than one-tenth 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 B89.6.2-1973 for further clarification). The resolution of thermometers shall be no greater than one-tenth 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.

9.2 Relative Vibration

Relative vibration shall be measured using a high-resolution, undamped displacement indicator. Resolution of 0.1 μm (approx. 0.000004 in.) or better is recommended. Such indicators shall also have a bandwidth of at least 1 kHz.

9.3 Displacement

9.3.1 Laser Interferometer. Laser interferometers shall have a frequency stability such that this long-term stability represents an error of less than ¼ of the uni-directional 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 ¼ of the uni-directional repeatability, linear axes.[60]

9.3.2 Grid Encoders. Grid encoders used for contouring performance testing shall be calibrated with an error of less than ¼ of the uni-directional repeatability, linear axes, of the machine. Calibrations traceable to NIST are preferred.

9.3.3 Precision Reference Ball(s). The precision reference ball(s) for ETVE, tool change and turret repeatability, and machine performance as measuring tool tests shall be spherical to within ¼ of the uni-directional repeatability, linear axes, of the machine tool. Reference balls used for the feature measurement accuracy test shall be calibrated for their diameter to within ¼ of the uni-directional repeatability, linear axes, of the machine. Diameter calibration, where required, shall be traceable to NIST.

9.3.4 Precision Disks. The precision disk(s) used for the contouring test shall be calibrated to an accuracy of ¼ of the uni-directional repeatability, linear axes. Calibrations traceable to NIST are preferred.

9.3.5 Telescoping Ball Bar. The balls on the end of the telescoping ball bar shall be spherical to within ¼ of the uni-directional repeatability, linear axes, of the machine tool and equal in diameter to within ¼ of the uni-directional 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 ¼ of the uni-directional repeatability, linear axes. Calibrations traceable to NIST are preferred.

9.4 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.

9.5 Humidity

Humidity measurement for correction of the laser interferometer wavelength shall be sufficiently accurate that it contributes no more than ¼ of the uni-directional repeatability, linear axes, to laser measurement error.

9.6 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.

9.7 Displacement Indicators

Displacement indicators used for the ETVE test, machine thermal tests, critical alignment, rotary axis alignments, tool change repeatability, and repeatability

[60] 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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in drift of tool-setting systems, as specified in this Standard, shall be calibrated to within ¼ of the uni-directional repeatability, linear axes, of the machine. Capacitance probes, laser interferometers, linear variable differential transformers (including air-bearing types),[61] 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.

9.8 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 uni-directional 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.

9.9 Polygons

Polygons used for the positioning accuracy and repeatability, rotary axes, shall be calibrated to within ¼ of the uni-directional repeatability, rotary axes, of the axis to be measured.

9.10 Indexing Tables

Indexing tables shall be calibrated to within ¼ of the uni-directional repeatability, rotary axes. The calibration may be performed by an appropriate agency, traceable to NIST, or by subdivision (a self-calibration procedure).

9.11 Rotary Encoders

Rotary encoders shall be calibrated to within ¼ of the uni-directional repeatability, rotary axes. The calibration may be performed by an appropriate agency, traceable to NIST, or by subdivision (a self-calibration procedure).

9.12 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 non-linear 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.

9.13 Differential Levels

Differential levels shall be calibrated to within ¼ of the uni-directional repeatability, angular positioning. Calibrations shall be performed on a regular basis, with traceability to NIST being highly recommended.

9.14 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 uni-directional repeatability, linear axes, and shall have a bandwidth of at least 10 kHz, or higher. 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.[62]

9.14.1 Commercial Instruments. Commercial instruments that measure spindle error motion shall have sensors that conform to the requirements for spindle error measurement given in Section 9.14 above. Furthermore, such instruments shall provide documentation to ensure that any internal algorithms conform to the measurement procedures as described in this Standard.

9.15 Indicators for Straightness Measurements

Indicators for straightness measurements shall conform to the requirements of Section 9.7.

9.16 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-R1997 (replaces B89.1.12M-1990)

[61] Air-bearing LVDTs are preferred for the part-trace tests on high-precision machines.

[62] 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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and have a working tolerance for volumetric performance less than one-fourth 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 one-tenth of the specified measurement accuracy for the test part.

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NONMANDATORY APPENDIX A
GUIDE FOR USING THE TURNING CENTER STANDARD

A1 GENERAL

The primary purpose of this Standard is to aid in the purchasing of machines to specification. When purchasing a new machine, the user should clearly specify the desired machine classification (Form 1) and the machine performance (Forms 4 and 5). The entries in Forms 4 and 5 will be considered the specification zones for the purchased machine. If desired, the user may also describe the proposed machine environment on Form 2; 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 can be useful but is not a substitute for testing after machine installation.

The tests described in this Standard are in logical sequence but not necessarily the most rapid sequence for machine testing. The time required for testing is primarily limited by the duration of the various thermal tests and the time required for the machine to reach equilibrium after these tests. The following is a suggested procedure for testing that the Committee currently believes will minimize the testing time. Only the testing of a simple two-axis lathe, with a single work spindle, is covered. Further, it is assumed that programs and all necessary fixtures have been prepared in advance. Users who follow this sequence should report their experiences to the ASME Secretary.

A1.1 Recommended Tests: Day 1

Tests should be performed in the order given below.

- Relative vibration test (Section 6.3)
- ETVE test (Section 6.2)
- Structural motion test (para. 7.5.2)
- Spindle thermal stability test (para. 7.6.2)
- Spindle error motions: fixed sensitive direction (para. 7.5.3)

Note that the spindle thermal stability test requires up to four hours to perform. After this test the machine must be allowed to return to equilibrium before other testing can proceed.

A1.2 Recommended Tests: Day 2

These tests require the use of a laser interferometer. They are as follows.

- Positioning accuracy and repeatability, X axis (Section 7.2)
- Angular error motion, X axis (Section 7.3)
- Positioning accuracy and repeatability, Z axis (Section 7.2)
- Angular error motion, Z axis (Section 7.3)
- 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 will need to return to equilibrium.

A1.3 Recommended Tests: Day 3

These tests require a calibrated telescoping ball bar, a test part and tooling or appropriate straightedges and indicators, and a power meter.

- Contouring performance using circular tests (Section 7.8)
- Critical alignments (Section 7.7)
- Spindle idle run loss test (para. 7.9.2)
- Composite thermal error (para. 7.6.4)

A1.4 Recommended Tests: Day 4

These tests require at least material and tooling. If other test parts are specified, a metrology laboratory for part measurement is required.

- Chatter limits test and full torque test (para. 7.9.3)
- Other test parts, as specified
- Multi-function cycle test (Section 7.10)

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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 which 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 ANSI B89.6.2 and ISO 10360-2:1994. It is the thesis of ANSI 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. 6.2.2. For a thorough discussion of the technical situation, the reader is referred to ANSI B89.6.2. The purpose of this Appendix is, however, to specify procedures and responsibilities for testing the thermal environment in the event that the ETVE, as measured in para. 6.2.1, is excessive. That is, the expanded thermal uncertainty exceeds that required for the machine, and the machine user contends that his environment meets the supplier's parameters. For the purpose of 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 METHOD OF TEST

In order 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 a period of 24 hours 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 ANSI B89.6.2. It is recommended that the instruments used be properly calibrated and the test personnel be 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 Section 9 of this Standard. 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).

[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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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 hours). 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 (maximum frequency) specified by the supplier shall be ignored. The daily variation shall be defined as the maximum range of temperature readings in 24 hours, 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 one-hour 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 minutes. 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 hours) and the greatest value of the gradient reported.

B3 ANALYSIS

If any of the parameters measured in Section 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 Section 6 of this Standard. 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 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 the Institute of Environmental Sciences Document IES-RP-CC024.1, "Measuring and Reporting Vibration in Microelectronics Facilities."

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. Depending on the type of criteria, the amplitude ordinate can be defined in either the time domain or frequency domain.

C3.1.1 Amplitude Units. Since the machine is a cutting tool, units of displacement are most useful in relation to machine performance. However, velocity and acceleration 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.

C3.1.2 Ordinate Units. The use of time or frequency for the ordinate 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 which provides ability to diagnose many dynamic events.

C3.2 Criteria Format

As defined in Section 5.3 of this Standard, 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 2), 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 Criteria. These types of criteria are specified as a vibration amplitude as a function at 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.

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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 level and a time period over which it applies. The vibration amplitude could be units of velocity or acceleration.

C4 INSTRUMENTATION

This section describes various instruments required to perform on-site vibration measurements. Various types of sensors, signal conditioners, recorders, computer programs, and signal analyzers are available which will acquire these data. It is not intended to single out any particular equipment manufacturer, but to recommend types of equipment which meet the requirements of this Standard.

C4.1 Transducers

Many types of transducers exist for various types of vibration measurements. The measurements specified 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/s^2 (386 in/s^2).

C4.1.2 Velocity Transducers. These sensors are also referred to as geophones. The sensitivity of the geophone should be 4 V/cm/s (approx. 10 V/in/s 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 below, 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 $dB/\sqrt{Hz}$.

(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 1600 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 1/2 Hz would need to be acquired with 200 lines of resolution. This document recommends that 0- to 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

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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 10 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 multi-channel 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 which 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 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 PROCEDURES

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 lab, traceable to NIST, in the past 12 months. 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 triaxial transducers in one device. When this mounting arrangement is used, all three channels should be acquired simultaneously. Time-independent triaxial measurements should not be performed.

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 (approx. 10 ft.) beyond this 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 vertical and horizontal criteria. It is important to compare the acquired data to the criteria in the appropriate direction.

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C5.4.2 Frequency Response Function. Comparison of frequency response function criteria to frequency domain vibration data can require 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 in order to conform to the specification, or else accept a performance derating as described in Section 6.3 of the Standard. Again, 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 shall be issued by the vibration specialist within approximately three weeks. The report shall include all back-up information and analyzed data with a comparison to the machine specification. The report shall include the following as a minimum:

- Title
- Dates (issued and when data were taken)
- Calibration information
- Description and diagram of test setup
- Procedure
- Analysis
- 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.

C8 FIELD INSTRUMENTATION DIAGRAM

A diagram of the instrumentation is given in Fig. C-1.

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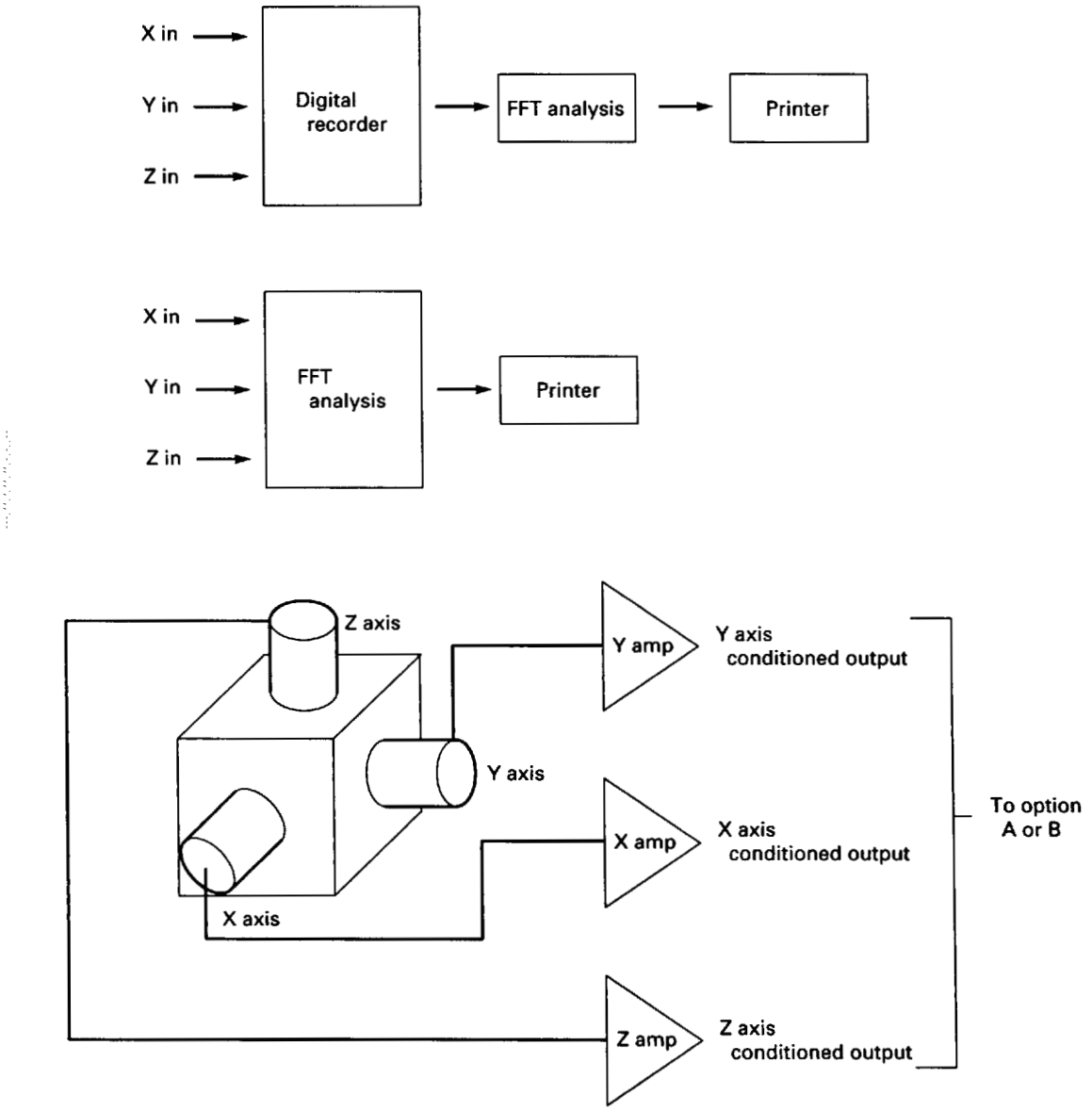


FIG. C-1 DIAGRAM OF SENSOR ARRANGEMENT AND INSTRUMENTATION CONFIGURATION

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NONMANDATORY APPENDIX D
ELECTRICAL POWER VERIFICATION 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 in the event that 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 disturbance analyzer be used for these tests because of the excessive labor required when individual instruments are used (an acceptable example of such an instrument would be the BMI 2400 series or the Dranetz Model 626-PA-600X). These units are designed to monitor a wide range of power line disturbances and are capable of continuous, unattended operation. Typical measured parameters include sags, surges, impulses, and line frequency.

Sags are sudden voltage drops which are detected by analyzing each cycle and comparing its root-mean-square level to a long time constant averaged steady state voltage value. When the cycle-to-cycle level deviates by more than the preselected threshold, a sag is detected.

Surges are sudden voltage increases which are normally detected with the same techniques used to detect sags. Again, a standard power line monitor will note and record both the values of the surge and the time at which it occurred. Impulses, in the technical language of power line monitoring, refer to short duration (approximately 1 to 1,000 μs) spikes superimposed upon the ac sine wave. Typically such impulses are measured as the amplitude of the spike alone with respect to the voltage level at the time the spike occurred, i.e., no subtraction or addition is made for the sinusoidal component.

Frequency changes in the line are also normally recorded by such instruments. Changes in frequency are self-explanatory.

D3 METHOD

In order to ensure proper monitoring, the power supply to the machine should be monitored for a period which 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-hour 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, surge, and impulse) 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.

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 non-conformance 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 in order that machine specifications are met.

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NONMANDATORY APPENDIX E
MACHINE AND CAD/CAM FUNCTIONAL TESTS (INCLUDING SPINDLE RPM, NOMINAL FEED RATES, AUXILIARY FUNCTIONS, AND TESTS OF THE MACHINE PROGRAMMING SYSTEM)

E1 GENERAL

The tests described in this appendix are to verify machine functional specifications that are important but do not directly influence machine accuracy. Tests are given for feed rate, spindle rpm, tool-change time, tool-setting system measuring time, pallet indexing time, and axis indexing time.

E2 FEED RATE MEASUREMENTS

This test is intended to verify whether the machine tool axis moves at the commanded feed rate. Variations of actual feed rate from the commanded feed rate affect the quality of parts produced. Velocity profiles, which give an indication of time required for the axis to reach the commanded feed rate (settling time), can be used to check the acceleration-deceleration settings and are useful for servo tuning and troubleshooting. Also, reduced settling time increases machine throughput. Dynamic measurements using a laser interferometer (used for measuring linear displacement accuracy) shall be used to measure the feed rate of machine tool motion.

E2.1 Measurement Procedure

The lines of measurement for feed rate measurement should be the same as those for the positioning accuracy and repeatability, linear axes (Section 7.2). The laser shall be aligned as specified in that section. Two sets of bi-directional measurements shall be made for each axis, with the laser interferometer in the velocity mode. If the machine has ranges of feeds, measurements shall be taken at the center of the feed range for all feed ranges of the machine tool and at the specified rapid traverse rates. Otherwise, the measurements shall be performed at five steps over the total range of feed rates and at the specified rapid traverse rates. At each rate, for each axis, the average feed rate in the forward and reverse direction shall be recorded. The differences between the nominal feed rates and the measured feed rates, in both the forward and reverse directions, shall be within acceptable tolerance, as specified between user and supplier.

E3 SPINDLE RPM MEASUREMENT

This test is intended to verify that the spindle is running at the commanded rpm. The spindle is run with no load at five different speeds equally spaced over its total speed range and the spindle rpm recorded using a strobe or other rpm indicator. (A spindle error analyzer can be used for this task; see Section 7.5 if such instrumentation is available.) At each rpm, a minimum of 100 revolutions shall be used to obtain an average rpm. The differences between the commanded rpm and the actual rpm are then reported for each of the five speeds. Differences should be within the range specified in the original machine specification.

E4 TOOL-CHANGE TIME

The machine shall be positioned at the center of the work envelope with the spindle stop. It shall then be commanded to perform a tool change and pick up the nearest tool in the magazine, and then return to the center of the work zone with that tool. This process shall be repeated 10 times. The average time period between the start of machine motion from the center of the work zone and the return of the machine with the tool to the center of the work zone shall be reported as the tool-change time. The difference between the specified tool-change time and the measured tool-change time shall be within the specification between user and supplier.

E5 TOOL-SETTING SYSTEM MEASUREMENT TIME

This test is applicable for machine tools with tool probes which are used to measure tool position (tool offsets). The machine shall be positioned at the center

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of the work zone. A program shall be written that will require the machine to perform a tool change, pick up the nearest tool in the tool magazine, and then perform a tool offset measurement using a tool-setting system and return back to the center of the work zone. This process shall be repeated 10 times. The average time period between the start of machine motion from the center of the work zone and the end of machine motion at the center of the work zone shall be reported as the tool-setting system measurement time. The difference between the specified tool-setting system measurement time and the measured tool-setting system measurement time shall be within the specification between user and supplier.

E6 PALLET-CHANGE TIME

The machine shall be positioned so that the tool is at the center of the work zone. A program shall be written to command the machine to perform a pallet change, loading the nearest pallet in the pallet-loading station into the machine, and then returning the tool to the center of the work zone. This process shall be repeated 10 times. The average time period between the start of machine motion in the center of the work zone and the end of machine motion in the center of the work zone shall be reported as the pallet-change time. The difference between the specified pallet-change time and the measured pallet-change time shall be within the specification between user and supplier.

E7 AXIS INDEXING TIME

This test is applicable only for machines that have indexing turrets. The indexing turret shall be positioned at zero degrees. The turret shall then be commanded to index to the next tool position and then return to the original tool position 10 times. One-half the average time period taken by the turret to index from zero to 90 degrees and return shall be reported as the turret indexing time. The differences between the actual turret indexing time and the specified turret indexing time shall be within the specification agreed between user and supplier. This test should be performed for all turrets and/or indexing axes.

E8 CAD/CAM PROGRAMMING TESTS

E8.1 Contouring Test Using A Precision Straightedge

For this test a precision straightedge is set up on diagonal paths in the XZ plane. Two paths are required. For the first path the straightedge should be inclined at an angle of 1 to 100 approximately parallel to the X axis. This measures the machine behavior for cuts that are primarily facing cuts. In the second position the straightedge is inclined 100 to 1, approximately parallel with the Z axis. In both cases an LVDT or other appropriate indicator, such as a capacitance gage, is swept along the straightedge when doing a G01 linear interpolation between two end points along the entire length of travel of the straightedge. (This is one-half the swing when the straightedge is approximately parallel to the X axis.) The feed rate for this test should be the feed rate determined in para. 8.5.3. The readings of the displacement indicator are recorded. The same linear move is then repeated using a CAD/CAM-generated program, with the same feed rate but with line segment lengths that are typical of the intended service of the machine. The default line segment length is 1 mm (approx. 0.04 in.). In each of the two positions the results of the two measurements are compared. The slopes and total ranges of the two measurements should agree within 5 percent.

E8.2 Contouring Test for CAD/CAM Performance Using a Telescoping Ball Bar[1]

A circular contouring test is performed using G02 and G03 programmed moves as described in Section 7.8. The contouring test is then repeated using a CAD/CAM-generated circle program, with the same feed rates as used previously. This CAD/CAM-generated circle should have at least 720 line segments. The difference between the circular deviation, in the clockwise and counterclockwise directions, between the two tests should be reported. Differences between the circular deviations, in both directions, should be less than 10 percent.

[1] During this test the average feed rate should be measured with a stopwatch to ensure that the programmed feed rate is realized.

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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, 10–12). 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 MULTI-POINT SUPPORTED MACHINES

Uniform distribution of loading on multi-point 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 Section 6).

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NONMANDATORY APPENDIX G
COMPLIANCE AND HYSTERESIS CHECKS

G1 COMPLIANCE AND MACHINE HYSTERESIS

G1.1 General

Compliance is ideally obtained by measuring the relative displacement of the tool point with respect to the workpiece when a static load is applied between the tool and the workpiece. The compliance may be linear or angular (see Glossary). The linear compliance for any axis is the ratio of the deflection to the force applied in the same direction. Units are microns per Newton (microinches per pound). The angular compliance is defined similarly but with the units of degrees per Newton meter (degrees per foot pound). Either compliance is, of course, a function of the position of the machine tool and as this position changes the compliance varies. For the purpose of this appendix 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.[1] In general, the supplier shall specify the maximum load and provide appropriate fixturing. This is important, as the loads applied in this test are large and appropriately tested fixturing is essential for the safety of personnel and the machine. If a load is not specified, suggested values are given in Table G1. The test prescribed does not exactly measure the linear compliance as described above but, rather, provides a simplified indication of what more rigorous compliance testing would measure. It is deemed to be adequate for the purposes of this appendix. This test is also designed so that it gives a measurement of the machine hysteresis, which is conceptually similar to the setup hysteresis except that it is normally caused by loose joints, backlash, dragging cables and way covers, imperfectly adjusted gibs, etc. Angular compliance is measured similarly but at positions as defined in the text and at loads to be specified by the machine supplier.

[1] Users desiring to measure compliance and hysteresis for rotary positioning axes are referred to ASME B5.54-1992.

G1.2 Compliance and Machine Hysteresis Test Setup — Linear Axes

The setup for measuring compliance and machine hysteresis for a Z axis is shown in Fig. G-1. (Details of the fixture design and the choice of displacement measurement method depend on the type of tool holder, the machine, the compliance of the load cell, and other parameters.) An electronic indicator, dial gage, or laser interferometer is set to read the relative motion between the tool holder and the table. (Details of this fixture design depend on the type of tool holder used on the machine.) The fixture is aligned with the machine axis to be tested and attached to a load cell of suitable capacity which is in turn attached rigidly to a bracket fixtured to the machine table. For speed of measurement the setup should be such that the load cell will function under tension and compression. The load cell should have the range and accuracy required for the test (see Table G1). The indicator is set to read in the direction of the applied force, as indicated in the figure. (Any other displacement measuring device of sufficient range and resolution may be substituted for the indicator, if desired. For example, if the fixtures are sufficiently tight and the machine sufficiently stiff, a capacitance gage reading against the test ball could be substituted, or even a laser interferometer could be used.) Since the forces applied in this test are large, care should be taken to make sure all fixtures are properly secured and that the supplier's recommendations, or approved fixtures, are utilized throughout. The suggested values for the loads to be used in this test are given in Table G1. Values other than those in the table shall be negotiated between user and supplier.

G1.3 Compliance and Machine Hysteresis Test Procedure — Linear Axes

At the beginning of each test the indicator is zeroed. If the machine has backlash compensation, this test is conducted with the backlash compensation on. Then, for each axis to be measured, the machine is commanded to move in small increments in the appropriate direction, so as to result in load cell indication until the maximum

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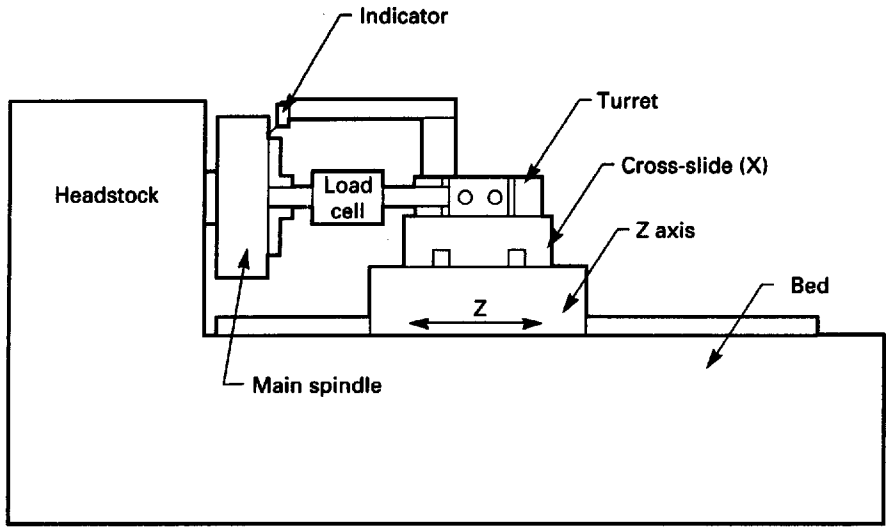


FIG. G-1 SETUP FOR MEASURING THE COMPLIANCE AND MACHINE HYSTERESIS IN THE Z DIRECTION

TABLE G-1 SUGGESTED MAXIMUM LOADS FOR THE COMPLIANCE AND MACHINE HYSTERESIS TEST

Spindle Torque (Newton meters)	Force (Newtons)
20	1100 (approx. 250 lbs)
50	2200 (approx. 500 lbs)
100	4500 (approx. 1000 lbs)
150	6650 (approx. 1500 lbs)
200	8900 (approx. 2000 lbs)
250 (and greater, at 600 rpm)	8900 (approx. 2000 lbs)

force specified for that axis in that direction, or a maximum deflection (the deflection is defined as the difference between the actual position and the commanded position) of 250 micrometers (approx. 0.01 in), has been reached. The restriction on the total deflection has been included to protect machines from possible damage. Suggested values for the loads are given in Table G1 as a function of spindle torque. Call the first direction the plus direction. At the position where the force is at its maximum in this direction, the command position, the actual position, and the force are recorded. Next the machine is jogged in the opposite direction until the force just reaches a small pre-load, which is specified for this test to be one percent of the maximum force. At this point, called the plus pre-load point, the commanded position, the actual position, and the force (which is the pre-load force) are again recorded. Jogging of the machine is now continued in this same direction (the negative direction) until the force reaches its maximum value in the opposite direction. Again the force, commanded position, and actual position are recorded. Finally, the machine is jogged back in the plus direction until the force just reaches one percent of the maximum force in the negative direction. This point is called the minus pre-load point. Again, the command position, actual position, and pre-load force are recorded. If the user so desires, the whole curve may be generated as shown in Fig. G-2; however, only the four points indicated above are used in the data analysis. The data analysis is described below. Note that this test measures the difference between the commanded motion and the actual motion. It is this difference that is plotted to obtain the compliance and hysteresis. Performing the test in this fashion removes any effects due to clearance in the test fixtures or deflections of the load cell.

G1.4 Compliance and Machine Hysteresis Data Analysis — Linear Axes

The data obtained from each machine axis are analyzed similarly. First, the deflection at each point, which is defined as the difference between the actual position and the commanded position (measured minus commanded), is computed. (If the machine is jogged, then the commanded position is simply the number of jogs in a given direction times the size programmed for each jog.) The compliance for that axis is defined as the total range of the deflections divided by twice the maximum force. The values to be used are clearly indicated in Fig. G-2. The machine hysteresis for this axis is defined as the range of deflection between the

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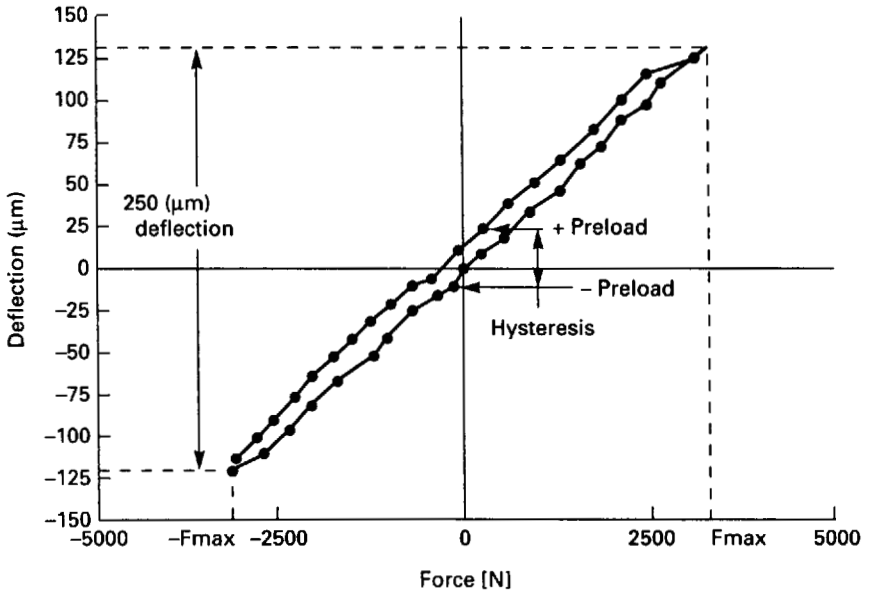


FIG. G-2 TYPICAL PLOT SHOWING THE RESULTS OF A COMPLIANCE AND AXIS HYSTERESIS TEST

points plus pre-load (approaching the pre-load force from the plus direction) and minus pre-load (approaching a negative pre-load force from the minus direction). Again, it is clearly labeled in the figure.

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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 Glossary). 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 Section 9).

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]

$$CLR = LDR\left[1 + Kt\left(T_s - 20\right) - Kp\left(P_s - 760\right) + Kh\left(V_s - 10\right)\right]$$

where

CLR = corrected laser reading

Kh = coefficient of refractive index change due to atmospheric humidity. The current best value is 0.05 x 10^{-6}/mm Hg partial pressure of water vapor. Because of the low value of this coefficient, the atmospheric humidity can be neglected for most applications.

Kp = coefficient of refractive index change due to atmospheric pressure. The current best value is 0.36 x 10^{-6}/mm Hg pressure.

Kt = coefficient of refractive index change due to atmospheric temperature. The current best value is 0.93 x 10^{-6}/°C

LDR = laser display reading

P_s = air pressure, mm Hg

V_s = partial pressure of water vapor in mm Hg[2]

T_s = mean air temperature, °C

The preceding equation is a linearization of the 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. In order 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

$$CMR = MDR\left[1 + \alpha\left(T - 20\right)\right]$$

where

CMR = corrected machine reading

MDR = machine display reading

α = effective thermal expansion coefficient of machine scales

T = scale temperature during measurements, °C, in the case where the machine was set up at 20°C (68°F)

[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 percent relative humidity at 20°C would yield a partial pressure of 0.5 × 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), the spindle thermal stability test (para. 7.6.2), thermal distortion caused by moving linear axes (para. 7.6.3), and the 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 time period 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 I-1 shows a cartridge-type linear variable differential transformer (LVDT) blocked by means of a cap or capture device which 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 which show that, for precision applications, the drifts inherent in the laser interferometer optics should be measured. In order to perform this drift check, the two retroreflectors are rigidly mounted to the remote interferometer as shown in Fig. I-2. The laser is then aligned with this interferometer and adjusted for maximum signal strength. The laser is zeroed and the drift of the system recorded over similar periods of time as used for the ETVE test (Section 6.2). If the drift is excessive for the application, then the supplier of the laser interferometer 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. I-3. The spacer between the interferometer and the retroreflector is made of steel and the laser system temperature and pressure sensors placed as 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 (approx. 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

[1] The supplier of the steel spacer shall provide an accurate measurement of its nominal length and its thermal expansion coefficient.

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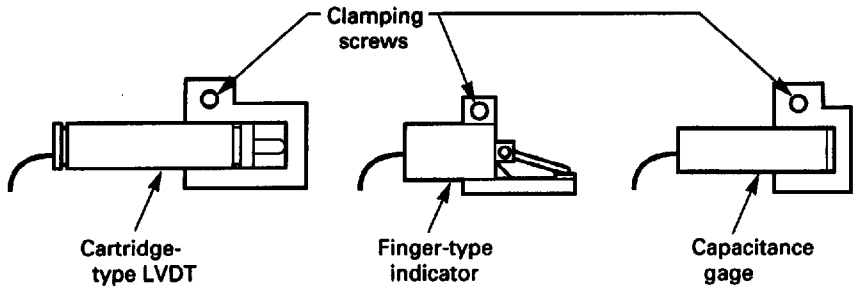


FIG. I-1 CAPTURE DEVICES FOR SEVERAL DISPLACEMENT INDICATOR TYPES

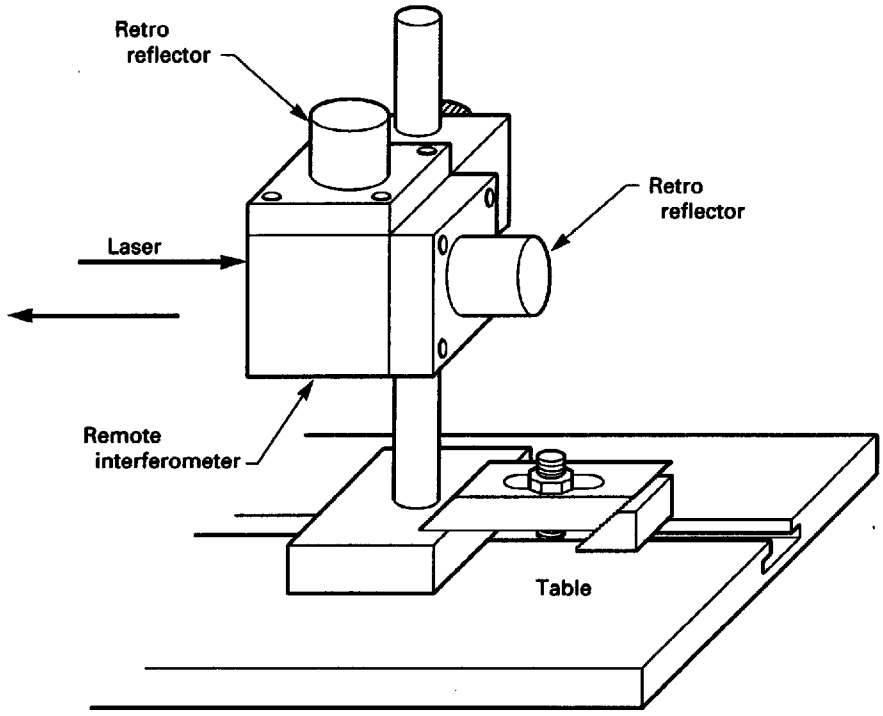


FIG. I-2 PROPOSED SETUP FOR MEASURING THE DRIFT OF THE LASER INTERFEROMETER OPTICS

measured over a period of time corresponding to the time of the proposed test (four hours for the thermal distortion caused by moving linear axes test). The drift of the system should be less than one-fourth of the repeatability for uni-directional 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 above. The drift of the system should be less than one-fourth of the repeatability for uni-directional positioning, linear axes. If the drift is larger, then the laser system and/or its supporting sensors should be repaired.

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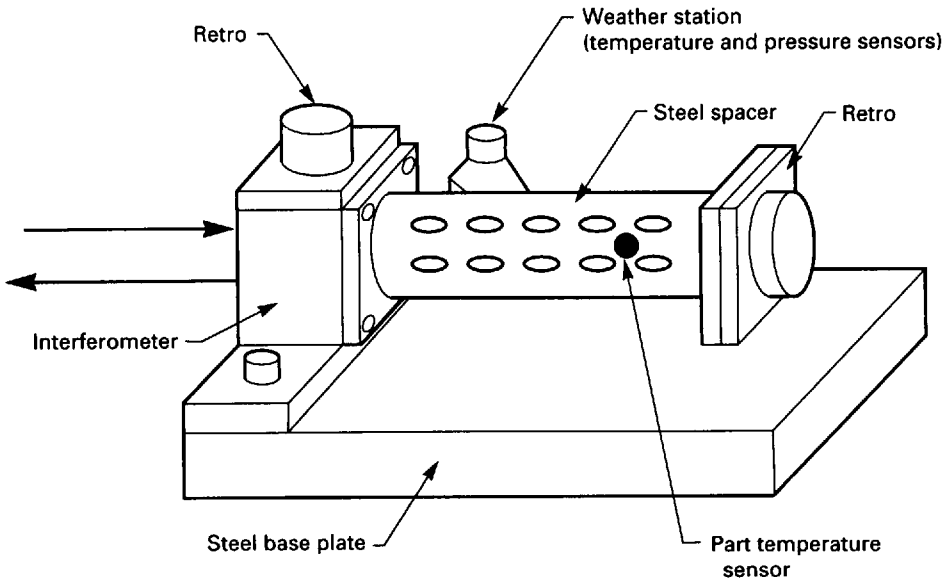


FIG. I-3 THE PROPOSED SETUP FOR MEASURING LASER MEASUREMENT SYSTEM STABILITY

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NONMANDATORY APPENDIX J
THE PART TRACE TEST

J1 GENERAL

The part trace test procedure consists of cutting a part and then replacing the tool with an appropriate displacement transducer[1] and repeating the original tool path, but with the spindle off. Readings from the transducer are recorded as the part is "traced." The part trace test is a simple method for separating the errors introduced by machine geometry from those introduced by process variables such as tool wear, tool roundness and size errors, cutting force deflection, hard spots in the material, thermal errors such as spindle growth, angular thermal drift of the C-axis average line, expansion of the tool holder toward the work, expansion of the work toward the tool, runout of the workpiece caused by radiation from the room lights when the spindle is stopped, and control system dynamic errors. If two-axis contour cuts are to be measured, it is necessary to use a round stylus having the same radius as the tool.

---

[1] Note: LVDTs are preferred over optical and capacitance indicators for part trace test purposes because LVDT transducers are not affected by coolant. They work equally well wet or dry. Air-bearing LVDTs are preferred over plain bearing LVDTs because their low stylus forces and absence of sliding friction avoid scratching of the work surface.

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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. From the Glossary,

$$NDE = \alpha L(T - 20) - \alpha_s L_s(T_s - 20) \qquad \text{(K-1)}$$

where variables are defined elsewhere. 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 equation (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 Glossary). 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 ±(ETVE/2)/($L\alpha$) for machine calibration, or ±(ETVE/2)/($L_s\alpha_s$) when the machine is used as the measurement standard. Therefore,

$$u^2(T)_{eff} = \left[\frac{ETVE/2}{L\alpha\sqrt{3}}\right]^2 + u^2(T) \qquad \text{(K-6)}$$

and

$$u^2(T_s)_{eff} = u^2(T_s) \qquad \text{(K-7)}$$

for calibration of a machine axis.
For use of the machine as the measurement standard,

$$u^2(T)_{eff} = u^2(T) \qquad \text{(K-8)}$$

and

$$u^2(T_s)_{eff} = \left[\frac{ETVE/2}{L_s\alpha_s\sqrt{3}}\right]^2 + u^2(T_s) \qquad \text{(K-9)}$$

In either case the combined standard thermal uncertainty is written as

$$u_{cT}^2(L) = L^2(T - 20)^2 u^2(\alpha) + L_s^2(T_s - 20)^2 u^2(\alpha_s) + L^2\alpha^2 u^2(T) + L_s^2\alpha_s^2 u^2(T_s) + u_{ETVE}^2$$

where

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u^2_{ETVE} = $ETVE^2/12$ arises from either equation (K-4) or (K-5)

The combined standard thermal uncertainty is used to derate performance specifications (Section 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 (Section 7.2). The specification zone is for the bi-directional accuracy of positioning, A.

Performance parameter:	Bi-directional accuracy of positioning
Specified accuracy:	33 μm/m (FIR)
Axis length:	1016 mm
Measurement devices:	Laser interferometer (displacement) Thermocouples (temperature of air and materials)
Mean temperature:	26°C
ETVE:	33 μm
Coefficient of thermal expansion of the machine scale, α:	11.7×10^{-6}/°C
Coeficient 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. 6.2.1):

$u^2_{ETVE} = ETVE^2/12 = 90.75\ \mu m^2$

Uncertainty of nominal expansion of the machine scale (para. 6.2.4, method c):

$$u(\alpha) = 0.1\,\alpha\sqrt{1/3} = 6.75 \times 10^{-7}/°C$$

$$u^2(\alpha) = 4.56 \times 10^{-13}/°C^2$$

$$(UNE)^2 = L^2(T-20)^2 u^2(\alpha) = \left[(1016\ mm)^2 (26°C - 20°C)^2 (4.56 \times 10^{-13}/°C^2)(10^3 \mu m/mm)^2\right]$$

Uncertainty of nominal expansion of the standard (para. 6.2.4, laser):

$$u(\alpha_s) = 0$$

$$(UNE)^2_s = L_s^2(T_s - 20)^2 u^2(\alpha_s) = 0$$

Length uncertainty due to temperature measurement (para. 6.2.5):

$$u^2(T) = [1 - (-1)]^2/12°C^2$$

$$u^2(T) = 1/3°C^2$$

$$u^2(T_s) = [1 - (-1)]^2/12°C^2$$

$$u^2(T_s) = 1/3°C^2$$

$$LUTM^2 = L^2\alpha^2 u^2(T) + L_s^2 \alpha_s^2 u^2(T_s)$$
$$= (1016\ mm)^2 (11.7 \times 10^{-6}/°C)^2 \, 1/3°C^2 (10^3\ \mu m/mm)^2$$
$$+ (1016\ mm)^2 (0.93 \times 10^{-6}/°C)^2 \, 1/3°C^2 (10^3\ \mu m/mm)^2$$
$$= 47.1\ \mu m^2 + 0.30\ \mu m^2 = 47.4\ \mu m^2$$

Combined standard thermal uncertainty (para. 6.2.3):

$$u^2_{cT}(L) = u^2_{ETVE} + (UNE)^2 + (UNE)^2_s + LUTM^2$$
$$= 90.8\ \mu m^2 + 16.9\ \mu m^2 + 0.00 + 47.4\ \mu m^2$$
$$= 155\ \mu m^2$$

$$u_{cT}(L) = 12.5\ \mu m$$

Expanded thermal uncertainty (para. 6.2.2):

$$\pm U_T(L) = \pm 2u_{cT}(L) \pm 24.9\ \mu m$$

$$U_T(L) = 2u_{cT}(L) = 24.9\ \mu m$$

Derating of specified parameter (para. 6.2.2):

$$U_T(L)/SZ = 24.9\ \mu m/33.5\ \mu m > 0.25$$

Because this ratio is greater than 0.25, a new acceptable limit must be specified.

SZ* = $U_T(L)/0.25$

SZ* = 100 μm (FIR)

SZ* = 100 μm/1.016 m = 98 μm/m

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TABLE K-1 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)]	Temp. measurement uncertainty = ±1°C	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 percent.

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. 6.2.1.1):

$$u^2 = ETVE^2/12 = (3.8 \times 10^{-5}\ \text{m})^2/12$$

$$u^2 = 1.20 \times 10^{-10}\ \text{m}^2$$

Uncertainty of nominal expansion of the part (para. 6.2.4, method b):

$$u(\alpha) = 0.05\,\alpha\sqrt{1/3}$$

$$u^2(\alpha) = (0.05)^2 (24.3 \times 10^{-6}/°\text{C})^2 (1/3)$$

$$(UNE)^2 = L^2 (T - 20)^2 u^2(\alpha)$$
$$= (4\ \text{m})^2 (22°\text{C} - 20°\text{C})^2 (0.05)^2$$
$$(24.3 \times 10^{-6}/°\text{C})^2 (1/3)$$

$$(UNE)^2 = 3.15 \times 10^{-11}\ \text{m}^2$$

Uncertainty of nominal expansion of the standard (para. 6.2.4, method b, machine):

$$u(\alpha_s) = 0.05\,\alpha_s\sqrt{1/3}$$

$$u^2(\alpha_s) = (0.05)^2 (11.7 \times 10^{-6}/°\text{C})^2 (1/3)$$

$$(UNE)_s^2 = L_s^2 (T_s - 20)^2 u^2(\alpha_s)$$
$$= (4\ \text{m})^2 (22°\text{C} - 20°\text{C})^2 (0.05)^2$$
$$(11.7 \times 10^{-6}/°\text{C})^2 (1/3)$$

$$(UNE)_s^2 = 7.30 \times 10^{-12}\ \text{m}^2$$

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. 6.2.5):

$$u^2(T) = [1 - (-1)]^2/12°\text{C}^2$$

$$u^2(T) = 1/3°\text{C}^2$$

$$u^2(T_s) = [1 - (-1)]^2/12°\text{C}^2$$

$$u^2(T_s) = 1/3°\text{C}^2$$

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$$LUTM^2 = L^2 \alpha^2 u^2(T) + L_s^2 \alpha_s^2 u^2(T_s)$$
$$= (4\text{ m})^2 (24.3 \times 10^{-6}/°\text{C})^2 1/3°\text{C}^2$$
$$+ (4\text{ m})^2 (11.7 \times 10^{-6}/°\text{C})^2 1/3°\text{C}^2$$

$$LUTM^2 = 3.87 \times 10^{-9}\text{ m}^2$$

Combined standard thermal uncertainty (para. 6.2.3):

$$u_{cT}^2(L) = u_{ETVE}^2 + (UNE)^2 + (UNE)_s^2 + LUTM^2$$

$$u_{cT}(L) = \left[1.20 \times 10^{-10}\text{ m}^2 + 3.15 \times 10^{-11}\text{ m}^2 + 7.30 \times 10^{-12}\text{ m}^2 + 3.87 \times 10^{-9}\text{ m}^2\right]^{1/2}$$

$$u_{cT}(L) = 0.063\text{ mm}$$

Expanded thermal uncertainty (para. 6.2.2):

$$\pm U_T(L) = \pm 2u_{cT}(L) \pm 0.126\text{ mm}$$

$$U_T(L) = 2u_{cT}(L) = 0.127\text{ mm}$$

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.

$$\text{NDE} = 0.00$$

Thermal error index:

$$\text{TEI} = \left[\left[|\text{NDE}| + U_T(L)\right]/\text{TOL}\right](100\%)$$

$$\text{TEI} = (0.00 + 0.127\text{ mm}/0.25\text{ mm})(100\%) = 51\%$$

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. 6.2.1.1):

$$u^2_{\text{ETVE}} = \text{ETVE}^2/12\ \ (0.0003\text{ in})^2/12$$

$$u^2_{\text{ETVE}} = 7.50 \times 10^{-9}\text{ in}^2$$

Uncertainty of nominal expansion of the part (para. 6.2.4, method b):

$$u(\alpha) = 0.05\,\alpha\sqrt{1/3}$$

$$u^2(\alpha) = (0.05)^2 (4.8 \times 10^{-6}\text{ in/in°F})^2 (1/3)$$

$$(\text{UNE})^2 = L^2(T - 68)^2 u^2(\alpha) = (20\text{ in})^2(75°\text{F} - 68°\text{F})^2 (0.05)^2(4.8 \times 10^{-6}\text{ in/in°F})^2(1/3)$$

$$(\text{UNE})^2 = 2.76 \times 10^{-10}\text{ in}^2$$

Uncertainty of nominal expansion of the standard (para. 6.2.4, method b, machine):

$$u(\alpha_s) = 0.05\,\alpha_s\sqrt{1/3}$$

$$u^2(\alpha_s) = (0.05)^2 (6.5 \times 10^{-6}\text{ in/in°F})^2 (1/3)$$

$$(\text{UNE})_s^2 = L_s^2 (T_s - 68)^2 u^2(\alpha_s) = (20\text{ in})^2(74°\text{F} - 68°\text{F})^2 (0.05)^2(6.5 \times 10^{-6}\text{ in/in°F})^2\ (1/3)$$

$$(\text{UNE})_s^2 = 5.07 \times 10^{-10}\text{ in}^2$$

Length uncertainty due to temperature measurement (para. 6.2.5):

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.

$$u(T_e) = (\tfrac{1}{2})(T_{\max} - T_{\min} + 2a)\sqrt{1/3}$$

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TABLE K-2 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[72]	Temperature measurement accuracy = ±1°F	T_m = 74°F (measured)
α_S = 6.5 μin/in.°F[72]		ETVE = 0.0003 in.

where it is assumed that the machine and part temperature at any time can be expected to have rectangular probability distributions with bounds $\geq(T_{max} - T_{min} + 2a)$. 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:

$$\text{LUTM}^2 = (1/12)(T_{max} - T_{min} + 2a)^2(L)^2(\alpha_s - \alpha)^2$$

$$\text{LUTM}^2 = (1/12)(78 - 70 + 2)^2(°\text{F})^2(20\ \text{in})^2\ (4.8 - 6.5)^2\ (\mu\text{in/in°F})^2$$

$$\text{LUTM}^2 = 9.63 \times 10^{-9}\ \text{in}^2$$

Combined standard thermal uncertainty (Section 6.2.3):

$$u_{cT}^2(L) = u_{ETVE}^2 + (UNE)^2 + (UNE)_s^2 + LUTM^2$$

$$u_{cT}(L) = \left[7.50 \times 10^{-9}\ \text{in}^2 + 2.76 \times 10^{-10}\ \text{in}^2 + 5.07 \times 10^{-10}\ \text{in}^2 + 9.63 \times 10^{-9}\ \text{in}^2\right]^{1/2}$$

$$u_{cT}(L) = 0.00013\ \text{in}$$

Expanded thermal uncertainty (Section 6.2.2):

$$\pm U_T(L) = \pm 2u_{cT}(L) \pm 2(0.00013\ \text{in})$$

$$U_T(L) = 2u_{cT}(L) = 2(0.00013\ \text{in})$$

$$U_T(L) = 0.00026\ \text{in}$$

Nominal differential expansion:

$$NDE = |4.8 \times 10^{-6}\ \text{in/in°F} - 6.5 \times 10^{-6}\ \text{in/in°F}|\ (20\ \text{in})\ |74 - 68|°\text{F}$$

$$NDE = 0.00020\ \text{in}$$

Thermal error index:

$$TEI = \left(\left(|NDE| + U_T(L)\right) / TOL\right)(100\%)$$

$$TEI = (0.00020\ \text{in} + 0.00026\ \text{in}/0.002\ \text{in})\ (100\%) = 23.5\%$$

K3.3 Summary

The different cases that can occur for temperature measurement are summarized in Table K3.

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TABLE K-3 SUMMARY OF EQUATIONS FOR THERMAL UNCERTAINTY CALCULATIONS

Note:
The object being calibrated or measured is simply the "object" in this table. The calibrator, or measuring device, is the "standard."

Symbol	Definition	Equation
TEI	Thermal error index	$\{[NDE + U_T(L)]/TOL\}100\%$
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	$L\alpha_S(T_m - 20)$
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	$\sqrt{(UNE)^2 + (UNE)_S^2 + (LUTM)^2 + u^2_{ETVE}}$
(UNE)	Uncertainty nominal expansion of object	$u(\alpha)L(T_m - 20)$
$u(\alpha)$	Uncertainty of object thermal expansion coefficient [for method of Sec. 6.2.4(c)]	$\sqrt{1/3}(0.1)\alpha$
$(UNE)_s$	Uncertainty of nominal expansion of standard	$u(\alpha_s)(T_m - 20)$
$u(\alpha_s)$	Uncertainty of standard thermal expansion coefficient [for method of Sec. 6.2.4(c)]	$\sqrt{1/3}(0.01)\alpha_S$
$LUTM$	Length uncertainty due to temperature measurement	
	For NDE correction	$\sqrt{\alpha^2L^2u(T)^2 + \alpha_s^2L_s^2u(T_s)^2}$
	For no NDE correction	$u(T_e)L(\alpha - \alpha_s)$
$u(T)$	Uncertainty of object temperature measurement	$\left(\frac{a^+ - a^-}{2}\right)\left(\sqrt{1/3}\right)$
$u(T_s)$	Uncertainty of standard temperature measurement	$\left(\frac{a^+ - a^-}{2}\right)\left(\sqrt{1/3}\right)$
$u(T_e)$	Uncertainty of environment temperature	$1/2\ (T_{max} - T_{min} + 2a)\ \sqrt{1/3}$
a	Accuracy of temperature measurement (±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
SZ	Specification zone (the zone specified for a parameter in a machine acceptance test)	specified
TOL	Tolerance [used for specification zone (SZ) when measuring parts]	for ±0.1 mm, TOL = 0.1 mm

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NONMANDATORY APPENDIX L
ONE-DAY TEST FOR MACHINE PERFORMANCE

L1 PURPOSE

When it is desired to estimate machine performance within one day, the following tests, taken from the body of the Standard, are recommended. These tests are for machines with only two linear axes and a single work spindle. Machines with more than two axes will require more testing. To perform these tests in one day requires advance preparation of test equipment and machine programming.

L1.1 Positioning Accuracy and Repeatability, Linear Axes, and Angular Error Motions, Linear Axes (Sections 7.2 and 7.3)

The positioning accuracy and repeatability and the angular error motion of both machine axes should be measured following the procedures outlined in Sections 7.2 and 7.3 of the Standard. The data shall be analyzed as described in paras. 7.2.7 and 7.3.1.

L1.2 Contouring Performance Using Circular Tests (Section 7.8)

The machine's contouring performance shall be measured using a telescoping ball bar, using the procedure as described in paras. 7.8.2, 7.8.3, or 7.8.4, whichever is applicable. The data shall be analyzed as described in para. 7.8.5.

L1.3 Critical Alignments (Section 7.7)

The squareness of the cross slide (X axis) with the work spindle axis (often a C axis) shall be measured as described in para. 7.7.2. The parallelism of the longitudinal slide (Z axis) with the work spindle (C axis) in the XZ plane shall be measured as described in para. 7.7.3.

L1.4 Structural Motion (para. 7.5.2)

The structural motion of the main spindle shall be measured in accordance with the procedures given in para. 7.5.2.

L1.5 Spindle Thermal Stability Test (para. 7.6.2)

The thermal stability of the main spindle shall be measured in accordance with the procedures given in para. 7.6.2.

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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 [ISO Guide to the Expression of Uncertainty in Measurement, 1993(E)]. 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

(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; and,

(d) inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions.

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. Thus, the uncertainties of the measurement results are nearly universally of Type B.[1] Because of the current accuracy level of the instrumentation (see Section 9), this uncertainty is correctly assigned to the machine tool, rather than the instrument system. (It is important to note that this is not the case for temperature-controlled, high-accuracy machines such as diamond turning machines, where errors in the measurement system begin to become the dominant sources of uncertainty. Users desiring to use this Standard on such machines must be prepared to address these issues. Although the procedures may appear to be identical, the assignment of lack of repeatability to the machine, rather than the measurement system, may be erroneous.)

In the body of this Standard, uncertainties have not been computed for a number of tests due to one of the following four 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 Standards Organization (ISO) and uncertainties were not computed there.

(c) The test duration was such that making enough repeated measurements to have statistical significance is impractical.

(d) The tests were such that there existed a significant historical precedent that the test results should be treated as tolerances rather than measurements with associated uncertainties.

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, it must be emphasized 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 Section 9.

M2 UNCERTAINTY CALCULATIONS CURRENTLY IN B5.57

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. 6.2.1), the relative vibration test (Section 6.3), the structural motion test (para. 7.5.2), the subsystems repeatability tests (Section 8.3), and the repeatability of tool-setting systems test (para. 8.4.1).

[1] ISO Guide to the Expression of Uncertainty in Measurement, 1993(E).

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Besides these general tests for repeatability, other tests where the uncertainty is estimated according to the standard methodology are positioning accuracy and repeatability, linear axes (Section 7.2), angular error (yaw) motions, linear axes (Section 7.3), positioning accuracy and repeatability, rotary axes (Section 7.4), original location of tool-setting system (para. 8.4.2), combination tests for tool-setting system drift (para. 8.4.3), machine performance as a measuring tool (Section 8.6), and parametric tests (Section 8.8). These 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 appropriate to assign an uncertainty. These are setup hysteresis (para. 7.1.4), periodic linear and angular positioning (paras. 7.2.8 and 7.4.8), cutting performance (Section 7.9), multi-function cycle test (Section 7.10), mechanical tail stock alignment (para. 8.2.5.1), CNC performance test (Section 8.5), and machining test parts (Section 8.7). 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.

M4 UNCERTAINTY COMPUTATIONS NOT PRESENTLY IN B5.57

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 (Section 7.5)

(b) machine thermal test (Section 7.6)

(c) critical alignment (Section 7.7)

(d) contouring performance using circular tests (Section 7.8)

(e) coaxiality of axes of rotation (Section 8.2)

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

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 turning 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 these measurements on aerostatic and hydrostatic spindles, it is the recommendation of this appendix that the complete test (20 revolutions) for each error motion be repeated 10 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:

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

where

q_j = the outputs of the measurement procedure for each complete test (average or asynchronous error motion)

q = the mean obtained from the 10 repeated trials

In the opinion of the authors of this appendix, following the above procedure will constitute unwarranted expense, as the information gained would not be particularly relevant to machine performance.

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 period of four hours or until "the maximum change in any sensor reading over any 30-minute period, at all the sensor locations, has reduced to 15 percent of the maximum of that sensor change over the first 30 minutes of the test." These tests are clearly of long duration. 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

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five times) and standard uncertainties in the reported parameters computed as described in Section M4.1 above. It is the recommendation of this appendix that this would constitute unwarranted expense.

M4.3 Critical Alignments

All measurements for critical alignments in this Standard require measuring two straightnesses (using either an artifact standard, a straightness interferometer, or a test part) and taking the difference in slopes between two lines fit to the respective two sets of straightness data. To compute the uncertainty to be assigned to this final alignment value (call it W; see para. 7.7.2), the following approximate procedure may be followed.

Each straightness measurement is performed five times. Data are acquired at the same positions used for the positioning accuracy and repeatability, linear axes (Section 7.2), or more densely, if desired, in both the forward and reverse directions. Note that if a straightness interferometer is used, each data point should be obtained from an average of many laser readings, as described in para. 7.7.4. The straightness deviations should now be averaged and a standard uncertainty computed at each measurement position. The procedure is conceptually similar to that used for linear positioning, except that no distinction is made between forward and reverse readings. That is, at each of the i^{th} measurement positions, compute a mean straightness deviation and the standard uncertainty. The standard uncertainty is given by

$$s_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(y_{ij} - \bar{y}_i)^2}$$

where

y_{ij} = j^{th}straightness deviation at position i
y_i = mean straightness deviation at position i
n = 10
s_i = estimate of the standard uncertainty of the straightness deviation at position i.

Next, for each of the two lines the mean straightness deviations, which are functions of the axis positions where the straightness deviations are measured, x_i (or z_i), are linear least-squares fit to a straight line using a least-squares fit, weighted with the standard uncertainties of the straightness deviations.[2]

[2] The procedures for performing such fits are available in almost any elementary statistics textbook. The weighting is necessary because, in general, the standard uncertainty of the straightness deviations will be a function of the axis position.

The standard uncertainties for the slopes of each line may be combined in quadrature to yield the square of the standard uncertainty for the alignment angle. That is,

$$u_w^2 = u_{B1}^2 + u_{B2}^2$$

where

u_{B1} = the standard uncertainty for the slope of the first line
u_{B2} = the standard uncertainty for the slope of the second line

M4.4 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, corrected to 20°C, as well as the measured feed rates in the clockwise and counterclockwise directions. The circular deviation is the minimum radial separation of two concentric circles that will envelop the actual path. The radial deviations are the maximum and minimum deviations from the circle radius, corrected to 20°C. In order to compute the standard uncertainties of these quantities, it is recommended that the circular test be conducted 10 times in both the clockwise and counterclockwise directions. For each set of 10 measurements, the artifact (ball bar, disk, or grid encoder) temperature is measured at the beginning and the end of the 10 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,

$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(d_{ij} - \bar{d}_i\uparrow)^2}$$

$$s_i\downarrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(d_{ij} - \bar{d}_i\downarrow)^2}$$

where

d_{ij} = the j_{th} circular deviation at the i_{th} angular position
d_i = the mean circular deviation at the i_{th} angular position

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n = 10
s_i = the estimate of the standard uncertainty of the circular deviations
↑ and ↓ = clockwise and counterclockwise rotation, respectively

M4.4.1 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

$$u_{Gu}{}^2 = s\uparrow_k{}^2 + s\uparrow_m{}^2$$

where
k = denotes the position where the maximum deviation occurred
m = denotes the position where the minimum deviation occurred

M4.4.2. 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 previously in Section M4.4. The square of the uncertainty is then computed as follows (where ↑ or ↓ has been eliminated for simplicity):

$$u_F^2 = s_k^2 + L_s^2 (T_s - 20)^2 u^2(\alpha_s) + L^2 (T - 20)^2 u^2(\alpha) + L_s^2 \alpha_s^2 u^2(T_s) + L^2 \alpha^2 u^2(T)$$

where
u_F = the standard uncertainty of the radial deviation
k = the angular position where the maximum radial deviation occurred
T_s = the mean temperature of the ball bar
T = the temperature of the machine scales which should be assumed to be equal to T_s
α_s = the thermal expansion coefficient of the ball bar
α = the thermal expansion coefficient of the machine scales
L_s = the calibrated ball bar length
L = the effective machine scale length, equal to the ball bar length
$u(q)$ = the standard uncertainty in the quantity, q

Although not a requirement of this Standard, a better estimate of the uncertainty could be obtained if the temperatures of the relevant machine scales were measured during this test and the actual measured values used for the computation. In that case, the average of the two scale temperatures should be used in the computation above.

M4.5 Coaxiality of Axes of Rotation

For computing the uncertainty in the coaxiality of axes of rotation (Section 8.2), it is recommended that the procedures outlined in the Standard be followed, except that the measurements be performed 10 times, rather than three. The uncertainties for directly measured quantities are computed using the general equation given in Section M4.1.

M4.5.1 "Rim and Face" Method. The standard uncertainties of the vertical and horizontal angles and offsets may be estimated as

$$u_{VO}^2 = \frac{(u_{RR0}^2 + u_{RR6}^2 + u_{RR_s}^2)}{4}$$

$$u_{VA}^2 = \frac{(u_{FR6}^2 + u_{FR0}^2 + u_{FR_s}^2)}{DIA^2}$$

$$u_{HO}^2 = \frac{(u_{RR3}^2 + u_{RR9}^2)}{4}$$

$$u_{HA}^2 = \frac{(u_{FR9}^2 + u_{FR3}^2)}{DIA^2}$$

where the subscripts indicate the quantity whose uncertainty is estimated. The notation is defined in para. 8.2.1.

M4.5.2 Reverse Indicator Method. The standard uncertainties of the vertical and horizontal angles and offsets may be estimated as

$$u_{VO}^2 = \frac{(u_{SR0}^2 + u_{SR6}^2 + u_{SR_s}^2)}{4}$$

$$u_{VA}^2 = \frac{(u_{SR0}^2 + u_{SR6}^2 + u_{SR_s}^2 + u_{MR0}^2 + u_{MR6}^2 + u_{MR_s}^2)}{4D_s^2}$$

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$$u_{HO}^2 = \frac{(u_{SR3}^2 + u_{SR9}^2)}{4}$$

$$u_{HA}^2 = \frac{(u_{SR3}^2 + u_{SR9}^2 + u_{MR3}^2 + u_{MR9}^2)}{4D_s^2}$$

Again, the subscripts indicate a quantity whose uncertainty is estimated. The notation is defined in para. 8.2.2.

M4.5.3 Optical Tailstock Alignment. If optical systems are used for tailstock alignment, the instrument manufacturer's recommendations for uncertainty calculations should be followed. There are currently several instruments on the market which function differently, so no specific equations can be provided.

M4.5.4 Two-Sphere Axis Alignment. The standard uncertainties of the vertical and horizontal angles and offsets are given by

$$u_{HO}^2 = u_{HO_1}^2 = u_{CX_1}^2$$

$$u_{HO_2}^2 = u_{CX_2}^2$$

$$u_{VO}^2 = u_{VO_1}^2 = u_{CY_1}^2 + \frac{u_{SR_1}^2}{4}$$

$$u_{VO_2}^2 = u_{CY_2}^2 + \frac{u_{SR_2}^2}{4}$$

$$u_{HA}^2 = \frac{(u_{HO_2}^2 + u_{HO_1}^2)}{D_s^2}$$

$$u_{VA}^2 = \frac{(u_{VO_2}^2 + u_{VO_1}^2)}{D_s^2}$$

The notation is defined in para. 8.2.4.

M4.5.5 Parallelism of the Z Axis With Other Linear Axes and the C Axis. Paragraphs 8.2.5 and 8.2.6 of the Standard describe optional Z-axis alignment measurements. The uncertainties in these alignments should be computed following the procedures of Section M4.3.

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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 response of the machine tool, minus the nominal or anticipated response. Errors are reported using the machine coordinate system. Positive values of displacement errors (e.g., positioning and straightness errors) indicate error motion in the positive direction of a coordinate axis. Thus, a positive positioning error of an axis indicates that the carriage 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. Users are advised to use ANSI/EIA-267-C-1990 for axis nomenclature.

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 nominal tool position. In all other cases measurements are made with respect to a nominal workpiece. For example, the main spindle carries the workpiece. Therefore, the spindle measurements are made with respect to the nominal tool position. In this case, a positive axial error motion of the spindle indicates movement of the spindle axis and the workpiece in the positive Z direction. For the positioning accuracy test of an axis that moves the turret, measurements are made relative to a nominal workpiece. In this case, a positive error indicates a positive error in the position of the tool relative to the workpiece.

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 degrees. 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
STRUCTURAL MOTION WITH THE SPINDLE RUNNING

O1 PURPOSE

Paragraph 7.5.2 calls for the assessment of structural error motion with the spindle off. The reason for this requirement is that it can be done with the same setup as total spindle error motion and quickly identifies the functional effect of building floor vibration and the various sources of machine-generated vibration other than the spindle drive.

Structural motion with the spindle running can, however, be the dominant source of total spindle error motion. The need for this measurement is not intuitive. Most machines appear to be so massive that it is hard to imagine structural error motions that are larger than those introduced by the spindle bearings. There are many well-documented cases in the literature that show movement of the spindle housing with respect to the tool to be as high as 95% and typically 50% of the total spindle error. The measurement of structural motion between the spindle housing and the tool requires another setup. For this reason, and because it is a diagnostic procedure, it is not a requirement of this version of the Standard.

This measurement is strongly recommended, however, before a decision is made to change spindle bearings.

The measurement data are to be reported as "radial structural motion between the spindle housing and the tool at a specific location on the housing" or "face structural motion between the spindle housing and the tool at a specific distance from the axis of rotation." Measurements should be taken at different spindle speeds.

Measurements can be made with eddy current gages as well as capacitance gages, since the eddy current gage always sees the same portion of the target surface.

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