IEEE Standard Specification Format Guide and Test Procedure for Nongyroscopic Inertial Angular Sensors: Jerk, Acceleration, Velocity, and Displacement

Sponsor
Gyro and Accelerometer Panel
of the
IEEE Aerospace Electronic Systems Society

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Foreword

(This Foreword is not a part of IEEE Std 671-11985, IEEE Standard Specification Format Guide and Test Procedure for Nongyroscopic Inertial Angular Sensors: Jerk, Acceleration, Velocity, and Displacement.)

This standard was prepared by the Gyro and Accelerometer Panel of the Aerospace and Electronic Systems Society of the Institute of Electrical and Electronics Engineers. It is a guide for the preparation of a specification and test procedure for an inertial angular sensor. It is intended to provide a common meeting ground of terminology and practice for manufacturers and users of an array of sensors which have been developed to meet needs not easily met by traditional spinning rotor gyroscopes. These needs have included greater dynamic range, lower noise, lower power, longer service life, and greater ruggedness. To cover this variety, the standard is written in black box input versus output terms which could be applied to any inertial angular sensor, including laser and conventional gyroscopes. It is not intended to compete with existing standards for specific devices with highly specific models and error sources, such as spring restrained rate gyros. Rather, the standard is to provide a uniform guide for those inertial angular sensors which have not been covered elsewhere.

The sensors described may have analog or digital outputs and may measure angular jerk, acceleration, rate or displacement with or without response down to zero frequency.

This standard consists of a main text and three appendixes. The main text is a specification format guide and test procedure for inertial angular sensors. The specification format guide is intended to provide a common format for manufacturers and users in the preparation of an angular sensor specification. The test procedure is intended to provide a means of verifying that the specifications have indeed been met.

Appendix A is a compilation of block diagrams characterizing the dynamic response of several types of inertial angular sensors.

Appendix B describes the modifications of some of the tests of this standard which are necessary to accommodate sensor classes other than the sensor which is used as an example in this standard, or for those sensors which have unusual error sources requiring specialized testing. The special problems and techniques of dynamic angular testing is also discussed in Appendix B.

Appendix C discusses some of the necessary accommodations which shall be made to the described tests of this standard when testing sensors with digital, rather than analog, outputs.

The user is cautioned not to overspecify; only those parameters that are required to guarantee proper performance in the specific application should be controlled. In general, the specification should contain only those requirements that can be verified by test or inspection. Parameters in addition to those given in this format are not precluded.

Blank spaces permit the insertion of specific parameter values and their tolerances. Brackets are used to enclose alternate choices of dimensional units, signs, axes, etc. The choices shown are the recommended options, but are not meant to include all possibilities. Boxed statements are included for information only and are not part of the specification format. The figures presented are to be used as a guide for the preparation of specific figures or drawings.

The terminology used conforms to ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms and IEEE Std 528-1984, IEEE Standard Inertial Sensor Terminology. The units used conform to ANSI/IEEE Std 268-1982, American National Standard Metric Practice. In this standard, the symbol *g* is used to denote a unit of acceleration equal in magnitude to the local value of gravity at the test site or other specified value of gravity. This symbol is thus distinguished from g which is the standard symbol for gram.

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IEEE Standard Specification Format Guide and Test Procedure for Nongyroscopic Inertial Angular Sensors: Jerk, Acceleration, Velocity, and Displacement

1. Scope

This standard defines the requirements and test procedures for a [single, multi-] axis nongyroscopic angular [jerk, acceleration, velocity, displacement] sensor. The output is [an analog electrical signal, a digital electrical pulse train] proportional to angular [jerk, acceleration, velocity, displacement]. The electronics are to be considered part of the sensor to the extent specified herein. All parameters specified in this standard refer to the overall sensor output unless otherwise specified. The device will hereafter be referred to as the sensor.

> In some instances, the sensor mechanism and the electronics may be housed in separate packages. In these cases, the term sensor may be reserved for the mechanism, while the overall device is called the transducer, accelerometer, etc.

2. Applicable Documents

The following documents of the issue in effect on the date of invitation for bids or request for proposal form a part of the specification to the extent specified herein. In the event of any conflict between the requirements of this standard and the listed documents, the requirements of this standard shall govern.

> Give identification number, title, date of issue, and revision letter of each listed document.

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2.1 Specifications

2.1.1 Government

2.1.2 Industry/Technical

2.1.3 Company

2.2 Standards

2.2.1 Government

2.2.2 Industry/Technical

2.2.2.1

ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms.[1]

2.2.2.2

IEEE Std 528-1984, IEEE Standard Inertial Sensor Terminology.

The units and symbols used in this standard comply with:

ANSI/IEEE Std 260-1978 (R1985), IEEE Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units)

ANSI/IEEE Std 268-1982, IEEE Standard Metric Practice

ANSI/IEEE Std 315-1975, IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams

2.2.3 Company

2.3 Drawings

2.3.1 Government

2.3.2 Industry/Technical

2.3.3 Company

2.4 Other Publications

Other applicable documents should be listed under the appropriate categories.

[1]These documents are available from the Sales Department, IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08854. They are also available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

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3. Requirements

3.1 General

3.1.1 Precedence

In the event of conflict among the purchase agreement, this standard, and other documents referred to herein, the order of precedence shall be as follows:

1) The purchase agreement
2) This standard and its applicable drawings
3) Other applicable documents

List other applicable documents in order of precedence. See Section 2.

3.1.2 Other

List other applicable general requirements.

3.2 Description

The angular [jerk, acceleration, velocity, displacement] sensor is a [single, multi-] axis, nongyroscopic device which provides [an analog electrical signal, a digital electrical pulse rate] proportional to angular [jerk, acceleration, velocity, displacement], and associated electronics as shown in Fig 1.

If a torque balance capture loop is used, specify if it is to be part of the device or the test equipment. The information shown in Fig 1 is intended to be suggestive only, due to the large variety of sensors which it can represent. Figure 1 is not intended as a replacement for the outline drawing, but rather provides a means of clearly distinguishing the device being specified from the remainder of the system.

3.2.1 Mechanical and Thermal Design

The following mechanical and thermal requirements apply to sensor package(s) to the extent specified.

The configuration should be specified to convey the user’s limitations and specific needs. The sensor may consist of more than one package.

3.2.1.1 Exterior Surface

All exterior surfaces shall withstand the environment specified herein and the handling expected in the normal course of operation, testing, and maintenance without deterioration which causes nonconformance to this standard.

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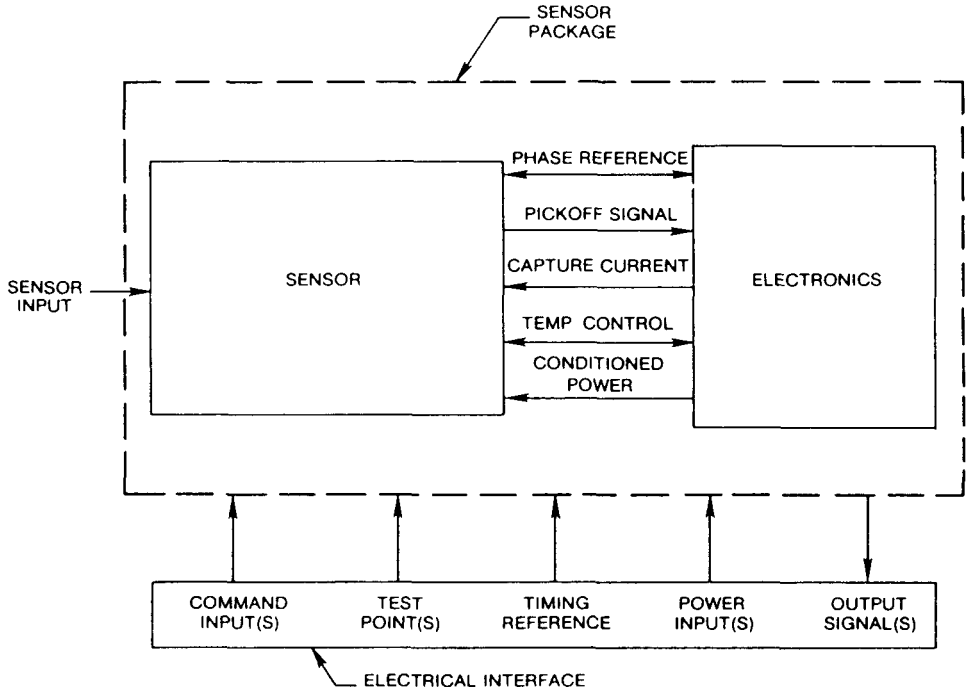


Figure 1—Angular Sensor Block Diagram

Additional requirements controlling surface finish protective treatment, metals, dissimilar metals, workmanship, etc, may be designated. Mounting surfaces which define the location of the input axis may require special consideration.

3.2.1.2 Dimensions

The outline and mounting dimensions shall conform to the outline of drawing number _____.

The center of gravity of each package may be specified with appropriate tolerances.

3.2.1.3 Identification of the Product

The sensor shall be marked as specified on the outline drawing.

The specification may require 1) Name of component 2) Part number 3) Serial number 4) Contract number 5) Manufacturer’s name and symbol.

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3.2.1.4 Sensor Reference Axes

The positive direction of the input [axis, axes] shall be defined by external markings and by a reference [surface, line] on the package which contains the sensor. The positive directions of the axes shall be as defined in 3.3.2 and drawing _____.

Physically significant axes orthogonal to the input reference may also be defined. See Fig 2.

3.2.1.5 Weight

The weight shall be _____ ± _____[g, kg]

If appropriate, only the maximum weight needs to be specified. When accessories such as cable and connector are to be included in the weight requirement, the specification shall so state. When the sensor consists of more than one package, the weight may be specified for each package.

3.2.1.6 Seal

The sensor package shall meet the following seal requirements:

Specify either (1) or (2), as appropriate. If required, specify the appropriate seal requirements for the other package(s).

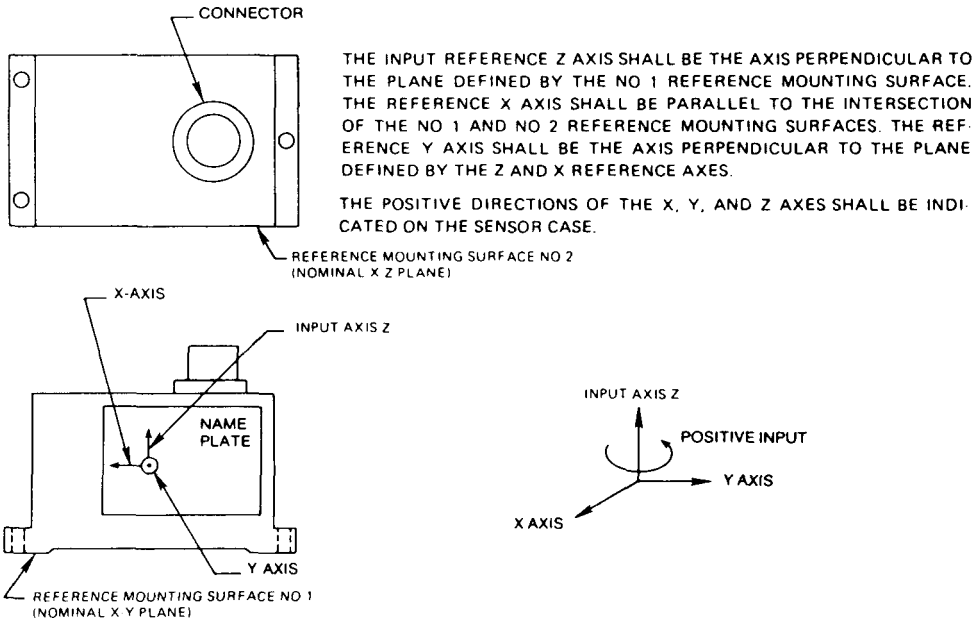


Figure 2—Sensor Reference Axes

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1) **Liquid Filled.** The sensor shall be sealed so that no liquid leakage is detected under _____ power magnification after being subjected to an external vacuum at _____ ± _____ Pa and a temperature of _____ ± _____ °C for a minimum period of _____ min.

In some cases, other procedures may be more appropriate, such as the use of fluorescent tracers in the fluid to facilitate leak detection.

2) **Gas Filled.** The sensor shall be sealed so that the maximum gas leakage rate shall not exceed _____ cm^3/s of _____ gas, measured at standard conditions for a minimum period of _____ min while being subjected to a vacuum of _____ ± _____ Pa at a temperature of _____ ± _____ °C.

Tracer gases may be added to the fill gas so as to facilitate leak detection.

3.2.1.7 Controlled Operating Temperature

The controlled operating temperature as indicated by a temperature sensor (on, within) the sensor shall be _____ ± _____ °C.

This requirement is applicable only to a sensor with its own temperature control. If electronics and the sensor are separately controlled, specify the operating temperature for each. In some applications, consideration should be given to the magnitude of the thermal gradients existing across the sensor.

3.2.2 Electrical Design

The sensor's electrical and magnetic design requirements shall be as specified below. The sensor shall meet the performance criteria of 3.3 during all permissible variations of the inputs of 3.2.2.1.

3.2.2.1 Electrical Interface

The electrical interface for the sensor consists of the signals, power, and test points listed below and illustrated in Fig 1.

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3.2.2.1.1 Power Inputs

Specify the characteristics of the power in put(s). For example:

1) Source impedance ____±____ [+, –] j____±____Ω
2) Load impedance ____±____ [+, –] j____±____Ω
3) Voltage ____±____[V ac, V dc]
4) Rise time _____ ms maximum
5) Frequency _____±_____Hz
6) Nominal current _____±_____A
7) Peak current _____A for _____[s, min]
8) Harmonic content _____ %

3.2.2.1.2 Output Signals(s)

Specify the characteristics of the output signal(s).

The output(s) may be characterized by analog variables) or by discrete variables), for example, pulse trains or binary word formats. The variables) may represent angular displacements) or any applicable time derivatives. For example (see Fig 1):

Type: Analog [voltage, current] proportional to the magnitude of the angular velocity input.

Characteristics:

1) Source impedance ____±____ [+,–] j____±____Ω
2) Load impedance ____±____[+,–] j____±____Ω
3) Polarity positive with [positive, negative] input
4) Voltage range ____±____V to ____±____V
5) Current range ____±____mA to ____±____mA

In some cases, output voltage or current limits may be specified to prevent overranging system inputs. Also, overrange voltage or current recovery time may be specified.

An example of a digital sensor may be found in Appendix C, Section C3.

3.2.2.1.3 Command Input(s)

Specify the type and characteristics of command input(s), if required. For example:

Type:

1) ON/OFF
2) Self test (see 3.3.17)

Characteristics:

1) Source impedance ____±____ [+,–] j____±____Ω
2) Load impedance ____±____ [+,–] j____±____Ω
3) Input voltate ____±____[V ac, V dc]

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3.2.2.1.4 Timing Reference

Specify the characteristics of the timing reference, if required. For example:

1) Source impedance ___±___ [+,–] j___±_____Ω
2) Load impedance ___±____[+,–] j___±___Ω
3) Repetition rate ___±____[pulse per second (p/s), Hz]
4) Wave shape (specify tolerance)
5) Stability ±_____ % per _____ [h, d]

3.2.2.1.5 Test Points

Specify the test points required for monitoring and testing the sensor. These may include test points provided for monitoring excitation voltage, pickoff output signal, torquer signal, and other control signals or temperature sensor resistances. Any special buffering or scaling requirements should be specified.

3.2.2.1.6 Grounding

Specify electrical grounding design requirements (for example, requirements for isolation between input, output, and power returns, and the grounding requirements for shields, chassis, and critical components).

3.2.2.2 Dielectric Strength

The leakage current shall not exceed _____ nA when _____ ± _____ V rms, at _____ Hz, are applied between isolated interface circuits, and between the case(s) and circuits isolated from the case(s), for _____ ± _____ s.

Different voltages may be specified for different circuits. In some instances, lower voltages may be specified for subsequent tests.

3.2.2.3 Insulation Resistance

The insulation resistance between isolated interface circuits and between the case(s) and circuits isolated from the case(s) shall not be less than ___ Ω measured at ___±___V dc, applied for _____±_____s.

Different voltages may be specified for different circuits.

3.2.2.4 Electromagnetic Interference

The maximum electromagnetic interference from the sensor package(s) shall conform to _____.

Describe the requirements. In the United States, a common standard is MIL-STD-461.[2]

[2]MIL publications are available from the Director, US Navy Publications and Printing Service, Eastern Division, 700 Robbins Avenue, Philadelphia, PA 19111.

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3.2.2.5 Electromagnetic Compatibility

Describe the requirements. MIL-STD-463 defines EMC as follows:

"**electromagnetic compatibility.** The capability of electronic equipment or systems to be operated with a defined margin of safety in the intended operational environment at designed levels of efficiency without degradation due to interference."

When applied to single electronic devices such as the sensor, this form of compatibility is sometimes referred to as susceptibility.

3.2.2.6 Magnetic Leakage

The magnetic leakage shall not exceed _____ mT at a distance of _____ cm from the sensor package(s) in any direction.

3.2.3 Maintainability

Maintenance for operational sensors shall provide fault isolation to a line replaceable unit (LRU) by use of [built in test equipment, special test equipment, or commonly available test equipment].

3.2.3.1 LRU Interchangeability

Each line replaceable unit shall be interchangeable with like units, with the same part number, without calibration or adjustment. The manufacturer of the angular sensor shall state whether it has fully interchangeable LRU capability, or if not, which aspects do not meet the full interchange LRU standard.

3.2.3.2 LRU Maintenance

LRU maintenance is generally limited to depot or manufacturers' level facilities.

3.3 Performance

For simplification, the example of this subsection refers to a single axis sensor. Suggestions regarding the specification of multi-axis sensors may be found in Appendix B, B3.5

3.3.1 General

The sensor shall comply with the performance requirements of this standard before, during (if applicable), and after exposure to any compatible combination of the environments specified in 3.4.

Generally, limits are specified for each individual requirement. In some cases it may be desirable to specify a root sum square (rss) limit of logically-grouped individual. requirements.

3.3.2 Polarity and Input Range

A positive rotation about the input axis shall result in a [positive, negative] output. See [Fig 2, Drawing_____]. The minimum input range shall be from – _____ input units to + _____ input units.

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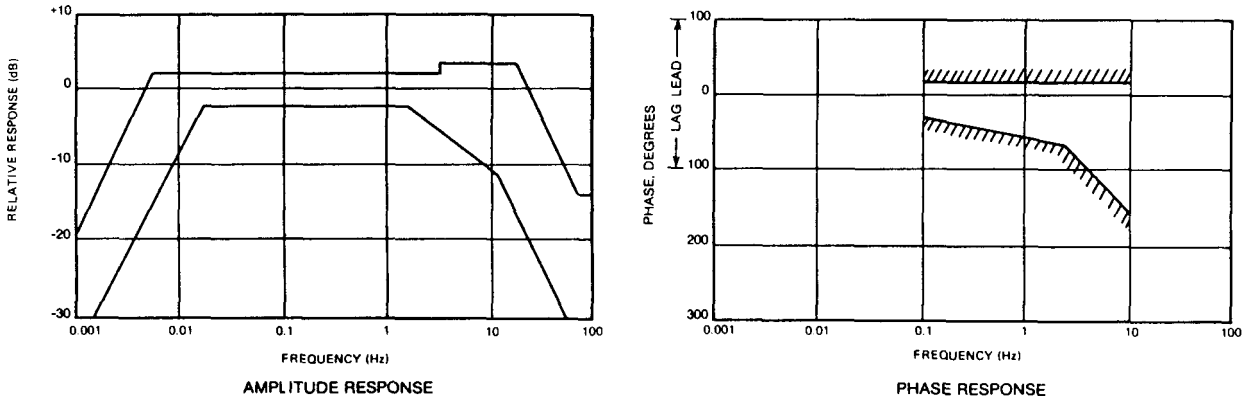


Figure 3—Frequency Response

> In some cases secondary limits, for example, angular acceleration on a rate output sensor, shall be specified to prevent internal overranging. A recommended format for a frequency sensitive input range can be found in Fig 3 and the related box note under 3.3.16.

3.3.3 Scale Factor

3.3.3.1 Absolute Value

The scale factor K_1 shall be _____ ± _____ output units per input unit (compare with 6.3.)

> The desired form of the output should be specified, for example, V, mA, or p/s.

3.3.3.2 Asymmetry

The difference between the scale factor measured with a positive applied input and a negative applied input shall not exceed ±_____% of the nominal absolute scale factor.

3.3.3.3 Short-Term Stability

The rms deviation of the scale factor from its mean value, over a period of___[h, d] of continuous operation, shall be less than _____%.

> Other criteria for establishing stability may be utilized, such as standard deviation, curve fitting for trend determination, or computer analysis to determine the auto-correlation time.

3.3.3.4 Long-Term Stability

The best-fit slope of the scale factor, over a period of, _____days of continuous operation, shall be less than _____%/d. The root-mean-square (rms) deviation of the scale factor data points, from the best-fit line, shall be less than _____%.

> The unbiased estimate of the standard deviation may be substituted for the rms deviation. Alternate means of specifying long-term bias stability may be used, for example, rms deviation about the first day mean or peak-to-peak deviation.

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3.3.3.5 Repeatability

The rms deviation of the scale factor from the mean of_____ measurements shall be less than _____%. Between successive measurements, the sensor shall be cooled to_____°C for at least_____ h.

> Other environmental exposures may be substituted or added to the temperature environment specified. In addition, combinations of various successive environments, for example, vibration, shock, and temperature may also be specified. Alternate means of specifying repeatability may be used, for example, rms deviation about the first day mean or peak-to-peak deviation.
>
> The cool-down time should be sufficient to attain thermal equilibrium. Other conditions for repeatability may be specified, such as turn-off with the sensor maintained at operating temperature.

3.3.3.6 Sensitivity

The absolute value of the sensitivity coefficient of the scale factor to variations from the standard test conditions of 4.5 shall not exceed the following limits:

1) Input voltage(s) _____ %/V
2) Power input frequency(ies)_____%/Hz
3) Operating temperature _____%/°C
4) Thermal gradients) _____ %/°C (across the instrument)
5) External magnetic field(s) _____%/mT [dc or ac, or both] per axis
6) Pressure _____ %/Pa

> The thermal gradient shall be defined for each application, for example, temperature difference, where it is to be measured, and the direction of application. In some cases, it may be desirable to specify a variation of scale-factor sensitivity induced by a thermal transient.

3.3.4 Bias

3.3.4.1 Absolute Value

The absolute value of the bias (K_0) shall not exceed _____ input units (IU). (Compare with 6.3.)

> Automatic bias nulling (washout) circuits may be desirable in some applications. Automatic bias nulling may operate continuously during operation of the sensor or during turn-on sequence only. It may also operate during both time periods, but in different modes; for example, with different time constants.

3.3.4.2 Short-Term Stability

The rms deviation of the bias, from its mean value over a period of _____ [h, d] of continuous operation, shall be less than _____IU.

> Other criteria for establishing stability may be utilized, such as standard deviation, curve fitting for trend determination, or computer analysis to determine the autocorrelation time.

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3.3.4.3 Long-Term Stability

The best fit slope of the bias over a period of _____days of continuous operation shall be less than _____IU/d. The rms deviation of the bias data points from the best-fit line shall be less than _____IU.

> The unbiased estimate of the standard deviation may be substituted for the rms deviation. Alternate means of specifying long-term bias stability may be used, for example, rms deviation about the first day mean or peak-to-peak deviation.

3.3.4.4 Repeatability

The rms deviation of the bias from the mean of _____ measurements shall be less than _____ IU. Between successive measurements, the sensor shall be cooled to _____°C for at least _____h.

> Other environmental exposures may be substituted or added to the temperature environment specified. In addition, combinations of various successive environments, for example, vibration, shock, and temperature may also be specified. Alternate means of specifying repeatability may be used, for example, rms deviation about the first day mean, or peak-to-peak deviation.
> The cool-down time should be sufficient to obtain thermal equilibrium. Other conditions for repeatability may be specified, such as turn-off with the sensor maintained at operating temperature.

3.3.4.5 Sensitivity

The absolute value of the sensitivity coefficients of the bias to variations from the standard test conditions of 4.5 shall not exceed the limits:

1) Input voltage(s) _____IU/V
2) Power input frequency(ies) _____IU/Hz
3) Operating temperature _____IU/°C
4) Thermal gradient(s) _____IU/°C (across the instrument)
5) External magnetic field(s) _____IU/mT [dc or ac, or both] per axis
6) Pressure _____IU/Pa

> The thermal gradient shall be defined for each application, for example, temperature difference, where it is to be measured, and direction of application. In some cases, it may be desirable to specify a variation of bias sensitivity induced by a thermal transient.

3.3.5 Input Axis Misalignment (IAM)

(Compare with 6.3.)

3.3.5.1 Absolute Value

The maximum value of the angle between the input reference axis and the input axis shall be less than _____rad.

> Physically significant axes orthogonal to the input reference axis may also be defined and misalignment components specified with respect to these axes.

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3.3.5.2 Short-Term Stability

The rms deviation of the IAM, from its mean value over a period of _____[h, d] of continuous operation, shall be less than_____rad.

> Other criteria for establishing stability may be utilized, such as standard deviation, curve fitting for trend determination, or computer analysis to determine the auto-correlation time.

3.3.5.3 Long-Term Stability

The best fit slope of the IAM over a period of_____d of continuous operation shall be less than _____rad/d. The rms deviation of the IAM data points from the best fit shall be less than _____rad.

> The unbiased estimate of the standard deviation may be substituted for the rms deviation. Alternate means of specifying long term IAM stability may be used, for example, rms deviation about the first day mean or peak-to-peak deviation.

3.3.5.4 Repeatability

The rms deviation of the IAM from the mean of_____measurements shall be less than_____rad. Between successive measurements, the sensor shall be cooled to _____°C for at least _____h.

> Other environmental exposures may be substituted or added to the temperature environment specified. In addition, combinations of various successive environments, for example, vibration, shock, temperature, etc, may also be specified. Alternate means of specifying repeatability may be used, for example, rms deviation about the first day mean or peak-to-peak deviation.
>
> The cool-down time should be sufficient to obtain thermal equilibrium. Other conditions for repeatability may be specified, such as turn-off with the sensor maintained at operating temperature.

3.3.5.5 Sensitivity

The absolute value of the sensitivity coefficients of the IAM to variations from the standard test conditions of 4.5 shall not exceed the limits:

1) Input voltage(s)_____ rad/V
2) Power input frequency(ies)_____ rad/Hz
3) Operating temperature_____ rad/°C
4) Thermal gradient(s)_____ rad/°C (across the sensor)
5) External magnetic field(s)_____ rad/mT [dc or ac, or both]
6) Pressure_____ rad/Pa

> The thermal gradient shall be defined for each application, for example, temperature difference, where it is to be measured, and the direction of application. In some cases it may be desirable to specify a variation of IAM sensitivity induced by a thermal transient.

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3.3.6 Warm-Up Time

The output of the angular sensor shall be within_____output units (OU) of steady-state value in no more than_____[s, min] after the initial application of power at _____±_____°C.

> The orientation of the input axis with respect to the gravity vector or earth's rate, or both, should be specified in the test method. It may be desirable to further specify maximum output permitted during the warm-up period or the maximum time until the sensor's output is functional (activation time), or both. These requirements should also be specified as maximum output deviations from steady state as a function of time. The output of the device may be electronically constrained to near zero output at the start of the warm-up period and then released before the end of the period, at which time the output shall be within the specified requirement. If necessary, define any power interrupt or overrange reset characteristics.

3.3.7 Turn-On Hysteresis

The absolute value of the turn-on hysteresis shall be less than _____ IU.

> Turn-on hysteresis associated with some types of sensors may be reduced or eliminated by means of an automatic bias nulling (washout) circuit.

3.3.8 Composite Error

_____% one-half output span, maximum.

> Specific terms comprising composite error may be specified in addition to, or instead of, composite error.

3.3.9 Rate-Squared Sensitivity

(Compare with 6.4.) An output due to an angular rate applied about any axis orthogonal to the input reference axis shall not exceed _____OU/(rad/s)^2.

> This response may be either a direct current offset or the peak value of a transient depending on sensor design. Where the distinction is significant it should be specified, or it may be desirable to impose two limits, or both.

3.3.10 Linear-Acceleration Sensitivity

The output due to an applied linear acceleration shall not exceed _____IU/*g*.

> The output change may be either a direct-current offset or the peak value of a transient depending on sensor design. It may also be specified as a sinusoidal response to a sinusoidal input at a specified frequency or frequencies, but in this case allowance shall be made for actual angular motion produced by nominally rectilinear vibration exciters. In some devices the effect may be a proportional error in scale factor.
>
> The linear acceleration sensitivities can also be a function of thermal gradients across the instrument, and the axis along which the acceleration is applied.

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3.3.11 Vibration-Induced Errors

When the output is low-pass filtered at_____Hz the rectification error due to an applied vibration input shall not exceed_____OU/(g rms)^2 when the sensor is subjected to the vibration input of 3.4.2.2 along any combination of axes.

> This response may be either a direct-current offset or the peak value of a transient depending on sensor design and test-vibration mode. The applied vibration may be either a specified random spectrum or a sine sweep at a specified amplitude and sweep rate. In the latter case, the transient criterion shall apply.

3.3.12 Other Motion-Induced Errors

> The following examples of motion-induced errors may be significant in a particular application. Other responses, including responses to combined linear and angular motion, may be added as required.

3.3.12.1 Angular-Vibration Rectification

The rectification error due to an applied angular vibration input shall not exceed_____ OU/(rad/s^2)^2 when the sensor is subjected to the vibration input of 3.4.2.2 about the input-reference axis.

> This motion error ordinarily will be significant in the event of resonances in the end use structure. Other axes may be defined if appropriate.

3.3.12.2 Angular Vibration Sensitivity

(Compare with 6.4.)

> Angular vibration sensitivity refers to significant odd power terms in the response of an angular sensor to angular acceleration about the input reference axis.

3.3.13 Threshold

Less than IU.

3.3.14 Resolution

The smallest recoverable quantization of the sensor output shall be _____IU.

3.3.15 Noise

3.3.15.1 Electrical

Output in the band-with_____Hz to_____Hz shall be less than _____equivalent input units rms.

> Noise may be specified in multiple band-widths and may also be specified by peak magnitude. For critical applications, power spectral density envelopes provide a more comprehensive specification. In some cases it may be necessary to specify noise both at null and with some steady-state input, for example, for sensors incorporating internal demodulation.

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3.3.15.2 Mechanical

In some cases, mechanical noise output from the sensor (acoustical and angular or translational, or both) may be critical relative to an application and shall be specified.

3.3.16 Frequency Response

3.3.16.1 Amplitude

The sinusoidal amplitude response shall be bounded by the limits shown in Fig 3.

3.3.16.2 Phase

The sinusoidal phase response shall be bounded by the limits shown in Fig 3.

The figures shown are examples of typical sensor response. The precise form of the envelopes may vary somewhat depending on whether the specification is based solely on system requirements or written around the known characteristics of a particular sensor. The former approach is recommended when practical. In addition, some sensors may have overrange characteristics which may be a significant function of frequency. Temperature variations in frequency response may be shown by families of envelopes and by imposing limits which include the effects of temperature. In the event that compensation will be used, response may also be described by means of a Laplace transfer function, with limits specified on the significant terms; otherwise the envelope method is preferred, since sensors frequently cannot be described by a simple transfer function, for example, second order.

3.3.17 Self-Test Scale Factor

The self-test scale factor shall be ±_____OU per test-excitation unit.

A self test of an instrument can be done only if a method of artificially exciting the instrument to produce an output is available. The self-test function may be redefined to supply only a simulated sensor output to processing electronics. If the self test is other than direct current in, direct current out, input and output wave forms should be specified.

3.3.18 Cross Coupling

(Compare with 6.4.) The output due to input rates up to full scale on an orthogonal axis shall not exceed_____% of full scale.

3.3.19 Cross-Axis Sensitivity (Dynamic)

The quadrature phase output shall be less than ±_____% of full scale when the sensor is oscillated at plus and minus full scale at_____Hz about an axis orthogonal to the true input axis.

3.4 Environmental Requirements

The environmental conditions listed in this subsection are those to which the sensor may be subjected during storage, transportation and handling or operation, or both. The equipment shall be designed to survive these environments and to successfully complete the environmental tests specified in Section 4.

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3.4.1 Nonoperating Environment

The following conditions, occuring separately or in combination, may be encountered during transportation and handling or storage, or both. The sensor shall conform to all the requirements of 3.3 after exposure to reasonable combinations of the specified service conditions.

Where appropriate, the environment specified shall be adjusted for the protection afforded by packaging.

3.4.1.1 Temperature and Thermal Radiation

Ambient temperature may vary from a minimum of_____°C to a maximum of_____°C under unsheltered ground conditions. Areas exposed to direct sunlight shall be considered as unsheltered conditions.

3.4.1.2 Thermal Shock

_____°C to_____°C. The heating and cooling rates of the ambient environment shall be_____±_____°C/s.

For cyclic conditions, specify temperature limits for each level, dwell time, and sequence.

3.4.1.3 Vibration

Describe the vibration environment. For sinusoidal vibration, include the specific vibration amplitude versus frequency, duration, or sweep rate and axes of application. For random vibration, specify power spectral density (provide a figure if complex), tolerance, bandwidth, peak acceleration level, total rms acceleration, duration, and axes of application.

3.4.1.4 Mechanical Shock

Specify the shock wave shape or shock spectrum, tolerances, number of shocks, and axes of application.

3.4.1.5 Pressure

_____[Pa, lbf/in^2] to _____[Pa, lbf/in^2]. The rate of change of pressure shall be nominally_____[Pa/s, (lbf/in^2)/s].

If desired, pressure may be expressed in terms of altitude during transportation and rate of climb.

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3.4.1.6 Magnetic Fields

Define magnitudes, directions of fields with respect to each axis, and duration. If exposure to fields resulting from alternating current is desired, specify intensity versus frequency.

3.4.1.7 Nuclear Radiation

Describe the nuclear environments). For each environment include the type of radiation (that is, X ray, gamma, etc) intensity, spectrum, exposure duration, and axes of application.

3.4.1.8 Storage Life

The life of the sensor shall be greater than _____ yr.

Describe storage environment, such as temperature, humidity, and pressure.

3.4.1.9 Other

Include any other appropriate nonoperating environmental conditions, such as acceleration, acoustic noise, rain, humidity, fungus, salt spray, sand, and dust.

3.4.2 Operating Environment

The following conditions, occurring separately or in combination, may be encountered during operation. The sensor shall conform to all of the requirements of 3.3 during, unless otherwise specified, and after exposure to any reasonable combination of the specified service conditions.

3.4.2.1 Thermal

3.4.2.1.1 Temperature (High and Low)

Ambient air temperature may vary from _____ °C to _____ °C under sheltered conditions (protected from direct sunlight).

3.4.2.1.2 Thermal Shock

_____ °C to _____ °C. The heating and cooling rates of the ambient environment shall be ___ ± ____ °C/s.

For cyclic conditions, specify temperature limits for each level, dwell time, and sequence.

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3.4.2.1.3 Other

Other thermal conditions which may affect performance shall be specified, for example, temperature gradients, equivalent heat sink, radiant energy from surrounding surfaces, and power distribution.

3.4.2.2 Vibration

Describe the vibration environment. For sinusoidal vibration, include the specific vibration amplitude versus frequency, duration, or sweep rate and axes of application. For random vibration, specify power spectral density (provide a figure, if applicable), tolerance, bandwidth, peak acceleration level, total rms acceleration, duration, and axes of application. Angular vibration environments may also be specified, if significant.

3.4.2.3 Mechanical Shock

Specify the shock wave shape or shock spectrum, tolerances, number of shocks, and axes of application.

3.4.2.4 Acceleration

Specify the maximum accelerate each of the three axes and the duration.

3.4.2.5 Angular Velocity

Angular velocity shall be_____ rad/s maximum.

3.4.2.6 Pressure

_____ [Pa, lbf/in^2] to _____ [Pa, lbf/in^2]. The rate of change of pressure shall be nominally _____ [Pa/s, (lbf/in^2)/s]

If appropriate, pressure may be expressed in terms of altitude and rate of climb.

3.4.2.7 Humidity

The operative relative humidity shall be ____ % maximum.

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3.4.2.8 Acoustic Noise

Describe the acoustical noise environment. Supply the specific noise spectrum in decible versus frequency, tolerance, bandwidth, peak level, and duration. Use a 0 dB reference of 20 μPa.

3.4.2.9 Magnetic Fields

Define magnitudes, directions of fields with respect to each axis, and duration. If exposure to fields resulting from alternating current is desired, specify intensity versus frequency.

3.4.2.10 Nuclear Radiation

Describe the nuclear environment(s). For each environment include the type of radiation (that is, X ray, gamma, etc) intensity, spectrum, exposure duration, and axes of application.

3.4.2.11 Operating Life

The sensor shall be capable of operating within the requirements of this specification for _____ h.

3.4.2.12 Other

Include any other appropriate operative environmental conditions such as fungus, salt spray, etc.

3.5 Reliability

3.5.1 Reliability Program

The reliability program shall be in accordance with _____.

In the United States, a commonly used standard is MIL-STD-785.

3.5.2 Mean Time Between Failures (MTBF)

The MTBF shall be a minimum of _____ h with a lower confidence limit of _____ %.

Other applicable reliability measures may be found in commercial/military standards.

4. Quality Assurance

All tests required by this standard shall be conducted in accordance with detailed test procedures prepared by the contractor and approved by the buyer.

4.1 Verification Methods

The methods of verification of the sensor shall be classified as follows:

1) *Acceptance Tests*. Those tests or inspections performed on sensors submitted for acceptance under contract

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2) *Qualification Tests*. Those tests or inspections performed on sensors submitted for qualification as a satisfactory-product
3) *Reliability Tests.* Those tests or inspections performed to demonstate the reliability specified in 3.5.
4) *Analyses.* Performed to ascertain form, fit, or function in cases where testing is difficult or unnecessary

Test requirements are summarized in Fig 4.

4.2 Acceptance Tests

Acceptance tests shall consist of individual and sample tests.

4.2.1 Individual Tests

Each sensor shall be subjected to the following tests (described under 4.7):

The list of individual tests shall be specified by the procuring organization based on the requirements. The number or type of individual tests specified is at the discretion of the procuring organization. Those tests frequently specified as individual tests are listed below.

Title	Section
(1) Examination of Product	4.7.1.1
(2) Seal	4.7.1.3
(3) Impedance	4.7.1.4
(4) Dielectric Strength	4.7.1.5
(5) Insulation Resistance	4.7.1.6
(6) Electrical Interface	4.7.2.2
(7) Scale Factor, Bias, and Composite Error	4.7.2.4
(8) Input Axis Misalignment	4.7.2.5
(9) Short-Term Stability	4.7.2.6
(10) Repeatability	4.7.2.8
(11) Turn-on Hysteresis	4.7.2.10
(12) Polarity and Input Range	4.7.2.11
(13) Linear Acceleration Sensitivity	4.7.2.12
(14) Frequency Response	4.7.2.14

There are other individual tests which are not generally specified, but which may be included, and there are some above which may be deleted depending on the requirements of the specific application. The environmental levels imposed for acceptance tests would normally be reduced from those imposed for qualification tests.

The information in Fig 4 is intended to be suggestive only, due to the number of verification techniques available. It is recommended that the end user application be evaluated for each individual requirement and to specify the requirements and verification methods which are appropriate.

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Requirements	Verification Method				Quality Assurance
	Acceptance Tests	Qualification Tests	Reliability Tests	Analysis	
3.2.1.1 Exterior Surface	X	X			4.7.1.1
3.2.1.2 Dimensions	X			X	4.7.1.1
3.2.1.3 Identification of the Product	X				4.7.1.1
3.2.1.4 Sensor Reference Axis	X			X	4.7.1.1
3.2.1.5 Weight	X			X	4.7.1.2
3.2.1.6 Seal	X				4.7.1.3
3.2.1.7 Controlled Operating Temperature	X	X			4.5.2.3
3.2.2.1.1 Power Inputs	X	X			4.7.2
3.2.2.1.2 Output Signals	X	X			4.7.2
3.2.2.1.3 Command Inputs	X	X		X	4.7.2
3.2.2.1.4 Timing Reference	X	X		X	4.7.2
3.2.2.1.5 Test Points	X	X			4.7.2
3.2.2.1.6 Grounding	X	X		X	4.7.2
3.2.2.2 Dielectric Strength	X	X			4.7.1.5
3.2.2.3 Insulation Resistance	X	X			4.7.1.6
3.2.2.4 Electromagnetic Interference		X			4.7.3
3.2.2.5 Electromagnetic Compatibility		X			4.7.3
3.2.2.6 Magnetic Leakage		X			4.7.2.18
3.2.3.1 LRU Interchangeability			X		*
3.2.3.1 LRU Maintenance			X		*
3.3.2 Polarity and Input Range	X	X			5.7.2.11
3.3.3 Scale Factor	X	X			5.7.2.4, 5.7.2.9
3.3.4 Bias	X	X			5.7.2.4, 5.7.2.9
3.3.5 Input Axis Misalignment	X	X			5.7.2.5, 5.7.2.9
3.3.6 Warm-Up Time	X	X			5.7.2.3
3.3.7 Turn-On Hysteresis	X	X			5.7.2.10
3.3.8 Composite Error	X	X			5.7.2.4
3.3.9 Rate Squared Sensitivity	X	X			5.7.2.15
3.3.10 Linear Acceleration Sensitivity	X	X			5.7.2.12
3.3.11 Vibration Induced Errors	X	X			5.7.2.16
3.3.13 Threshold	X	X		X	5.7.2.13
3.3.14 Resolution	X	X			5.7.2.13
3.3.15 Noise	X	X			5.7.2.19, 5.7.2.20
3.3.16 Frequency Response	X	X			5.7.2.14
3.3.17 Self Test Scale Factor	X	X			5.7.2.17
3.3.18 Cross Coupling	X	X			†
3.3.19 Cross-Axis Sensitivity	X	X			†
3.4.1.1 Temperature and Thermal Radiation		X			5.7.3.3.3
3.4.1.2 Thermal Shock		X			5.7.3.3.5
3.4.1.3 Vibration		X			5.7.3.3.6
3.4.1.4 Mechanical Shock		X			5.7.3.3.7
3.4.1.5 Pressure		X			5.7.3.3.10
3.4.1.6 Magnetic Fields		X			5.7.3.3.13
3.4.1.7 Nuclear Radiation		X		X	5.7.3.3.14
3.4.1.8 Storage Life		X		X	5.7.3.3.15
3.4.2.1.1 Temperature (High, Lo)	X	X			5.7.3.3.4
3.4.2.1.2 Thermal Shock		X			5.7.3.3.5
3.4.2.2 Vibration	X	X			5.7.3.3.6
3.4.2.3 Mechanical Shock		X			5.7.3.3.7
3.4.2.4 Acceleration	X	X			5.7.3.3.8
3.4.2.5 Angular Velocity	X	X			5.7.3.3.9
3.4.2.6 Pressure		X			5.7.3.3.10
3.4.2.7 Humidity		X			5.7.3.3.11
3.4.2.8 Acoustic Noise		X			5.7.3.3.12
3.4.2.9 Magnetic Fields	X	X			5.7.3.3.13
3.4.2.10 Nuclear Radiation		X		X	5.7.3.3.14
3.4.2.11 Operating Life				X	5.7.3.3.16
3.5.2 Mean Time Between Failure		X			5.4.1

*For a specific application, a suitable set of criteria defined is in accordance with 3.2.2.1.
†For a specific application, a suitable test is defined. See Appendix B3.

NOTE: The information in Fig 4 is intended to be suggestive only, due to the number of verification techniques available. It is recommended that the end user application be evaluated for each individual requirement and the requirements and verification methods which are appropriate specified.

Figure 4—Test Requirement Matrix and Cross Reference Table

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4.2.2 Sampling Plan and Tests

4.2.2.1 Sampling Plan

Sensors selected shall be subjected to the tests specified in 4.2.2.2.

This subsection is intended to designate a sampling plan whereby samples are periodically selected for more complete tests, if required. Sampling plans are at the discretion of the procuring organization based upon usage, size of contract, individual requirements, etc.

In the United States, selection according to MIL-STD-105 is common.

4.2.2.2 Sampling Tests

Sensors selected in accordance with 4.2.2.1 shall be subjected to the following tests (described under 4.7):

The procuring organization shall specify those tests which shall be performed on sensors selected in accordance with the sampling plan (see 4.2.2.1). Those tests frequently specified for sample tests are listed below. Sampling-plan units may be used for delivery unless the procuring organization specifies life tests or other destructive tests under the sampling plan.

Title	Section
(1) Individual Tests	4.2.1
(2) Weight	4.7.1.2
(3) Warm-up Time	4.7.2.3
(4) Linearity Test	4.7.2.4
(5) Threshold and Resolution	4.7.2.13
(6) Magnetic Leakage	4.7.2.18
(7) Temperature (High, Low)	4.7.3.3.3

4.2.3 Rejection and Retest

When a unit from the production run fails to meet the specification requirements, the procuring organization shall be notified of the failure. The cause of failure shall be determined and rejection and retest shall be accomplished in accordance with the following plan. [Describe rejection and retest plan.] After corrections have been made, the complete test under which failure occurred, and any tests which might have been affected by the corrective measures taken, shall be defined and approved by the procuring organization. The unit shall complete the retest without further failure before it will be considered to have passed the test. For operational and production reasons, individual tests may be continued pending the investigation of the failure.

4.2.4 Defects in Accepted Items

The investigation of a test failure could indicate that defects may exist in items already accepted. If so, the manufacturer shall fully advise the procuring organization of defects likely to be found and of methods for detecting and correcting them.

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4.3 Qualification Tests

4.3.1 Qualification Tests Samples

A quantity of _____ sensors manufactured in accordance with the requirements of this specification shall be subjected to qualification tests specified herein. The procuring organization may designate an independent facility at which one or more of these tests may be performed.

If the product is later modified in any way, the modified form shall be subjected to and pass those qualification tests designated by the procuring organization.

4.3.2 Qualification Test Methods

The procuring organization shall specify from 4.7 those tests which shall be performed on the qualification test samples. It is usual to require all the individual tests as listed in 4.2.1, selected sampling tests from 4.2.2.2, the sensitivity test from 4.7.2.9, and all of the environmental tests in 4.7.3.

4.4 Reliability Tests

Mean Time Between Failure (MTBF). The MTBF requirements shall be demonstrated by testing _____ production units for _____ h minimum each and a minimum time of _____ h combined.

A demonstration test plan may be prepared to define test conditions, types of tests, failures, etc. As an alternate to demonstration testing, MTBF may be calculated. In some cases, it may be desirable to combine the reliability tests with the life tests.

4.5 Standard Test Conditions

4.5.1 Ambient Environment

The conditions listed below define the requirements for the test environment. They are not intended as environmental tests, which are described in 4.7.3.

4.5.1.1 Atmospheric Conditions

Pressure _____ ± _____ [Pa, lbf/in^2]

Ambient temperature _____ °C ± _____ °C

Relative humidity _____% to _____%

4.5.1.2 Other Conditions

Specify other test area environmental conditions as required (for example, magnetic field, radiation, and vibration).

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4.5.2 Installation Requirements

4.5.2.1 Mounting Fixture(s)

The mounting fixture(s) design requirements shall be specified (for example, alignment for reference axes, surface(s) conditioning, thermal considerations, and simulation of in-service installation).

4.5.2.2 Electrical Interconnections

The electrical interconnections may be specified in a schematic (included as a figure) or as a separate engineering drawing. Several schematics may be required for the various test arrangements required. Each schematic shall indicate such things as:

1) Grounding
2) Test points
3) Circuit protection
4) Precautionary notes
5) Allowable lead length
6) Shielding

The detailed test procedures shall ensure that all electrical parameters are set within the allowable tolerances specified for the electrical interface.

4.5.2.3 Operating Temperature

The operating temperature shall be in accordance with 3.2.1.7.

4.6 Test Equipment

Selection. The selection of test equipment shall be based on accuracy requirements compatible with the performance specifications. Similarly, the bandpass of the measuring devices should be chosen so as to provide information within the frequency spectrum of interest for the tests.

Test equipment should be specified in general terms to the extent required to cover test requirements and methods to the accuracy required. Specification of test equipment by proper name, model or part number, and calibration requirements shall be normally covered by the detailed test procedures.

4.7 Test Methods

4.7.1 Nonoperating Tests

These methods are intended to ensure the conformance of the sensor to the nonoperating mechanical and electrical requirements.

1) Unless otherwise specified, all non-operative tests shall be performed in a normal laboratory environment, as described in 4.5.1.
2) After examination, the sensor shall be mounted on a simple mounting fixture that will minimize the chances for accidental mechanical damage.

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3) The electrical leads, if required, shall be brought out to a junction box or equivalent device that will minimize the chance of accidental electrical damage due to shorting across leads, etc. Terminal designations shall be as shown in the electrical schematic.

> Care shall be taken in the choice of the junction box and the size and length of leads to avoid affecting the characteristics of the sensor circuits.

4.7.1.1 Examination of Product

The sensor shall be examined visually for proper identification markings, surface finish, workmanship, and dimensional conformance to the outline drawing no_____.

4.7.1.2 Weight

Measure the weight of the sensor. The weight shall conform to the requirements of 3.2.1.5.

4.7.1.3 Seal

The purpose of this test is to determine that the sensor is properly sealed.

> This procedure is written to accommodate either liquid- or gas-filled sensors. The appropriate subsections should be chosen.

4.7.1.3.1 Test Equipment

The following test equipment is required for this test:

1) Liquid-Filled Sensor
   a) Binocular microscope
   b) Vacuum enclosure
2) Gas-Filled Sensor
   a) Leak detector or immersion fluid (specify)
   b) Vacuum enclosure

4.7.1.3.2 Test Method

1) *Liquid-Filled Sensor*. After a thorough cleaning of all surfaces, the sensor shall be placed in a vacuum enclosure at _____ ± _____Pa and at a sensor temperature of _____ ± _____°C for a minimum period of _____ min. The sensor shall then be removed and visually examined for evidence of leakage at a magnification of _____.
2) *Gas Filled Sensor.* The sensor shall be placed in a vacuum enclosure at _____ ± _____Pa and _____ ± _____ °C sensor temperature. External gas leakage shall then be measured using the leak detector.

As an alternate test, the sensor shall be submerged in liquid and placed in a vacuum enclosure at _____ ± _____Pa and _____ ± _____°C temperature for a period of _____ min. The presence or absence of a flow of bubbles after _____ min shall be noted. Care shall be taken to distinguish bubbles due to leakage from those due to adsorbed gases on the outer surface.

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4.7.1.3.3 Test Results

The seal integrity shall conform to the requirements of 3.2.1.6.

> In some cases other procedures may be more appropriate, such as the use of fluorescent tracers in liquids or the measurement of weight loss.

4.7.1.4 Impedance

The purpose of this test is to measure the impedance of the sensor electrical interface circuits.

4.7.1.4.1 Test Equipment

The following test equipment is required for this test:

1) Impedance measuring equipment
2) Resistance measuring equipment

4.7.1.4.2 Test Method

Measure the impedances of each circuit listed below:

> Appropriate circuits at the sensor's electrical interface shall be selected for impedance or resistance tests, or both. In some cases, it may be necessary to measure the impedance while operating.

4.7.1.4.3 Test Results

Measured impedances shall conform to the requirements of 3.2.2.1.

4.7.1.5 Dielectric Strength

The purpose of this test is to ascertain that the separate sensor circuits are isolated from each other and from the case by measuring the leakage current between these circuits and the case.

4.7.1.5.1 Test Equipment

The following test equipment is required for this test:

An adjustable alternating-current high-voltage source equipped with voltage and current measuring capabilities.

4.7.1.5.2 Test Method

Apply _____ ± _____ V rms at_____ Hz between mutually isolated circuits and between each circuit and the sensor case. The test voltage shall be raised from zero to the specified value as uniformly as possible, at a rate of _____ V rms/s. The test voltage shall then be gradually reduced to zero. During each test the current meter shall be monitored and the maximum leakage current recorded.

4.7.1.5.3 Test Results

The measured leakage current(s) shall conform to the requirements of 3.2.2.2.

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4.7.1.6 Insulation Resistance

The purpose of this test is to measure the insulation resistance between isolated circuits and between the sensor case and circuits insulated from the case.

4.7.1.6.1 Test Equipment

The following test equipment is required for this test:

Megohmmeter

4.7.1.6.2 Test Method

Apply _____ ± _____ V dc for a period of _____ ± _____ s between mutually isolated circuits and between each circuit and the sensor case.

> It is recommended that all grounded circuit connections be tied together to prevent possible damage during this test.

4.7.1.6.3 Test Results

The measured insulation resistance shall conform to the requirements of 3.2.2.3.

4.7.2 Operating Tests

These tests are intended to determine the sensor performance characteristics, as defined by Eq 22.

> The following operating tests are intended to serve as an example of testing one type of sensor. The assumed sensor has a single sensitive axis, measures angular rate down to zero frequency, has an analog output, and has orthogonal axes labeled *x*, *y*, and input reference axis *z*. The sensor has a significant linear acceleration sensitivity which may have components along any or all of the three axes. A model equation for this sensor is the example given in 6.3.
>
> The sensor output measurement test equipment and techniques may significantly influence the test results. Specify the sequence of operations required to bring the sensor and test equipment to operating conditions for each test setup.
>
> Because of the choice of sensors, the following performance specifications are not verification tested in this section (see the Foreword and Appendix B3.):
>
> 1) 3.3.3.2 Asymmetry
> 2) 3.3.9 Rate-Squared Sensitivity
> 3) 3.3.12 Other Motion-Induced Errors
> 4) 3.3.15.2 Mechanical Noise
> 5) 3.3.18 Cross Coupling
> 6) 3.3.19 Cross-Axis Sensitivity (Dynamic)

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4.7.2.1 Test Setup

It may be necessary to specify the true position of the input reference axis with respect to the rate table axis if linear acceleration sensitivity is significant.

4.7.2.1.1 Mounting Position No. 1 (Input Reference Axis Parallel to Rate Table Axis)

1) Unless otherwise specified, the sensor shall be operated under the standard test conditions of 4.5.
2) Ensure that the positive rotation axis of the rate table is vertical (up) within____mrad.
3) Attach the sensor to the mounting sur face of the rate table so that its positive input reference axis is parallel to the axis of rotation within____mrad.
4) With the rate table stationary, allow____min for the sensor and its immediate environment to reach thermal equilibrium.

4.7.2.1.2 Mounting Position No 2 (*X*-Axis Parallel to Rate Table Axis)

1) Unless otherwise specified, the sensor shall be operated under the standard test conditions of 4.5.
2) Ensure that the positive rotation axis of the rate table is vertical (up) within____mrad.
3) Attach the sensor to the mounting surface of the rate table so that its positive *x*-axis is parallel to the axis of rotation within____mrad.
4) With the rate table stationary, allow____min for the sensor and its immediate environment to reach thermal equilibrium.

4.7.2.1.3 Mounting Position No 3 (*Y*-Axis Parallel to Rate Table Axis)

1) Unless otherwise specified, the sensor shall be operated under the standard test conditions of 4.5.
2) Ensure that the positive rotation axis of the rate table is vertical (up) within____mrad.
3) Attach the sensor to the mounting surface of the rate table so that its positive *y*-axis is parallel to the axis of rotation within____mrad.
4) With the rate table stationary, allow____min for the sensor and its immediate environment to reach thermal equilibrium.

4.7.2.1.4 Mounting Position No 4 (Input Reference Axis Parallel to Dividing Head Axis)

1) Unless otherwise specified, the sensor shall be operated under the standard test conditions of 4.5.
2) With the rotation axis of the dividing head horizontal within____mrad, attach the mounting fixture to the face plate of the dividing head so that the sensor, when mounted, will satisfy the requirements of 4.7.2.1.4(3).
3) With the dividing head set at 0°, mount the sensor on the reference mounting surface(s) so that the input reference axis is parallel to the axis of rotation within_____mrad, the *x*-axis is vertical (pointed upward) within_____mrad, and the *y*-axis moves toward the vertical (upward) when the head is rotated to 90°.
4) With the dividing head set at 0°, allow____min for the sensor and its immediate environment to reach thermal equilibrium.

4.7.2.1.5 Mounting Position No 5 (*X*-Axis Parallel to Dividing Head Axis)

1) Unless otherwise specified, the sensor shall be operated under the standard test conditions of 4.5.
2) With the rotation axis of the dividing head horizontal within____mrad, attach the mounting fixture to the face plate of the dividing head so that the sensor, when mounted, will satisfy the requirements of 4.7.2.1.5(3).
3) With the dividing head set at 0°, mount the sensor on the reference mounting surface(s) so that the *x*-axis is parallel to the axis of rotation within____mrad, the input reference axis is vertical (pointed upward) within____mrad, and the *y*-axis moves toward the vertical (upward) when the head is rotated to 90°.
4) With the dividing head set at 0°, allow____min for the sensor and its immediate environment to reach thermal equilibrium.

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4.7.2.1.6 Mounting Position No 6 (*Y*-Axis Parallel to Dividing Head Axis)

1) Unless otherwise specified, the sensor shall be operated under the standard test conditions of 4.5.
2) With the rotation axis of the dividing head horizontal within____mrad, attach the mounting fixture to the face plate of the dividing head so that the sensor, when mounted, will satisfy the requirements of 4.7.2.1.6(3).
3) With the dividing head set at 0°, mount the sensor on the reference mounting surface(s) so that the positive *y*-axis is parallel to the axis of rotation within____mrad, the *x*-axis is vertical (pointed upward) within____mrad, and the input reference axis moves toward the vertical (upward) when the head is rotated to 90°.
4) With the dividing head set at 0°, allow____min for the sensor and its immediate environment to reach thermal equilibrium.

With the exception of an optional test in 4.7.2.12, the dividing head may be replaced by alternate fixturing, such as an orthogonal block.

4.7.2.1.7 Mounting Position No 7 (Input Reference Axis Parallel to Shaker Axis)

1) Unless otherwise specified, the sensors shall be operated under the stated conditions of 4.5.
2) Measure the magnetic field at the position where the sensor is to be located on the shaker. This field shall be less than____mT.
3) The shaker axis is vertical within____mrad.
4) Attach the sensor to the mounting surface of the shaker so that its input reference axis is up and parallel to the shaker axis within____mrad.
5) With the vibration field stationary, allow____min for the sensor and the immediate environment to reach thermal equilibrium.

4.7.2.1.8 Mounting Position No 8 (*X*-Axis Parallel to Shaker Axis)

1) Unless otherwise specified, the sensors shall be operated under the stated test conditions of 4.5.
2) Measure the magnetic field at the position where the sensor is to be located on the shaker. The field shall be less than____mT.
3) The shaker axis is vertical (up) within____mrad.
4) Attach the sensor to the mounting surface of the shaker so that its positive *x*-axis, is up and parallel to the shaker axis within____mrad.
5) With the vibration field stationary, allow____min for the sensor and the immediate environment to reach thermal equilibrium.

4.7.2.1.9 Mounting Position No 9 (*Y*-Axis Parallel to Shaker Axis)

1) Unless otherwise specified, the sensors shall be operated under the stated test conditions of 4.5.
2) Measure the magnetic field at the position where the sensor is to be located on the shaker. The field shall be less than____mT.
3) The shaker axis is vertical (up) within____mrad.
4) Attach the sensor to the mounting surface of the shaker so that its positive *y*-axis is up and parallel to the shaker axis within____mrad.
5) With the vibration field stationary, allow____min for the sensor and the immediate environment to reach thermal equilibrium.

4.7.2.2 Electrical Interface

The purpose of this test is to determine that all of the operational electrical interface functions are within their allowable tolerances.

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4.7.2.2.1 Test Equipment

The following equipment specified in 4.6 is required for this test:

1) Rate table and mounting fixture
2) Electronic equipment required to operate the sensor and to measure its output

Specify additional test equipment required to make measurements at the electrical interface such as

1) Variable power supplies
2) Variable frequency supplies
3) Oscilloscopes
4) Electronic counters
5) Ammeters
6) Precision voltmeters

4.7.2.2.2 Test Setup

The sensor setup shall be in accordance with 4.7.2.1.1.

Other positions may be specified during the test to evaluate interface functions with various values of rate and *g* as inputs.

4.7.2.2.3 Test Methods

Specify the test methods which are required to determine that the functions at the electrical interface are within their allowable tolerances. For example:

1) Measure the input current
2) Measure the test point wave shapes
3) Measure the output signal wave shapes
4) Measure the test point wave shape with input line voltages at the allowable extremes
5) Measure the output signal wave-shape characteristics with input line voltages at the allowable extremes
6) Measure the phase relations between critical signals
7) Measure the distortion of critical signals, etc

4.7.2.2.4 Test Results

The measured test results shall conform to the requirements of 3.2.2.1.

4.7.2.3 Warm-Up Time

The purpose of this test is to determine the time required for the sensor output to come and remain within a specified value of the steady-state or final indicated output following power turn-on in a specified ambient environment.

4.7.2.3.1 Test Equipment

The following equipment specified in 4.6 is required for this test:

1) Rate table or stable reference surface
2) Electronic equipment required to operate the sensor and to measure its output
3) Equipment required to establish the specified ambient environment

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4.7.2.3.2 Test Setup

The test setup shall be in accordance with 4.7.2.1.

> The mounting position(s) selected should be determined by the application.

4.7.2.3.3 Test Method

1) Establish the ambient thermal environment at_____±_____°C. Allow_____min for the sensor to reach thermal equilibrium.
2) Energize the sensor.
3) Record the sensor output as a function of time until a steady state is reached.

4.7.2.3.4 Test Results

The sensor output shall conform to the requirements of 3.3.6.

> This method may also be used to test power-interrupt response. In some applications it may be necessary to mount the sensor to the optional rate table so that a specified input can be applied during power interruption. Activation time and overrange reset characteristics are also tested with an applied input.

4.7.2.4 Scale Factor, Bias, and Composite Error

The purpose of this test is to establish the value of the scale factor K_1, the bias K_0, and to measure the composite error of the output.

4.7.2.4.1 Test Equipment

The following equipment, specified in 4.6, is required for this test:

1) Rate table and mounting fixture
2) Electronic equipment required to operate the sensor and to measure its output

4.7.2.4.2 Test Setup

The test setup shall be in accordance with 4.7.2.1.1, with provision for inverting the input axis.

4.7.2.4.3 Test Method

1) With the axis inverted and the rate table stationary, record the output as E_{0-}.
2) With the input axis vertical (as in 4.7.2.1.1) and the rate table stationary, record the output as E_{0+}.
3) Rotate the rate table counterclockwise (as viewed from above) in_____increasing approximately equal increments ending near, but not exceeding, the positive full-scale value. Record the input rate ω_{j+} and the sensor output E_{j+} at each of the input rates.
4) Rotate the rate table clockwise (as viewed from above) in_____increasing approximately equal increments ending near, but not exceeding, the negative full-scale value. Record the input rate ω_{j+} and the sensor output E_{j-} at each of the input rates.

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4.7.2.4.4 Test Results

1) Calculate the value of the scale factor K_1, OU/(rad/s) as the slope of the least squares straight-line fit to the data points obtained in 4.7.2.4.4 (2), (3), and (4).
2) Calculate the value of the bias K_0, input units, as

$$K_0 = \frac{E_{0+} + E_{0-}}{2K_1} \tag{2}$$

3) Calculate the composite error E_c, as follows:
Determine the deviations of the data points E_{j+}, E_{j-} from a straight line as

$$\Delta E_j = E_j - K_1\,\omega_j - E_{0+} \tag{3}$$

Select the largest absolute valued ΔE_j as ΔE.
then

$$E_c = \frac{(2 \cdot \Delta E) \cdot 100}{\text{output span}}\ \% \tag{4}$$

4) The scale factor K_1 shall conform to the requirements of 3.3.3.1.
5) The bias K_0 shall conform to the requirements of 3.3.4.1.
6) The composite error E_c shall conform to the requirements of 3.3.8.

> In some cases, it may be desirable to obtain scale factor through the use of a two-point test, in which case bias and composite error cannot be established.

4.7.2.5 Input Axis Misalignment

The purpose of this test is to determine the absolute value of the misalignment between the input reference axis and the input axis.

4.7.2.5.1 Test Equipment

The following test equipment specified in 4.6 is required for this test:

1) Rate table and sensor mounting fixture
2) Electronic equipment required to operate the sensor and to measure its output

4.7.2.5.2 Test Setup (Misalignment about the *Y*-Axis).

The test setup shall conform to 4.7.2.1.2.

4.7.2.5.3 Test Method (Misalignment about the *Y*-Axis)

1) Rotate the rate table counterclockwise (as viewed from above) at_____rad/s (ω_1) and record the sensor output as E_1
2) Rotate the rate table clockwise (as viewed from above) at_____rad/s (ω_2) and record the sensor output as E_2

4.7.2.5.4 Test Setup (Misalignment about the *X*-Axis).

The test setup shall conform to 4.7.2.1.3.

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4.7.2.5.5 Test Method (Misalignment about the X-Axis)

1) Rotate the rate table counterclockwise (as viewed from above) at_____rad/s (ω_3) and record the sensor output as E_3
2) Rotate the rate table clockwise (as viewed from above) at_____rad/s (ω_4) and record the sensor output as E_4

Normally, the applied inputs will be plus or minus full scale.

4.7.2.5.6 Test Results

1) Calculate the misalignment about the *y*-axis from Eq 5.

$$\delta_y = \frac{E_1 - E_2}{[K_1(|\omega_1| + |\omega_2|)]} \text{ rad} \quad (5)$$

2) Calculate the misalignment about the *x*-axis from Eq 6.

$$\delta_x = \frac{E_3 - E_4}{[K_1(|\omega_3| + |\omega_4|)]} \text{ rad} \quad (6)$$

3) The quantity $\sqrt{\delta_x^2 + \delta_y^2}$ shall conform to the requirements of 3.3.5.1.

4.7.2.6 Short-Term Stability

The purpose of this test is to determine the short-term stability of the sensor bias K_0, scale factor K_1, and the input axis misalignments δ_y, δ_x.

3) Repeat step (2)_____times per day for _____[h, d] of continuous operation. Measurements are to be made at least_____[min, h] apart.

sensor and to measure its output

4.7.2.6.1 Test Setup

The test setup shall be in accordance with 4.7.2.1.1, 4.7.2.1.2, and 4.7.2.1.3 respectively.

4.7.2.6.2 Test Method

1) Stabilize the sensor at the standard operating conditions specified in 4.5.
2) Determine and record the bias, scale factor, and input axis misalignment using the procedures in 4.7.2.4 and 4.7.2.5.
3) Repeat step (2)_____times per day for _____h, d] of continuous operation. Measurements are to be made at least_____[min, h] apart.

4.7.2.6.3 Test Results

1) Determine the root mean square (rms) deviation of the bias, scale factor, and input axis misalignments from their mean values.
2) The sensor short-term stability shall conform to the requirements of 3.3.3.3, 3.3.4.2, and 3.3.5.2.

In some applications it may be desirable to modify the test to determine the stability of additional parameters, such as linear acceleration sensitivity.

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4.7.2.7 Long-Term Stability

The purpose of this test is to determine the long-term stability of sensor bias K_0, scale factor K_1, and input axis misalignments by δ_y, δ_x.

4.7.2.7.1 Test Equipment

The following test equipment, specified in 4.6, is required for this test:

1) Rate table and sensor mounting fixture
2) Electronic equipment to operate the sensor and to measure its output

4.7.2.7.2 Test Setup

The test setup shall be in accordance with 4.7.2.1.1, 4.7.2.1.2, and 4.7.2.1.3 respectively.

4.7.2.7.3 Test Method

1) Stabilize the sensor at the standard operating conditions specified in 4.5.
2) Determine and record the bias, scale factor, and input axis misalignment using the procedures of 4.7.2.4 and 4.7.2.5.
3) Repeat step (2) _____ times per day for _____ h, d] of continuous operation. Measurements are to be made at least _____ [min, h] apart.

4.7.2.7.4 Test Results

1) Obtain the best-fit slopes of the bias, scale factor, and input axis misalignments by the method of least squares. Determine the deviation of the data points from the best-fit straight lines.
2) The sensor long-term stability shall conform to the requirements of 3.3.3.4, 3.3.4.3, and 3.3.5.3.

> In some applications it may be desirable to modify the test to determine the stability of additional parameters such as linear acceleration sensitivity.

4.7.2.8 Repeatability

The purpose of this test is to determine the repeatability of the bias K_0, scale factor K_1, and input axis misalignments δ_y, δ_x, with cool-downs to the specified temperature.

4.7.2.8.1 Test Equipment

The following test equipment specified in 4.6 is required for this test:

1) Rate table and sensor mounting fixture
2) Electronic equipment to operate the sensor and to measure its output

4.7.2.8.2 Test Setup

The test setup shall be in accordance with 4.7.2.1.1, 4.7.2.1.2, and 4.7.2.1.3 respectively.

4.7.2.8.3 Test Method

1) Stabilize the sensor at the standard operating conditions specified in 4.5

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2) Determine and record the bias, scale factor, and input axis misalignment using the procedures of 4.7.2.4 and 4.7.2.5
3) De-energize and cool the sensor to _____ ± _____ °C. Soak at least _____ h
4) Repeat steps (1), (2), and (3) _____ times

4.7.2.8.4 Test Results

The sensor repeatability shall conform to the requirements of 3.3.3.5, 3.3.4.4, and 3.3.5.4.

Other changes in environmental conditions may be specified as desired.

4.7.2.9 Sensitivity

The purpose of this test is to determine the changes in sensor bias K_0, or scale factor K_1, or input axis misalignment δ_y, δ_x, or any combination thereof, caused by variations in the following:

1) Input voltages
2) Power input frequency(ies)
3) Operating temperature
4) Thermal gradient(s)
5) External magnetic field(s) [dc or ac, or both]
6) Pressure

For some applications, it may be desirable to increase or decrease the number of test conditions to be varied, or to test for the sensitivity of other sensor parameters, or both.

4.7.2.9.1 Test Equipment

The following test equipment, specified in 4.6 is required for this test:

1) Rate table and sensor mounting fixture
2) Electronic equipment to operate the sensorand to measure its output
3) Equipment required to produce the excitation variations and environmental changes

4.7.2.9.2 Test Setup

The test setup shall be in accordance with 4.7.2.1.1, 4.7.2.1.2, and 4.7.2.1.3 respectively.

4.7.2.9.3 Test Method Pickoff Excitation Voltage

This test is performed by varying each parameter individually while maintaining all other test conditions constant, in accordance with 4.5. An example illustrating sensitivity to pickoff excitation voltage is presented below.

1) Determine the sensor bias, scale factor, and input axis misalignments using the procedures in 4.7.2.4 and 4.7.2.5 with the pickoff excitation voltage set at _____ + _____ V [V_a]

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2) Change the pickoff excitation voltage to _____ + _____ V [V_b] and repeat the test.

For other parameter variations repeat the test described in 4.7.2.9.3 for each parameter listed in 4.7.2.9.

Select the appropriate parameter change for each test.

Generally, the conditions of environmental exposure should be specified, such as rate of change of temperature and pressure changes, and the direction of magnetic fields. Care shall be taken to separate or eliminate the effect of changes in test equipment characteristics caused by variations in environment. In thermal testing, care should be taken to simulate the heat-transfer conditions expected in the application.

4.7.2.9.4 Test Results

1) Calculate the sensitivity coefficients using Eqs 7, 8, 9, and 10.
Scale factor sensitivity to variations in pickoff excitation voltage =

$$\frac{100\ (K_{1a} - K_{1b})}{K_1\ (V_a - V_b)}\ \%/\text{V} \tag{7}$$

where

V_a = maximum excitation voltage
V_b = minimum excitation voltage
K_1 = scale factor
K_{1a} = scale factor measured with V_a applied
K_{1b} = scale factor measured with V_b applied

Bias sensitivity to variations in pickoff excitation voltage =

$$\frac{K_{0a} - K_{0b}}{V_a - V_b}\qquad \text{IU}/\text{V} \tag{8}$$

where
$K_{0\,a}$ = bias measured with V_a applied
$K_{0\,b}$ = bias measured with V_b applied

Input axis misalignment sensitivity to variations in pickoff excitation voltage =

$$\frac{\delta_{ya} - \delta_{yb}}{V_a - V_b}\ \text{rad}/\text{V}\ [y\text{-axis}] \tag{9}$$

$$\frac{\delta_{xa} - \delta_{xb}}{V_a - V_b}\ \text{rad}/\text{V}\ [x\text{-axis}] \tag{10}$$

where
δ_{ya} = y-axis misalignment measured with V_a applied
δ_{yb} = y-axis misalignment measured with V_b applied
δ_{xa} = x-axis misalignment measured with V_a applied
δ_{xb} = x-axis misalignment measured with V_b applied

2) The sensitivity coefficients shall meet the requirements specified in 3.3.3.6, 3.3.4.5, and 3.3.5.5.

Note that if a particular sensitivity is non-linear, the result obtained from the above procedure can be misleading. It may be desirable to obtain more data points to determine such characteristics as linearity, maximum slope, or hysteresis.

4.7.2.10 Turn-On Hysteresis

The purpose of this test is to determine the turn-on hysteresis.

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4.7.2.10.1 Test Equipment

The following equipment, specified in 4.6, is required for this test:

1) Rate table and mounting fixture
2) Electronic equipment required to operate the sensor and measure its output

4.7.2.10.2 Test Setup

The test setup shall conform with 4.7.2.1.1.

4.7.2.10.3 Test Method

1) Rotate the rate table counterclockwise (as viewed from above) at _____ rad/s. Remove power from the sensor and then slow the rate table at_____ ± _____ rad/s^2 to a complete stop.
2) Apply power to the sensor again within _____s. Record the sensor output as E_1.
3) Rotate the rate table clockwise (as viewed from above) at _____ rad/s. Remove power from the sensor and then slow the rate table at ____ ± _____ rad/s^2 to a complete stop.
4) Apply power to the sensor again within _____s. Record the sensor output as E_2.

4.7.2.10.4 Test Results

1) Calculate the turn-on hysteresis H_t from Eq 11.

$$H_t = \frac{E_1 - E_2}{K_1} \text{ IU} \tag{11}$$

2) The turn-on hysteresis shall conform to the requirements of 3.3.7.

4.7.2.11 Polarity and Input Range

The purpose of this test is to establish that the sensor output polarity and input rate range are as specified.

4.7.2.11.1 Test Equipment

The following equipment, specified in 4.6, is required for this test.

1) Rate table and mounting fixture
2) Electronic equipment required to operate the sensor and to measure its output

4.7.2.11.2 Test Setup

The test setup shall be in accordance with 4.7.2.1.1. Care shall be taken that the attachment of the test equipment maintains the polarity indicated in the electrical interface diagram [Fig 2, Drawing _____].

4.7.2.11.3 Test Method

1) Rotate the rate table counterclockwise (as viewed from above) at _____ ± _____ rad/s. Record the sensor output voltage as E_1.
2) Rotate the rate table clockwise (as viewed from above) at _____ ± _____ rad/s. Record the sensor output voltage as E_2.

4.7.2.11.4 Test Results

The polarity and input range shall conform to the requirements of 3.3.2.

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1) The polarity of E_1 shall be positive and its magnitude shall satisfy Eq 12.

$$|E_1| \geq \text{———OU} \tag{12}$$

2) The polarity of E_2 shall be negative and its magnitude shall satisfy Eq 13.

$$|E_2| \geq \text{———OU} \tag{13}$$

This example assumes a sensor with a positive scale factor, both plus and minus outputs, and input axis sense assigned according to the right-hand rule. The limits on $|E_1|$ and $|E_2|$ shall take into account 3.3.3, 3.3.5, and 3.3.6, and 3.3.2. In special cases more elaborate tests may be devised, or this test may be made part of the composite error test (see 4.7.2.4).

4.7.2.12 Linear Acceleration Sensitivity

The purpose of this test is to determine if changes in the sensor output due to changes in applied linear acceleration are within specified limits.

4.7.2.12.1 Test Equipment

The following equipment, specified in 4.6 is required for this test:

1) Dividing head and mounting fixture
2) Electronic equipment required to operate the sensor and measure its output

4.7.2.12.2 Test Setup

The test setup shall be in accordance with 4.7.2.1.4 and 4.7.2.1.5.

4.7.2.12.3 Test Method

1) With the sensor mounted in position 4 (input reference axis horizontal, see 4.7.2.1.4) read the output at 0°, 90°, 180°, and 270°. Record these outputs as E_1, E_2, E_3, and E_4 respectively.
2) Remount the sensor in position 5 (*x*-axis horizontal, 4.7.2.1.5). Read the outputs at 0° and 180°. Record these outputs as E_5 and E_6 respectively.

4.7.2.12.4 Test Results

1) Compute the linear acceleration sensitivities along the three axes from Eqs 14, 15, and 16.

$$K_z = \frac{E_5 - E_6}{2K_1} \tag{14}$$

$$K_x = \frac{E_1 - E_3}{2K_1} \tag{15}$$

$$K_y = \frac{E_2 - E_4}{2K_1} \tag{16}$$

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2) The quantity $\sqrt{K_z^2 + K_x^2 + K_y^2}$ shall conform to the requirements of 3.3.10.

> In some cases, linear acceleration sensitivity may be confined by construction to a particular axis or a particular plane. The scope of this test may then be appropriately reduced. In other cases, reading uncertainties may be significant compared to the effects of 1 g on the sensor. It may be desirable to use multipoint tumbles and leastsquare fits to define the coefficients. This method may also yield higher order coefficients, for example, g^2 terms.
>
> In some sensors, especially fluid-filled devices, linear acceleration sensitivity is strongly affected by the presence of thermal gradients. This should be a consideration in the test set-up design.
>
> In the case of multiple-axis devices, this test will be applied to one axis at a time.
>
> Sensors which lack direct-current response pose a special problem for this test. This problem is discussed in Appendix B.

4.7.2.13 Threshold and Resolution

The purpose of this test is to determine if the changes in sensor output are greater than the specified values for given changes in input level.

4.7.2.13.1 Test Equipment

The following equipment, specified in 4.6, is required for this test:

1) Rate table and mounting fixture
2) Electronic equipment required to operate the sensor and to measure its output

4.7.2.13.2 Test Setup

The test setup shall conform to 4.7.2.1.1.

4.7.2.13.3 Test Method (Threshold)

1) With the rate table stationary record the sensor output as E_0.
2) Rotate the rate table counterclockwise (as viewed from above) at rates ω_i in increments of_____rad/s. At each rate, record the sensor output as E_i.
3) Rotate the rate table clockwise (as viewed from above) at rates ωj in increments of _____rad/s. At each rate record the sensor output as E_j.

> The rate ω_i, ω_j should be corrected for the vertical component of the earth's rate when it is significant compared to the threshold specification.

4.7.2.13.4 Test Method (Resolution)

1) Rotate the rate table counterclockwise (as viewed from above) at _____ ± _____ rad/s (ω_1) and record the sensor output as E_1.
2) Increase the table angular rate in steps of _____ rad/s and at each rate ω_j record the sensor output as E_j.

> Ordinarily, a single step equal to the specification limit is sufficient for acceptance testing.

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4.7.2.13.5 Test Results

1) Calculate the indicated changes in sensor output (ΔO) at each input.

$$\Delta O_{+\,\mathrm{ind}} = \frac{E_i - E_0}{K_1} \tag{17}$$

$$\Delta O_{-\,\mathrm{ind}} = \frac{E_j - E_0}{K_1} \tag{18}$$

where

K_1 = scale factor obtained from 4.7.2.4
E_0 = sensor output at zero rate in output units
E_i = sensor output at *i*th positive rate in output units
E_j = sensor output at *j*th negative rate in output units

2) Tabulate the output units and ΔO_{+ind} and ΔO_{-ind}.
Threshold is the smallest input at which ΔO_{+ind} and ΔO_{-ind} are at least 50% of the input. Record the threshold for both positive and negative inputs.
3) Calculate the indicated changes at each input rate.

$$\Delta O_{\mathrm{ind}} = \frac{E_1 - E_j}{K_1} \tag{19}$$

where

K_1 = scale factor obtained from 4.7.2.4,
E_1 = sensor output at reference rate
E_j = sensor output at the *j*th rate in output units

4) Tabulate the change in input units and ΔO_{ind}.
Resolution is the smallest change in input at which ΔO_{ind} is at least 50% of the input change.
5) Threshold and resolution shall conform to the requirements of 3.3.13 and 3.3.14.

4.7.2.14 Frequency Response

The purpose of this test is to establish that the phase and amplitude responses of the sensor as a function of frequency are contained within specified limits.

4.7.2.14.1 Test Equipment

The following test equipment, specified in 4.6, is required for this test:

1) Rate table configured for oscillatory inputs and mounting fixture
2) Electronic equipment required to operate the sensor and to measure its output

4.7.2.14.2 Test Setup

The test setup shall be in accordance with 4.7.2.1.1.

4.7.2.14.3 Test Method

1) Apply a sinusoidal rate of _____ ± _____ rad/s [measured peak-to-peak] at_____± _____Hz
2) Measure and record the output amplitude and phase with respect to the input motion
3) Repeat at_____, _____, _____, and _____Hz

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4.7.2.14.4 Test Results

1) Compute the amplitude response in decibels for the above frequencies. The lowest test frequency will be used as the amplitude reference. Determine the phase lag for the above frequencies.
2) The sensor frequency response shall conform to the requirements of 3.3.16.

Electrical stimulation in place of seismic inputs may be used for some forms of frequency response testing, particularly for very-low frequencies, for example, below 1 Hz. It should be noted however that this method of testing is valid only in very restricted ranges for many sensors. The special problems of applying and measuring dynamic angular motions are discussed in more detail in Appendix B.

For some kinds of testing, on some sensors, the best reference frequency may be other than the lowest test frequency.

4.7.2.15 Rate-Squared Sensitivity

Rate-squared sensitivity, as distinguished from square-law nonlinearity, is a characteristic of angular accelerometers and angular accelerometer based (nondirect-current response) rate sensors. The test is accordingly described in Appendix B.

4.7.2.16 Vibration Rectification

The purpose of this test is to determine that the operational performance characteristics of the sensor are within their allowable tolerances for vibration.

4.7.2.16.1 Test Equipment (Sinusoidal Vibration)

The following equipment, specified in 4.6, is required for this test:

1) Sinusoidal vibration table and mounting fixture
2) Electronic equipment required to operate the sensor and to measure its output

Specify additional test equipment required to make measurements at the electronic interface.

4.7.2.16.2 Test Setup (Sinusoidal Vibration, Mounting Position No 7)

The sensor test setup shall be in accordance with 4.7.2.1.7.

Other positions may be specified during the tests to evaluate interface functions with various values of vibration frequencies, *g* as inputs, and time of sweep.

4.7.2.16.3 Test Method (Sinusoidal Vibration, Mounting Position No 7)

Specify the test methods which will be required to determine the *g* levels and sweep times of the sinusoidal inputs. Associated output signals will be monitored.

4.7.2.16.4 Test Setup (Sinusoidal Vibration, Mounting Position No 8)

The sensor test setup shall be in accordance with 4.7.2.1.8.

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4.7.2.16.5 Test Method (Sinusoidal Vibration, Mounting Position No 8)

Specify the test methods which will be required to determine the *g* levels and sweep times of the sinusoidal inputs. Associated output signals will be monitored.

4.7.2.16.6 Test Setup (Sinusoidal Vibration, Mounting Position No 9)

The sensor test setup shall be in accordance with 4.7.2.1.9.

4.7.2.16.7 Test Method (Sinusoidal Vibration, Mounting Position No 9)

Specify the test methods which will be required to determine the *g* levels and sweep times of the sinusoidal inputs. Associated output signals will be monitored.

4.7.2.16.8 Test Equipment (Random Vibration)

The same equipment is required in 4.7.2.16.1, with additional equipment necessary to generate and monitor the required random vibration input.

4.7.2.16.9 Test Setup (Random Vibration, Mounting Position No 7)

The sensor test setup shall be in accordance with 4.7.2.1.7.

Other positions may be specified during the tests to evaluate interface functions with various values of vibration frequencies, *g* as inputs, and time of sweep.

4.7.2.16.10 Test Method (Random Vibration, Mounting Position No 7)

Specify the test methods which will be required to determine spectrum levels and application times of the random vibration. Associated output signals will be monitored.

4.7.2.16.11 Test Setup (Random Vibration, Mounting Position No 8)

The sensor test setup shall be in accordance with 4.7.2.1.8.

4.7.2.16.12 Test Method (Random Vibration, Mounting Position No 8)

Specify the test methods which will be required to determine spectrum levels and application times of the random vibration. Associated output signals will be monitored.

4.7.2.16.13 Test Setup (Random Vibration, Mounting Position No 9)

The sensor test setup shall be in accordance with 4.7.2.1.9.

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4.7.2.16.14 Test Method (Random Vibration, Mounting Position No 9)

Specify the test methods which will be required to determine spectrum levels and application times of the random vibration. Associated output signals will be monitored.

4.7.2.16.15 Test Results

The test results shall conform to the requirements of 3.3.11.

4.7.2.17 Self-Test Scale Factor

The purpose of this test is to determine the scale factor of the self-test circuit.

4.7.2.17.1 Test Equipment

The following test equipment, specified in 4.6, is required for this test:

1) Stable surface and mounting fixture, if required
2) Electronic equipment required to operate the sensor and to measure its output
3) Direct current or voltage supply

4.7.2.17.2 Test Setup

The sensor shall be oriented (specify the desired orientation).

4.7.2.17.3 Test Method

1) Apply_____±_____[mA dc, V dc] to the self-test circuit. Record the sensor output as E_1.

Specify a current or voltage that will not damage the sensor.

2) Reverse the polarity of the applied self-test excitation. Record the sensor output as E_2.

4.7.2.17.4 Test Results

1) Calculate the self-test scale factor K_s by Eq 20.

$$K_s = \frac{E_1 - E_2}{2I_s} \text{ OU per excitation unit} \quad (20)$$

where
I_s = self-test input in [mA, V]

2) The self-test scale factor shall conform to the requirements of 3.3.17.

4.7.2.18 Magnetic Leakage

The purpose of this test is to determine the magnitude and location of the maximum magnetic field(s) emanating from the sensor.

4.7.2.18.1 Test Equipment

The following test equipment, specified in 4.6, is required for this test:

1) Electronic equipment required to operate the sensor

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2) Magnetic field measuring equipment
3) Nonmagnetic mounting fixture

The earth's magnetic field will influence the measurements. If this effect is significant, shielding or compensation should be specified.

4.7.2.18.2 Test Setup

Secure the non-magnetic fixture to a suitable base. Install the sensor.

4.7.2.18.3 Test Method

1) Stabilize the sensor at the standard test conditions of 4.5.1
2) Search for the maximum magnetic leakage at a distance of _____ cm from the surface of the sensor package(s)
3) Record the maximum leakage and location

4.7.2.18.4 Test Results

The leakage shall conform to the requirements of 3.2.2.6.

4.7.2.19 Electrical Noise

The purpose of this test is to determine the electrical noise output of the sensor.

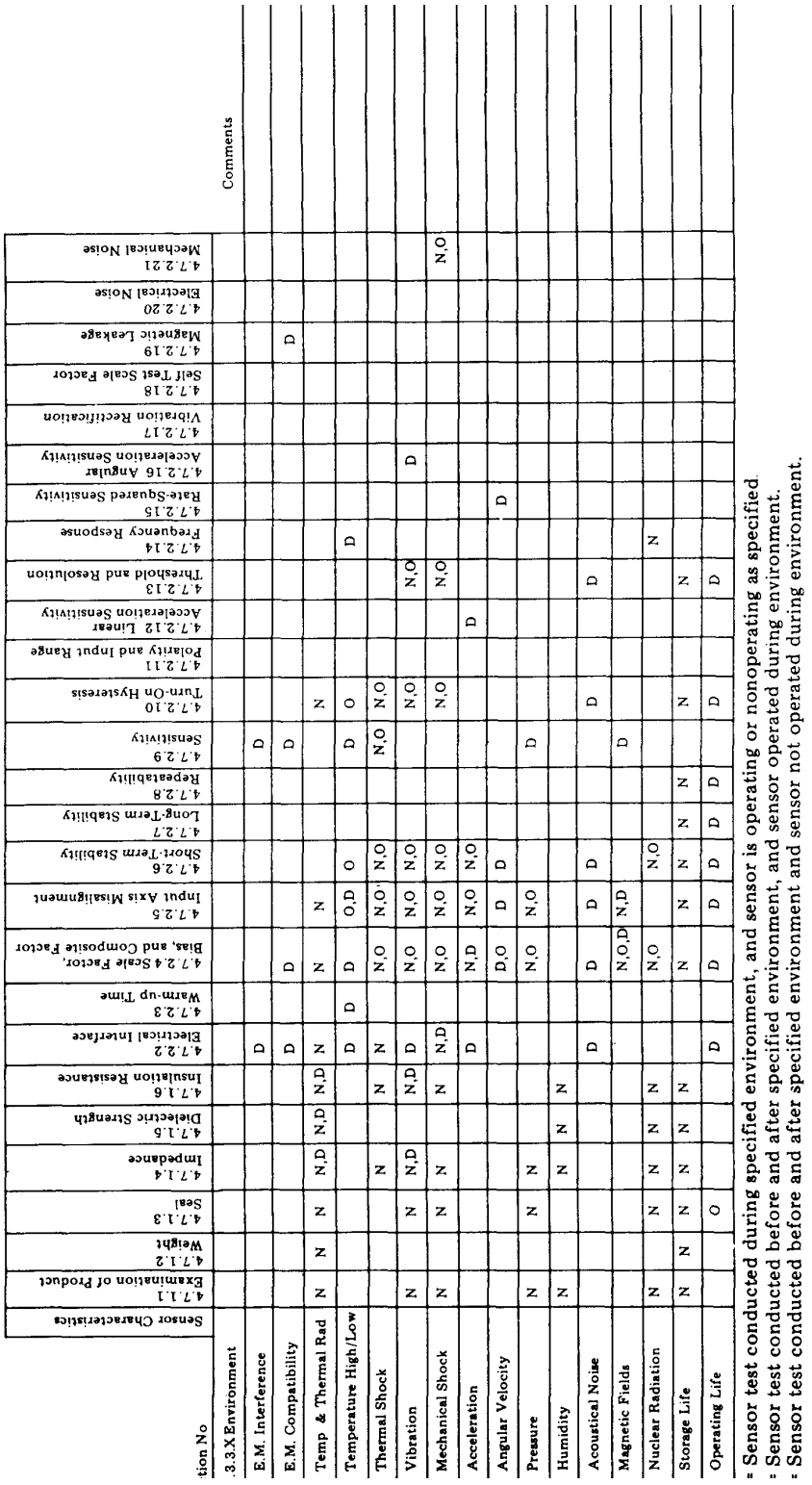
4.7.2.19.1 Test Equipment

The following test equipment, specified in 4.6, is required for this test:

1) RMS voltmeter
2) Selectable bandpass filter
3) Sensor-mounting fixture
4) Electronic equipment required to operate the sensor

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= Sensor test conducted during specified environment, and sensor is operating or nonoperating as specified.
= Sensor test conducted before and after specified environment, and sensor operated during environment.
= Sensor test conducted before and after specified environment and sensor not operated during environment.

Figure 5—Suggested Sensor Environmental and Test Combinations

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4.7.2.19.2 Test Setup

1) Place the sensor in its mounting fixture on a mechanically quiet surface oriented _____. (Specify the desired orientation.)
2) Energize the sensor and allow _____ min for the sensor and its environment to reach thermal equilibrium.

4.7.2.19.3 Test Method

1) Connect the sensor output to the filter and rms voltmeter and record the noise voltage, E_0.

> In critical cases, it may be necessary to measure the background noise power of the test equipment with the input shorted and subtract the reading in an rss sense from the measured noise.

4.7.2.19.4 Test Results

1) Compute the equivalent input noise from Eq 21.

$$N = \frac{E_0}{K_1} \tag{21}$$

where
K_1 = sensor scale factor determined from 4.7.2.4
2) The electrical noise shall conform to the requirements of 3.3.15.1.

4.7.2.20 Mechanical Noise

> Testing for mechanical noise requires careful simulation of the mechanical interface to be utilized in the intended application. Test setups will vary with the nature of the anticipated interaction and may require testing at the systems level, for example, axis-to-axis interactions. The mechanical noise shall conform to the requirements of 3.3.15.2.

4.7.3 Environmental Tests

4.7.3.1 Purpose

The purpose of these tests is to verify that the sensor performs as specified during or before and after, or both, exposure to environments in excess of the standard operating condition, but within the specified environmental limits.

4.7.3.2 Test Equipment

The following test equipment shall be included for each environmental test:

1) Equipment for providing the specified environment
2) Means of measuring environment and time
3) Means of adapting the sensor to environmental equipment, such as special holding fixtures, cables, etc
4) Equipment for each sensor test, chosen from 4.7.1 and 4.7.2

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4.7.3.3 Test Procedure and Results

Detail the procedure for the control of the environment, including tolerances and rates of change, integrated with the procedure for the sensor test. Caution notes on overload limits on the environmental intensity applied to the sensor can be specified if required. Compliance with the specification performance requirements should be demonstrated prior to, during if appropriate, and upon completion of the environmental test sequence.

Procedures for most environmental tests are well covered by existing industry, government, and military documents such as MIL-E-5272 Environmental Testing, Aeronautical and Associated Equipment. Rather than duplicate samples of existing procedures, the present standard provides (in Fig 5) assistance in selecting the sensor parameters which will be most important to measure in each environment. This selection is made on the expected environmental sensitivities of the sensor and the cost effectiveness of the testing.

The application of the sensor will determine which tests or combination of tests are to be performed and their sequence. Figure 5 is intended as a guide for the selection of the sensor test which should be conducted in association with the environmental tests which are chosen dependent on the application of the sensor. In some cases it may be desirable to combine environments to simulate the expected operating conditions.

4.8 Data Submittal

The format for all data organization and the method of submittal shall be specified.

5. Preparation for Delivery

Give detailed procedures for:

1) Preservation and packaging
2) Packing
3) Marking of shipping containers

A common US specification covering preservation and packaging is MIL-P-116. Other organizations use different supporting documents.

6. Notes

6.1 Intended Use

Describe the application if it is considered necessary or helpful.

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6.2 Ordering Data

Procuring documents should specify the title, number, and date of this specification. In addition, the following, or other, items should be specified as applicable:

1) Level of packaging and packing desired
2) Mode of shipment required
3) Whether sampling plan tests are to be conducted
4) Number of preproduction samples to be submitted for qualification testing
5) Data pacakge

6.3 Model Equation

A model equation of a sensor is defined as an equation which mathematically relates the output of the sensor to the environmental inputs (both vector and scalar) applied to the sensor. The model equation is given in Eq 22.

$$\begin{aligned}\omega_{ind} &= \frac{E}{K_1} \\ &= K_0 + \omega_z + \delta_y\omega_x - \delta_x\omega_y + K_z a_z \\ &\quad + K_x a_x + K_y a_y\end{aligned} \tag{22}$$

where

ω_{ind} = angular rate indicated by the sensor
E = electrical output of the sensor
K_1, = sensor scale factor (electrical output/input rate)
K_o = sensor bias (rate)
ω_z = input rate about the sensor *z*-axis (input axis)
ω_x = input rate about the sensor *x*-axis,
ω_y = input rate about the sensor *y*-axis
δ_y = sensor input axis misalignment about the sensor case *y*-axis
δ_x = sensor input axis misalignment about the sensor case *x*-axis
a_x = acceleration input to the sensor case *x*-axis
a_y = acceleration input to the sensor case *y*-axis
a_z = acceleration input to the sensor case *z*-axis
K_x, K_y, K_z = acceleration sensitive coefficients (output rate/input acceleration)

In general, only one model equation representative of the design is specified. The coefficients of the model equation may be functions of other variables such as voltage, temperature, time, and linear acceleration. Some of the terms may be deleted or others added as appropriate, for the type of sensor and its application. In some cases it may be desirable to model some coefficients with .sufficient accuracy that they may be used to compensate the sensor output. In these cases, modeling uncertainties such as test repeatability and coefficient standard error should be considered. Only a sufficient number of terms to adequately describe the response should be used. Equation 22 describes the example sensor used in 4.7.

7. Definitions

The following definitions are provided for convenience in using this standard. Additional definitions are found in ANSI/IEEE Std 100-1984 and in IEEE Std 528-1984. [3]

[3]See 2.2.2.1.

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cross-axis sensitivity (dynamic): That component of the output of an angular sensor which remains when it is vibrated along, or oscillated about, an axis which is precisely orthogonal to its true input axis. Precise orthogonality is defined by disappearance of the in-phase, or out-of-phase components of output. Therefore, the cross-axis output is quadrature phase.

cross coupling: That component of the output of an angular sensor which arises from changes in the input-axis alignment due to specified inputs on some axis. For example, one type of test consists of monitoring sensor output while applying input rates up to full scale on an orthogonal axis. Output is plotted as a function of input and a least squares straight-line through zero fitted to the data. The slope of this line is defined as misalignment and the largest residual is defined as cross-coupling, usually expressed as a percentage of full scale.

IU Input units: The initials are used where a finished specification would use a defined symbol with defined units.

OU Output units: The initials are used where a finished specification would use a defined symbol with defined units.

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Annex A Sensor Dynamic Block Diagrams

(Informative)

This Appendix presents typical block diagrams for the dynamic response of several representative sensors as normally operated. Some of the sensors are inherently open-loop devices, while others are normally operated in a closed-loop mode.

The sensor shown in Fig A.1 is a closed-loop device, an angular analog of a pendulous linear servo accelerometer.

S = laplace operator
ϕ = laplace transform of input rotation angle, rad
J_1 = effective input moment of inertia, [N·m/(rad/s^2), g·cm^2]
J_D = dynamic moment of inerita about the output axis, [g·cm^2, N·m^2]
C = damping torque coefficient, [N·m/(rad/s)]
K_e = moving system elastic restraint, [N·m/rad]
$K_{po}(S)$ = transfer function of pickoff, V/rad
$K_a(S)$ = transfer function of servo or output buffer amplifier, V/V
K_T = torquer scale factor, [N·m/A]
R = torquer resistance, Ω
L = torquer inductance, H
$V_o(S)$ = laplace transfer of sensor output, V

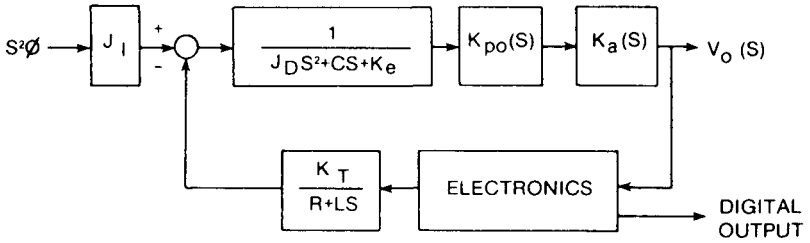


Figure A.1—Angular Accelerometer or Closed-Loop Dynamic Angular Displacement Sensor

The symbols for the angular accelerometer portion of the block diagram are as defined in Fig 1. The remaining symbols are defined as follows:

K_1 = integrator high-frequency gain constant, V/(V·s)
τ_1 = integrator first-order roll-off time constant, s
τ_2 = "washout" integrator time constant, s

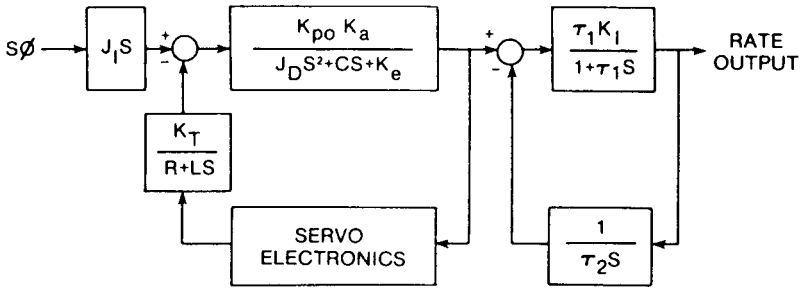
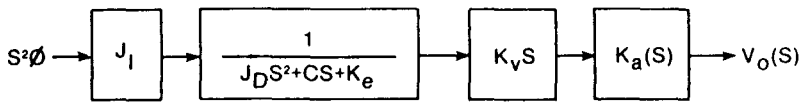


Figure A.2—Integrated Angular Accelerometer Rate Sensor

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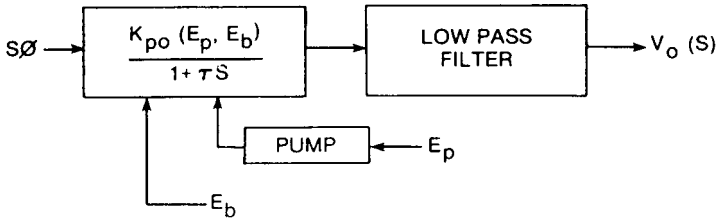
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All symbols are as defined in Fig A1 except as follows:

K_V = velocity pickoff scale factor, V/(rad/s)

Figure A.3—Angular Accelerometer or Displacement Sensor with Velocity Pickoff



Definitions in Fig A1 apply where appropriate. The remaining symbols are defined as follows:

E_p = pump supply, V
E_b = bridge supply, V
= fluid jet transit time, s
K_{po} = transfer function of bridge pickoff, V/(rad/s), a function of E_p and E_B. With K_{po} assumed to have no frequency dependence, the form shown in the block is an adequate low-frequency approximation, assuming that the cut-off frequency of the filter indicated is less than, or equal to, 1 rad/s.

Figure A.4—Fluid Jet Rate Sensor

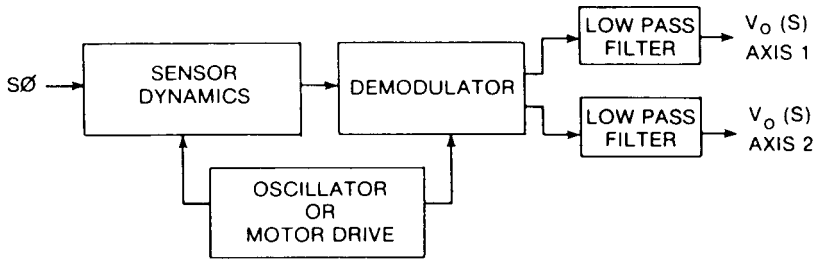


Figure A.5—Vibrational or Rotational (Coriolis) Rate Sensor (Two-Axis Version Illustrated)

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Annex B Notes on Dynamic Testing of Inertial Angular Sensors

(Informative)

B1. Introduction

The operative test section of this standard (see 4.7.2) describes in detail the testing of an example sensor which measures angular rate down to zero frequency, has an analog output, and has a single sensing axis. Many of the tests described are directly applicable to much wider classes of inertial angular sensors, but some tests shall be modified significantly to suit other sensor classes and some sensors have special error sources which require the addition of specialized tests. In addition, even the example sensor can be fully characterized only with the aid of several dynamic angular tests, that is, tests in which the input angular rate is changing fairly rapidly with time.

One purpose of this Appendix is to present a discussion of the special concepts, problems, and techniques associated with dynamic angular testing. Another purpose is to describe those modifications which are most likely to be needed in 4.7.2 to accommodate inertial angular sensors from classes other than the chosen example. This Appendix is concerned with the dynamics of the test environment, while Appendix C provides a similar treatment of the accommodations which shall be made when the specified sensor has a digital rather than analog output.

Sensors which may require reference to this Appendix include, but are not limited to

1) Angular accelerometers
2) Dynamic angular displacement sensors
3) Multi-axis sensors
4) Sensors which lack zero-frequency response or respond at zero frequency to some quantity, for example, angular acceleration, which is impractical to use as a test input

B2. Dynamic Testing Problems and Techniques

B2.1 The Nature of the Dynamic Angular Test Problem

Dynamic sensor testing can be loosely defined as testing in which the quantity to be measured is changing fairly rapidly with time. Thus calibration of an accelerometer by sinusoidal or random inputs would be a dynamic test, but calibration of a rate sensor by means of a fixed angular rate would not, even though both tests involve sensor motion. To tighten the definition somewhat, the National Bureau of Standards places the dividing line between static and dynamic measurements at 0.001 Hz.

Dynamic testing introduces a whole class of problems which are not seen in static tests, and dynamic angular testing adds several special problems to the list. This situation is due to the strong past industry emphasis on gyroscopic sensors, in which static accuracy is stressed almost to the exclusion of dynamic measurements. Commercially available angular test equipment usually has some dynamic capability built-in, but accuracies have rarely been quoted except for static operation, and this situation has tended to be perpetuated by a marked lack of recognized standards for dynamic angular motion.

Static measurements of any given accuracy are comparatively simple to make. For rate sensors, for example, a table capable of turning at a reasonably constant speed and a stopwatch can provide a primary standard for input, and output measurements can be made with any of a number of direct-current volt-meters.

Noise filtering is readily accomplished by arbitrarily long-period low-pass filters or equivalent long-time averaging digital sampling systems.

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For dynamic angular motions, standards are more difficult. Many of the frequencies of greatest interest, corresponding, for example, to the rigid body and first few structural modes of aircraft and spacecrafts, are in the range from 0.001 Hz to 50 Hz, where the National Bureau of Standards for many years was unable to provide acceptable standards even for voltage measurements. For inputs, the selection has been limited primarily to a variety of rate tables with tachometer references. These are generally served tables with bandwidths up to approximately 50 Hz and are frequently of great sophistication, but designed primarily with fixed rates in mind. In addition to the scarcity of dynamic calibration data already mentioned, all but the most expensive suffer from varying degrees of waveform distortion which result from stick-slip phenomena when the angular rate passes through zero.

These equipment limitations interact in numerous subtle ways with the basic problem of making accurate electrical measurements of two or more time-varying voltages and then interpreting the results. Rapid advances in digital technology are eliminating many of the problems in this area, but since much of this equipment is highly specialized and correspondingly expensive, it is realistic to assume that measurements with less sophisticated general purpose test gear will continue to be made for a long time.

B2.2 Electrical Measurements — Low Frequency Alternating Current and Transient

This subsection will consider the strengths and potential pitfalls of a representative, though obviously not exhaustive, list of measurement techniques.

For measurement of signals which are at least stationary processes and most commonly periodic the following are used:

Averaging meters
True rms meters
Zero-to-peak or peak-to-peak
Signal nulling, or alternating-current bridge
Frequency-selective or frequency-tracking volt-meters, and phase-sensitive voltmeters
Spectrum analyzers

For measurement of both stationary processes and transients the following are used:

Digital oscilloscope
Digital data logger with processing capability for digital filtering, FFT, and transfer function computation

The first five measurement techniques are most commonly used for sinusoidal or nearly sinusoidal signals. All are subject to some degree to errors due to the harmonic content of the signals, that is, waveform distortion. The detailed nature of these errors is well documented already and need not be belabored here, except to note that the magnitude of the errors can range from root-sum-square, independent of phasing (for example, true rms voltmeter) to |error||distortion|, depending on phasing (for example, peak-to-peak measurement). It is worthwhile however to list the more important error sources and techniques for minimizing them within the context of dynamic angular testing. An important feature of this context is the frequent need to compare two signals. The remarks which follow relate to amplitude errors, but most have obvious corollaries for phase measurement.

1) When comparing a reference and a test output, the effect of harmonic distortion disappears if it is the same on both signals. When the harmonics arise from distorted table motion, this requirement can be met to a good approximation by using a reference standard which has approximately the same frequency response over the range of interest as the test sensor, for example, a tachometer and a rate sensor will show similar harmonic distortion in the presence of distorted table motion, but a tachometer and an angular accelerometer will not. The accelerometer will have twice as much second harmonic content, three times as much third, and so on. One useful way to satisfy this criterion is to use an integrator of known characteristics to convert an accelerometer to a rate sensor or a tachometer to a displacement sensor.
2) Special attention shall be paid to incompatible combinations of test signals and measurement techniques. For example, peak-to-peak measurements using an oscilloscope and a direct-current offset voltage are capable of

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great precision with relatively inexpensive equipment over a much greater bandwidth than most alternating-current meters, but the results are very sensitive to local distortions at the peak. One place where these can arise is in signal generators which synthesize a sine wave from small straight line segments. Another is the case of an angular accelerometer on a ball bearing rate table. Bearing friction related anomalies which occur when the velocity reverses show rather innocuously at the zero crossings of a rate signal, but are precisely at the peaks, and much amplified, on an acceleration signal.

3) Conversely, certain kinds of equipment are especially suited to certain measurement techniques. An example of this is given in B2.2(4).

4) Alternating-current bridge techniques (Fig B.1) are a convenient way to compare the amplitude of two signals in the presence of irregular motions, even at very-low frequencies, for example, 0.1 Hz, since all in-phase common mode signals vanish at the null. Small residual differences from noise or mismatch of the references and test transfer functions can be averaged out as quadrature signals at the null, if they are not too large, or else removed by filtering, as shown in Fig B.1, to improve the resolution of the null. There is a not altogether obvious error associated with this technique, however, given by Eq B-1.

$$\text{error } (\%) = \left[-\frac{1}{2}\theta_1^2 + \theta_1\,\theta_2\right] \cdot 100 \qquad \text{(B-1)}$$

where

θ_1 = phase lag from reference output to test sensor output, in radians
θ_2 = phase lag in the summing junction filter, in radians

This technique is therefore restricted to frequencies where the phase difference θ_1 is quite small unless additional circuitry is provided to permit nulling of both the phase and amplitude of the test sensor signal, that is, a true alternating-current bridge.

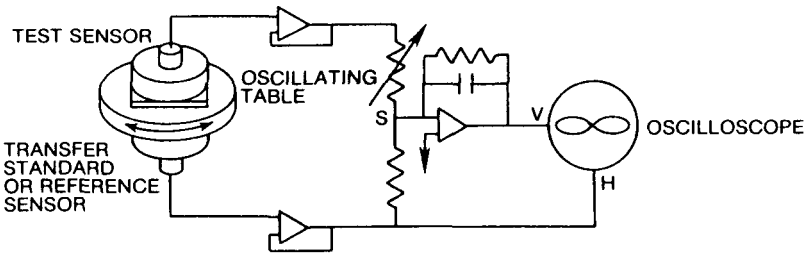


Figure B.1—Simple Bridge Nulling Circuit

5) A spectrum analyzer can be used in a manner similar to a frequency selective voltmeter, and may be used to analyze multiple frequencies simultaneously by using broad-band signals. Limitations of this class of equipment, at least in the simpler forms, are relatively low accuracy and lack of phase information.

6) Digital oscilloscopes can be used in essentially a peak-to-peak mode for steady-state measurements and for transient analysis. Short of point-to-point digitizing and offline data processing, which is generally impractical, error sources and capabilities are similar to those already discussed for peak-to-peak measurements.

7) Digital systems capable of taking extended samples of two waveforms simultaneously and then digitally processing them to obtain phase and amplitude ratios as a function of frequency obviously dispose of all the problems noted above, and their increasing availability will eventually cause the measurement problem to essentially disappear. A word of caution remains to be mentioned, though, since such systems frequently use fairly exotic analog filters to avoid aliasing errors, and filter matching may be a significant accuracy limitation.

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B2.3 Operation and Calibration of Dynamic Angular Test Equipment

A dynamic angular calibration system typically consists of an oscillating table to apply motion, one or more reference sensors to quantify the motion, and electronics to compare the reference output(s) to the test sensor output. In some cases, the motion in itself is considered an absolute, and the need for a dynamic reference is avoided, but these are comparatively rare. Error can arise from inaccuracies in the applied motion and limitations of the reference sensors, and in the electrical measuring process.

Motion inaccuracies can appear as waveform distortion, uncertainties in the center of rotation, and direct amplitude errors (where the motion is intended to be absolute). Waveform distortion can arise from either mechanical or electronic sources. Some examples of the former are bearing friction in ball bearing rotary tables or suspension hysteresis (especially at low frequencies) in oscillating tables driven by linear shakers. Electronics can contribute by having a dead band in the power amplifier, which may appear only when the system is operated dynamically, as a result of decreasing excess gain with increasing frequency. The effects of friction can be eliminated by using gas or magnetic bearings, but usually at high cost. Good metal flexures are also helpful but rarely available commercially. Flexures also limit angular motion typically to a fraction of a radian, which makes it difficult to determine alignment of the working surface to the axis of rotation, as required for measurement of input axis misalignment.

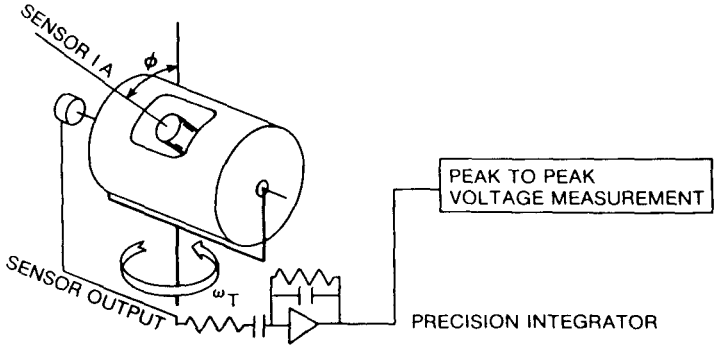


Figure B.2—Conceptual Satellite Table

Uncertainties in the center of rotation, especially as a function of frequency, are of particular concern when linear accelerometers are used to provide an angular acceleration reference.

Absolute systems are comparatively rare because they tend to be cumbersome, but two which may be encountered are torsional pendulums and satellite tables. Torsional pendulums can be considered absolute because of the mathematical relationships between angle, angular rate, angular acceleration, and oscillation frequency for precisely sinusoidal motion.

$$\theta = \theta_o \sin 2\pi ft \quad \text{(for example, radians, or degrees)} \tag{B-2}$$

then

$$\begin{aligned} \theta &= \omega \\ &= 2\pi f \theta_o \cos 2\pi ft \text{ (for example, rad/s, or °/s)} \\ \theta &= \alpha \\ &= -4\pi^2 f^2 \theta_o \sin 2\pi ft \text{ (for example, rad/s}^2\text{, or °/s}^2\text{)} \end{aligned}$$

However, these are useful only if the Q is sufficiently large that the table is able to oscillate through several cycles at substantially constant amplitude. Otherwise, the statically measured, initial offset cannot be used as the value of θ_o and some other reference shall be provided.

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The principle of the satellite table is illustrated in Fig B.2. A rate sensor, or an angular accelerometer which produces a dynamic rate output with the aid of a precisely calibrated auxiliary integrator, is mounted to a small rotating table with a horizontal axis, which is in turn mounted to a larger table which rotates at a constant rate about a vertical axis. The sensor is thus rotated so that it alternately sees plus and minus the main table rate, and its peak-to-peak output is thus proportional to the main table rate even though the satellite table rate may not be quite uniform. In this case, short term variations in main table rate introduce only nonsynchronous measuring noise when the average speed is accurately known. The satellite table is also a prime example of a system attuned to a particular electrical measurement system, that is, peak-to-peak.

All but a few absolute systems require a reference motion sensor which is traceable to some standard. Standards to be used shall be agreed upon in individual cases until such time as one or more of several candidate standards become widely accepted to be formally adopted. Viable candidates at the time of publication include the torsional pendulum, the satellite table, and a number of mirror/light beam schemes usually based on laser sources. Arrays of linear accelerometers may also sometimes be considered as standards, but traceability is rather involved because of the necessity to perform accurate dynamic linear acceleration calibrations, for example, by reciprocity techniques, and the separate measurements to determine the accurate locations of effective centers of mass (ECM) for angular acceleration.

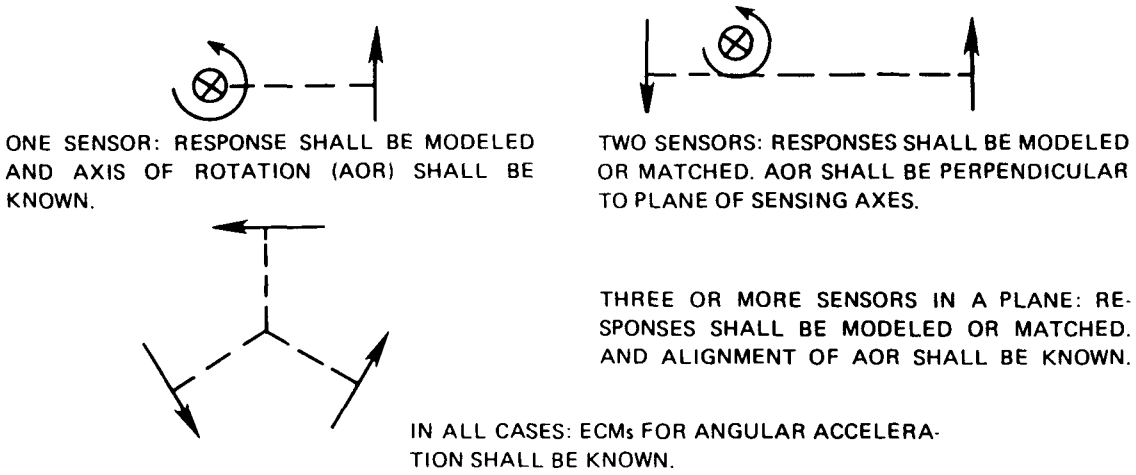


Figure B.3—Measurement of Angular Acceleration by Linear Sensor Arrays

Motion references most commonly are inertial transfer standards, such as dynamic rate sensors or angular accelerometers which have been calibrated by means of an acceptable standard. Since these sensors typically have bandwidths not much greater than the instruments to be calibrated, it is essential that they be calibrated for at least amplitude and preferably both phase and amplitude across the bandwidth of use. Arrays of linear accelerometers can be used, but they introduce a number of unique problems. A single accelerometer can sometimes be used, but only if the location and alignment of the table axis of rotation are accurately known. At high frequencies, where the applied motions are in the milliradian range, it may be difficult to prove those parameters to sufficient accuracy. Two accelerometers require only that the motion axes be accurately perpendicular to the sensing axis/separation axis plane (see Fig B.3), while three or more allow complete freedom. Multiple accelerometers, however, add the problem that phase and amplitude curves shall be not only accurately known but precisely matched. The problem is reduced by using piezoelectric accelerometers, which are nearly flat and almost zero phase at high frequencies, but one shall not forget that these sensors, as typically used, are neither, flat amplitude nor zero phase at low frequencies, being typically 3 dB down and 45° phase lead at from 2 Hz to 5 Hz.

Many references for angular velocity or angular displacement fall into the category of devices which are calibrated statically and whose lowest comer frequencies (poles or zeros) are so far beyond the bandwidth of test frequencies that the static calibration also can be assumed valid dynamically. Capacitive and inductive rotation sensors may be included

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in this class if the mechanical design is carefully done, since they lend themselves to small, extremely rigid, table designs. The ubiquitous tachometer is often assumed to be in this category, but the user is advised to confirm that with the manufacturer. The degree of flatness needed for loop closure is not nearly as demanding as is sensor calibration and most tachometer readout commercial tables are designed primarily with constant rates in mind. Apart from the possibility of significant mechanical compliances in structures more than a few inches in size, there have been instances of tables being provided with low-pass filters as low as 20 Hz to reduce noise at the tachometer monitoring terminals.

B3. Modifications to 4.7.2 for Exceptional Sensors

The subsections listed below require modification as shown. Subsections not mentioned may be used as is.

B3.1 Rate Sensors Without Response at Zero Frequency

4.7.2.2.1, 4.7.2.4.1, 4.7.2.5.1, 4.7.2.6.1, 4.7.2.7.1, 4.7.2.8.1, 4.7.2.9.1, 4.7.2.10.1, 4.7.2.11.1, and 4.7.2.13.1: insert the words *configured for oscillatory inputs* after *rate table.*

4.7.2.4 Scale Factor, Bias, and Composite Error

4.7.2.4.3 Test Method

1) With the input axis inverted and the rate table stationary, record the output as E(dc)-.
2) With the input axis vertical (as in 4.7.2.1.1) and the rate table stationary, record the input as E(dc)+.
3) With the rate table still stationary record the rms output as E_o.
4) Oscillate the table at _____ ± _____Hz at _____ amplitudes in increasing approximately equal increments ending near but not exceeding the full-scale value. Record the rms input rate ω_j and the rms sensor output E_j, at each of the input amplitudes.

4.7.2.2.4 Test Results

1) Compute an adjusted set of voltage readings by subtracting the rms noise

$$E'(j) = E_j^2 - E_o^2 \tag{B-3}$$

2) Calculate the value of scale factor K_1, OU/(rad/s), as the slope of the zero intercept straight line which is least-squares fitted to the adjusted data set ω_j, E'_j
3) Calculate the bias K_0, input units, as

$$K_0 = \frac{[(E(\text{dc}) +) + (E(\text{dc})) -]}{2\ K_1} \tag{B-4}$$

4) Calculate the composite error E_c, as follows:
Determine the deviations of the adjusted data points $E'(j)$ from the straight line as

$$\Delta E'_j = E'_j - K_1\omega_j \tag{B-5}$$

Select the largest absolute valued
$\Delta E'_j$ as ΔE
then

$$E_c = \frac{100\ \Delta E}{\text{full scale rms output}}\ \% \tag{B-6}$$

The remainder of 4.7.2.4 applies as written, except that (4), (5), and (6) become (5), (6), and (7), respectively.

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The test described compromises the usual definition of composite error in the interest of defining a simple and repeatable test. In critical cases it may be desirable to adjust the specification limit or to perform a more comprehensive test using a Fourier analyzer. Hysteresis in a sensor without response at zero frequency shows only as a nonfrequency sensitive component of phase shift. Its effects are absent from this test, but are included in 4.7.2.14.

4.7.2.5 Input Axis Misalignment

4.7.2.5.3 Test Method (Misalignment about *Y*-Axis).

Oscillate the table at_____± _____ rad/s peak-to-peak at _____ ±_____Hz. Record the peak-to-peak table amplitude as ω_1 and the peak-to-peak sensor response as E_1.

4.7.2.5.5 Test Method (Misalignment about the *X*-Axis).

Oscillate the table at _____±_____ rad/s peak-to-peak at_____± _____Hz. Record the peak-to-peak table amplitude as ω_2 and the peak-to-peak sensor response as E_2.

4.7.2.5.6 Test Results

1) Calculate the misalignment about the *y*-axis from Eq B-7.

$$\Delta y = \frac{E_1}{K_1 \omega_1} \text{ rad} \tag{B-7}$$

2) Calculate the misalignment about the *x*-axis from Eq B-8.

$$\Delta_x = \frac{E_2}{K_1\ \omega_2} \text{ rad} \tag{B-8}$$

3) The quantity $\sqrt{(\Delta x)^2 + (\Delta y)^2}$ shall conform to the requirements of 3.3.5.1.

4.7.2.11 Polarity and Input Range

4.7.2.11.3 Test Method

Oscillate the rate table at a peak-to-peak amplitude of _____±_____ rad/s at _____±_____ Hz. Record the peak-to-peak magnitude of the sensor response and its phase with respect to the table rate.

4.7.2.11.4 Test Results

The polarity and input range shall conform to the requirements of 3.3.2.

1) The peak-to-peak magnitude shall be ≥ _____ OU
2) The phase shall be approximately [0°, 180°]

4.7.2.12 Linear Acceleration Sensitivity

Linear acceleration sensitivity is most easily measured in a rate sensor which lacks response at zero frequency by means of access to an auxiliary output which does provide response down to zero frequency (for example, an angular acceleration output). If such an output is available, the test can be run exactly as written, but there shall be an appropriate secondary limit called out in 3.3.10. If there is no such auxiliary output the test can be run only by means of a rectilinear shake test. Such a test would require means to control or compensate the actual rotations of a rectilinear shaker to a suitable accuracy. This is a very difficult test, and is recommended only as a last resort.

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4.7.2.13 Threshold and Resolution

4.7.2.13.3 Test Method (Threshold)

1) With the table stationary, record the rms sensor output as E_o.
2) Oscillate the rate table at rms rates ω_i at a frequency of_____Hz in increments of _____rad/s. At each rate record the rms sensor output E_i.
3) Delete box note.

4.7.2.13.4 Test Method (Resolution)

1) Oscillate the rate table at_____rad/s, rms at a frequency of_____Hz. Record the rms sensor output E_1.
2) Increase the angular rate amplitude in steps of_____rad/s. Record the sensor output E_j, at each input ω_j.

4.7.2.13.5 Test Results

1) Calculate the indicated changes in sensor output at each input.

$$\Delta O_{ind} = \frac{\sqrt{E_i^2 - E_o^2}}{K_1} \quad \text{(B-9)}$$

where

K_1 = scale factor obtained from 4.7.2.4
E_o = sensor output at zero rate
E_i = sensor output at *i*th input rate

2) Tabulate the input units and ΔO_{ind}. Threshold is the smallest input at which ΔO_{ind} is at least 50% of the input.
3) Calculate the indicated changes at each input rate.

$$\Delta O_{ind} = \frac{\sqrt{E_1^2 - E_o^2}}{K_1} \quad \frac{\sqrt{E_j^2 - E_o^2}}{K_1} \quad \text{(B-10)}$$

where

E_1 = sensor output at the reference rate amplitude
E_j = sensor output at the *j*th rate amplitude

4) Tabulate the change in input units and ΔO_{ind}. Resolution is the smallest change in input at which ΔO_{ind} is at least 50% of the input change
5) Threshold and resolution shall conform to the requirements of 3.3.13 and 3.3.14

NOTE — In some cases it may be necessary to use a bandpass filter tuned to the test frequency to remove excess noise. The test frequency should be one which is well within the flat portion of the sensor's frequency response.

B3.2 Angular Accelerometers

A test procedure for an angular accelerometer may be written exactly according to the format of B3.1, with the following modifications or exceptions:

General — Wherever B3.1 uses the term *input rate*, substitute *input acceleration.* Wherever B3.1 uses the symbol ω, substitute the symbol α. Whenever input units are given as rad/s, substitute rad/s^2.

In addition, the following specific changes should be made:

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4.7.2.10 Turn-On Hysteresis

4.7.2.10.3 Test Method

1) Accelerate the rate table counter-clockwise (as viewed from above) at_____rad/s^2 to_____rad/s. [Accelerate, decelerate] the rate table at_____±_____rad/s^2. Remove power from the sensor_____s after the rate table deceleration has begun. Bring the table to a complete stop, without reversing direction.
2) Apply power to the sensor within_____s. Record the sensor output as E_1.
3) Accelerate the rate table clockwise (as viewed from above) at_____rad/s^2 to_____ rad/s. [Accelerate, decelerate] the rate table at_____±_____rad/s^2. Remove power from the sensor_____s after the rate table deceleration has begun. Bring the table to a complete stop, without reversing direction.
4) Apply power to the sensor within_____s. Record the sensor output as E_2.

NOTE — The rate table deceleration should be close to, but should not exceed, the sensor's full-range acceleration. The rate table acceleration rate may be any value that does not exceed the sensor's range.

4.7.2.10.3 Alternative Test Method

NOTE — Turn-on hysteresis is often tested by slowly varying the servo gain. The accelerometer user, however, does not always have access to the gain critical components. Slowly changing the input voltage to the sensor is a useful alternative test.

1) Remove the power to the sensor using the higher voltage input. Slowly increase the input voltage at_____V/s until the nominal input voltage is attained. Record the sensor output as E_1.
2) Remove the power to the sensor using the lower input voltage. Slowly increase the input voltage at_____V/s until the nominal input voltage is attained. Record the sensor output as E_2.

4.7.2.11 Polarity and Input Range

The phase comparison for this test requires that the table output be in terms of either acceleration or displacement, with the observation that these quantities differ in phase by 180°.

4.7.2.14 Frequency Response

Perform this test as written, with the substitutions of *acceleration* for *rate* and rad/s^2 for rad/s, where appropriate.

B3.3 Dynamic Angular Displacement Sensors (ADS)

A test procedure for a dynamic angular displacement sensor may be written exactly according to the format of B3.1 with the following modifications or exceptions:

General — A dynamic ADS can be tested on a rate table configured for oscillatory inputs, but a special table designed for angular displacement testing with wider frequency response and angle, rather than rate, readout is preferable. Therefore, in all equipment paragraphs and wherever else the term appears, substitute *angular displacement table* for *rate table*. Wherever B3.1 uses the term *input rate* substitute *input angle*. wherever B3.1 uses the symbol ω substitute the symbol θ. Whenever input units are given as rad/s, substitute rad.

In addition, the following specific changes should be made:

4.7.2.10 Turn-On Hysteresis

This test is not usually performed on this class of sensors, but when required it may be run by either of the methods described under B3.2. For sensors which have a servo capture loop, the output measurements will be made at an auxiliary output terminal connected within the loop, and the limits on angular acceleration and output voltage will be those appropriate to that output terminal.

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4.7.2.11 Polarity and Input Range

4.7.2.11.3 Test Method

Change *table rate* to *table angular displacement*.

4.7.2.12 Linear Acceleration Sensitivity

The notes under B3.1 typically apply here also. Sensors which have only mechanical capturing and velocity coil readout may experience primarily a modulation of scale factor under linear acceleration. This test, which involves measuring K_1 as a function of orientation in a 1*g* field, is straightforward but lengthy. Since it is uncommon it will not be described in detail here.

4.7.2.14 Frequency Response

Perform this test as written, with the substitutions of *angular displacement amplitude* for *rate*, and rad for rad/s, where appropriate.

B3.4 Angular Jerkmeters

Angular jerkmeters or rate-of-angular-acceleration meters (ROAM) may be tested in accordance with B3.2 with the appropriate substitution of input units, with two exceptions:

1) Linear-acceleration sensitivity will follow the format of B3.1.
2) In some applications, angular acceleration may be the actual quantity of interest, and a suitable integrator may be specified to test as an angular accelerometer. The integrator may be chosen to simulate end-use circuitry or as a special test device with frequency limits and gains chosen to retain required accuracy over the band width and dynamic range specified.

B3.5 Multiaxis Sensors

B3.5.1 Arrays of Single-Axis Sensors

All tests may be conducted on each axis sequentially using the procedures defined for single-axis sensors. There are endless possibilities for special forms of specifications, for example, orthogonality of two or more sensing axes and alignment to a specified reference surface or surfaces, but the extensions from the established tests are usually straightforward and obvious.

B3.5.2 Rotating Rate Sensors with Dual-Axis Discriminators

In most cases these sensors may be treated as a special case of in which the orthogonality of the two axes is established electronically and may therefore be separately specified. In some cases, the common mode alignment of the two axes with respect to a reference surface or mark may be a function of applied rate. This situation requires a special combined test for input axis misalignment and cross coupling, described in B3.6.2.

B3.6 Tests Which are Unusual or Specific to One Sensor Family

Tests described in this subsection are uncommon, because their purpose is to evaluate error sources which are only rarely significant, or because they apply to a small number of sensor types, or both. The descriptions are accordingly in more condensed form than those above.

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B3.6.1 Rate-Squared Sensitivity

This test is specific to angular accelerometers or to angular rate sensors or angular displacement sensors which operate by summing torques on a rigid mass about some hinge or output axis. Such sensors may exhibit a spurious rate effect if the moments of inertia about the two principal axes orthogonal to the hinge axis are unequal. Specifically, if the principal axes are labeled *x*, *y*, and *z*, with *z* being the hinge axis, there will be an offset proportional to $(J_y - J_x)\ \omega_x\ \omega_y$, and therefore proportional to ω^2 for a fixed-rotation axis. For rotation axes in the *xy* plane, $\omega_x\ \omega_y = \omega \sin\theta\ \omega \cos\theta = {}^1/_2\ \omega^2 \sin 2\theta$ so that maximum offset occurs for spin about an axis midway between the *x*- and *y*-axes.

There are three conditions under which this test may be performed.

1) Directions of all three principal axes are known
2) Only the direction of the hinge axis is known
3) Orientation of axes are completely unknown

The first two conditions are likely to be common situations and are fairly simple tests. The last condition should rarely occur, and involves a test sequence which is fairly straightforward but messy and lengthy to describe. If need be it can be worked out from the aforementioned information with the aid of the equations of coordinate transformation.

For (1) the test is particularly simple. Mount the sensor on a rate table in a manner similar to 4.7.2.1 with one of the two axes of maximum sensitivity to the rate squared effect parallel to the rotation axis. Measure the sensor output with the rate table stationary and also at one or more fixed rates, the maximum rate to be determined by the application. By suitable means, for example, least squares fit, determine the coefficient K_{RS} for Eq B-11.

$$\text{offset (output units)} = K_{RS}\ \omega^2 \tag{B-11}$$

K_{RS} shall then conform to the requirements of 3.3.9.

In (2) it will be necessary to repeat the test just described for two or more orientations of the spin axis in the *xy* plane, preferably at intervals of 45°, and then evaluate the maximum response by fitting to the known relationship.

$$\text{offset (output units)} = K_{RS}\ \omega^2 \sin 2\theta \tag{B-12}$$

B3.6.2 Cross Coupling

Cross coupling, as defined in 6.4, is a rotation of input axis due to an angular input. Specifically, for the class of dual-axis sensors designated as *rotating rate sensors with dual-axis discriminators*, it refers to rotation of the alignment of one axis as a result of rate inputs on the opposite (nominally orthogonal) axis. The test may be performed as follows:

1) Mount the sensor on a rate table in a manner similar to 4.7.2.1 with, for example, the input 1 reference axis aligned to the spin axis.
2) Monitor the output of axis 2 while the table is rotated at various speeds between plus and minus full scale and convert these readings to equivalent input units.
3) Fit a straight line in the least squares sense to the plot of output versus input. The slope of this line is the misalignment of axis 2, and the maximum output deviation from this line, expressed as a percentage of full scale, is the cross coupling. The results shall conform to the requirements of 3.3.5 and 3.3.18.

B3.6.3 Angular-Vibration Rectification

This test will be performed in a manner completely analogous to 4.7.2.16, except that the inputs will be angular rather than linear acceleration. Because of equipment limitations, it will usually be necessary to test for sinusoidal effects only. The results shall conform to 3.3.12.1.

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B3.6.4 Angular-Vibration Sensitivity

B3.6.3 evaluates the net effect of even terms in the polynomial expansion of nonlinear response to angular acceleration about the input reference axis. To evaluate the odd terms, when significant, it will be necessary to evaluate nonlinearity as a function of frequency by repeating the frequency response test of 4.7.2.14 at several different amplitude levels. The precise statement of requirements in 3.3.12.2 and the precise interpretation of the results will depend heavily on the intended application.

B3.6.5 Cross-Axis Sensitivity

Cross-axis sensitivity refers to the existence of a nonzero amplitude quadrature-phase output from an angular sensor when subjected to an oscillating input precisely orthogonal to its true sensitive axis. The test is conducted in a manner similar to the input-axis misalignment test described in B3.1, except that alignment will be shimmed or adjusted through some small angle, for example, ±5° above and below the nominal cross-axis condition to determine the point at which the output of the sensor leads or lags its in-axis response to the same stimulus by 90°. The amplitude of the response at this alignment, divided by the amplitude of the input, is the cross-axis sensitivity defined in 3.3.19. The frequency of oscillation should be specified. When not separately specified, this term is included as part of the IAM.

B4. Bibliography

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PETERS, R. B. *A Dynamic Angular-Calibration System for Broadband Microradian Inertial Sensors.* AIAA Guidance and Control Conference, no 78-1253, Aug 1978.

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Annex C Digital Sensors and Some Comments Concerning Their Test Methods (Informative)

C1. Introduction

There is an increasing trend toward interfacing sensors directly with digital computers. Because of this, sensors provided with digital outputs are becoming more and more common. This Appendix presents a brief description of the more commonly used types of digital sensor outputs, followed by a number of comments concerning the testing of instruments which have digital outputs.

C2. Description of Commonly Encountered Digital Output Formats

C2.1 Sample and Hold with an Analog-to-Digital Converter

One of the simplest schemes for digitizing the output of an analog sensor is to utilize a sample-and-hold circuit with its output fed into an analog-to-digital converter (adc). Typically, the sample-and-hold circuit is commanded to sample the analog output signal in synchronism with an external clock signal of the desired sampling frequency. The *hold* portion of the circuit is designed to retain the level of the analog signal as it was at the instant of sampling. The signal serves as the input to an adc which typically generates the closest binary number; the digital representation of the analog input at the time of sampling. A sign bit may or may not be provided, depending on the application, and other digital formats such as binary coded decimal (bcd) are sometimes utilized. Depending on the application, the number generated can be read out in series or in parallel.

C2.2 Digitally Captured Sensors

In these applications the sensor contains an internal sensing element that is rebalanced to null by a control loop generating torque or force. It is usually possible to provide the rebalance by means of a train of fixed area pulses which are selected by logic circuitry so as to return the internal sensing element toward its null position. The type of rebalance loop is generally defined by the pulse sizes and types available to the logic circuit. Those pulses typically consist of a fixed electric current applied for a fixed time interval.

The output is obtained by observing logic signals which indicate the time of pulse application and which of the allowable types of pulses were applied.

These approaches typically use an analog pick-off signal from the sensor to detect deviations from null.

C2.2.1 Binary

A binary pulse capture loop generally implies that the logic selects from either of two kinds of pulses, positive or negative, to rebalance the sensing element. The two kinds of pulses are of fixed and nominally equal area. The pulses are usually applied in synchronism with an external clock. For example, with this type of loop, zero input usually implies that the output will oscillate alternately between single positive and negative pulses at the clock frequency. Sensor saturation in one direction implies that all available pulse slots will be filled with the sign of pulse appropriate to the input direction. Between saturation and zero input, one observes a mix of pulses. The average frequency obtained by counting the number of pulses (positive minus negative) over the output sampling interval is proportional to input and is often taken as the sensor output.

It is frequently appropriate to accumulate the positive and negative pulses in an up/down counter which continuously generates the net count as a function of time. This represents the integral of the average frequency output mentioned in C2.2 and it can be sampled as required by the application.

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A characteristic of this approach is that it results in a constant power pulse train.

C2.2.2 Ternary

A ternary pulse capture loop is similar to a binary loop except that three states are available to the logic:

1) Positive
2) Negative
3) No pulse

This loop is sometimes referred to as *pulse on demand* since positive and negative pulses are applied to the sensing element only when they are needed. Thus, zero input is nominally indicated by no pulse indicators on the output. Positive and negative saturation are indicated by the filling of all available pulse slots with the appropriate pulse signs. The output can be taken as the average net pulse frequency or the accumulation of net pulses as described in C2.2.1.

In some applications additional pulse scalings are utilized. This is typically done in applications where improved resolution is desired when the input is relatively low but where high-level spurts of input are expected.

A characteristic of this approach is that it results in a minimum power pulse train.

C2.2.3 Time Modulated

One form of time modulated capturing utilizes a current waveform consisting of alternating positive and negative portions which are synchronized by one frequency (*forced-limit-cycle*) but time modulated in pulse duration by a closed loop control; the time modulation is synchronized by a higher frequency. This frequency is typically a synchronous multiple of the forced-limit-cycle frequency.

The result is that under steady-state conditions, the sensing element oscillates or limit cycles around its null position as forced by the current pulse. The output is proportional to the net number of minor clock periods (that is, the number of minor clock periods that the limit-cycle pulse was positive minus the number that it was negative). For example, with zero input, the transition from positive to negative would nominally occur at the midpoint. Sensor saturation in one direction implies that the transition point occurs at the beginning or the end of the limit cycle, depending on the sign of the input. The sensor output can be taken as the average frequency of net minor clock periods over a fixed number of limit-cycle periods, or the output can be integrated by accumulating net minor clock periods.

This forced limit cycle approach to time modulated rebalance current results in a constant power waveform as does the binary discrete pulse method. A time modulated ternary system is also possible where pulses of variable width can be quantized on demand by the control loop, while otherwise zero current will result.

C2.3 Analog Sensor with a Voltage-to-Frequency Converter

Another technique for digitizing the output of an analog sensor is to convert the output by means of a voltage-to-frequency (V/F) converter. This unit produces an output pulse frequency which is proportional to the analog output. Most V/F converters consist of an operational amplifier integrator equipped with a ternary pulse capture loop, although it is possible to utilize other pulse rebalance formats. With careful circuit design the conversion can be very accurate. As before, the V/F converter output can be sensed as average frequency or the net counts can be accumulated and read out at the sampling frequency.

C3. Comments Concerning Test Methods Associated with Digital Sensors

C3.1 Aliasing

Reading out a digital sensor inherently involves digital sampling which can lead to a phenomenon known as aliasing or frequency folding. If there are significant signal components at frequencies higher than one half the sampling

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frequency (Nyquist frequency), these components will be indistinguishable from those signal components that are in the frequency range up to the Nyquist frequency and may result in misinterpretation of the output sensor data. Because of this situation, it is necessary to select a sample frequency that is more than twice as high as the highest significant signal component. In some cases, it is possible to insert a low-pass analog filter in the system ahead of the digitizer to attenuate unwanted high frequencies and thus prevent aliasing.

C3.2 One-Count Uncertainty and Moding

In some applications the measurement of digital outputs involves measurement uncertainty associated with counting. For example, the possibility of counting one pulse more or one pulse less than ideal in the test interval can occur because of the location of the beginning and ending of the interval relative to the pulse train being measured. The statistics associated with this granularity shall be taken into consideration when designing tests for digital instruments.

Some digital sensors exhibit moding, that is, the digital output tends to overshoot in a recognizable pattern. An example of 3:3 moding in a sensor with binary output is that it will provide a pattern of three positive pulses followed by three negative pulses when the input is zero. Moding should be checked because it may indicate a system malfunction and will increase granularity and therefore test uncertainty.

C3.3 Period Measurement Versus Measurement of the Number of Pulses Over a Fixed Time Interval

In some cases the resolution associated with the one-count uncertainty can be dramatically reduced by measuring the time period of *n* pulses rather than counting the number of pulses in a fixed time interval (which is assumed roughly equivalent to the period of *n* pulses). This improvement is obtained by using a relatively high frequency clock signal for making the period measurement. The one-count uncertainty is now made on the clock counter and because of its high frequency, can usually be acceptably small relative to the count associated with the total period determination. If the pulse train being measured contains jitter, then the trial-to-trial uncertainty may be greater than that predicted by the one-count-clock uncertainty, and this possibility should be checked.

C3.4 Measurement of Positive and Negative Pulses Provided on Separate Data Lines

In this situation, it is sometimes beneficial to count the output pulses with separate counters and obtain the net output by subsequent subtraction. A more conventional approach might be to use an up/down counter which automatically increments for positive pulses and decrements for negative ones. The advantage of using two counters is that this configuration readily detects the mixing of pulses. Such occurrences, when not expected, may indicate a system malfunction that would go undetected with an up/down counter.

C3.5 Asymmetry

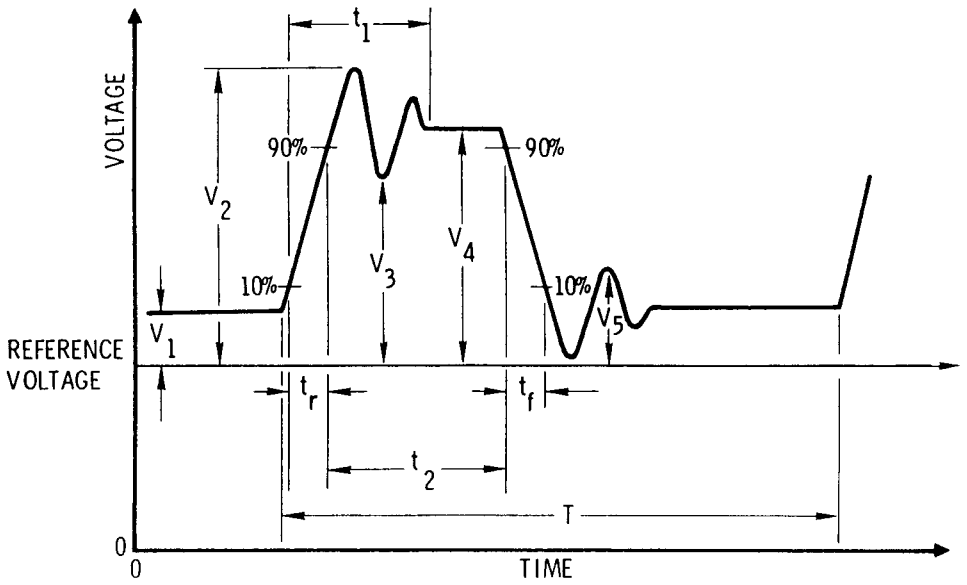
Many digital sensors exhibit scale factor or bias asymmetries, or both. That is, the input/output function is separately linear in the positive and negative regions; however, the two halves are best represented by straight lines having different slopes or intercepts, or both. For example, ternary capture loops often exhibit scale-factor asymmetry. This results because separate circuits are utilized to generate the positive and negative pulses. Because of circuit tolerances or imperfections, or both, the areas of the positive and negative pulses are typically different, a situation which leads directly to scale-factor asymmetry. The sensor testing should consider this possibility, as erroneous results can be obtained if the sensor has one or both of these problems and simple linearity is assumed.

C3.6 Biased Outputs

In some sensors the output frequency is biased so that, for example, zero-frequency output represents negative full-scale input, maximum frequency represents positive full-scale input, and one-half maximum frequency represents zero input. This situation can lead to confusion between bias and scale-factor effects. An example of this is the presence of a scale-factor temperature sensitivity.

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	Units	Maximum	Minimum	Remarks
V_1	volts	_____	_____	steady-state low voltage
V_2	volts	_____	N/A	overshoot voltage
V_3	volts	N/A	_____	undershoot voltage
V_4	volts	_____	_____	steady-state high voltage
V_5	volts	_____	N/A	maximum low voltage transient
t_r	seconds	_____	_____	rise time
t_f	seconds	_____	_____	fall time
t_1/t_2	—	_____	N/A	ratio of the TURN-ON transient time to required ON time
t_2	seconds	_____	_____	duration of high voltage ON time
t_2/T	—	_____	_____	(t_2/T) (100) = % duty cycle
T	seconds			waveform period

N/A — not applicable

Figure C.1—Wave Shape Requirements for Direct Coupled Pulse-Type Signals

If the data is normalized at each test temperature with the apparent scale factor, then an apparent bias temperature sensitivity(and the scale factor temperature sensitivity) will be indicated. This arises because the bias frequency is being normalized by the varying scale factor when in reality the bias frequency may not be sensitive to temperature at all. Care should be taken in processing data in these situations.

C4. Modification to 3.2.2 for Digital Sensors

When the sensor has digital inputs or outputs, the specifications in 3.2.2.1.2 through 3.2.2.1.4 will more adequately be described by the modified paragraphs in the following example:

3.2.2.1.2 Output Signals(s)

Specify the type and characteristics of the output signal(s) required. For example:

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Type: Pulses indicating positive velocity increments on one signal line and pulses indicating negative velocity on a second line.

Characteristics:

1) Source impedance_____±_____[+,–]*j* ____±_____Ω
2) Load impedance_____±_____[+,–]*j* ____±_____Ω
3) Phasing with respect to clock reference [+,–]_____±_____S
4) Polarity of output signal with +l*g* along the input
5) Reference axis
6) Wave shape (see Fig 2)
7) Repetition rate_____p/s

3.2.2.1.3 Command Input(s)

Specify the type and characteristics of the command input(s). For example:

Type:

1) ON/OFF
2) Self test

Characteristics:

1) Source impedance_____±_____[+,–]*j* ____±_____Ω
2) Load impedance_____±_____[+,–]*j* ____±_____Ω
3) Input voltage____ ±_____[V dc, V ac]

3.2.2.1.4 Clock Reference

Specify the characteristics of the clock reference. For example:

1) Source impedance____±_____[+,–]*j* ____±_____Ω
2) Load impedance____±_____[+,–]*j* ____±_____Ω
3) Repetition rate____±____p/s
4) Wave shape (see Fig 2)
5) Stability____% per ____[h,d]

C5. Modification to 4.7.2 for Digital Sensors

C5.1 Threshold and Resolution (See 4.7.2.13)

The existing test paragraphs may be used as written but with two cautionary notes. For threshold, it shall be noted that a digital angular sensor instrumentated with a pulse rate output per unit input can resolve no less than one pulse. For a rate sensor, for example, each output pulse represents an increment of angle. It would theoretically be necessary to wait for an infinite time period to define zero indicated angular rate. For this test, a measurement period corresponding to a detectable rate of 50% of the specified threshold is recommended.

$$\text{Measurement period} = \frac{\text{minimum unit of angular increment (rad)}}{\text{desired angular rate of threshold (rad/s)}} \qquad \text{(C-1)}$$

For resolution, there is no exactly analogous limitations, but the comments on *period measurement versus frequency measurement* should be noted.

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