

IEEE Standard Specification Format Guide and Test Procedure for Linear Single-Axis, Nongyroscopic Accelerometers

IEEE Aerospace and Electronic Systems Society

Sponsored by the
Gyro and Accelerometer Panel

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New York, NY 10016-5997
USA

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Abstract: The specification and test requirements for a linear, single-axis, nongyroscopic accelerometer for use in inertial navigation, guidance, and leveling systems are defined. A standard specification guide and a compilation of recommended test procedures for such accelerometers are provided. Informative annexes are given on the various types of such accelerometers (force or pendulous torque rebalance with analog or digital output, vibrating beam, and micromechanical) and error effects, on filtering, noise, and transient analysis techniques, and on calibration and modeling techniques (multipoint tumble analysis, vibration and shock test analyses, and geophysical effects in inertial instrument testing).

Keywords: accelerometer, geophysical effects, IEEE 1293TM, inertial instrument, inertial sensor, micromechanical accelerometer, pendulous accelerometer, power spectral density, specification, testing, vibrating beam accelerometer, vibration and shock

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Sid Bennett, *Chair*

David Anderson
Michael E. Ash
Cleon H. Barker
Steve F. Becka
Joseph S. Beri
Stephen Bongiovanni
Pierre Bouniol
James Brewer
Herbert T. Califano
A. T. (Ted) Campbell*
Joseph J. D'Angello Jr.
George W. Erickson
Joseph Ficalora

Scott A. Finken
Thomas A. Fuhrman
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Bert Katz
Jean-François Kiefer
Lalit Kumar
Kurt Lantz
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R. D. (Sam) Marquess
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Bart Morrow Jr.

Jay Murphy
Rex B. Peters*
Loren Richardson
Gerald L. Shaw
Phillip B. Simpson
Clifford O. Swanson*
Mohammad Tehrani
Leroy O. Thielman
Christopher V. Trainor
Akira Umeda
Bud J. Wimber*
David J. Winkel
Bruce R. Youmans

***Past Chair**

A total of 62 individuals attended 30 bimonthly meetings of the Gyro and Accelerometer Panel during preparation of this standard. At the time this standard was completed, the Sensors Working Group had the following membership:

Austin Prach, *Chair*

Cleon H. Barker
Steve F. Becka
Jason Bingham
Timothy Buck
Calvin Burrell
Randall Curey
Harry Davis
Rayna DeMaster-Smith

George W. Erickson
Marius Gheorghe
Kamal Joshi
Jean-Francois Kieffer
Ken Marino
Edward Schlatter
Reese Sturdevant

David Syse
David Tarrant
Daniel Tazartes
Leroy O. Thielman
Margaret Trevino
Randy Wells
David J. Winkel
Bruce R. Youmans

The following members of the individual balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Cleon H. Barker
Jason Bingham
Demetrio Bucaneg Jr.
Keith Chow
Randall Curey

Randall C. Groves
Werner Hoelzl
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Introduction

This introduction is not part of IEEE Std 1293-2018, IEEE Standard Specification Format Guide and Test Procedure for Linear Single-Axis, Nongyroscopic Accelerometers.

This standard is provided as a guide for the preparation of an accelerometer specification (Part I) and an accelerometer test procedure (Part II). The accelerometer considered in this standard uses a linear, single-axis, nongyroscopic acceleration sensor. The capture-loop, pickoff, oscillator, and readout electronics, when used, can be considered either as a part of the accelerometer or as separately provided by the user. The format was prepared by the Gyro and Accelerometer Panel of the Aerospace and Electronic Systems Society of the Institute of Electrical and Electronics Engineers (IEEE). It is intended to provide a common meeting ground of terminology and practice for manufacturers and users.

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, sign, axes, and so on. Boxed statements are included for information only and are not part of the specification format nor test procedure. The figures presented are to be used as a guide for the preparation of specific figures or drawings.

The annexes are informative and cover

- Typical block diagrams for accelerometer response
- The various types of accelerometers considered (including pendulous torque rebalance, vibrating beam, and micromechanical)
- Error effects
- Filtering, noise, and transient analysis techniques
- Calibration and modeling techniques (multipoint tumble analysis, vibration and shock test analyses, and geophysical effects in inertial instrument testing)

The following documents were used in the development of this standard:

IEEE/ASTM SI 10TM-1997, Standard for Use of the International System of Units (SI): The Modern Metric System.

IEEE Std 260.1TM-1993, American National Standard Letter Symbols for Units of Measurement.

IEEE Std 280TM, IEEE Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering.

IEEE Std 315TM-1975, IEEE Standard, American National Standard, Canadian Standard Graphic Symbols for Electrical and Electronics Diagrams (Including Reference Designation Letters).

IEEE Std 315ATM, Supplement to IEEE Std 315.

IEEE Std 528TM-1994, IEEE Standard for Inertial Sensor Terminology.

IEEE 100TM, *The Authoritative Dictionary of IEEE Standards Terms*.

In this standard, the symbol *g* (italic) is used to denote an acceleration equal in magnitude to the local value of gravity at the test site. This symbol is thus distinguished from *g* (nonitalic), which is the standard symbol for gram. The standard value of gravity *g*₀ is 9.806 65 m/s².

The accelerometer is used to provide an analog, digital, or frequency output that is a measure of acceleration or velocity increment, or both. An acceleration applied along the input axis of the acceleration sensor causes its proof mass to deflect. For open-loop accelerometers, the pickoff error signal caused by this motion is the measure of acceleration.

For force-rebalance accelerometers, the pickoff error signal is used in the electronics to produce a restoring force or torque. When static equilibrium is reached, the reaction force or torque of the proof mass to the average acceleration is balanced by the mean value of the restoring force or torque. The average rebalance current or pulse rate required to maintain this equilibrium condition is proportional to the average acceleration and provides the analog or digital output signal.

For vibrating beam accelerometers (VBAs), acceleration causes one resonator to increase in frequency (f_1) and the other resonator to decrease in frequency (f_2). The difference ($f_1 - f_2$) is a measure of the applied acceleration. The VBA difference frequency scale factor is the sum of the individual resonator scale factors. Thus, using the difference frequency observable in a dual-resonator VBA doubles the scale factor as well as rejects many common mode error effects.

In this standard, no distinction is made between input axis (IA) and input reference axis (IRA) [similarly between output axis (OA) and output reference axis (ORA) and pendulous axis (PA) and pendulous reference axis (PRA)]. When dealing with the accelerometer, sensor physics IA, OA, and PA would typically be used. When orienting the accelerometer, package IRA, ORA, and PRA would typically be used. In some cases, it may be desirable to attempt to orient the IA, OA, and/or PA by observing a signal (such as the output or a reference voltage). Even in these cases, the IRA, ORA, and/or PRA can be used as a check if the approximate orientation between IA, OA, and PA and the IRA, ORA, and PRA is known. In all cases, users should determine which set of axes is appropriate for their application.

Contents

1. Overview	14
1.1 Scope	14
1.2 Purpose	14
1.3 Document structure.....	14
2. Normative references.....	15
Part I—Specification format.....	15
3. Overview	15
3.1 Scope	15
3.2 Purpose	16
4. Applicable documents	16
4.1 Specifications	17
4.2 Standards	17
4.3 Drawings.....	17
4.4 Bulletins.....	17
4.5 Other publications.....	17
5. Requirements.....	17
5.1 Description	17
5.2 General requirements.....	20
5.3 Performance.....	21
5.4 Mechanical requirements.....	38
5.5 Electrical and magnetic requirements.....	42
5.6 Environmental requirements.....	46
5.7 Reliability	49
6. Quality assurance.....	49
6.1 Classification of tests.....	50
6.2 Acceptance tests	52
6.3 Qualification tests	54
6.4 Reliability tests	54
6.5 Test conditions and equipment	55
6.6 Test methods.....	55
6.7 Data submittal.....	58
7. Preparation for delivery.....	58
8. Notes.....	58
8.1 Intended use.....	58
8.2 Ordering data	58
8.3 Model equation	58
Part II—Test procedure	63
9. Test procedure overview	63
10. Description	63

11. Test conditions and equipment	63
11.1 Standard test conditions.....	63
11.2 Test equipment	65
12. Test procedure	68
12.1 Test setup.....	68
12.2 Accelerometer nonoperating tests.....	69
12.3 Accelerometer operating tests.....	74
12.4 Electromagnetically torqued pendulous accelerometer tests	105
12.5 VBA tests.....	115
12.6 Micromechanical accelerometer tests	117
12.7 Life tests	121
12.8 Reliability tests	123
12.9 Environmental tests	124
Part III—Accelerometer descriptions	128
Annex A (informative) Accelerometer dynamic block diagrams	128
A.1 Introduction	128
A.2 Open-loop operation	128
A.3 Closed-loop operation.....	129
A.4 Open-loop operation of closed-loop accelerometer	130
A.5 Operation with voltage-to-frequency conversion.....	130
A.6 Operation with digital capture loop	131
A.7 Accuracy of capture-loop readout.....	131
Annex B (informative) Digital accelerometers and comments concerning their test methods.....	132
B.1 Introduction.....	132
B.2 Description of commonly encountered digital output formats.....	132
B.3 Comments concerning test methods associated with digital instruments.....	134
Annex C (informative) Characteristics of pendulous accelerometers	137
C.1 Design principles	137
C.2 Applications	137
C.3 Error sources	138
C.4 Trade-offs.....	143
C.5 Environmental effects	144
C.6 Testing	144
C.7 Special requirements in the specification.....	144
C.8 Advantages and disadvantages.....	145
Annex D (informative) Overview of the characterization and use of the VBA.....	146
D.1 Introduction	146
D.2 Historical background.....	146
D.3 VBA—Theory of operation.....	147
D.4 VBA signal processing	151
D.5 VBA error sources	155
D.6 Related developments	159
Annex E (informative) VBA resonator frequency as a function of applied acceleration	160
E.1 Geometry and elastic properties of vibrating beam.....	160
E.2 Square-root relationship derived from energy considerations.....	161
E.3 Direct frequency versus force relation	164
E.4 Frequency versus force numerical evaluation	169
E.5 Comparison of fit coefficients and square-root Taylor coefficients	171

Annex F (informative) Micromechanical accelerometers	173
F.1 Micromachining	173
F.2 Micromachined silicon accelerometer—flexured-mass configurations	173
F.3 Micromachined silicon VBAs	183
Annex G (informative) Outline of error sources in accelerometers.....	188
G.1 Introduction	188
G.2 Sensor characterization by mechanization	188
G.3 Typical sensor characterization by manufacturing process.....	189
G.4 Error categories.....	189
G.5 Sensor physics	190
Part IV—Filtering, noise, and transient analyses	192
Annex H (informative) Digital filtering	192
H.1 Types of filtering and decimation	192
H.2 Rectangular filtering	193
H.3 Triangular filtering.....	193
H.4 Higher order filtering.....	194
Annex I (informative) Noise characterization	195
I.1 Stochastic processes	195
I.2 Autocorrelation function of a stochastic process.....	195
I.3 Estimation of the autocorrelation function	196
I.4 Power spectral density (PSD) of a stationary stochastic process.....	197
I.5 Estimation of the PSD	198
I.6 Numerical evaluation and plotting of the PSD	202
I.7 Characteristic PSD noise slopes	203
I.8 Characteristic Allan variance noise slopes	207
I.9 Estimation of Markov noise parameters.....	208
Annex J (informative) Characterization of transient behavior	213
J.1 Types of transient behavior	213
J.2 Second-order ordinary differential equation transient.....	213
J.3 Exponential, square root, and logarithmic transients	214
J.4 Estimation of transient parameters	216
Part V—Calibration and modeling techniques	217
Annex K (informative) Calibrating accelerometer model coefficients from static multipoint tumble data.....	217
K.1 Multipoint tumble test and analysis procedures.....	217
K.2 Model equation for multipoint tumble analysis	221
K.3 Multipoint tumble analysis with a single accelerometer observable.....	227
K.4 Multipoint tumble analysis with dual orthogonal accelerometer observables	233
K.5 Multipoint tumble analysis with orthogonal accelerometer magnitude-squared-of-g observable	235
K.6 Least-squares maximum likelihood estimation.....	236
Annex L (informative) Vibration test equipment, test procedures, and analysis techniques.....	242
L.1 Test equipment and test fixtures.....	242
L.2 Test scenarios	245
L.3 Error sources	246
L.4 Test instrumentation and procedures.....	247
L.5 General comments on analysis techniques	248
L.6 Calibration of nonlinear coefficients from vibration along different instrument axes	249
L.7 Summary	259

Annex M (informative) Geophysical effects in inertial instruments testing.....	260
M.1 Introduction.....	260
M.2 Seismic environment.....	260
M.3 Tilt and azimuth variations.....	261
M.4 Effect of lunar–solar earth tides	261
M.5 Effect of ocean tides.....	263
M.6 Variations in earth rotation.....	264
Annex N (informative) Bibliography	266

IEEE Standard Specification Format Guide and Test Procedure for Linear Single-Axis, Nongyroscopic Accelerometers

1. Overview

1.1 Scope

The specification and test requirements for a linear, single-axis, nongyroscopic accelerometer for use in inertial navigation, guidance, and leveling systems are defined. A standard specification format guide and a compilation of recommended test procedures for such accelerometers are provided. Informative annexes are given on the various types of such accelerometers (force or pendulous torque rebalance with analog or digital output, vibrating beam, and micromechanical) and error effects, on filtering, noise, and transient analysis techniques, and on calibration and modeling techniques (multipoint tumble analysis, vibration and shock test analyses, and geophysical effects in inertial instrument testing).

1.2 Purpose

A standard specification format guide is provided, along with a compilation of recommended test procedures for the preparation of a linear, single-axis, nongyroscopic accelerometer specification. These test procedures are derived from those currently in use in the industry.

1.3 Document structure

This standard consists of five parts: The first two parts are in the normative portion of the standard, and the other three are in the informative portion. Part I is a specification format guide for the preparation of a linear single-axis, nongyroscopic accelerometer specification. Part II is a compilation of recommended procedures for testing a linear single-axis, nongyroscopic accelerometer. Part III contains descriptions of various types of accelerometers. Part IV discusses filtering, noise, and transient analysis. Part V contains calibration and modeling techniques.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI/ASQ Z1.4, Sampling Procedures and Tables for Inspection by Attributes.¹

IEEE Std 836TM, IEEE Recommended Practice for Precision Centrifuge Testing of Linear Accelerometers.^{2, 3}

IEEE Std 1332TM, IEEE Standard Reliability Program for the Development and Production of Electronic Products.

ISO 5347, Parts 1–21 and Part 23, Methods for the Calibration of Vibration and Shock Pick-Ups.⁴

MIL-STD-461, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment.⁵

MIL-STD-810, Environmental Engineering Considerations and Laboratory Tests.

MIL-STD-1916, DoD Preferred Methods for Acceptance of Product.

MIL-STD-2073-1, DoD Standard Practice for Military Packaging.

Part I—Specification format

3. Overview

This specification defines the requirements for a linear, single-axis, nongyroscopic accelerometer. The accelerometer is used as a sensing element to provide an electrical signal proportional to acceleration or velocity change with a transfer function that is nominally low pass (rather than bandpass). The output is [an analog voltage, an analog current, a binary pulse train, a ternary pulse train, pulse width modulated, a frequency output, _____] representing [acceleration, velocity change].

This specification defines not only the performance requirements of an inertial accelerometer as a unique device but also its specific variational but repeatable and predictable performance parameters.

3.1 Scope

This specification defines requirements for [accelerometer type].

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This specification format guide and test procedure standard applies to force-rebalance accelerometers (pendulous or translational proof mass), vibrating beam accelerometers (VBAs), and micromechanical accelerometers (see 5.1).

All accelerometers have biases, scale factors, misalignments, nonlinearities, noise characteristics, and other parameters. Many of the specification requirements and verification test methods for these parameters; their stabilities; their temperature, magnetic, and other sensitivities; the accelerometer behavior through and across vibration, shock, and other environments; and the accelerometer lifetime and reliability are independent of the accelerometer type. Requirements and tests that are specific to a particular accelerometer type are described separately.

Only the clauses applicable to the given accelerometer type should be used.

This specification is not intended to define requirements for the pendulous integrating gyroscopic accelerometer (PIGA) or for the specific force integrating receiver (SFIR). These high-precision single degree-of-freedom (DOF) accelerometers use gyroscopic precessional torque to rebalance the specific force effect of nongravitational acceleration acting on a pendulous proof mass on the gyro float.

This specification also does not apply to devices (such as seismometers or open-loop piezoelectric accelerometers) that measure ac rather than low-pass and dc accelerations. Gravimeters are also not considered.

3.2 Purpose

This specification describes the design and performance requirements for _____ [model number, part number, change letter (if any), other identification], manufactured by _____ [name, address].

4. Applicable documents

The following documents form a part of the specification to the extent specified herein. For dated documents, only the edition cited applies. For undated documents, the latest edition of the document (including any amendments, change notices, etc.) applies. In the event of a conflict between this document and the listed documents, this document shall govern.

Give the identification number, title, date of issue, and revision letter of each document referenced in the completed specification.

4.1 Specifications

4.1.1 Government

4.1.2 Industry/technical

4.1.3 Company

4.2 Standards

4.2.1 Government

4.2.2 Industry/technical

4.2.3 Company

4.3 Drawings

4.3.1 Government

4.3.2 Industry/technical

4.3.3 Company

Figure 1, Figure 3, and Figure 4 are conceptual examples of the types of drawings that might be delivered with an accelerometer.

4.4 Bulletins

4.4.1 Government

4.4.2 Industry/technical

4.4.3 Company

4.5 Other publications

Other applicable documents should be listed under appropriate subclauses.

5. Requirements

5.1 Description

The accelerometer shall comprise a single-axis, nongyroscopic acceleration sensor [operating, to be operated] with [its own, user-supplied] electronics.

Figure 1a, Figure 1b, and Figure 1c apply to pendulous proof-mass accelerometers. The forcer in Figure 1a is called a *torquer*. The figures must be appropriately modified for a translational proof-mass accelerometer.

Torque-rebalance, capture-loop electronics and/or pickoff electronics are shown in Figure 1a. VBA oscillator electronics are shown in Figure 1b and Figure 1c. The accelerometer may employ a temperature sensor for thermal modeling, control, or monitoring.

The dashed lines in Figure 1a, Figure 1b, and Figure 1c enclose the sensor part of the accelerometer, which responds to the acceleration input. The term “seismic system” is sometimes used in place of the term “acceleration sensor.”

The electronics outside the dotted lines used to generate the accelerometer output and the temperature output, if needed, may be self-contained within or separate from the accelerometer package. The user-supplied electronics may include such items as power conditioner, capture electronics, output signal conditioner, temperature controller, reference clock, and test points.

The sensor may employ stops to limit proof-mass displacement.

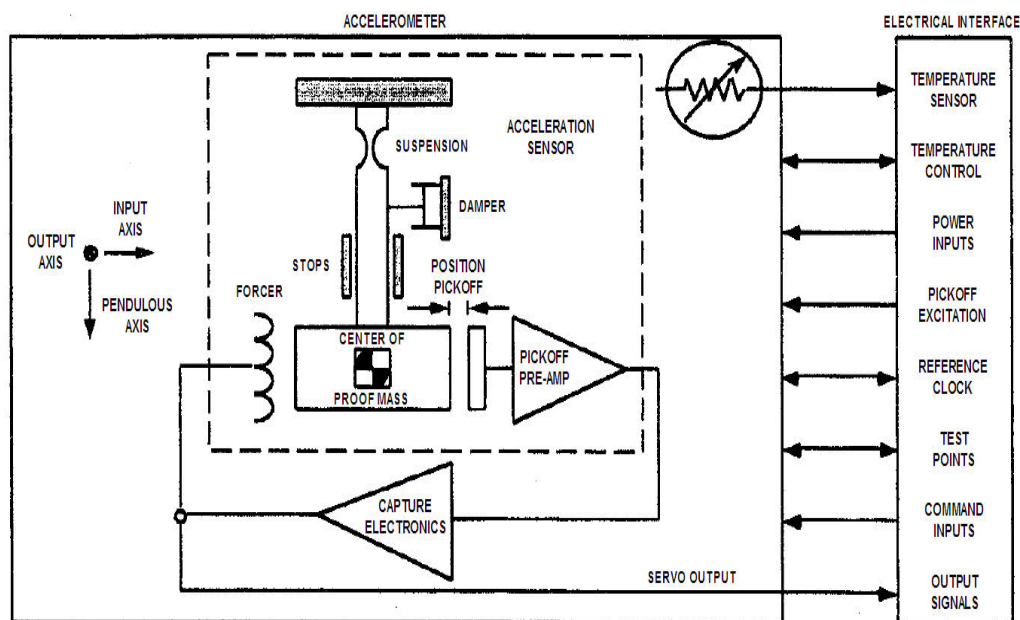


Figure 1a—Diagram of torque-rebalance accelerometer system

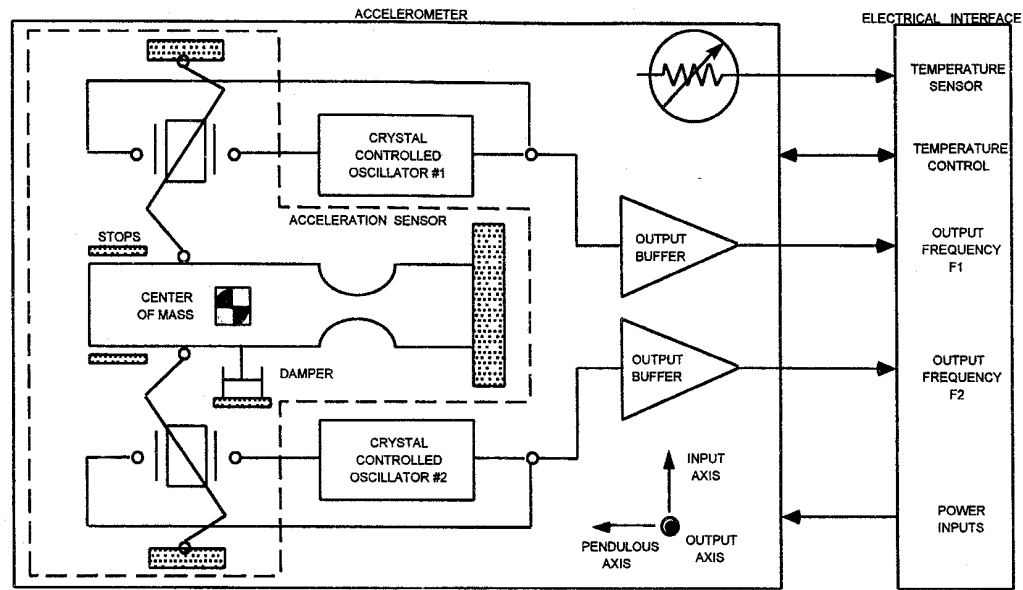


Figure 1b—Diagram of single proof-mass VBA system

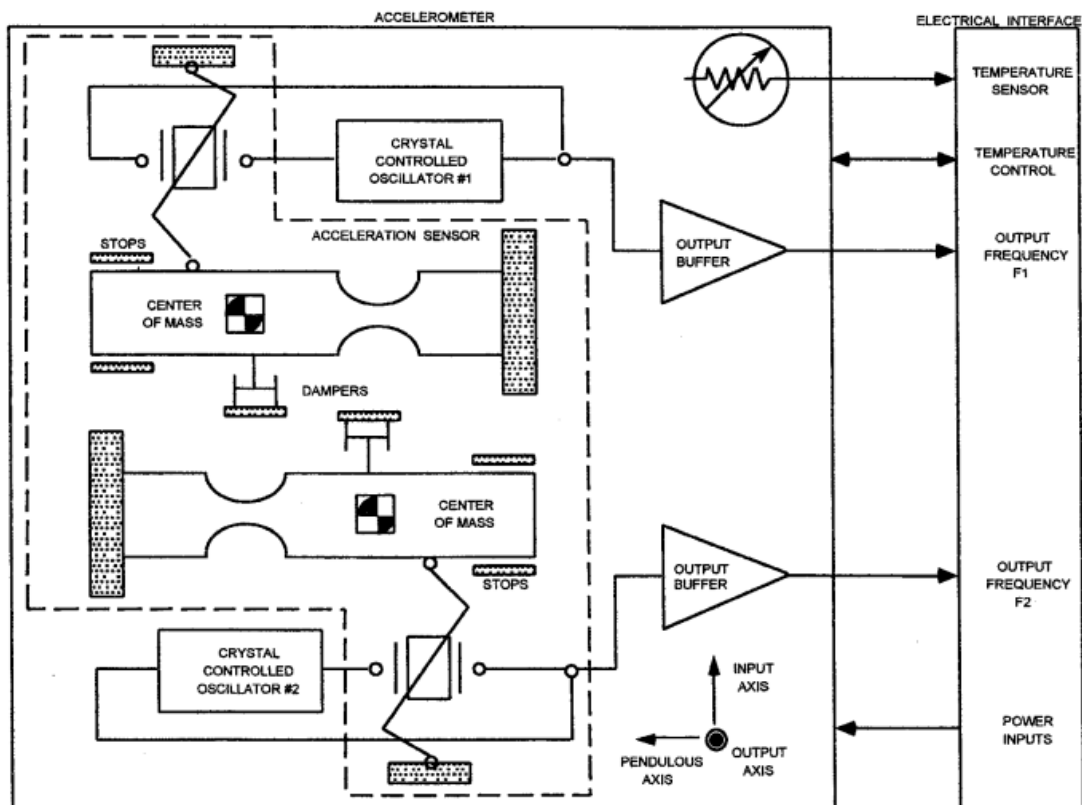


Figure 1c—Diagram of dual proof-mass VBA system

The torque-rebalance capture-loop electronics in Figure 1a may be analog-torque feedback or pulsed-torque feedback, providing as an output either an analog voltage signal proportional to acceleration or a pulse-train, each pulse representing an increment of velocity gained or lost. The method of pendulum torquing or proof-mass forcing may be specified (for example, binary pulse, ternary pulse, pulse-width modulation, analog, or analog converted into pulse-train output by use of a voltage- or current-to-frequency converter).

The pickoff could be electromagnetic, capacitive, optical, or piezoresistive.

Figure 1a applies to a closed-loop micromechanical accelerometer as well as to a macro-sized pendulous accelerometer, although electrostatic capacitive forcing might be used in the former rather than the electromagnetic torquing commonly used in the latter.

An open-loop micromechanical accelerometer dispenses with the servoed capture-loop electronics and measures acceleration by the movement of the proof mass as restrained by the suspension flexure(s). The position pickoff could be capacitive, or the movement of the proof mass could be measured piezoresistively from the strain in the flexure(s).

Open-loop piezoelectric accelerometers, which measure acceleration by the voltage generated by the strain in a piezoelectric proof-mass support, are not considered in this document because leakage of the piezoelectrically generated charge restricts these devices to measuring ac rather than dc accelerations.

VBAs are by their nature open-loop devices as far as proof-mass movement is concerned. That movement is mostly restrained by the stiffness of the crystal resonators (usually piezoelectric quartz or silicon). Usually two crystal resonators are kept vibrating at their resonant frequency by oscillator circuits with a piezoelectric drive for quartz and a capacitive drive for silicon.

The resonators are mounted in a push-pull mode with a single proof mass (Figure 1b) or separate proof masses (Figure 1c). Under acceleration, one resonator goes into tension and increases in frequency and the other goes into compression and decreases in frequency. The measure of acceleration is the difference frequency, in order to obtain improved linearity and lower sensitivities to clock errors, physical environment, and aging effects (see Annex D for more details). The oscillator electronics are usually self-contained within the accelerometer package.

The VBA acronym (see D.3) is commonly applied to all vibrating resonator accelerometers, even if the resonator has other-than-beam geometry (e.g., a double-ended tuning fork).

5.2 General requirements

5.2.1 Precedence

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

- a) Purchase agreement
- b) This specification and its applicable drawings
- c) Other applicable documents

List other applicable documents in order of precedence; see Clause 2 and Clause 4.

5.2.2 Deliverables

The deliverable item includes the serialized inertial accelerometer plus any accompanying serialized numerical data representing the predictable parameters, such as bias, scale factor, scale factor nonlinearity, and misalignment as defined in this specification.

5.2.3 Other

The application of this accelerometer may require performance parameters defining bias, scale factor, scale factor nonlinearity, and input axis (IA) misalignment with a degree of accuracy not achievable without analytical modeling based on *a priori* knowledge of repeatable variation of these parameters. Bias, scale factor, and IA misalignment may be modeled as polynomial functions of the internal temperature indication of the sensor, whereas scale factor nonlinearity may be modeled as a function of indicated acceleration independent of temperature.

List other applicable general requirements.

5.3 Performance

The following clauses are used to specify the performance of a complete accelerometer or an acceleration sensor only, with 5.3.24 through 5.3.29.2 being applicable to an acceleration sensor only.

Table 3 lists the test procedure clauses for verifying the 5.3 through 5.7 requirements clauses.

If modeling is necessary to meet performance requirements, then during the acceptance testing of each accelerometer for this application, the bias, scale factor, two components of the IA misalignment, nonlinearities, and other parameters if necessary shall be determined over the operating temperature range. The output of the temperature sensor as well as the ambient temperature shall be determined at each temperature data point.

The form of the model and the number and precision of the coefficients shall be mutually agreed to by the producer and the user. The minimum model requirements will be shown in 8.3.

Each serialized accelerometer shall be accompanied by serialized coefficients as defined in this specification. These serialized items shall be a matched set reflecting proven test data derived from acceptance testing and calibration of the matched set of coefficients.

In the performance paragraphs affected by the need for modeling, each paragraph shall include both the uncompensated error allowable and the magnitude of the allowable error after compensation.

5.3.1 General

When tested with its capture or other electronics, the acceleration sensor shall comply with the performance requirements of this specification before, during (if applicable), and after exposure to the defined combinations of environments specified in 5.6.

Turn-on transients may affect accelerometer performance, and this issue shall be addressed as required for the specific application. For these cases, power-on time and other test conditions prior to taking data should be specified.

Define critical combinations of environments in 5.6.

5.3.2 Input range

The minimum input range shall be $\pm$ _____ [m/s², ft/s², _____].

The specified input range shall be large enough to include the maximum (peak) translational acceleration combined with the maximum response to vibration falling within the bandwidth of the sensor. The input range need not be symmetrical about the null.

5.3.3 Overload capacity

The accelerometer shall perform to all specification requirements after an acceleration of _____ $[m/s^2, ft/s^2, \text{_____}]$ has been applied along the _____ [axis, axes] for _____ s a total of _____ times.

5.3.4 Accelerometer temperature

The accelerometer may be specified for thermally controlled applications at a specified temperature or for operation over a wide range of temperatures.

5.3.4.1 Operating temperature

The operating temperature shall be $[\text{_____} \pm \text{_____} \text{ } ^\circ\text{C}, \text{_____} \text{ } ^\circ\text{C} \text{ minimum to } \text{_____} \text{ } ^\circ\text{C} \text{ maximum}]$ at point _____ in the accelerometer.

The point within the accelerometer at which the operating temperature range is specified could be at the mounting flange or at the location of the accelerometer's temperature sensor (if any).

For temperature-controlled operation, the mounting flange temperature and surrounding ambient temperature (unless the accelerometer were surrounded with insulation with the heat flow path out through the mounting flange) could be specified, with the interior control set point temperature also specified (which is particularly important for fluid-filled or floated accelerometers).

5.3.4.2 Temperature sensor

A temperature sensor shall be provided [on, within] the accelerometer to indicate the accelerometer temperature over the operating range. The temperature sensor output shall be definable by a model equation that permits recovery of accelerometer temperature to an accuracy of $\pm \text{_____} \text{ } ^\circ\text{C}$. The form of the temperature model and the number and precision of the coefficients shall be mutually agreed to.

For thermally controlled applications, it may be appropriate to specify the absolute value and tolerance of the sensor output and its temperature coefficient at the nominal operating temperature.

For temperature-compensated applications, instead of converting the temperature sensor output in, for example, volts to $^\circ\text{C}$ for compensating the accelerometer output as a function of $^\circ\text{C}$, the calibration of the compensation model could be in terms of temperature sensor output directly (i.e., volts in this example). In this case, a precise calibration of the relationship between temperature sensor output and $^\circ\text{C}$ would be unnecessary.

5.3.5 Scale factor

5.3.5.1 Absolute value

The scale factor K_1 shall be $\text{_____} \pm \text{_____} [\text{V, mA, p/s, Hz}]/[m/s^2, ft/s^2, \text{_____}]$, measured to an uncertainty of _____ [%, ppm], under the standard test conditions of 11.1.

When verifying accelerometer scale factor via a tumble test and tracking its variation over time or over changes in temperature and other environments, it is natural to express the scale factor in terms of the local acceleration due to gravity. Alternatively, the scale factor could be expressed in terms of absolute units, such as m/s^2 .

When expressing the scale factor in terms of the local acceleration due to gravity, if the accelerometer is used in a location that is different than the calibration site or scale factors are measured on the same accelerometer at different test sites, then the scale factor has to be expressed in terms of g_0 (standard gravity) or m/s^2 .

The scale factor K_1 when expressed in terms of p/s may be used to obtain velocity quantization.

When K_1 is expressed in $(\text{p/s})/g$

$$\text{velocity quantization in } (\text{m/s})/\text{p} = \frac{\text{local value of gravity in } (\text{m/s}^2)/g}{K_1 \text{ in } (\text{p/s})/g}$$

or when expressed in $(\text{p/s})/(\text{m/s}^2)$

$$\text{velocity quantization in } (\text{m/s})/\text{p} = \frac{1}{K_1 \text{ in } (\text{p/s})/(\text{m/s}^2)}$$

The VBA difference frequency scale factor is the sum of the individual resonator scale factors. Thus, using the difference frequency observable in a dual-resonator VBA doubles the scale factor as well as rejects many common mode error effects. Typical VBA scale factor units are Hz/g or $\text{Hz}/(\text{m/s}^2)$.

5.3.5.2 Asymmetry

The difference between the scale factor measured with positive applied acceleration and with negative applied acceleration shall not exceed $\pm$ _____ [%, ppm] of the average scale factor for both positive and negative accelerations.

Separate scale factors may be supplied for positive and negative applied accelerations to better define scale factor asymmetry (see 8.3).

5.3.5.3 Short-term stability

The standard deviation of the scale factor from its mean value over a period of _____ [s, min, h, d] of continuous operation under constant conditions shall be less than _____ [%, ppm].

Alternative means of specifying stability may be used, such as curve fitting for trend determination, or frequency domain analysis.

5.3.5.4 Long-term stability

The least-squares straight line slope of the scale factor over a period of _____ [h, d, yr] of continuous operation measured under constant conditions shall be less than _____ [%, ppm]/[h, d, yr]. The standard deviation of the scale factor data points from the best fit line shall be less than _____ [%, ppm].

Other criteria for establishing stability may be used, such as the root mean square (rms) about the mean, or frequency domain analyses. Stability tests have constant conditions between calibrations, whereas repeatability tests have temperature cycles or other variations between calibrations.

5.3.5.5 Repeatability

The standard deviation of the scale factor from the mean of measurements taken under constant conditions shall be less than _____ [%, ppm]. Between successive measurements, the accelerometer shall be [heated, 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 (e.g., vibration, shock, temperature, remount, and power interrupt of specified duration) may be specified. Sufficient time should be allotted to attain thermal equilibrium before making a measurement. Other conditions for repeatability may be specified, such as power-off time with the accelerometer maintained at some fixed temperature.

Alternative means of specifying repeatability may be used, for example, rms deviation about the first day mean, or peak-to-peak deviation.

5.3.5.6 Sensitivity

The absolute value of the sensitivity coefficients of scale factor to variations from the standard test conditions of 11.1 shall not exceed the limits listed as follows:

- a) Input excitation voltage(s): _____ [%, ppm]/V
- b) Input excitation frequency(ies): _____ [%, ppm]/Hz
- c) Operating temperature: _____ [%, ppm]/°C
- d) Temperature gradient: _____ [%, ppm]/Δ°C
- e) Temperature rate of change: _____ [%, ppm]/(°C/min)
- f) External magnetic induction [ac, dc, or both]: _____ [%, ppm]/[mT, G] per axis
- g) Pressure: _____ [%, ppm]/Pa

One of several methods of curve fitting (such as least-squares straight line or polynomial fit) should be specified to determine the value of each sensitivity coefficient since the scale factor may not be a linear function of the input variable (see 12.3.11).

An accelerometer could have one or several input dc or ac voltage excitations, with or without internal regulation. The sensitivity of the accelerometer output to independent variations in each of these voltages and in the frequency of each ac input voltage (such as for a pickoff excitation) must meet these requirements.

Tesla ($\text{Wb/m}^2 = \text{V} \cdot \text{s/m}^2$ in SI units) and gauss (10^{-4} tesla in cgs electromagnetic units) are units of magnetic induction B . The relation between B in tesla and the magnetic field H in A/m in an isotropic homogeneous medium is $B = \mu H$, where μ is the permeability of the medium. The permeability of empty space is $\mu_0 = 4\pi \times 10^{-7}$ H/m in SI units. In the cgs electromagnetic system of units in which B is measured in gauss, the permeability of empty space is $\mu_0 = 1$, so that $B = H$, where H has units of oersteds. Hence, magnetic induction sensitivity per gauss has often been referred to as magnetic field sensitivity.

5.3.6 Nonlinearity

The absolute values of the second-order nonlinearity coefficient K_2 and the third-order nonlinearity coefficient K_3 shall be less than _____ $[(\text{m/s}^2)/(\text{m/s}^2)^2, \text{ }]$ and _____ $[(\text{m/s}^2)/(\text{m/s}^2)^3, \text{ }]$, respectively. The absolute value of the odd quadratic coefficient K_{eq} shall be less than _____ $[(\text{m/s}^2)/(\text{m/s}^2)^2, \text{ }]$.

The standard deviation of the residuals shall be less than _____ $[\text{m/s}^2, \text{ft/s}^2, \text{ }]$.

The K_2 , K_{0q} , and K_3 coefficients are also commonly expressed in g/g^2 , g/g^2 and g/g^3 , respectively.

A simpler means of specifying nonlinearity for lesser accuracy accelerometers is to place limits on composite error as a function of input acceleration, that is, what is commonly known as an envelope specification.

The simplest envelope is to specify that the maximum error over the operating range is a specified percentage of the accelerometer full-span output, especially for lesser accuracy accelerometer applications where it is not intended to compensate for accelerometer nonlinearities that meet the specifications.

Acceleration nonlinearities typically arise from structural compliance. Changes in accelerometer temperature that occur under acceleration (such as due to varying current through an electromagnetic torquer) could manifest themselves as an apparent acceleration nonlinearity. The maximum such effect could be required to be less than the nonlinearity requirement, or the heating could be regarded as a separate temperature sensitivity problem with compensation using temperature sensor measurements if possible.

5.3.7 Bias

5.3.7.1 Absolute value

The absolute value of bias K_0 shall not exceed _____ [m/s^2 , ft/s^2 , _____], measured to an uncertainty of _____ [m/s^2 , ft/s^2 , _____], under the standard test conditions of 11.1.

5.3.7.2 Asymmetry

The difference between the bias measured with positive applied acceleration and with negative applied acceleration shall not exceed _____ [m/s^2 , ft/s^2 , _____].

Separate biases may be supplied for positive and negative applied accelerations to define bias asymmetry better (see 8.3).

5.3.7.3 Short-term stability

The standard deviation of the bias from its mean value over a period of [s, min, h, d] of continuous operation shall be less than _____ [m/s^2 , ft/s^2 , _____].

Alternative means of specifying stability may be used, such as curve fitting for trend determination or frequency domain analysis.

5.3.7.4 Long-term stability

The least-squares straight line slope of the bias over a period of _____ [h, d, yr] of continuous operation, measured under constant conditions, shall be less than _____ [m/s^2 , ft/s^2 , _____]/[h, d, yr]. The standard deviation of the bias data points from the best fit line shall be less than _____ [m/s^2 , ft/s^2 , _____].

Other criteria for establishing stability may be used, such as the rms about the mean or frequency domain analyses. Stability tests have constant conditions between calibrations, whereas repeatability tests have temperature cycles or other variations between calibrations.

5.3.7.5 Repeatability

The standard deviation of the bias from the mean of _____ measurements taken under constant conditions shall be less than _____ [m/s^2 , ft/s^2 , _____]. Between successive measurements, the accelerometer shall be [heated, cooled] to _____ $^{\circ}\text{C}$ for at least _____ h.

Other environmental exposures may be substituted or added to the temperature environment specified. In addition, combinations of various successive environments (e.g., vibration, shock, temperature, remount, power interrupt of specified duration) may be specified. Sufficient time should be allotted to attain thermal equilibrium before making a measurement. Other conditions for repeatability may be specified, such as power-off time with the accelerometer maintained at some fixed temperature.

Alternative means of specifying repeatability may be used, for example, rms deviation about the first day mean or peak-to-peak deviation.

5.3.7.6 Sensitivity

The absolute value of the sensitivity coefficients of the bias to variations from the standard test conditions of 11.1 shall not exceed the limits listed as follows:

- a) Input excitation voltage(s): _____ [m/s^2 , ft/s^2 , _____]/V
- b) Input excitation frequency(ies): _____ [m/s^2 , ft/s^2 , _____]/Hz
- c) Operating temperature: _____ [m/s^2 , ft/s^2 , _____]/ $^{\circ}\text{C}$
- d) Temperature gradient: _____ [m/s^2 , ft/s^2 , _____]/ $\Delta^{\circ}\text{C}$
- e) Temperature rate of change: _____ [m/s^2 , ft/s^2 , _____]/ $^{\circ}\text{C}/\text{min}$
- f) External magnetic induction [ac, dc, or both]: _____ [m/s^2 , ft/s^2 , _____]/[mT, G, _____] per axis
- g) Pressure: _____ [m/s^2 , ft/s^2 , _____]/Pa

One of several methods of curve fitting (such as least-squares straight line or polynomial fit) should be specified to determine the value of each sensitivity coefficient since the bias may not be a linear function of the input variable (see 12.3.11).

5.3.8 IA misalignment

Only IA misalignment components about pendulous axis (PA) and output axis (OA) are considered because misalignments of the other axes about IA do not have a material effect on the performance of a single-axis accelerometer.

5.3.8.1 About pendulous axis (PA)

The absolute value of the IA misalignment about the PA, δ_p , shall be less than _____ [μrad , mrad, $^{\circ}$, $^{\circ}$], measured to an uncertainty of _____ [μrad , mrad, $^{\circ}$, $^{\circ}$], under the standard test conditions of 11.1.

5.3.8.2 About output axis (OA)

The absolute value of the IA misalignment about the OA, δ_o , shall be less than _____ [μrad , mrad, $^{\circ}$, $^{\circ}$], measured to an uncertainty of _____ [μrad , mrad, $^{\circ}$, $^{\circ}$], under the standard test conditions of 11.1.

Since misalignment angles (δ_o , δ_p) are typically small, an alternative method is to specify the total misalignment angle using small angle approximation as follows:

$$\delta_t = \sqrt{\delta_o^2 + \delta_p^2}$$

5.3.8.3 Short-term stability

The standard deviation of the two IA misalignment angles from their mean values over a period of _____ [s, min, h, d] of continuous operation and measured under constant conditions shall be less than _____ [μ rad, mrad, ", °].

Alternative means of specifying stability may be used, such as curve fitting for trend determination or frequency domain analysis.

5.3.8.4 Long-term stability

The least-squares best fit slope of the IA misalignment angle data points over a period of _____ [h, d, yr] shall be less than _____ [μ rad, mrad, ", °]/[h, d, yr]. The standard deviation of the misalignment angle data points from the best fit line shall be less than _____ [μ rad, mrad, ", °].

Other criteria for establishing stability may be used, such as the rms about the mean or frequency domain analyses. Stability tests have constant conditions between calibrations, whereas repeatability tests have temperature cycles or other variations between calibrations.

5.3.8.5 Repeatability

The standard deviation of the IA misalignment angles from the mean of _____ measurements taken under constant conditions shall be less than _____ [μ rad, mrad, ", °]. Between successive measurements, the accelerometer shall be [heated, 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 (e.g., vibration, shock, temperature, remount, and power interrupt of specified duration) may be specified. Sufficient time should be allotted to attain thermal equilibrium before making a measurement. Other conditions for repeatability may be specified, such as power-off time with the accelerometer maintained at some fixed temperature.

Alternative means of specifying repeatability may be used, for example, rms deviation about the first day mean or peak-to-peak deviation.

5.3.8.6 Sensitivity

The absolute value of the sensitivity coefficients of the IA misalignments to variations from the standard test conditions of 11.1 shall not exceed the limits listed as follows:

- a) Input excitation voltage(s): _____ [μ rad, "]/V
- b) Input excitation frequency(ies): _____ [μ rad, "]/Hz
- c) Operating temperature: _____ [μ rad, "]/°C
- d) Temperature gradient: _____ [μ rad, "]/Δ°C
- e) Temperature rate of change: _____ [μ rad, "]/(°C/min)
- f) External magnetic induction [ac, dc, or both]: _____ [μ rad, "]/[mT, G] per axis
- g) Pressure: _____ [μ rad, "]/Pa

One of several methods of curve fitting (such as least-squares straight line or polynomial fit) should be specified to determine the value of each sensitivity coefficient since the misalignment may not be a linear function of the input variable (see 12.3.11).

5.3.9 Temperature model and temperature hysteresis

5.3.9.1 Temperature-controlled operation

For temperature-controlled operation in the range $T \pm$ _____ °C, the temperature sensitivities of the scale factor, bias, and IA misalignments for variations about T °C, as determined by least-squares straight line fits to calibrated values at temperature set points in the operating temperature range $T \pm$ _____ °C, shall be less than the values specified in 5.3.5.6, 5.3.7.6, and 5.3.8.6. These sensitivities can be used for linear temperature model compensation for temperature variations measured by the temperature sensor around the control set point T °C.

The temperature hysteresis of the scale factor, bias, and misalignments over the operating temperature range shall be less than _____ [%, ppm], _____ [m/s², ft/s², _____], and _____ [μrad, "], respectively.

The temperature hysteresis in a parameter is the width of the plot of the calibrated value of the parameter versus temperature sensor output for increasing and then decreasing values of temperature over the operating temperature range. A measure of the lumped bias and misalignment temperature hysteresis is provided by the width of the plot of the accelerometer output in the IA horizontal orientation versus the temperature sensor output for increasing and then decreasing values of temperature. This same test in the IA vertical orientation gives the lumped scale factor and bias temperature hysteresis.

The temperature hysteresis value indicates how closely the output of the accelerometer at a temperature arrived at in the increasing temperature direction is equal to its output arrived at in the decreasing temperature direction. The error caused by hysteresis after appropriate modeling is half the hysteresis width.

5.3.9.2 Non-temperature-controlled operation

For non-temperature-controlled, temperature-compensated operation in the temperature range _____ °C to _____ °C, the scale factor, bias, and IA misalignments shall be modeled as polynomials of order _____ in the temperature sensor output relative to the reference temperature _____ °C.

The reference temperature is typically midway in the temperature range. The temperature model could be expanded to include the effects of temperature gradients and/or temperature rates of change.

For approximately _____ equally spaced temperature set points in an increasing and then decreasing temperature variation over the temperature range, the results of polynomial fits to the calibrated scale factor, bias, and IA misalignments from four-point or other tumble tests at each temperature set point shall satisfy the values in Table 1.

Table 1—Temperature model calibration requirements

Quantity	Scale factor [% , ppm]	Bias [m/s ² , ft/s ² , ____]	Misalignments [μrad, °]
[First-order coefficient]	< _____ per °C	< _____ per °C	< _____ per °C
[Second-order coefficient]	< _____ per °C ²	< _____ per °C ²	< _____ per °C ²
etc.			
Rms residual	< _____	< _____	< _____
Hysteresis	< _____	< _____	< _____

5.3.10 Cross-axis nonlinearity

The absolute value of the cross-axis nonlinearity coefficients K_{00} , K_{pp} shall be less than _____ [(m/s²)/(m/s²)², ____].

The K_{00} and K_{pp} coefficients are commonly expressed in g/g².

A common cause of cross-axis nonlinearity is case compliance, which allows the IA to move relative to the case reference axes. As such, cross-axis nonlinearity can be specified as a structural compliance in _____ μrad/g.

5.3.11 Cross coupling

The absolute values of the cross-coupling coefficients K_{ip} , K_{io} , and K_{po} shall be less than _____ [(m/s²)/(m/s²)², ____].

5.3.12 Warm-up time

The output of the accelerometer shall be within _____ [m/s², ft/s², ____] of its steady-state value in no more than _____ [s, min] after power application [from _____ °C, over the temperature range _____ °C to _____ °C].

To define the turn-on characteristics fully, several individual items could be specified, such as the peak deviation from the steady-state or final value of the output along with the time constant of the transient, beginning at a specific point in time after turn-on.

Alternatively, one could specify the maximum output drift rate averaged over a specified period of time, beginning at a specific point in time after power application, in output units per time increment. The allowable drift could also be specified in terms of the maximum integral of the deviation of the output from its steady-state or final value, in velocity units, beginning at a specific point in time after power application.

One could also define limits for the output transient and/or lost information resulting from a specified power interruption.

5.3.13 Acceleration threshold

The threshold shall be less than _____ [m/s², ft/s², ____].

5.3.14 Acceleration resolution

The resolution shall be less than _____ [m/s², ft/s², ____].

5.3.15 Acceleration dead band

5.3.15.1 Force-rebalance dead band

The dead band shall be less than _____ [m/s^2 , ft/s^2 , ____].

5.3.15.2 Vibrating beam accelerometer (VBA) frequency lock

The effect of VBA frequency lock shall be less than _____ [m/s^2 , ft/s^2 , ____] peak to peak.

5.3.15.3 VBA activity dips

Activity dips shall be less than _____ [m/s^2 , ft/s^2 , ____] peak to peak within the plus or minus local gravity range.

Activity dips shall be less than _____ [m/s^2 , ft/s^2 , ____] peak to peak within the range of _____ [m/s^2 , ft/s^2 , ____] to _____ [m/s^2 , ft/s^2 , ____].

Activity dips need to be smaller in the plus or minus local gravity range as they can affect the calibration of the instrument error terms.

5.3.16 Repeatability across shut-down or nonoperational environment

After the output has stabilized, the standard deviation of a series of _____ turn-on measurements shall be less than _____ [m/s^2 , ft/s^2 , ____] under the standard test conditions of 11.1.

Application of environments between measurements may be specified, such as vibration, shock, and temperature cycling, either singly or in combination. In addition, turn-on repeatability may be specified in various orientations with respect to the gravity vector. Alternative means of specifying turn-on repeatability may be used, such as peak-to-peak deviation from the mean of the ensemble of data.

5.3.17 Turn-on hysteresis

The absolute value of the turn-on hysteresis shall be less than _____ [m/s^2 , ft/s^2 , ____].

5.3.18 Inversion transient

The output of the accelerometer shall be within _____ [m/s^2 , ft/s^2 , ____] of its steady-state value in no more than _____ [s, min] after inversion. The magnitude of the inversion transient shall be less than _____ [m/s^2 , ft/s^2 , ____].

When an accelerometer is rotated from +1 g to -1 g, or vice versa, transient settling behavior may be significant in high-precision applications. The shift and/or transient across an inversion could vary at different temperature set points within the operating temperature range. To define the inversion transient characteristics fully, several individual items could be specified, such as the peak deviation from the steady-state or final value of the output along with the time constant of the transient beginning at a specific point in time after the inversion is completed. See Annex J.

5.3.19 Velocity storage

The time integral of acceleration (velocity) stored in an accelerometer as a result of its dynamics is a function of accelerometer design. It is sometimes verified by analysis rather than by actual test.

The velocity storage of a fluid damped accelerometer is linearly proportional to the viscosity of the damping fluid, which can vary greatly with non-temperature-controlled operation.

5.3.19.1 Normal operation

The maximum velocity stored in the accelerometer during normal operation shall not exceed _____ [m/s, ft/s, _____].

For a force-rebalance accelerometer, the amount of velocity stored in normal operation is a function of the tightness of the torque loop. For a pulse-torqued accelerometer, it is a function of the pulse quantization as well as of the dynamics of the torque loop (including moding effects).

5.3.19.2 Over-range operation

The minimum velocity storage for an over-range acceleration pulse shall exceed _____ [m/s, ft/s, _____].

The amount of velocity that can be stored in over-range operation or across a power interrupt before the pendulum hits the stops is larger with fluid damping than it is with gas damping.

5.3.19.3 Across power interrupt

The velocity storage for normal operation across a power interrupt up to _____ [μ s, ms] in duration shall exceed _____ [m/s, ft/s, _____].

The velocity stored across a power interrupt or over-range input is recovered in the accelerometer output when, for instance, a torque-rebalance loop is reclosed, except for any error effects that have accumulated while the loop was open.

For a VBA, the resonator(s) keep vibrating because of their high quality factor Q when power is interrupted. Velocity storage in a VBA is accomplished by reconstructing the unobserved cycles that have occurred during the power interrupt using analytic algorithms in a microprocessor attached to the VBA.

5.3.20 Noise

The power spectral density (PSD) of the self-generated output noise when measured at _____ [m/s², ft/s², _____] with the power supply noise less than _____ mV rms from _____ Hz to _____ Hz shall have an average not exceeding _____ [(m/s²)², (ft/s²)², _____]/Hz from _____ Hz to _____ Hz and not exceeding _____ [(m/s²)², (ft/s²)², _____]/Hz from _____ Hz to _____ Hz.

The velocity random walk due to the white noise portion of the acceleration PSD shall be less than _____ [m/s, ft/s, _____]/ $\sqrt{h}$.

PSD limits of the output noise are sometimes defined in graphical form and in the velocity domain rather than in the acceleration domain. Allan variance can also be used to define noise requirements. See Annex I.

With the IA vertical, the standard deviation of the accelerometer output, with a filter output interval of _____ s, shall be less than _____ [m/s², ft/s², _____] for _____ [h, d].

5.3.21 Frequency response

The frequency response of the accelerometer shall meet the requirements given in [Table, Equation, Figure] _____.

System frequency response for linear analog capture loops may be specified by defining the required amplitude and phase behavior versus frequency using equations or tables, which may include allowable limits. For nonlinear capture loops, such as the pulse-rebalance type, the describing function interpretation may be invoked, whereby the response is derived as the ratio of the output at the fundamental frequency to the input, neglecting the output harmonics generated by the nonlinear system. Caution must be exercised to assure that the describing function exists for a given system. Frequency response may be determined by either analysis or test, which should include the effects of temperature, pressure, and so on. Note that generally the undamped natural frequency is

$$f_n = \sqrt{f_{45}f_{135}}$$

where

f_n is the natural frequency
 f_{45} is the frequency at which the phase shift is 45°
 f_{135} is the frequency at which the phase shift is 135°

5.3.22 Vibration-induced errors

The rectification error shall not exceed _____ [m/s², ft/s², ____] while the accelerometer is subjected to the vibration environment of Figure _____ along any combination of axes.

Vibropendulous and anisoelastic effects are two causes of rectification errors, as is asymmetry. Vibropendulous error shall be specified for vibration acceleration applied in a plane normal to the OA and at 45° to the IA. Most vibration-induced errors are approximately proportional to the square of the vibration input, although scale-factor asymmetry is an example of one that is not.

Rectification errors maybe specified for specific environments that best represent the actual application environment, such as sine vibration with specific amplitude and frequency or random vibration with PSD as a function of frequency.

5.3.23 Self-test scale factor

The accelerometer self-test scale factor shall be _____ ± _____ [m/s², ft/s², ____]/mA.

In some cases, the self-test scale factor may be specified in units of (p/s)/V or as a response to a logic or fixed input.

Subclauses 5.3.24 through 5.3.29.2 are necessary to specify the interface between the acceleration sensor and its analog or digital capture loop, which is required when *only* the *acceleration sensor* is being specified. (These clauses are *not* required when the *complete* accelerometer is being specified.)

5.3.24 Pickoff characteristics

5.3.24.1 Pickoff excitation

Pickoff excitation parameters shall not exceed the following limits:

- a) Voltage: _____ ± _____ V [ac, dc]
- b) Frequency: _____ ± _____ Hz

- c) Nominal current: _____ A
- d) Harmonic content: _____ %, maximum

This specification may be necessary for both sensor only and complete accelerometer.

5.3.24.2 Scale factor

The pickoff scale factor shall be _____ $\pm$ _____ V [ac,dc]/[rad,cm] at nominal pickoff excitation.

In some cases, it may be desirable to specify the pickoff linearity.

5.3.24.3 Phase/polarity

For a square-wave excitation, it may be necessary to specify the duty cycle and logic state voltages in addition to the following characteristics:

- a) *Sensor with ac output.* When the displacement of the proof mass is positive, the output voltage measured from terminal _____ (high) to terminal _____ (low) shall [lead, lag] the pickoff excitation by _____ $\pm$ _____ $^{\circ}$.

For opposite displacement, the output voltage (high to low) shall [lead, lag] the pickoff excitation by _____ $\pm$ _____ $^{\circ}$. These requirements shall be met for all output voltages greater than _____ V rms.

- b) *Sensor with dc output.* For positive displacement of the proof mass, the pickoff output (high-to-low) shall be _____ [positive, negative], and for opposite displacement, _____ [negative, positive].

5.3.24.4 Electrical null

The minimum electrical output shall not exceed _____ V rms when normally loaded.

In ac output cases, it may be desirable to specify the fundamental, its harmonics, and the quadrature components of the residual null. The rms output includes random noise.

5.3.24.5 Output limits

The magnitude of the output voltage for maximum proof-mass deflection in each direction shall be _____ $\pm$ _____ V [rms, dc].

The output limits need not be symmetrical about the null.

5.3.24.6 Output impedance

The pickoff output impedance at nominal excitation frequency shall be _____ $\pm$ _____ Ω .
[+,-] j _____ $\pm$ _____ Ω .

5.3.24.7 Frequency response

The transfer function of the pickoff shall meet the requirements given in [Table, Equation, Figure] _____.

5.3.25 Reference constants

Some users may request the manufacturer to supply nominal values of the following reference constants for use in users' servo analyses or evaluation of proposed acceleration sensors. Nominal values can be obtained from mathematical analysis or from physical measurements. Although analyses may be carried out without knowledge of these constants by use of data required in other portions of the document, they provide insight into the design of the sensor.

The VBA dual-resonator crossover frequency should be outside the $\pm 1\text{-g}$ range, where the input is likely to dwell (see D.5.9). The resonator zero temperature coefficient (ZTC) temperatures should be matched as closely as possible to obtain the greatest common mode rejection of temperature effects (see D.5.2). Operation near the ZTC temperature yields the lowest noise performance.

Table 2—Reference constants for acceleration sensors

Reference constant	Nominal value
Pendulum parameters (rotational proof mass)	
Effective moment of inertia	_____ $\pm$ _____ $\text{g}\cdot\text{cm}^2$
Pendulosity	_____ $\pm$ _____ $\text{g}\cdot\text{cm}$
Damping coefficient	_____ $\pm$ _____ $\text{dyn}\cdot\text{cm}\cdot\text{s}$
Anisoinertia	_____ $\pm$ _____ cm
or Translational proof mass	_____ $\pm$ _____ g
Force-rebalance parameters	
Forcer or torquer scale factor	
Electromagnetic	_____ $\pm$ _____ $[\text{dyn}, \text{dyn}\cdot\text{cm}]/[\text{mA}, \text{mA}^2]$
Electrostatic or capacitive	_____ $\pm$ _____ $[\text{dyn}, \text{dyn}\cdot\text{cm}]/[\text{V}, \text{V}^2, \text{V}^2\cdot\text{s}]$
Pickoff sensitivity	
Rotational proof mass	_____ $\pm$ _____ V/rad
Translational proof mass	_____ $\pm$ _____ V/cm
VBA resonator parameters	
Quality factor Q	$>$ _____
Unstressed frequency	
Individual resonator	_____ $\pm$ _____ Hz
Dual-resonator match	_____ $< f_1 - f_2 <$ _____ Hz
Zero temperature coefficient (ZTC) temperature	
Nominal	_____ $\pm$ _____ $^{\circ}\text{C}$
Dual-resonator match	_____ $^{\circ}\text{C}$

5.3.26 Torquer polarity

With a positive voltage applied to terminal _____ (high) referenced to terminal _____ (low), the pickoff output voltage shall be [in phase, out of phase, positive, negative] with respect to [pickoff excitation voltage, ground reference].

5.3.27 Sensor transfer function

The open-loop transfer function of the acceleration sensor as measured from forcer current input to pickoff output shall fall within the limits given in [Table, Equation, Figure] _____ for magnitude and phase over the specified frequency range.

The open-loop transfer function of the acceleration sensor must be specified in absolute terms, defined, and toleranced so that when it is combined with the transfer function of the associated capture-loop specified in 5.3.29.2, the required servo stability of the accelerometer is attained. The limits specified in 5.3.27 must be defined in cooperation with the acceleration sensor manufacturer.

5.3.28 Proof-mass elastic restraint

The elastic restraint K_r for a rotational proof-mass pendulum shall be _____ $\pm$ _____ $[\text{m/s}^2, \text{ft/s}^2, \text{_____}]/\text{rad}$ for displacements within the range of $0 \pm$ _____ radians. The elastic restraint K_r for a translational proof mass shall be _____ $\pm$ _____ $[(\text{m/s}^2)/\text{cm}, (\text{ft/s}^2)/\text{in}, \text{_____}]$.

Proof-mass elastic restraint includes all restraints such as flex lead spring restraint, pivot spring restraint, and pickoff reaction torque, but it does not include the principal restraint (rebalance torque provided by the capture loop). K_r is related to K_e of Annex A by the following relationship: $K_r = K_e / (980 \times \text{pendulosity})$, where 980 cm/s^2 is the approximate value of the local acceleration due to gravity.

5.3.29 [Analog, Pulse-rebalance] capture-loop electronics

The capture-loop electronics shall have the following characteristics to achieve the specified acceleration sensor performance.

The following parameters are for a capture loop that uses an input from a typical ac pickoff and must be modified for other pickoff types.

5.3.29.1 Capture-loop input characteristics

Capture-loop input characteristics shall not exceed the following limits:

- a) Input impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
- b) Input voltage, maximum: _____ V [ac, dc]
- c) Input voltage, quadrature: _____ V [rms, peak to peak]
- d) Input voltage, harmonics: _____ V [rms, peak to peak]
- e) Input phase angle (relative to reference voltage): _____ $\pm$ _____ $^\circ$
- f) Pickoff excitation frequency: _____ $\pm$ _____ Hz

5.3.29.2 Capture-loop frequency response

The transfer function of the [analog, digital] capture loop shall meet the requirements given in [Table, Equation, Figure] _____.

The specification must define the transfer function of the capture loop required to produce the desired closed-loop response characteristics. See box note under 5.3.21.

Subclauses 5.3.29.3 through 5.5.5 are general and are **required** regardless of whether the sensor only or the complete accelerometer is being specified.

5.3.29.3 Capture-loop output characteristics

Capture-loop output characteristics shall not exceed the following limits:

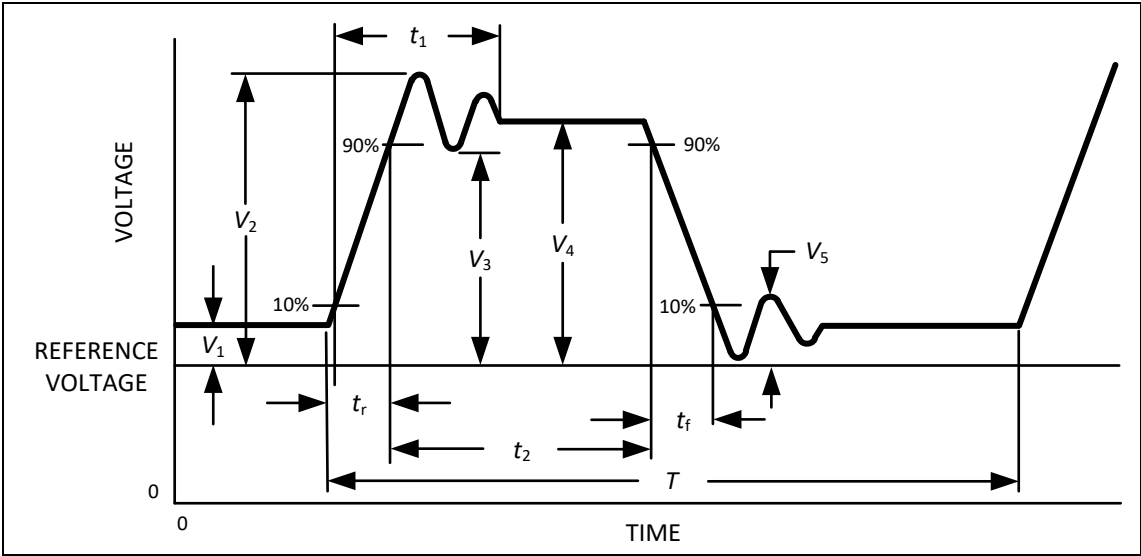
a) Analog output characteristics

- 1) Load impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
- 2) Output impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
- 3) Polarity positive with [in-phase, out-of-phase] input
- 4) Voltage range: + _____ $\pm$ _____ V to – _____ $\pm$ _____ V
- 5) Current range: + _____ $\pm$ _____ mA to – _____ $\pm$ _____ mA
- 6) With grounded input, output: < _____ Vdc
- 7) Quadrature rejection: > _____ dB (applicable only to ac-pickoff servo)
- 8) Noise: < _____ mV rms, 0 to _____ Hz for all input conditions of 5.3.29.1
- 9) Gain K_A : _____ $\pm$ _____ Vdc/V [rms, dc] with the above specified output load impedance

b) Digital output characteristics

Digital output pulses indicating positive velocity increments on one signal line and pulses indicating negative velocity increments on a second line are assumed. Other types of outputs are possible, depending on the user's interface. See Annex B.

- 1) Source impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
- 2) Load impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
- 3) Phasing with respect to clock reference: $[+, -]$ _____ $\pm$ _____ s
- 4) Polarity of output signal with +g along the input reference axis
- 5) Wave shape: (see Figure 2)
- 6) Repetition rate: _____ pulses/s (p/s)



Units	Maximum	Minimum	Results
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 seconds	_____	_____	Duration of turn-on transient time
t_2 seconds	_____	_____	Duration of high voltage on time
t_1/t_2	_____	N/A	Ratio of the turn-on transient time to required on time
T seconds	_____	_____	Waveform period
t_2/T	_____	_____	duty cycle

Figure 2—Wave shape requirements for pulse-type signals

5.3.29.4 Command input(s)

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

- a) Type
 - 1) On/Off
 - 2) Self Test
- b) Characteristics
 - 1) Source input impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
 - 2) Load impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
 - 3) Input voltage: _____ $\pm$ _____ [V dc, V ac]

5.3.29.5 Clock reference

Specify the characteristics of the clock reference, which are necessary only for digital output sensors. For example,

- a) Source input impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
- b) Load impedance: _____ $\pm$ _____ $[+, -] j$ _____ $\pm$ _____ Ω
- c) Repetition rate: _____ $\pm$ _____ p/s
- d) Wave shape: (see Figure 2)
- e) Stability: _____ ppm per _____ [h, d, yr]

5.4 Mechanical requirements

The following mechanical requirements apply to the external case to the extent specified.

5.4.1 Exterior surfaces

All exterior surfaces must withstand the environment specified herein and the handling expected in the normal course of operation, testing, transportation, and maintenance without deterioration that would cause nonconformance to this specification.

Additional requirements controlling surface finish, protective treatment, metals, dissimilar metals, workmanship, and so on, may be designated. Mounting surfaces that define the location of the IA usually require special consideration.

5.4.2 Dimensions

The outline, mounting dimensions, and center of gravity shall conform to Figure _____.

Figure 3 is a sample outline drawing. Controlled dimensions should be required only for critical parameters, as dictated by the application.

5.4.3 Identification of product

The accelerometer sensor case shall be marked _____.

The following information is typically required by the purchase agreement, although additional information may be specified:

- a) Name of component
- b) Model number
- c) Vendor code
- d) Part number
- e) Contract number
- f) Unit serial number
- g) Manufacturer's name or symbol

5.4.4 Sensor axes

The input reference axis (IRA), pendulous reference axis (PRA), and output reference axis (ORA) are nominally along the sensor IA, PA, and OA, respectively, and are defined with respect to the accelerometer mounting surfaces. The axes are designated so that the cross product of the IRA and PRA is along the ORA.

The positive directions of the reference axes shall be identified by external markings, and by reference mounting surface(s) on the case, or by other means to allow for correct installation (see Figure 3).

A micromechanical accelerometer for which IA misalignment and cross-axis error compensation is not employed may have only the IA direction marked on the external package.

For a pendulous accelerometer, the PA points toward the pendulosity from the center of rotation of the pendulum, when the pendulum is at the neutral position. Nongravitational acceleration along the IA causes the pendulum to rotate about the OA. The amount of this sensed rotation against elastic restraint is the measure of acceleration for an open-loop accelerometer or is used to determine the commanded torque to return the pendulum to the neutral position for a closed-loop accelerometer. The amount of commanded torque is then the measure of acceleration.

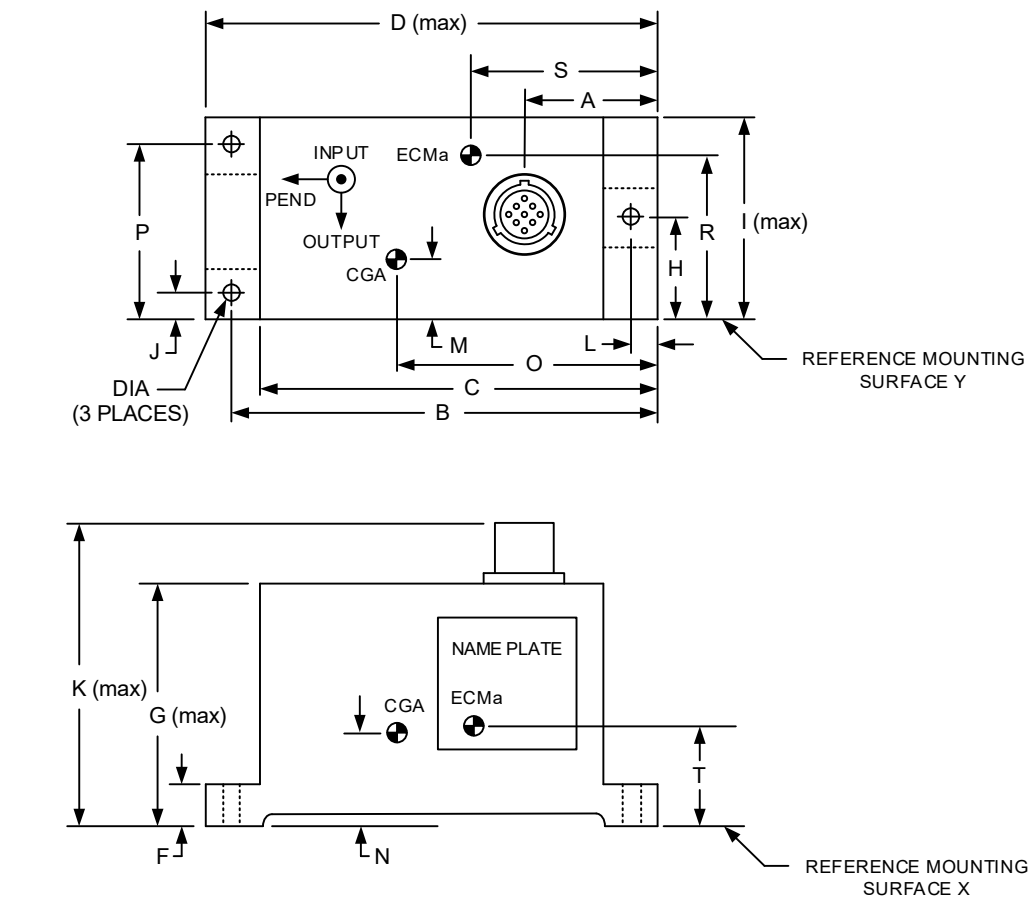
Hence the designations *IA*, *PA*, and *OA* are natural terminologies for open-loop or torque-rebalance pendulous accelerometers. One example of a pendulous accelerometer has a cylinder with a pendulosity along a radial axis that is neutrally buoyant in a fluid with any off-buoyancy compensated by magnetic suspensions. The OA is along the cylindrical axis. There is essentially no physical contact between the pendulous cylinder and the accelerometer case. The more common pendulous accelerometer design has the pendulum constrained to rotate about the OA by a hinge or flexure (see Annex C). The OA is then sometimes called the *hinge axis* (HA) or the *flexure axis* (FA), with various conventions for the axis orientation (see F.2.4).

A VBA commonly has its resonators attached to pendulous proof mass(es) with nongravitational acceleration along the IA putting one resonator in tension and the other in compression. The measure of acceleration is the difference frequency of the two resonators. The PA is naturally chosen to be the PA of one of the pendulums. The cross product of the IA and PA is still designated the OA, even though sensed rotation about the OA is not the measure of acceleration nor is it used in a torque-rebalance loop.

For a translational proof-mass accelerometer, the motion in response to nongravitational acceleration along the IA is also along the IA. The natural designation of the axes other than the IA would depend on the particular design.

In the design in which the translational motion is restrained and guided by flexures [e.g., see c) of F.2.2], there might be a natural designation for a FA. The third axis (the cross product of the IA and FA) would then have no relationship to the terminology “OA.”

A translational proof-mass design used to measure low-level nongravitational accelerations in space has capacitive sensing of the position of a proof mass in a cavity with the electrostatic force required to keep the proof mass centered being the measure of acceleration. One device can potentially measure all three acceleration DOFs; therefore, the natural designation of the accelerometer axes is IA_1 , IA_2 , and IA_3 .



PIN	DESCRIPTION
A	
B	
C	
etc	

CGA = CENTER OF GRAVITY OF THE ACCELEROMETER

ECMa = EFFECTIVE CENTER OF MASS (PERCUSSION)

THE REFERENCE MOUNTING SURFACES X AND Y ARE USED FOR LOCATING THE INPUT REFERENCE AXIS

It is not intended that this sample drawing offer specific information, but it is intended to be used as a guide. The accelerometer may be cylindrical, square, and so on. Give nominal dimensions and tolerances.

Figure 3—Outline drawing

5.4.5 Weight or mass

The mass of the [acceleration sensor, accelerometer] shall be _____ ± _____ [g, kg, _____].

If appropriate, only the maximum mass need be specified. When accessories such as cable and connector are to be included in the mass requirement, the specification shall so state.

5.4.6 Seal

The following requirements shall be met:

Specify either item a), item b), or item c) as appropriate.

- a) *Fluid filled.* No fluid leakage shall be detected under _____ power magnification after being subjected to an external vacuum at _____ $\pm$ _____ Pa and a temperature of _____ $\pm$ _____ °C for a minimum period of _____ [s, min].
- b) *Gas-filled or evacuated.* Maximum gas leakage rate shall not exceed _____ cm³/s of _____ gas measured at standard conditions for a minimum period of _____ [s, min] while being subjected to a vacuum of _____ $\pm$ _____ Pa at a temperature of _____ $\pm$ _____ °C.
- c) There shall be no flow of bubbles after _____ [s, min].

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

5.5 Electrical and magnetic requirements

The accelerometer's electrical and magnetic design requirements shall be as specified as follows and shall meet the performance criteria of 5.3 during all reasonable variations of the inputs of 5.5.1.

5.5.1 Electrical interface

The electrical interface may consist of the connections illustrated in Figure 4a and Figure 4b, as modified for the particular accelerometer under test.

Other connections may also be included for which electrical characteristics must be specified.

The following characteristics are measured in nonoperating tests, whereas the electrical characteristics in 5.3.24 and 5.3.29, for example, are measured in operating tests.

5.5.1.1 Torquer or forcer characteristics

Torquer or forcer characteristics shall not exceed the following limits:

- a) Resistance: _____ $\pm$ _____ Ω
- b) Inductance: _____ $\pm$ _____ H
- c) Capacitance: _____ $\pm$ _____ F

These data are needed for acceleration sensor-only specification.

5.5.1.2 Pickoff characteristics

Pickoff characteristics shall not exceed the following limits:

- a) Resistance: _____ $\pm$ _____ Ω
- b) Inductance: _____ $\pm$ _____ H
- c) Capacitance: _____ $\pm$ _____ F

5.5.1.3 Heater characteristics

Heater characteristics shall not exceed the following limits:

- a) Resistance: _____ $\pm$ _____ Ω
- b) Inductance: _____ $\pm$ _____ H

The nonoperating measurement of the heater characteristics is done with a small current level at room temperature unless otherwise specified. The resistance will change at operating current levels and temperature.

5.5.1.4 Temperature sensor characteristics

Temperature sensor characteristics shall not exceed the following limits:

- a) Resistance: _____ $\pm$ _____ Ω
- b) Inductance: $\pm$ _____ $\pm$ _____ H

The nonoperating measurement of the temperature sensor characteristics is done at room temperature. The resistance will vary as the temperature varies during operation. Other types of temperature sensors may have different characteristics and outputs (e.g., frequency and current).

5.5.1.5 Self-test torquer or forcer characteristics

Self-test torque or forcer characteristics shall not exceed the following limits:

- a) Resistance: _____ $\pm$ _____ Ω
- b) Inductance: _____ $\pm$ _____ H
- c) Capacitance: _____ $\pm$ _____ F

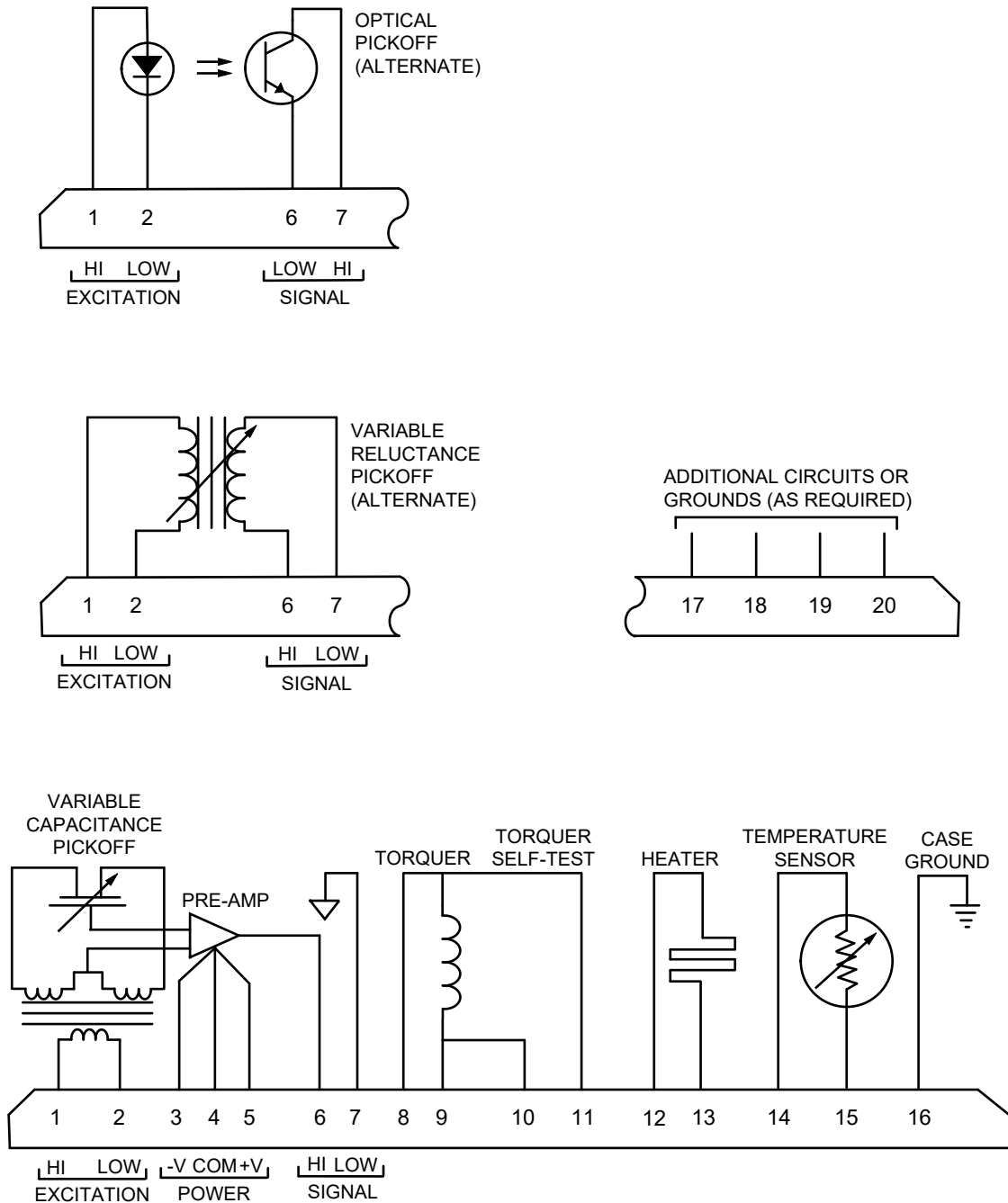


Figure 4a—Example of torque-rebalance electrical interface

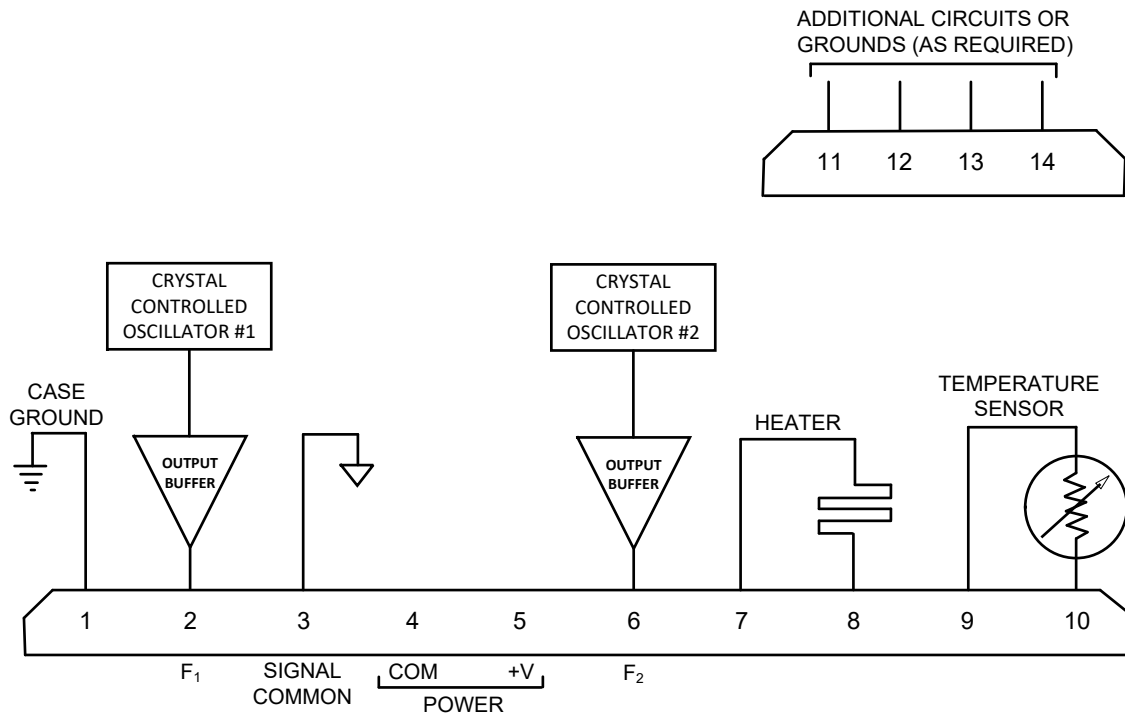


Figure 4b—Example of VBA electrical interface

5.5.2 Electromagnetic interference/compatibility

Describe the requirements for electromagnetic radiated and conducted emissions and susceptibility. In the United States, the requirements and test methods may be selected from MIL-STD-461.⁶

5.5.3 Insulation resistance

The insulation resistance between the isolated interface circuits and the case shall not be less than _____ MΩ measured at _____ ± _____ V dc applied for _____ ± _____ s.

Different voltages may be specified for different circuits. A time duration is specified for the measurement to detect any breakdown phenomenon in the resistance between the isolated circuits at the applied voltage.

5.5.4 Dielectric strength

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

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

5.5.5 Magnetic leakage

The magnetic leakage shall not exceed _____ [mT, G] at a distance of _____ m from the accelerometer sensor in any direction.

⁶ Information on references can be found in Clause 2.

5.6 Environmental requirements

The accelerometer may be subjected to the environmental conditions in this clause during storage, transportation, handling, or operation. The accelerometer shall be designed to satisfy the performance requirements in 5.3 during (if appropriate) and after exposure to these environments.

5.6.1 Nonoperating environment

The following conditions, occurring separately or in combination, may be encountered during transportation, handling, or storage. The accelerometer shall conform to all the performance requirements of 5.3 after exposure to any reasonable combination of the specified conditions.

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

5.6.1.1 Temperature

Ambient temperature may vary from a minimum of _____ °C to a maximum of _____ °C.

5.6.1.2 Thermal shock

From _____ °C to _____ °C, the heating and cooling rates of the ambient environment shall not exceed _____ °C/s.

For cyclic conditions, temperature limits must be specified for each level, with dwell times and sequence.

5.6.1.3 Vibration

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

5.6.1.4 Mechanical shock

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

5.6.1.5 Pressure

The ambient pressure shall be in the range _____ [Pa, psia] to _____ [Pa, psia]. The rate of change of pressure shall be nominally _____ [Pa/s, psia/s].

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

5.6.1.6 Humidity

The relative humidity shall not exceed _____ % RH.

5.6.1.7 Magnetic induction

Define magnitude, direction with respect to each axis, and duration. If there is exposure to magnetic induction resulting from ac, specify the intensity versus frequency.

5.6.1.8 Nuclear radiation

Describe the nuclear environment(s). For each environment, include the type of radiation (e.g., X-ray, gamma, and neutron), intensity, spectrum, exposure duration, and axes of application.

5.6.1.9 Other nonoperating environments

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

5.6.1.10 Storage life

Under the storage conditions of 5.6.1, the accelerometer shall meet the requirements of this specification after a storage interval of _____ yr. The maximum allowed parameter changes across the storage environment are as follows:

- a) Bias: _____ [m/s^2 , ft/s^2 , _____]
- b) Scale factor: _____ ppm
- c) IA misalignment: _____ [μrad , "]

Maximum allowed changes in nonlinearity and other parameters may also be specified. Any allowed repairs during the storage life may also be specified.

5.6.2 Operating environment

The following conditions, occurring separately or in combination, may be encountered during operation. The accelerometer shall conform to all the performance requirements of 5.3 during, unless otherwise specified, and after exposure to any reasonable combination of the specified service conditions.

5.6.2.1 Temperature (high and low)

Ambient air temperature may vary from _____ $^{\circ}\text{C}$ to _____ $^{\circ}\text{C}$.

5.6.2.2 Thermal shock

From _____ $^{\circ}\text{C}$ to _____ $^{\circ}\text{C}$, the heating and cooling rates of the ambient environment shall not exceed _____ $^{\circ}\text{C/s}$.

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

5.6.2.3 Other thermal conditions

Other thermal conditions that may affect performance shall be specified, for example, equivalent heat sink, radiant energy from surrounding surfaces, and power dissipation. Restrictions on allowable heat transfer may also be specified as, for example, conduction only, radiation only, or convection only. If cooling air is available, its characteristics must be specified, providing volume, rate, and air temperature.

5.6.2.4 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 figure if applicable), tolerance, bandwidth, peak acceleration level, total rms acceleration, duration, and axes of application.

5.6.2.5 Mechanical shock

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

5.6.2.6 Acceleration

Specify the maximum acceleration along each of the three axes and the duration.

5.6.2.7 Pressure

The ambient pressure shall be in the range _____ [Pa, psia] to _____ [Pa, psia]. The rate of change of pressure shall be nominally _____ [Pa/s, psia/s].

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

5.6.2.8 Humidity

The operating relative humidity shall not exceed _____ % RH.

5.6.2.9 Acoustic noise

Describe the acoustic noise environment. Supply the specific noise spectrum in decibels versus frequency, tolerance, bandwidth, peak level, and duration. Use a 0-dB reference of 20 μ Pa.

5.6.2.10 Magnetic induction

Define magnitude, direction with respect to each axis, and duration. If there is exposure to magnetic induction resulting from ac, specify the intensity versus frequency.

5.6.2.11 Nuclear radiation

Describe the nuclear environments(s). For each environment, include the type of radiation (e.g., X-ray, gamma, and neutron), intensity, spectrum, exposure duration, and axes of application.

5.6.2.12 Other operating environments

Include any other appropriate operating environmental conditions, such as rain, fungus, salt spray, sand, and dust.

5.6.2.13 Operating life

Under the specified operating conditions of 5.6.2, the accelerometer shall be capable of operating and performing within the requirements of this specification for a minimum accumulated operating period of _____ [h, d, yr] for a minimum of _____ and a maximum of _____ on-off cycles. The maximum allowed lifetime parameter changes are as follows:

- a) Bias: _____ [m/s^2 , ft/s^2 , _____]
- b) Scale factor: _____ ppm
- c) IA misalignment: _____ [μrad , "]

Maximum allowed changes in nonlinearity and other parameters may also be specified. Any allowed repairs during the operating life may also be specified.

5.6.3 Dormancy environment

The following conditions, occurring separately, in combination, or in a defined sequence, may be expected during dormant storage.

The temperature, pressure, vibration, shock, radiation, and other environments shall be specified.

The accelerometer shall perform to the requirements of 5.3 after _____ [d, yr] of dormancy. The maximum allowed parameter changes across dormancy are as follows:

- a) Bias: _____ [m/s^2 , ft/s^2 , _____]
- b) Scale factor: _____ ppm
- c) IA misalignment: _____ [μrad , "]

Periodic monitoring may be a condition of dormancy. The parameters to be monitored and the period of monitoring shall be specified. Maximum allowed changes in nonlinearity and other parameters may also be specified.

5.7 Reliability

5.7.1 Reliability program

The reliability program shall be in accordance with _____.

In the United States, a commonly used standard is IEEE Std 1332TM.

5.7.2 Mean time between failure (MTBF)

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

6. Quality assurance

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