



IEEE Recommended Practice for Inertial Sensor Test Equipment, Instrumentation, Data Acquisition, and Analysis

IEEE Aerospace and Electronic Systems Society

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Abstract: Test equipment, data acquisition equipment, instrumentation, test facilities, and data analysis techniques used in inertial sensor testing are described in this recommended practice.

Keywords: data acquisition, data analysis techniques, gyro and accelerometer testing, inertial sensor testing, instrumentation, test equipment

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Introduction

This introduction is not part of IEEE Std 1554-2005, IEEE Recommended Practice for Inertial Sensor Test Equipment, Instrumentation, Data Acquisition, and Analysis.

This document gives recommended practices for gyroscope and accelerometer testing and test data analysis. General and sensor specific equipment and instrumentation are described, including mounting fixtures, dividing heads and rotary test tables, vibration and shock machines, centrifuges, radiation test facilities, and thermal and other environmental chambers. Inertial sensor readouts, test control, data acquisition, filtering, and analysis are discussed. Analysis procedures include plotting, least-square polynomial and other fits, power spectral density and Allan variance noise analysis, and performance model parameter calibration estimation.

This recommended practice represents a consensus of manufacturers and users in industry, government agencies, and other interested groups. When necessary, the needs of the inertial sensor community have been given preference over general technical usage.

This recommended practice was prepared by the Gyro and Accelerometer Panel of the Aerospace Electronics System Society of the Institute of Electrical and Electronic Engineers. This document represents a group effort on a large scale. A total of 81 individuals attended 31 meetings of the Gyro and Accelerometer Panel while this standard was in preparation.

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IEEE Recommended Practice for Inertial Sensor Test Equipment, Instrumentation, Data Acquisition, and Analysis

1. Overview

1.1 Scope

Recommended practices for gyroscope and accelerometer testing are discussed, ranging from the equipment and instrumentation employed to the way that tests are carried out and data are acquired and analyzed.

Normative references are given in Clause 2, and a bibliography is given in Annex A. Test planning is described in Clause 3. General equipment and sensor-specific equipment for testing gyroscopes and accelerometers are described in Clause 4 and Clause 5. Mounting fixtures, test piers, accelerometer dividing heads, and gyroscope rate tables are discussed in Clause 6, Clause 7, Clause 8, and Clause 9. Three-axis tables for inertial sensor assembly (ISA) testing are described in 9.4.

Vibration and shock equipment, centrifuges, and environmental chambers are described in Clause 10, Clause 11, and Clause 12. Nuclear radiation facilities are discussed in Clause 13. Special readout instrumentation required in gyroscope and accelerometer testing is discussed in Clause 14, Clause 15, Clause 16, and Clause 17. Such instrumentation includes counter and frequency readouts, analog-to-digital (A/D) conversion readouts, temperature monitoring, and other monitoring and commanding functions over various types of interfaces and buses.

Computer data acquisition, control, filtering, and storage are described in Clause 18. The analysis of test data is discussed in Clause 19. Such analysis includes the plotting of data channels versus time and other data channels, least-squares fits of polynomials and other models to data, power spectral density (PSD) and Allan variance noise analysis, and regression analysis and parameter estimation.

Geophysics instrumentation is discussed in Clause 20 because inertial sensors are tested on the earth, which provides seismic, tilt, and other disturbances, but also provides the fundamental gravity and earth rotation inputs against which sensor parameters (such as scale factor) are calibrated. Therefore, the acceleration due to gravity at a test site and the site latitude and longitude must be accurately determined.

The calibration of test site coordinates and gravity acceleration, the calibration of test station electrical and other equipment, and fundamental time and frequency references are discussed in Clause 21.

1.2 Purpose

This recommended practice is intended for people who test inertial sensors and analyze the results from such testing. The general and specialized test equipment employed in such testing is described, and recommendations are made on techniques for acquisition, filtering, storage, and analysis of the test data in keeping with modern practice.

2. Normative references

The following referenced documents are indispensable for the application of this recommended practice. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies. In the event of any conflict, the recommended practices of this document shall have precedence over the documents listed in this clause.

2.1 IEEE standards

IEEE/ASTM SI 10, Standard for Use of the International System of Units (SI): The Modern Metric System.¹

IEEE Std 260.1TM, American National Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units).²

IEEE Std 292TM, IEEE Specification Format for Single-Degree-of-Freedom Spring-Restrained Rate Gyros.

IEEE Std 293TM, IEEE Test Procedure for Single-Degree-of-Freedom Spring-Restrained Gyros.

IEEE Std 315TM, IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams.

IEEE Std 517TM, IEEE Standard Specification Format Guide and Test Procedure for Single-Degree-of-Freedom Rate-Integrating Gyros.

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

IEEE Std 529TM, IEEE Supplement for Strapdown Applications to IEEE Standard Specification Format Guide and Test Procedure for Single-Degree-of-Freedom Rate-Integrating Gyros.

IEEE Std 647TM, IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Laser Gyros.

IEEE Std 671TM, IEEE Standard Specification Format Guide and Test Procedure for Nongyroscopic Inertial Angular Sensors: Jerk, Acceleration, Velocity, and Displacement.

IEEE Std 813TM, IEEE Specification Format Guide and Test Procedure for Two-Degree-of-Freedom Dynamically Tuned Gyros.

IEEE Std 836TM, IEEE Recommended Practice for Precision Centrifuge Testing of Linear Accelerometers.

IEEE Std 952TM, IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros.

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IEEE Std 1293™-1998, IEEE Standard Specification Format Guide and Test Procedures for Linear, Single-Axis, Non-Gyroscopic Accelerometers.

IEEE Std 1431™, IEEE Standard Specification Format Guide and Test Procedure for Coriolis Vibratory Gyros.

2.2 ISO standards

ISO 8568, Mechanical Shock — Testing machines — Characteristics and performance.³

ISO 16063 series, Methods for the calibration of vibration and shock transducers.

2.3 Nuclear radiation test standards

ASTM F 744M, Standard Test Method for Measuring Dose Rate Threshold for Upset of Digital Integrated Circuits (Metric).⁴

ASTM F 773M, Standard Practice for Measuring Dose Rate Response of Linear Integrated Circuits (Metric).

ASTM F 980M, Standard Guide for Measurement of Rapid Annealing of Neutron-Induced Displacement Damage in Silicon Semiconductor Devices (Metric).

ASTM F 1190, Standard Guide for Neutron Irradiation of Unbiased Electronic Components.

ASTM F 1192M, Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices (Metric).

ASTM F1262M-95, Standard Guide for Transient Radiation Upset Threshold of Digital Integrated Circuits.

ASTM F 1892, Standard Guide for Ionizing Radiation (Total Dose) Effects Testing of Semiconductor Devices.

ASTM F 1893, Standard Guide for Measurement of Ionizing Dose-Rate Burnout of Semiconductor Devices.

EIA JESD 57, Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation.⁵

MIL-STD-750, Test Method Standard for Semiconductor Devices.⁶

MIL-STD-883E, Test Method Standard for Microcircuits.

³ISO publications are available from the ISO Central Secretariat, Case Postale 56, 1 rue de Varembe, CH-1211, Genève 20, Switzerland/ Suisse (<http://www.iso.ch/>). ISO publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

⁴ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (<http://www.astm.org/>).

⁵EIA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).

⁶MIL publications are available from Customer Service, Defense Printing Service, 700 Robbins Ave., Bldg. 4D, Philadelphia, PA 19111-5094.

3. Test planning

3.1 Classification of tests

The inspection and testing of inertial sensors can be classified into the following categories:

- a) *Characterization tests* and *evaluation tests*, performed on a device that is under development. *Requalification tests* to verify design changes. *Development tests* to design improved test methodologies and test equipment.
- b) *Acceptance tests*, performed on production or repaired sensors submitted for acceptance under contract in environments expected to be encountered in the intended application.
- c) *Diagnostic tests* and/or *anomaly investigation*, performed on devices that pass acceptance test procedures (ATP), but subsequently exhibit nontypical performance.
- d) *Calibration tests*, such as for scale factor, bias, and misalignments, can be performed during acceptance testing and throughout the lifetime of the sensor at the inertial-navigation-system level as well as the individual-sensor level. Some parameters, such as temperature sensitivities and model nonlinearities, require factory calibration and may have to be valid for the lifetime of the sensor. Calibration of model parameters to be used in an inertial navigation mission is accomplished before a mission by estimating the parameters from data collected when the sensor is provided with known inputs, such as from tumbling in the earth's gravity field, slewing about various axes, or from vibration or centrifuge tests. Parameter calibration can also be accomplished during a mission using external aids to the inertial navigation system, such as from a radio navigation receiver or a star tracker, or during periods of zero velocity update when it is known that the inertial navigation system is stationary.
- e) *Qualification tests*, performed on samples submitted for qualification as a satisfactory product. Qualification test environments may be more severe than environments used in acceptance testing because the purpose of qualification testing is to demonstrate design margin. Sensors that have undergone qualification testing are usually not considered mission-worthy.
- f) *Reliability tests* and *life tests*, performed to demonstrate the level of reliability and mean time before failure (MTBF) and to assure the ability to maintain, with a certain confidence level, the required reliability. Accelerated reliability and life testing may involve environments more severe than environments encountered in operational use.
- g) *Analysis*, a process used in lieu of or in addition to testing to verify compliance with specifications. The technique typically includes interpretation or interpolation/ extrapolation of analytical or empirical data under defined conditions or reasoning to show theoretical compliance with requirements.

3.2 Calibrated parameter characteristics

The variation in a gyroscope's angular rate bias or in an accelerometer's acceleration bias can be due to systematic effects, such as trend (due to such things as stress relaxation and magnetic decay) or environmental sensitivities, or to random effects, such as flicker noise or random walk. White process noise in bias does not cause changes in bias on average, but does cause angle random walk in gyroscope output or velocity random walk in accelerometer output, with a standard deviation that grows as the square root of time. The measurement and process noise in an inertial sensor's output can be determined by PSD and Allan variance analysis (see 19.5 through 19.9).

- a) *Stability*. Calibration of bias, scale factor, input axis (IA) misalignment, and other inertial sensor model parameters over time determines
 - 1) *Short-term stability*, allowed variation over the duration time of a mission or over a specified segment of this duration time.

- 2) *Long-term stability*, allowed variation over the period from the last time a parameter is calibrated until it is used in a mission or over some defined time period if calibration occurs just prior to or during the first part of a mission.
- b) *Repeatability*. Calibration of parameters before and after environmental excursions, such as vibration and shock, temperature cycle, radiation exposure, or turn-off and turn-on, determines
 - 1) *Repeatability characteristics* of a parameter from before to after an environmental excursion, including the magnitude of any shift, the magnitude and time constant of any transient, and any change in trend from before to after the environmental excursion.
 - 2) *Turn-on and warm-up characteristics* (magnitude and time constant) measured during a repeatability test across shutdown to ambient temperature and turn-on to operating temperature.
 - 3) *Service life uncertainty* over the useful life of a sensor when periodically removed from storage conditions and measured at constant operating conditions (particularly important for those parameters that are calibrated only in the factory).
- c) *Sensitivity*. Calibration of parameters at various temperature settings, magnetic fields, or other environmental states within the operating environment of the sensor determines sensitivity, which is the change in output or a parameter due to a change in an undesirable or secondary input. For example, a scale factor temperature sensitivity of a gyro or accelerometer is the change in scale factor due to a change in temperature.

The variation in a parameter over time and environmental variations after compensation with a calibrated model, such as for temperature, should be less than requirements. Normally, the variations are specified as 1-sigma in order to be able to root-sum-square their effects together. However, some other measure of allowed variation could be used, such as 2-sigma, 3-sigma, or maximum magnitude.

3.3 Test plan outline

Before performing a given class of tests on an inertial sensor, a test plan must be written. The overall table of contents for such a test plan could be as follows.

- 1) Overview (including description of sensor being tested and the types of tests)
- 2) References
- 3) Applicable documents (including contractual and performance and other specification documents)
- 4) Test conditions and equipment
- 5) Data acquisition equipment and software
- 6) Test procedures
- 7) Data analysis procedures

The IEEE standards listed in 2.1 describe the types of tests and the test procedures that are done on various types of gyroscopes and accelerometers. The remainder of this IEEE recommended practice describes the supporting facilities, equipment, and techniques for carrying out these tests and analyzing the results.

3.4 Test station log book

Each test station or series of tests should have a log book, where the test engineer or test technician notes the date, time, and information concerning events that occur during testing, such as

- a) Calibration of test station equipment
- b) Troubleshooting of problems

- c) Test setup, test conditions (such as temperature or magnetic field), and test table orientation and/or angular rate
- d) Start of a given test (namely, sensor serial number, type of test)
- e) Name of the data acquisition file written by the data acquisition computer
- f) Events that occur during a test, including changes in test conditions and test table orientation and/or angular rate
- g) Termination of test

4. General equipment

4.1 Calibration of equipment

Test station equipment should be calibrated relative to primary standards periodically, such as once per year or at the start of a long test sequence (see Clause 21). This service could be provided by a calibration laboratory in a test organization as part of the total quality management effort of the organization.

4.2 Test station power supplies and grounds

There should be surge protection, regulation, and fuses or circuit breakers between the commercial ac electrical supply and the test station equipment. Fuses are a safety device to prevent a sensor under test from being damaged. In an expendable vehicle, such as a missile, fuses are usually not allowed because they provide an additional point of failure and because turning off a sensor is as bad as damaging it as far as completion of the mission is concerned.

An uninterruptible power supply (UPS) would keep a test running across momentary or long-duration power failures. An UPS could range from batteries charged by the commercial electrical supply to a large flywheel attached to a generator, where the flywheel is kept rotating by the commercial electrical supply or by, for example, a diesel engine if there is a commercial power failure.

Commercial equipment generally plugs into the commercial ac electrical supply outlets. Other devices and the inertial sensor under test could need special ac power supplies (such as for wheel motors) and dc power supplies (such as +5 V or ± 15 V; see Clause 5) that plug into ac outlets. These power supplies could be in an equipment rack adjacent to the test table if there are direct lines to the inertial sensor with acceptable cable wrap as the test table rotates. If there is continuous table rotation, then ac and dc power could go through slip rings. Alternatively, the ac and dc power supplies could be on the table top with the inertial sensor under test, with only the source power going through the slip rings.

Ground lines would go through slip rings. Power supply grounds should not share the same line as the grounds for the inertial sensor under test and other devices, such as thermistors. Ground lines should come to a common point, with ground loops avoided. There should be optical isolation between the data acquisition computer and the signals from the inertial sensor under test.

4.3 Time and frequency standard

When testing high-precision sensors, an inertial sensor test station should have an external frequency reference for timing interrupts and running counters because a data acquisition computer's internal clock is inadequate.

The test station frequency reference could be a quartz crystal frequency standard, an embedded atomic clock, or a remotely located atomic clock whose output is piped into the test station. The quartz crystal

frequency standard, which could be on the table top with the inertial sensor under test, should be calibrated against an atomic standard before and/or after an experiment. The atomic clock could be kept close (within a few milliseconds) to the absolute time provided by a national time service radio broadcast (see 21.2).

For inertial sensor testing, the absolute value of time is not as important as is the precision and accuracy of the frequency reference. The absolute time of the start of a test should be noted within a few seconds accuracy, and the time of data points relative to the start of the test should be inferred from the count of data acquisition computer interrupts and the precise time between interrupts provided by the frequency standard.

An error in the frequency reference would directly affect the sensor scale factor measured in a test, namely, a ppm error in the frequency reference would, in general, cause a ppm error in a gyroscope or accelerometer scale factor measurement.

4.4 Precision voltage reference

The process of A/D or voltage-to-frequency conversion needs a precision voltage reference, which could be internal to a commercial device, such as a voltmeter, or could be a reference for the test station as a whole.

The accuracy of the precision voltage reference used in the readout of an inertial sensor, such as for an integrating voltmeter's reading of an analog-torque-loop voltage output or for controlling the height of a torque pulse in a digital torque loop, sets a limit on the measurement accuracy of an inertial sensor that needs such a reference in its readout.

The accuracy of a precision voltage source is typically no better than a ppm for nonsuper-conducting technology.

4.5 Voltmeters

A commercial integrating dc voltmeter can be used to measure the output of a torque-rebalance inertial sensor, where the dc voltage is integrated in the voltmeter for a given period of time, displayed on, for example, a seven-decimal-digit display, and output over a bus (such as IEEE 488™ [B6]⁷) to the data acquisition computer (see 15.1). There is typically a dead zone between the end of one measurement and the start of the next, which could be undesirable for reading the primary output of an inertial sensor.

A simple rectifying ac voltmeter might be adequate for some applications. A true root-mean-square (rms) voltmeter may be called for when greater precision is required.

4.6 Ammeters and wattmeters

Commercial devices such as ammeters and wattmeters are less frequently used in inertial sensor performance testing, except for monitoring auxiliary signals, such as the power drawn by a mechanical gyro's wheel motor. The current through an inertial sensor's torquer is usually converted to a voltage by a precision resistor and read by an integrating voltmeter.

4.7 Resistance references

A reference resistor is used as a current-to-voltage conversion reference for the current output of an inertial sensor analog torque loop so the torque loop output can be read by a voltmeter. A solid-state temperature-to-current converter would also need a reference resistor to change its output to a voltage that can be read

⁷Numbers in brackets correspond to the numbers in the bibliography in Annex A.

by an A/D converter or voltmeter. Reference resistors are used in a bridge circuit for measuring the resistance of a thermistor or other such device whose resistance varies with temperature.

The performance of the bridge or current-to-voltage conversion circuit could be tested by replacing the thermistor or other such resistance by a decade resistance box, where desired resistances can be added together. The resistors in the decade box would need periodic calibration (see 4.1).

4.8 Magnetic field shielding

An inertial sensor under test could be covered with magnetic shielding for an experimental sensor that did not have such shielding. A production sensor would normally have magnetic shielding integrally designed into its case, if the sensor had magnetic sensitivities, so that the magnitude of the magnetic field seen in the application (such as from gimbal motors) multiplied by the magnetic sensitivity of the sensor after attenuation by the magnetic shielding is less than requirements.

Magnetic shielding is provided by an appropriate thickness of a material such as μ -metal, which will attenuate magnetic fields from penetrating into the interior it surrounds. Care must be taken to have shielding overlap areas where wires, etc., penetrate into the interior of the sensor.

4.9 Magnetic field generation and measurement

Magnetic sensitivity measurements of an inertial sensor involve placing a Helmholtz coil around the device. The Helmholtz coils have cylindrical symmetry to generate a uniform magnetic field within the cylinder. Structural support for the coils is provided by wooden or other such nonmagnetic framework.

With the sensor not in the coil, current is put through the coil, and the resulting magnetic induction strength within the coil is measured with a commercial Gauss meter (or with a magnetometer for low magnetic fields). Then the inertial sensor is placed within the coil, and the desired magnetic field is generated by putting appropriate current through the coils.

The magnetic induction levels would be of the order of the levels to be encountered in a mission, such as from nearby gimbal motors and from the 5 mT magnetic induction⁸ from the earth's magnetic field; or they could be larger to amplify effects. An example magnetic induction sensitivity test schedule is

0, +50, +100, +50, 0, -50, -100, -50, 0 mT

If the inertial sensor were in a fixed orientation, such as IA vertical, while the magnetic field was varied, then a lumped bias and scale factor magnetic sensitivity would be measured by fitting a linear or higher order polynomial in magnetic induction strength to the inertial sensor output. Orienting an accelerometer IA up and down or rotating a gyroscope at various rates about IA at each magnetic induction level would allow the bias and scale factor magnetic sensitivities to be separated if the magnetic field were kept at a constant orientation relative to the inertial sensor axes during sensor reorientations.

4.10 Frequency synthesizers

Some readout systems read a frequency output from an inertial sensor (see 4.15). A commercial frequency synthesizer can be used to test such a readout scheme by generating a sinusoid or square wave at a specified frequency to determine whether the readout measures that frequency.

The frequency generated is more precise if an external frequency reference, such as a 10 MHz atomic standard, is input to the frequency synthesizer, rather than using the internal frequency reference within the frequency synthesizer.

⁸0.5 Gauss.

4.11 Oscilloscopes

An oscilloscope is a useful tool for looking at inertial sensor test points for debugging purposes. An A/D converter reads the voltages in electrical waveforms and plots the waveforms on a screen versus time or versus each other. The plot can scroll off the screen as time progresses, or it can be repeated on the screen at a specified repetition frequency, which can be adjusted to match the repetition frequency of the signal so that slowly varying changes relative to the repetition frequency can become apparent on the screen.

4.12 Spectrum analyzer

There are commercial spectrum analyzers that will compute the frequency spectrum of a voltage waveform or a digital input. The same can be accomplished by acquiring the signal and passing it through the analysis software described in 19.5 if appropriate data acquisition and analysis hardware and software have been set up for inertial sensor testing.

4.13 Signal analyzer

A signal analyzer is a commercial piece of equipment that calculates the transfer function from one signal to another. The same can be accomplished by acquiring the signals and passing them through the cross PSD analysis mentioned in 19.10.2.

4.14 Voltage- or current-to-frequency converters

If a voltage or current is integrated and the accumulated value is converted to a square wave for which the time between rising edges represents a given increment of voltage or current integral, then the measurement of the frequency of the square wave gives a measure of the voltage or current, averaged over the acquisition interval. This can be a very elegant way of accurately measuring voltage or current, especially in inertial sensor testing that is interested in time integrals because frequency or period can be measured very accurately (see 4.15).

Commercial voltage- or current-to-frequency converters are available. However, the accuracy often required in inertial sensor testing is such that a specially built piece of equipment is likely required (see 15.3).

4.15 Frequency counters

There are commercial frequency counters that take a square or sinusoidal wave input and then output the frequency of the wave in its display or, for example, over the IEEE 488 bus. Such a device needs a timing reference, which can be either internally generated or from an external source. The latter option can provide greater accuracy than that obtained with an internally generated quartz crystal reference, especially when an atomic clock is used.

The frequency f_{in} of an input signal is typically determined by counting the number M of clock cycles for a given number N of rising edges of the input signal. The frequency of the input signal is

$$f_{\text{in}} = \frac{N}{M} \times f_{\text{clk}} \quad \text{Hz}, \quad (1)$$

where

f_{clk} is the clock frequency (Hz)
 M is much greater than N

The quantization error in this measurement arises from the fractional timing pulse that is not counted at the rising edge interrupt. The quantization error decreases linearly with the number N of input rising edges that are measured. Some commercial frequency counters increase the resolution of a timing pulse by charging a capacitor at the moment of a rising edge interrupt until the next or second next rising clock edge. The fractional pulse missed in the counter is determined from the voltage on the capacitor.

A commercial frequency counter will often have a dead band between measurements made every few seconds. Coherency is thereby lost from one measurement to the next. In order to retain this coherency, which can be important for inertial sensor testing, continuous counter readouts are desirable, probably as a specially built piece of equipment (see Clause 14).

4.16 Temperature controllers

Temperature control of an inertial sensor itself would be provided by manufacturer-supplied electronics (see Clause 5).

If the inertial sensor were mounted on a thermally controlled mounting flange (see 6.2) or in a thermally controlled oven (see Clause 12), then commercial temperature control electronics would be required. The thermal controller would put current through heater strips or thermoelectric heater-coolers or command the flow of refrigerant to maintain temperature at a given set point, as monitored by a thermistor or other such device (see 4.17).

Care must be taken that the electric current that controls the temperature of an oven or mounting fixture does not interfere with the performance of the inertial sensor through self heating, electrical or magnetic interference, or other mechanisms. Such interference could more likely occur with a bang-bang rather than proportional controller.

4.17 Temperature-monitoring equipment

Temperature sensors can be placed on or within an inertial sensor, on a mounting fixture, or in electronics enclosures or exposed to the laboratory air. These temperature sensors should have good thermal contact with the parts whose temperatures are being monitored. One such solid-state temperature-sensing device has a current output that is proportional to the temperature. Another commercially available temperature-monitoring device is a quartz crystal oscillator whose frequency varies with temperature.

Another temperature sensor is a thermistor or platinum resistor, whose resistance varies with temperature. Hence, a small current has to flow through the device in order to measure the resistance with a bridge circuit. The bridge could be at a certain set point, with temperature variations around that set point creating a voltage output that can be read by a data acquisition computer's A/D converter. Because a thermistor's resistance is a nonlinear function of temperature, a look-up table or model is required to determine the temperature from the output voltage. For small temperature variations around the set point, a linear scale factor can be used.

Care must be taken that the current flowing through a temperature-monitoring device does not interfere with the performance of the inertial sensor. Some inertial sensors have an output signal that can measure temperature for compensation and/or control, independent of the primary output of the sensor that measures inertial input (angle change for a gyro or nongravitational acceleration for an accelerometer).

4.18 Bubble levels and tilt meters

A precision bubble level read by eye can be used in aligning a test fixture relative to the local vertical to within a few arcseconds (see 8.4).

A tilt meter measures the small deviation from horizontal as well as the horizontal acceleration. It has an electrical output that can be read by a data acquisition computer. Outputs below 0.1 Hz are normally considered to be due to tilt, whereas outputs above 0.1 Hz are normally considered to be due to horizontal acceleration. Examples of tilt meters are an electronically read bubble level or a pendulous device. A pendulous tilt meter that can measure large angular deviations is called an *inclinometer*.

Tilt angles are usually measured as rotations about east and rotations about north. The scale factor of the voltage output from a tilt meter can be calibrated by rotating the tilt meter a known angle from the horizontal (see 21.5). Measured tilt variations during an inertial sensor test can be used to compensate gyroscope output for motion of the gyro IA relative to the earth's rotation vector and to compensate accelerometer output for motion of the accelerometer IA relative to the local vertical.

An accelerometer with IA nearly horizontal can be used to measure tilt variations. Tilt variations during an accelerometer tumble test as well as angle setting errors can be compensated using dual orthogonal accelerometers (see Annex K of IEEE Std 1293-1998⁹).

4.19 Autocollimator

An autocollimator is an optical measurement system that measures the deviation angle of a fixture or a test assembly. A reflective mirror is attached to the item to be aligned, and the deviation between the primary and reflected image is measured using collimated light.

A plane mirror allows measurement of angular deviation in two directions. A porro prism with two orthogonal reflectors restricts measurement to deviation about one axis, but facilitates alignment about this axis because of insensitivity to misalignments in the orthogonal direction.

4.20 Displacement measurement systems

4.20.1 Capacitive

Capacitive displacement sensing can be accomplished with atomic-dimension precision for small gaps, for example, in inertial sensors themselves.

For micro- and macro-sized accelerometers, capacitive sensing is often used as the pickoff of proof mass motion, where the measure of acceleration is the proof mass displacement against an elastic restraint or it is the force or torque required to restore the proof mass to the null position relative to the case. See F.2.4 of IEEE Std 1293-1998 for a discussion of capacitive pickoffs in silicon chip accelerometers.

For spinning wheel gyroscopes, the movement of the spinning wheel relative to the case is often measured capacitively (electromagnetic and optical pickoffs are also used for gyroscopes and accelerometers). For a rate gyro, this movement against an elastic restraint is the measure of input angular rate. Other implementations restore the spinning wheel to a null position relative to the case by torquing the gyro (where the integral of the torque is the measure of angular displacement) or by torquing gimbals of the platform in which the gyro resides (to keep the platform inertially oriented).

Capacitive displacement sensing is also used in micro- and macro-sized Coriolis Vibratory Gyros for measuring vibration amplitudes and the out-of-vibration-direction motions that are the measure of input angular rate in these devices. These out-of-vibration-direction motions are just observed in an open-loop device, but suppressed in a closed-loop device.

For an example of capacitive displacement sensing in inertial sensor test equipment, see 11.5.2.2 on measuring centrifuge arm stretch.

⁹Information on references can be found in Clause 2.

4.20.2 Laser interferometer

Laser interferometry can be used to check the flatness of planar surfaces or the radius of curvature of spherical surfaces. Laser interferometry is also widely used to measure displacements of components in the direction of a collimated laser beam. The phase of the light reflected by a reflector attached to the component is compared in the interferometer to the phase of the light emitted by the laser, and relative displacement is deduced. Precision of the order of a fraction of the wavelength of light can be obtained in this manner.

A coordinate measurement machine (CMM) can be built by using three interferometers having mutually orthogonal beams. Another way of creating a precision CMM for measuring large components is to use a laser tracker. A laser tracker is composed of an electronic distance measurement (EDM) using a laser beam in the same optical head of a tracking theodolite. A corner cube retroreflector is moved over the surface of the component to be measured. The tracking theodolite measures angles, and the EDM provides the third dimension. Commercial distance measurement interferometers and laser trackers are available.

Environment affects interferometric measurements because the quantity measured is in fact the optical distance traveled by light, namely, $n \times d$, the product of the index of refraction n of the media in which light is traveling (air in general) and the actual distance d . The index n is a function of air composition (including humidity level), temperature, and pressure. For highly precise measurements, environment monitors have to be used to compensate for changes in environment factors. Shielding protection against transient air currents or averaging may also have to be used, although averaging reduces the measurement bandwidth.

4.20.3 Fiber-optic probe

Two classes of fiber-optics-based sensors can be used to monitor displacements.

The first class is based on deformation of somewhat straight fiber-optics embedded or rigidly attached to a large component. It is assumed that fiber deformation reproduces the component deformation of interest. The fiber-optics probe has to be judiciously located within or on the surface of the component, usually in conjunction with creating a structural model of the component. The model is also useful for interpreting the results. Deformation of the fiber is sensed by measuring the phase of coherent laser light traveling in the fiber probe. This sensing technique is somewhat akin to extensometry (namely, measurement of stress or differential elongation).

In the second class of fiber sensor, displacement is measured between the end of the probe and a reflective component closely located in front of the probe end. The sensing is based on the amount of light reflected back into the probe. This kind of sensor has a short distance range, but is very useful for vibration measurements.

4.21 Other general commercial equipment

It is often useful to measure the barometric pressure, relative humidity, and air temperature in the test laboratory. Commercial instrumentation for accomplishing these functions can have output on circular strip chart recorders or, more usefully, as voltage variations proportional to environmental changes that are input to the data acquisition computer.

Microscopes are used to examine silicon chip inertial sensors. A stroboscope can freeze the observed motion of vibrating elements.

4.22 Specially built equipment

Test equipment should be bought if possible as commercial-off-the-shelf (COTS) procurements. Readout of the primary output of an inertial sensor is one area where precise enough commercial equipment is often not available. For instance, equipment such as voltage-to-frequency converters (see 4.14 and 15.3), continuous frequency counters (see 4.15 and 14.1), and phase-locked loops (PLLs) (see 14.4) must often be specially built.

5. Sensor-specific equipment

Inertial sensors require various power supplies, such as

- a) Low-voltage dc supplies as required by the sensor, single-sided or bipolar, such as +5 V for transistor-transistor logic or ± 15 V for crystal oscillators. Devices with small feature sizes, such as computer chip central processing units (CPUs) or field-programmable gate arrays (FPGAs), use 3 V or lower voltages.
- b) Voltage for analog torquer or for the digital torque pulse height.
- c) Higher voltage ac power supplies for wheel motors (such as 70 V), magnetic or electrostatic suspensions, resolver readouts, etc.
- d) High-voltage (~ 1000 V) dc supply for laser gyro excitation.

These various power supplies should be regulated to keep the voltage level constant (both at dc and at frequency bands of interest) in the face of variations in the external voltage from which they are derived. Care should be taken in the design so that the power supplies do not interfere with the performance of the inertial sensor.

In laboratory testing, the power supplies are derived from the electric utility supply (see 4.2). During a mission, the power supplies are derived from the vehicle's power supply, which could be a turbine generator or a battery with or without an alternator or generator charging system. Examples of vehicle battery power supplies that drive dc-dc converters to other voltage levels are

Automobiles:	12 V open circuit (14 V under charge)
Trucks:	24 V open circuit (28 V under charge)
New automotive:	36 V open circuit (42 V under charge)

A missile power supply might be a 28 V battery, where the voltage under load is greater than 28 V at the start of the mission and less than 28 V at the end of the mission.

The cable with power, grounds, input commands, and output signal lines is attached to an inertial sensor with a manufacturer-specific connector.

Output signals can go through control loop electronics to apply torque, control an oscillator, control temperature, etc. Some electronics, including buffer amplifiers and perhaps some control loops, are within the inertial sensor case. Other electronics can be contained in a rack separate from the inertial sensor, including any special readout electronics.

Although sometimes not possible, it is desirable to have mission-level control and other electronics used in instrument-level tests of an inertial sensor.

6. Mounting fixture

6.1 Fixture mechanical design

An inertial sensor to be tested is attached to a mounting fixture or block with bolts torqued to a specified level. Fixture materials should be selected with due consideration of thermal coefficients of expansion and conductivity, magnetic permeability, durability, etc., relative to the requirements of the sensor being tested. Hard-coated aluminum fixtures with stainless steel thread inserts meet many of these desirable characteristics. Stainless steel mounting bolts are often used because of their nonmagnetic characteristics.

The mounting fixture is then bolted to other test equipment, such as a dividing head, rate table, vibration and shock machine, or centrifuge arm. The parallelism and perpendicularity of the mounting faces to the other equipment and to the sensor or sensors under test should be within specified tolerances. An adapter plate might be required between the mounting fixture and the other equipment, with due consideration for the effects on alignment, parallelism, and mechanical resonances.

The mounting fixture might contain one inertial sensor or contain two or more sensors with IAs parallel or antiparallel in order to increase test productivity by testing several sensors simultaneously. Simultaneous sensor testing can also help distinguish between noise inherent to the individual sensors and noise from common seismic and other input.

Care must be taken to avoid sensor-to-sensor crosstalk, such as mechanical coupling through the mounting fixture, electronic coupling through a common power supply system, or electromagnetic coupling between closely spaced sensors or signal lines.

Orienting sensors in the mounting fixture with IAs orthogonal is used in accelerometer testing to allow compensation for dividing head angle-setting errors in tumble testing (see 8.4 and 19.13.2.1).

6.2 Thermal control of fixture

The mounting fixture might be thermally controlled, in which case a thermal shim or spacer might be required between the mounting fixture and the other equipment to which it is attached. A fixture that is temperature controlled as a whole could surround the sensor under test. If only the mounting flange is temperature controlled, the sensor could be covered with insulation so that the heat flow path from the sensor is through the mounting flange.

If the control set point is sufficiently above room temperature, thermal control can be accomplished with electric strip heaters. Alternatively, the mounting flange could be attached to Peltier thermoelectric heater-coolers, which have the property that electric current flowing in one direction heats one side and cools the other, and vice versa if the current direction is reversed. Thus the temperature control point can be well above or below room temperature, which allows temperature sensitivity testing over a wide temperature range. Water condensation should be avoided at the lower temperatures.

Temperature control of the mounting fixture may not be required if the fixture and sensor under test are inside a heated and/or refrigerated chamber (see 12.1.2 and 12.2).

6.3 Vibration fixture

The vibration fixture should be designed to not have any structural resonances near the resonance frequencies of the sensor under test. This requirement implies that the fixture be fairly massive. The vibration fixture could be made of aluminum or magnesium. The latter is better because magnesium has high internal damping.

The fixture would be tested for resonance frequencies by mounting a dummy mass on it and conducting a frequency sweep (see 10.2.6). The accelerometers used to monitor the vibration amplitude should be mounted in close proximity to the instrument under test to minimize fixture resonance effects. Piezoelectric accelerometers are commonly used for this purpose.

A vibration fixture should allow different orientations of the inertial sensor IA and other axes relative to the vibration axis.

6.4 Centrifuge fixture

Analogously to the vibration fixture, a centrifuge fixture should allow different orientations of the inertial sensor IA and other axes relative to the centrifuge arm, if required. The centrifuge fixture may have to accommodate the mounting of a second accelerometer that is used to measure arm stretch (see 11.5.2.1).

6.5 Radiation test fixture

Besides providing required thermal and other environments, a radiation test fixture has to be able to orient an inertial sensor appropriately relative to the radiation source and the local vertical. To accomplish various orientations, the fixture could be cantilevered off a rotary table with the inertial sensor and its proximity electronics in the radiation beam and with the rotary table and the inertial sensor's nonproximity electronics out of the beam. The nonproximity electronics could, in addition, be shielded if the effects of radiation on the sensor and its proximity electronics were being determined separately from the effects of radiation on the nonproximity electronics.

The test fixture could have a second shielded inertial sensor out of the radiation beam to allow simultaneous testing of exposed and shielded sensors. The subtraction of the data from IA-parallel sensors (or addition for IA-antiparallel sensors) eliminates the effects from the exposed sensor's data of seismic, tilt, and other nonradiation common-mode effects during the experiment. Faraday shielding on both the exposed and shielded sensors and electronics might be required if an electromagnetic pulse (EMP) in addition to a seismic pulse is generated by the radiation source that is not in the natural environment being simulated, such as when using an X-ray machine.

The shift and transient in an inertial sensor's output during and after a radiation exposure in a single orientation contains the lumped effects on bias and scale factor.

If the effects of radiation on an accelerometer's bias and scale factor are to be separated, data can be taken before, during, and after a radiation exposure of a given magnitude with IA up and then with IA down. The average of the data at comparable time points in the two time series gives the time history of bias before, during, and after the radiation exposure, whereas half the difference of the data gives a similar result for the scale factor.

Similarly, the effects of radiation on a gyroscope's bias and scale factor can be separated by taking the sum and difference of data taken when rotating the gyroscope in one direction during a radiation exposure and then in the opposite direction during a second radiation exposure at the same level (see 19.13.3.1).

The variation of radiation levels from one test to another can obfuscate the above-described calibrations of gyroscope and accelerometer bias and scale factor. However, if radiation effects are linear with dose, appropriate dosimeter instrumentation allows the scaling of the effects from one radiation exposure to another, even if the radiation level in each exposure cannot be well controlled.

7. Test piers

7.1 Location of test piers

A test laboratory should be in a location as seismically quiet as possible. A remote location is preferable to an urban location, although this preference is not always possible.

The upper floors of a building have a more severe vibration environment than the ground floor. Therefore, inertial sensor test laboratories should be on the ground floor or in a basement. Moreover, test tables within the laboratory should be on piers or pads isolated from the floor, to minimize the effect of tilt and other motions when testing high-precision inertial sensors. Depending on local geologic conditions, a massive concrete test pier could be resting in soil or go down to bedrock.

The vibration and tilt environment of a test table should be evaluated so that environmental effects can be accounted for in test data.

7.2 Vibration environment of test pier

An inertial instrument test station receives vibration input from local cultural activity and from the general seismic background of the earth. Seismic amplitudes tend to die out within a few hundred wavelengths, where the speed of sound in soil is of the order of a kilometer per second. The frequency spectrum of the vibration input depends on the particular site and whether it is in an urban or isolated location. It is generally above 1 Hz, possibly with discrete spikes due to resonances in the local geology and test table. Earthquake frequencies can be below 0.1 Hz.

Local cultural activity (such as automobile and other traffic, rotary equipment in the building in which the test station is housed, fans in test equipment, and even people walking by the test station) causes horizontal and vertical vibration inputs and lower frequency tilts. Effects can be amplified or damped by local geologic conditions, such as land fill over bed rock, where surface vibrations are reflected from the bed rock to cause constructive interference at certain frequencies and destructive interference at others.

The general seismic background of the earth includes such phenomenon as the vibrations from ocean waves striking the sea shore. The surface and solid body seismic waves from an earthquake thousands of kilometers away can cause disturbances in inertial instrument test data. The different modes of vibration have different arrival times because of differing paths through the earth and differing speeds of travel. There can be considerable ringing in the earth for several hours after an earthquake, in addition to the initial and after-shock disturbances.

Seismic input averages zero over the averaging time of many types of measurements, either as a natural consequence of the measurement system itself (such as low-rate counter readings) or because high-rate sampling followed by digital filtering is employed. But such averaging cannot eliminate all seismic aliasing and other corruption, such as from earthquakes, parking lot speed bumps, or construction pile drivers. Some tests, such as noise measurements, might require use of a site remote from the usual facility.

7.3 Tilt and azimuth motion of test pier

A test table on a pier or laboratory floor will have diurnal, seasonal, and long-term tilt variations relative to the local vertical due to temperature, solar heating, ground water, and other local geophysical effects. There could be several microradians of tilt variation over a day and tens of microradians of tilt variation over weeks.

The data from an IA vertical accelerometer test are insensitive to such tilt variations, whereas the data from off-vertical positions in a tumble test are sensitive to them. Tilt meters could be monitored during a test in order to correct the tumble test angle readings for tilt errors relative to the local vertical. Alternatively, the

analysis technique of orthogonal accelerometer tumble testing described in Annex K of IEEE Std 1293-1998 can be used to correct for tilt errors, if accuracy warrants.

Tilt variations also affect the results of gyroscope testing, in that they change the orientation of the gyroscope IA or axes relative to the earth's rotation vector. Azimuth variations of the test station can be of the same order of size as tilt variations and similarly affect the results of gyroscope testing, but not those of accelerometer testing. Optical monitoring of test station azimuth variations by sighting on an external target can be corrupted by movements of the target due to the same geophysical causes (such as temperature) that cause the test station to rotate in azimuth and tilt.

Monitoring the azimuth variation of a tilt-stabilized platform or dual gyroscope testing may be required when testing high-accuracy (< 0.0005 °/h) gyroscopes.

7.4 Active control of test pad

A test pad could be on pneumatic isolators to attenuate vibration inputs. Tilt and azimuth monitoring equipment can be used to actively control a test pad if the pad is mounted on actuators. The monitoring equipment would have to be more accurate than the sensors under test in responding to the movements being controlled.

8. Accelerometer dividing heads (or turntables)

8.1 Use of accelerometer dividing heads

An accelerometer in its fixture is mounted on a dividing head (such as indexing head or turntable with rotation axis horizontal) to perform various gravity field laboratory tests. The accelerometer IA is usually perpendicular to the horizontal dividing head rotation axis (see Figure 1). Long-term drift and noise tests are done with the dividing head in a fixed position, usually with IA vertical, where the accelerometer output is insensitive to tilt variations.

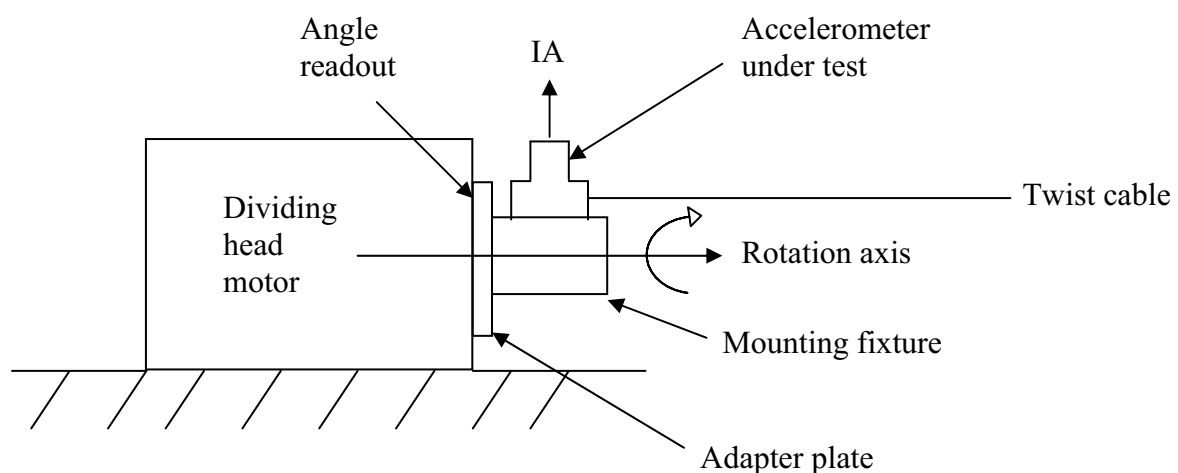


Figure 1— Dividing head for accelerometer tumble testing

In Figure 1, the accelerometer under test has IA perpendicular to the dividing head's horizontal rotation axis for calibrating bias and scale factor using the local gravity as a reference, IA misalignment using the local vertical as a reference, and some accelerometer nonlinearities. Sometimes tumble tests are done with the accelerometer IA parallel to the dividing head horizontal rotation axis for calibrating cross-IA effects.

Rotation of the dividing head between IA up and down is used to determine whether there is any shift or transient in an accelerometer's output across a change in input between plus and minus the local value of gravity. Up-down testing is also used to calibrate accelerometer scale factor and bias, with results that are insensitive to misalignments although the results could be aliased by other model parameters, such as nonlinearities, if they are not known from other tests.

Even if the scale factor and bias calculated in an up-down test are aliased by uncalibrated accelerometer nonlinearities, a sequence of such up-down calibrations over time at a given site gives valid measures of the stability of scale factor and bias. Similarly, a sequence of up-down calibrations across environmental variations (such as temperature, magnetic field, or vibration and shock) at a given site gives valid measures of the stability or repeatability of scale factor and bias. The stability and repeatability statistics of the bias and scale factor are also independent within required accuracy of the particular value of the acceleration due to gravity used as a calibration reference at the test site, even though the absolute value of the scale factor as a whole is very dependent on the value of this gravity reference.

For calibrating accelerometer bias, scale factor, IA misalignment, and other model parameters and for greater calibration accuracy, a dividing head or indexing table is required for placing the accelerometer IA at various discrete positions relative to the gravity vector besides just IA up and down (see 19.13.2.1; see also 12.3.4, 12.3.5, and Annex K in IEEE Std 1293-1998). Calibration tumble tests of a complete guidance system are sometimes done with continuous rather than discrete rotations.

The dividing head could be commanded to rotate continuously to calibrate accelerometer angular velocity and angular acceleration sensitivity model coefficients if the dividing head were equipped with slip rings. However, such calibration is probably best carried out on a rotary table (see Clause 9) and at the guidance system level rather than at the sensor level.

If great accuracy is not required for positioning accelerometer axes in the gravity field for calibrating scale factor and bias, a dividing head can be dispensed with. It is sufficient to attach the accelerometer to a block that is oriented by hand on a table surface to place the accelerometer IA in the up and down orientations.

8.2 Placement of dividing head

The dividing head table could be placed on a rigid table on a concrete seismic pier or slab isolated from the building floor to minimize tilt and azimuth movements, such as caused by diurnal and seasonal heating and ground water effects. The seismic and tilt environment of the pier and test table should be evaluated, including recording tilt data during tumble tests.

The horizontal dividing head rotation axis could be in any direction, unless a gyroscopic accelerometer was being tested. In that case, the horizontal dividing head rotation axis is usually oriented north, in order to simplify the correction to the gyroscopic accelerometer's output due to the effect of the earth's angular velocity.

8.3 Thermal control on dividing head

The accelerometer is mounted in a fixture (see Clause 6) that is attached to the dividing head faceplate with the use of an adapter plate if necessary. Insulation spacers or shims might be required between a temperature-controlled mounting fixture and the dividing head or adapter plate (see 12.1.1).

Alternatively, the dividing head mounting fixture could be inserted into a temperature-controlled chamber through a hole in the side of the chamber (see 12.1.2 and 12.2).

8.4 Alignment of dividing head and mounting fixture

The mounting fixture might have several accelerometer mounting surfaces to allow multiple accelerometer testing (such as IAs parallel, antiparallel, or orthogonal). The accelerometer IA is usually perpendicular to the horizontal dividing head rotation axis with either the output axis or pendulous axis (PA) parallel to the dividing head rotation axis, depending on which IA misalignment angle is to be estimated. Some tests are done with IA parallel to the horizontal dividing head rotation axis.

The dividing head angle at which a given mounting surface is perpendicular to the gravity vector can be determined by placing a horizontal precision bubble level approximately perpendicular to the dividing head rotation axis on the mounting surface in the up orientation. Precision bubble levels with a few arcsecond accuracy are commercially available. The calibration of the bubble level can be checked by the technique described in 21.5.

For a fine-resolution angle readout, the angle reading at bubble level null defines the up position of the dividing head for a tumble test. For discrete angle readout, such as every 1° , some dividing heads have a vernier adjustment to bring the nearest 1° angle position to the up position.

A bubble level positioned on the given mounting surface in the up orientation approximately parallel to the dividing head rotation axis can be adjusted to null by putting shims under the dividing head or using leveling jacks. In this manner, the dividing head rotation axis can be made horizontal within required tolerances.

Adjustment of the mounting surface so that it is vertical in the IA vertical position can be accomplished to within a few arcseconds with a precision bubble level. Electronic levelers and/or lasers can also be used. However, the internal misalignments of an accelerometer due to manufacturing tolerances could make the alignment of the accelerometer IA differ from the vertical in this orientation by several milliradians.

The IA misalignment about the dividing head rotation axis can be estimated by fitting to multi-position tumble test data and is generally ignorable if only IA up and down data are being used to estimate scale factor and bias. The misalignment of the IA from being perpendicular to the dividing head rotation axis and the coning of the dividing head about its rotation axis will alias the estimate of scale factor in an accelerometer-level tumble test. For measuring the stability of accelerometer model coefficients over time and their sensitivities to environmental variations at a given test station, this aliasing or biasing is ignorable.

For lesser accuracy accelerometers, the aliasing from milliradian misalignments is ignorable in determining absolute calibrations of model coefficients. For higher accuracy accelerometers, bias, scale factor, and IA misalignments are usually estimated in an inertial guidance system calibration before a mission, in which data from three nearly orthogonal accelerometers are used to eliminate the aliasing effect of misalignments and thus determine absolute calibrations (see K.2.6 in IEEE Std 1293-1998).

Dual orthogonal accelerometer testing can also be done on a dividing head to eliminate the aliasing from one misalignment angle (but not from the other IA misalignment angle or from dividing head coning) for testing accelerometers that are more accurate than the angle-setting precision of the dividing head (see Annex K of IEEE Std 1293-1998).

8.5 Wiring to dividing head

The electrical power, ground lines, and control signals to the accelerometer under test and for thermal control could go through slip rings on the dividing head, as can the output signals from the accelerometer and temperature monitors.

Because a dividing head does not rotate continuously, a more practical approach is to have these lines go through a cable that has sufficient slack to allowing twisting through a complete revolution. A discrete

position tumble test can be commanded for 360° in one direction and then 360° in the reverse direction to unwrap the cable.

8.6 Rotation of dividing head

Some dividing heads require manual rotation. A brake is released, the head is rotated manually to a new position and centered at the new angle by visual means (in some cases by looking through a microscope at a vernier scale), and then the brake is applied. Data are taken at the position, and then the process repeated for the angle sequence defined for the accelerometer tumble calibration test that is being performed.

Other dividing heads allow an angle to be commanded, and the table will automatically rotate to that angle. The table might have locking teeth (typically referred to as Hirth coupling) at certain discrete positions (such as every 1°), and/or there could be servo control at each commanded angle. In the latter case, a brake might have to be applied once the desired position is reached in order to obtain the quietest data. The time to go from one position to another should be noted. The rotation speed could be specified by the user, or it could be fixed in the equipment. Shocks involved in rotating the dividing head and engaging gear teeth or a brake could be measured by attaching piezoelectric accelerometers to the mounting fixture with epoxy or other means.

If the commanded angle has to be entered manually, there is a great deal of test technician involvement in carrying out an accelerometer tumble test. It is more desirable to command the dividing head angle under computer control, such as over the IEEE 488 bus (see 17.6).

The sequence of angle commands, the dwell time at each discrete position, and the amount of settling time before data are collected at a position could be specified in a test scenario file. Rotating the dividing head between IA up and down and determining the transient after reaching a new position can be used as a measure of the transient at any position. One cause of such a transient could be changes in thermal gradient when an accelerometer's orientation is changed. Whatever the cause, the inversion transient phenomenon should be characterized so that the settling time required before data are taken at each position in a tumble test can be rationally determined.

During a tumble test, the computer data acquisition system can read the test scenario file and issue dividing head rotation commands at the right times. The computer could also be controlling a thermal chamber in which the dividing head fixture is inserted so that a tumble test can be carried out at each temperature setting in the operating temperature range of the application for which the accelerometer is intended. Accelerometer model coefficients (including bias, scale factor, IA misalignment, and acceleration nonlinearities) are estimated at each temperature setting. Polynomial fits of the model coefficient estimates versus temperature yield calibrations of the model coefficients as functions of temperature.

Besides temperature, other environmental quantities (such as excitation voltage or magnetic field) can be varied, and tumble tests performed to determine the sensitivities of model coefficients to these environmental variations.

Automatic computer control of the dividing head rotation and environmental state increases productivity for production acceptance and characterization testing.

8.7 Readout of dividing head angles

If dividing head angles are commanded or manually set at given discrete values, it is not necessary to read out the dividing head angles, except for the human who is setting a manual angle or the servo or other equipment (provided by the manufacturer of the dividing head) that carries out the command to go to a certain angle. However, if the angle readout is available to the data acquisition computer, it could serve as a confirmation that the commanded angle has been obtained. The dividing head angle (either the commanded

or readout value) should be recorded along with the accelerometer output data by the data acquisition computer.

The dividing head manufacturer will specify the precision of the dividing head, such as an angle setting accuracy of 5 μrad and a repeatability of 1 μrad , with an accuracy of 1 μrad and a repeatability of 0.1 μrad being about the best possible. The tilt variation of the test pier or slab, which could be several microradians per day, has to be added to the angle setting error to obtain the total angle error because what matters in accelerometer testing is angle accuracy relative to the local vertical.

If tilt were constant during a tumble test, then tilt error and any overall bias in angle setting error would be absorbed in the estimate of IA misalignment. The measured stability of IA misalignment over days or weeks would have to be interpreted in light of possible variations in the tilt of the test table, which could be monitored with a tilt meter. The stability of bias and scale factor over days or weeks at a given test station would not be so affected if tilt were essentially constant during each tumble test lasting some number of minutes or hours.

If only IA up and down data are used to calibrate scale factor and bias, the calibration results are insensitive to small angle-setting and tilt errors because the cosine of a small angle is very close to 1. Similarly, if the dividing head is rotated 360°, any change in the IA vertical accelerometer output from before to after the rotation cannot be caused by the dividing head's not returning to the same angle value.

The technique of dual orthogonal accelerometer testing eliminates the effect of angle-setting errors and tilt variations during a test for testing of accurate accelerometers (see Annex K of IEEE Std 1293-1998).

9. Rate tables

9.1 Use of rate tables

A gyroscope in its fixture is mounted on a rate table to perform various laboratory tests. Long-term drift and noise tests are done with the rotary table in a fixed position, such as with IA vertical or with IA parallel or perpendicular to the earth's rotation vector.

Continuous rotations of the rate table at different rates and directions about the axis parallel to the gyro IA are used to calibrate gyroscope bias and scale factor (see 9.2.6 and 9.3.8), although gyro bias is more accurately calibrated in a drift test, after compensation for sensed earth rotation rate.

A gyroscope's dead zone is evaluated as follows: First, place the gyro IA perpendicular to the table rotation axis. Second, rotate the table slowly through the position where its IA is perpendicular to the earth's rotation vector. The dead zone, if any, typically occurs where the bias is cancelled by the input rate.

9.2 Single-axis rate table

9.2.1 Placement of rate table

The single-axis rate table depicted in Figure 2 has a vertically oriented ball- or gas-bearing rotation axis. For horizontally orientated single-axis rate tables, see Clause 8.

Precision bubble levels can be used to align the rate table axis along the vertical within specified tolerances by putting shims under the rate table base or using leveling jacks. The orientation of the vertical rate table relative to east-west and north-south is not particularly important if the single-axis rate table is used only for gyroscope scale factor measurements using complete table revolutions.

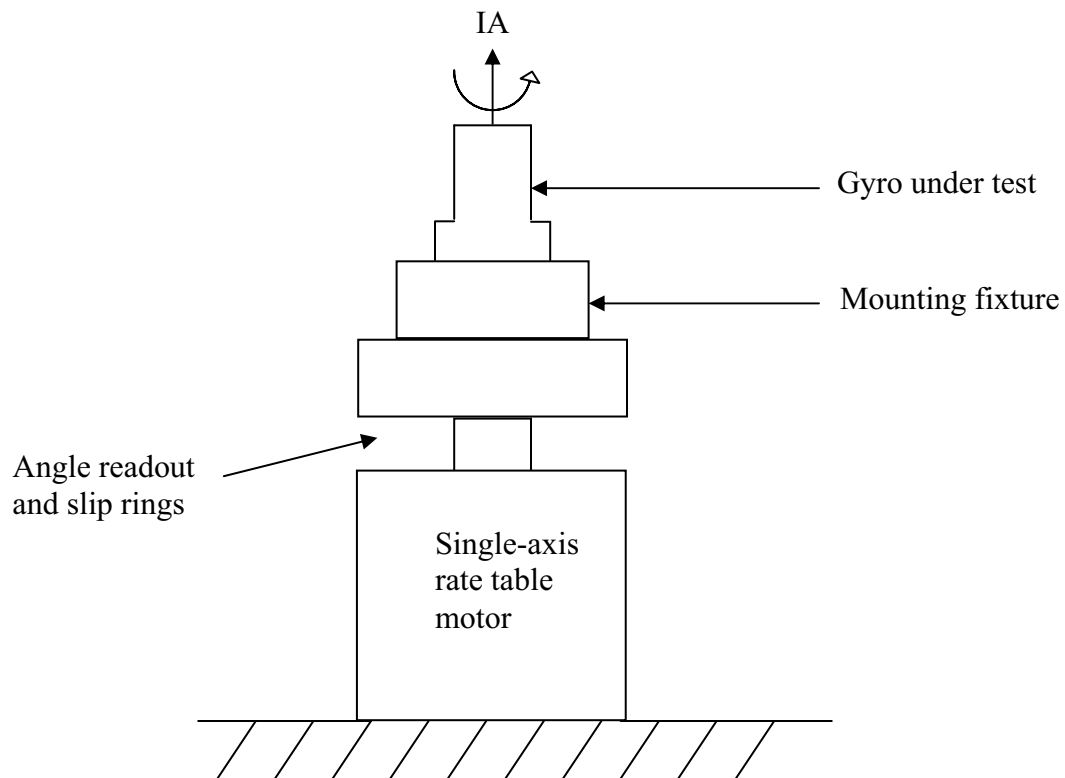


Figure 2— Single-axis rate table

9.2.2 Thermal control on rate table

The gyroscope is mounted in a fixture (see Clause 6) that is attached to the rate table faceplate with the use of an adapter plate if necessary. Insulation spacers or shims might be required between a temperature-controlled mounting fixture and the rate table or adapter plate (see 12.1.1).

Alternatively, the rate table mounting fixture could be inserted into a temperature-controlled chamber through a hole in the bottom of the chamber (see 12.1.2 and 12.2).

9.2.3 Control of rate table rotation

Manufacturer-supplied control electronics enable the rate table to be commanded to a desired position or at various rotation rates, such as between $0.1^\circ/\text{s}$ to $1000^\circ/\text{s}$. Also, a sinusoidally or other varying rate with the rate table oscillating back and forth can be commanded.

9.2.4 Wiring to rate table

The electrical power, ground lines, and control signals to the gyroscope under test and for thermal control could go through slip rings on the rotary table, as could the output signals from the gyroscope temperature monitors (see 9.3.6).

The output signals could also go through a radio link (see 9.3.7).

9.2.5 Gyroscope oscillation on rate table

With the gyroscope IA along the rate table rotation axis, the rate table can be oscillated back and forth through an angle $\pm \theta$ at various frequencies, for example, using a periodic or linear chirp function, to measure the gyroscope transfer function.

If the rate table motor cannot input oscillations above a certain frequency, an eccentric mass can be rotated on the rim of the rate table plate at the high frequency. The oscillating mass unbalance causes the rate table to oscillate back and forth and thus input the desired high-frequency sinusoidal oscillation to the gyroscope.

9.2.6 Gyroscope scale factor calibration on rate table

Gyroscope scale factor is calibrated by continuously rotating the rate table at various rates with the gyroscope IA parallel to the rate table rotation axis and by analyzing the results as in 19.13.3. The scale factor calibration is only as good as the accuracy with which the rotary table rate can be controlled by the manufacturer-supplied inductosyn or other angle readout and the control electronics, except that the revolution trigger technique of 9.3.4 can be used to obtain more accurate results than allowed by the table rate control. If the rotary rate table is placed in a temperature-controlled oven (see 12.1.2 and 12.2), then the bias and scale factor calibrated at each temperature setting can be fit to polynomials in temperature to determine the gyroscope model coefficients as functions of temperature.

If scale factor asymmetry is known to be ignorable, then a possible test scenario is

+10°/s and then −10°/s
+100°/s and then −100°/s
+200°/s and then −200°/s
+400°/s and then −400°/s
etc.

Data from the + and − rotation rates are used to determine scale factor at that absolute value of rotation rate (see 19.13.3.1). Polynomial fits to the bias and scale factor as functions of absolute value of rotation rate determine whether there are any nonlinearities in these quantities (see 19.13.3.3).

To test for scale factor asymmetry, a test scenario as in Table 1 (in 9.3.8) can be used, and the scale factor and bias can be determined from data at adjacent rate table rates of the same sign or from a fit of a model to all the data (see 19.13.3.2 and 19.13.3.3).

9.2.7 Accelerometer testing on rate table

Pendulous and other accelerometers have angular velocity and angular acceleration sensitivities (see Annex C in IEEE Std 1293-1998). The angular-velocity-sensitive and angular-acceleration-sensitive coefficients in the accelerometer performance model can be calibrated using high-rate rotations on a rate table (see 12.3.21 in IEEE Std 1293-1998).

Accelerometer-level rotation rate tests would be done for characterization purposes. Rotation rate tests for strapdown guidance systems would be done in the normal calibration procedure to calibrate the radius vectors from the navigation center of the guidance system to the effective centers of mass of the accelerometer pendulums and to calibrate the angular-velocity-sensitive and angular-acceleration-sensitive model coefficients.