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IEEE Recommended Practice for Precision Centrifuge Testing of Linear Accelerometers

Sponsor

**Gyro and Accelerometer Panel
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IEEE Aerospace and Electronics Systems Society**

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Abstract: A guide to the conduct and analysis of precision centrifuge tests of linear accelerometers is provided, covering each phase of the tests beginning with the planning. Possible error sources and typical methods of data analysis are addressed. The intent is to provide those involved in centrifuge testing with a detailed understanding of the various factors affecting accuracy of measurement, both those associated with the centrifuge and those in the data collection process. Model equations are discussed, both for the centrifuge and for a typical linear accelerometer, each with the complexity needed to accommodate the various identified characteristics and error sources in each. A new iterative matrix equation solution for deriving from the centrifuge test data the various model equation coefficients for the accelerometer under test is presented.

Keywords: accelerometer; linear accelerometer; centrifuge; accelerometer test

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Foreword

(This Foreword is not a part of IEEE Std 836-1991, IEEE Recommended Practice for Precision Centrifuge Testing of Linear Accelerometers.)

This standard was prepared by the Gyro and Accelerometer Panel of the Aerospace and Electronic Systems Society of the Institute of Electrical and Electronics Engineers. It is a guide to the conduct and analysis of precision centrifuge tests of linear accelerometers and includes discussions of possible error sources in those tests. It provides guidance for each phase of the tests beginning with planning, and ends with a discussion of typical methods of data analysis.

A discussion of model equations is provided, both for the centrifuge and for a typical linear accelerometer, each with the complexity needed to accommodate the various identified characteristics and error sources in each. This standard also presents a new and unique iterative matrix equation solution for derivation of the various model equation coefficients for the accelerometer under test, from the centrifuge test data. The matrix solution provides a two-quadrant best-fit of the centrifuge data to the chosen model equation.

This standard is intended to provide those involved in centrifuge testing with a detailed understanding of the various factors affecting accuracy of measurement, both those associated with the centrifuge and those in the data collection process. Numerical examples are provided so that each factor can be quantitatively evaluated and its contribution to system error compared with the user's required accuracy. This allows the user to identify and evaluate those factors that are critical to a specific planned test. The matrix equation method of data reduction also provides a means of determining data validity as well as model equation adequacy, and yields the confidence intervals for each of the model equation coefficients.

This standard consists of a main text and four appendices. The main text provides the recommended practice for precision centrifuge testing following a tutorial section that is intended to provide the user with the understanding of critical factors in centrifuge testing as well as the best methods for taking and reducing data.

Appendix A is a compilation of the characteristics of known precision centrifuges from data provided from both users and manufacturers. The listing is intended as a guide to available facilities at the time of publication of this standard. Data provided should be considered as merely advisory and not as specifications for the listed machines.

Appendix B provides a discussion of evaluation of centrifuges, with references provided to sections of the standard that pertain to the attribute discussed.

Appendix C provides a more general discussion of fitting theory, with particular regard to the often unique character of centrifuge data and corresponding accelerometer performance requirements. It discusses the application of the method of least squares by which matrix solutions such as that in the main text are generated. It also describes the proper application of commonly used approximate methods that can be justified by their ease of understanding and use. These approximate methods generally address some measure of composite error, rather than directly evaluating model equation coefficients. For example, a common specification limits allowable deviations from a straight line determined by two specified points, such as zero- g and some specific value of input g .

Appendix D discusses the limitations of and alternatives to centrifuge testing. Problems produced by the g -gradient, the spin rates required, and the difficulty of producing short high- g input pulses are among those discussed. Alternatives such as use of dividing heads and earth's gravity are discussed, along with sled testing and vibration testing.

The terminology used conforms to ANSI/IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms and IEEE Std 528-1984, IEEE Standard Inertial Sensor Terminology. The units used conform to ANSI/IEEE Std 268-1982, IEEE American National Standard for Metric Practice. In this standard, the symbol g is used to denote a unit of acceleration equal in magnitude to the local value of gravity at the test site. This symbol is thus distinguished from g , which is the standard symbol for gram.

This publication represents a group effort on a large scale. The major contributors to this standard were as follows:

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While the development of this standard was a group effort, the contributions of one member were fundamental to its preparation and he clearly deserves special recognition. George H. Neugebauer developed the iterative matrix data reduction technique outlined in sections 7.3.3, 7.3.4, and 7.3.5. In addition, he was extremely active in the development and subsequent refinement of most of the rest of the document. In large measure, the technical quality of this standard resulted from his efforts.

The following persons were on the balloting committee that approved this document for submission to the IEEE Standards Board:

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IEEE Recommended Practice for Precision Centrifuge Testing of Linear Accelerometers

1. Scope

1.1 Scope

This recommended practice describes the conduct and analysis of precision tests that are to be performed on linear accelerometers using centrifuge techniques. The term “precision,” in this context, refers to tests that are conducted to evaluate accelerometer parameters, as opposed to those conducted to establish environmental survivability only. Evaluation may take the form of determining the coefficients of the accelerometer’s model equation, except for bias and scale factor, which are most accurately determined by static multi-position tests. Alternatively, evaluation may only establish that the accelerometer output complies with specific error limit criteria.

1.2 Reference Documents

The following documents form a part of this Recommended Practice. In the event of any conflict, the recommended practices of this document shall have precedence over those in the listed documents.

1.2.1 Standards

- [1] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms.
- [2] IEEE Std 260-1978, IEEE Standard Letter Symbols for Units of Measurement (SI Units, Customary Inch-Pound Units, and Certain Other Units).
- [3] IEEE Std 268-1982, IEEE Standard for Metric Practice.
- [4] IEEE Std 315-1975, IEEE Standard Graphic Symbols for Electrical and Electronics Diagrams.
- [5] IEEE Std 337-1972, IEEE Standard Specification Format Guide and Test Procedure for Linear, Single-Axis, Pendulous, Analog Torque Balance Accelerometer.
- [6] IEEE Std 528-1984, IEEE Standard Inertial Sensor Terminology.

[7] IEEE Std 530-1978, IEEE Standard Specification Format Guide and Test Procedure for Linear, Single-Axis, Digital, Torque Balance Accelerometer.

1.2.2 Documents

[8] G. H. Neugebauer, Precision Centrifuge Testing of an Accelerometer. The Aerospace Corporation, San Bernardino Operations, Report No. APP-72 (S2970-11)-1, 16 May 1972. Published in the *Proceedings of the Sixth Guidance Test Symposium*, Holloman Air Force Base, New Mexico, October, 1972.

[9] G. H. Neugebauer, An Improved Data Reduction Procedure for Accelerometer Centrifuge Data. *Proceedings of the Thirteenth Guidance Test Symposium*, Holloman Air Force Base, New Mexico, October, 1987.

[10] Peters, R. B., Use of Multiple Acceleration References to Obtain High Precision Centrifuge Data at Low Cost. *Proceedings of the First International Symposium on Inertial Components*, Institute of Mechanical Engineers, Newcastle upon Tyne, 1987.

1.3 Definitions Specific to Centrifuge Testing

arm stretch (ΔR_{AS}): Elongation, due to centrifugal loading, of the mechanical structure connecting an accelerometer to the centrifuge spin axis beyond the static value (R_0).

bucking: An unusually strong interaction between certain terms in a non-orthogonal series due to a similarity in the functions that they represent.

Central Limit Theorem: A theorem that states that the means of any measurement set will approach normal distribution if the individual noise contributors are random and the data set is sufficiently large. *Syn:* **Normal Convergence Theorem.**

centrifuge: An electromechanical device consisting of a motor-driven arm structure of sufficient dimensions and strength to allow the rigid mounting and subjecting of one or more inertial-grade accelerometers to centripetal acceleration levels ranging from fractions of one g to over 2000 g .

centrifuge arm axis: A line perpendicular to the axis of rotation of a centrifuge through the effective center of mass of the accelerometer under test.

coning: Precession of a centrifuge due to imbalance.

dynamic error: An error that is present when a centrifuge is rotating.

dynamic leveling error: Any angular deflection of the accelerometer mounting fixture from a horizontal line perpendicular to the centrifuge centripetal acceleration vector.

ECM: Effective center of mass for angular velocity.

gravity (g_L): *See:* **plumb-bob gravity.**

IA: Input axis.

Normal Convergence Theorem: *See:* **Central Limit Theorem.**

plumb-bob gravity: The force per unit mass exerted by the Earth on a mass that is at rest relative to the Earth; the direction of the force defines the local vertical, and its magnitude is that of the vector sum of Newtonian gravitational force per unit mass and the centripetal force arising from the Earth's rotation divided by the mass.

precision: Accurate measurement of accelerometer parameters.

radial stiffness: A direct measure of the resistance of the centrifuge axis to deflection due to a horizontal force at the center of rotation; it must take into account the effects of all compliances of the structure, including the bearings, connection to the floor, and the foundation upon which the machine is mounted.

static error: An error that is present when a centrifuge is not rotating; it may change with arm position.

static leveling error: An error in the acceleration seen by a test item due to misalignments of the accelerometer input axis to the centrifuge and gravity vector.

2. Introduction

The term “centrifuge” is used in this document to mean an electromechanical device consisting of a motor-driven arm structure with sufficient dimensions and strength to allow the rigid mounting and subjecting of one or more inertial-grade accelerometers to centripetal acceleration levels ranging from fractions of 1 *g* to over 200 *g*. The term “precision” suggests an exactness or advancement in the state-of-the-art over and above environmental survivability centrifuge testing. “Precision,” when applied to inertial accelerometers, means the accurate measurement of accelerometer parameters. The accuracy of this measurement depends on the application of the instrument. Typical applications may be as shown in the following table:

Table 1—Accelerometer Precision

Maximum Range (g)	Super Precision (10 ppm CE) *†	High Precision (100 ppm CE)	Medium Precision (1000 ppm CE)	Low Precision (1% CE)
1 to 20	Inertial navigation	Guidance (ship/aircraft)	Attitude control	Attitude control Switch-stage separation Instrumentation
20 to 100	Ballistic missile	Cruise missile	Ordinance	Instrumentation
>100	Planetary re-entry	Planetary re-entry	Switch-fuzing Missile re-entry	Instrumentation

*The acronym, “ppm CE,” means “parts per million composite error” [6]†.

†Numbers in brackets correspond to those in the References in 1.2.

It is standard practice of both manufacturers and users to first characterize inertial accelerometers in a 1-*g* field through the use of an earth-bound dividing head or precision rotational device of some kind [7]. This allows “precise” graduations of 1 *g* acceleration to be applied to an accelerometer for the purpose of measuring its scale factor and error coefficients. Unfortunately, the 1 *g* maximum limit that can be reached using this method is usually far less than the acceleration level experienced in the application. A common test for force rebalance accelerometers is to insert a current into the accelerometer’s torquer in an attempt to simulate the acceleration levels required in the application. This test, however, only demonstrates that the accelerometer electronics will handle currents associated with the higher *g* levels expected.

Linear vibrators and rocket sleds may also, in certain cases, be used to measure accelerometer performance characteristics. The fact remains, however, that centrifuge testing must generally be used to perform precision measurements.

The practice recommended in this document is intended to be useful to a broad spectrum of centrifuge users. Since the needs of a user interested in routine testing of a high-volume 1% accelerometer differ substantially from those of a designer doing developmental testing on a highly specialized 10 ppm accelerometer, each section contains information that pertains to the different levels of precision. Therefore, one may extract the information pertinent to any desired level without becoming deeply involved in considerations that are inappropriate.

In addition to the procedures and supporting theory, which are the heart of the document, there are four appendices. Appendix A describes the features of some typical centrifuge installations, including a look at hardware designed for different production rates and different levels of precision. Appendix B continues this analysis with a description of methods for evaluating a given centrifuge installation. Appendix C provides further background for the data reduction

section by presenting a limited treatment of the theory of fitting model equations to noisy test data, including such variations as percentage-weighted fits and “min-max” fitting. Appendix D describes the theoretical and practical limitations of centrifuge testing, and outlines some alternative test methods that might be used to evaluate certain aspects of accelerometer behavior at high g levels.

Distributed through the document are treatments of special subjects, such as the use of supplemental tests and supplemental analyses to support centrifuge testing, and recommendations about the use of combined environments.

3. Model Equations

Centrifuge testing, while capable of great precision, must be a carefully designed experiment to minimize the many possible error sources peculiar to this type of testing.

In order to develop centrifuge test techniques and understand error mechanisms, mathematical models showing input/output relationships for the centrifuge and accelerometer are developed in this and subsequent sections. The accelerometer to be modelled is based on the pendulous torque-balance type instrument, but the principles are applicable to other types.

In centrifuge testing, the accelerometer is mounted on the centrifuge arm in a fixture that holds it in fixed alignment with respect to the acceleration vector. Assume a coordinate system X , Y , and Z with the origin at the intersection of the arm and the centrifuge spin axis with X along the arm and Z along the spin axis. The spin axis is aligned with the local vertical and the directed distance from the spin axis to the effective center of mass (ECM) is defined as R , as shown in Fig 1.

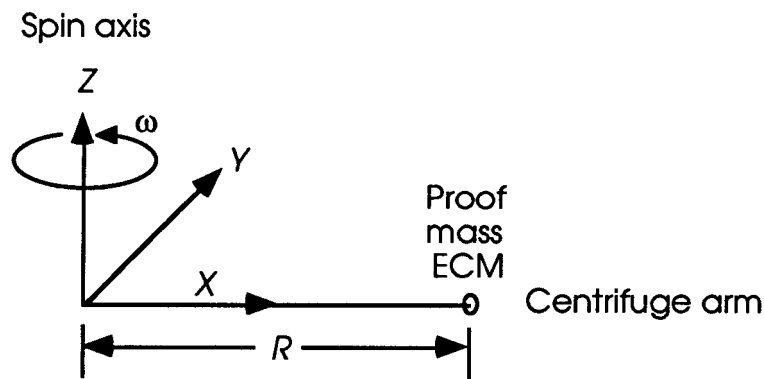


Figure 1—Accelerometer Mounted on Centrifuge

3.1 Simplified Accelerometer Model

Ideally, the acceleration indicated by the accelerometer is expressed as:

$$a_s = E/K_1 = K_0 + a_i$$

where:

- a_s = indicated sensor output (g)
- E = sensor output (output units)
- K_1 = sensor scale factor (output units per g)
- K_0 = bias (g)

$a_i =$ acceleration along sensor input axis (IA) (g)

Although the primary unit of acceleration is length per unit time squared, accelerometer output is usually normalized to earth's gravity (see 3.3) and expressed in g units.

This simplified model may be satisfactory for some applications, but for more precise applications a model equation including nonlinear and cross-axis terms may be required (see section 5.).

3.2 Simplified Centrifuge Model

Ideally, the centripetal acceleration of the centrifuge ($\vec{a}_c$) imposed on the instrument under test is expressed as:

$$\vec{a}_c = \vec{\omega} \times (\vec{\omega} \times \vec{R}) \text{ (length per unit time squared)}$$

where:

$\vec{\omega} =$ rotational speed (rad/sec)

$\vec{R} =$ directed distance from rotation axis to the ECM (length units)

and since $\vec{R}$ is perpendicular to $\vec{\omega}$:

$$a_c = -\omega^2 R$$

the magnitude is then defined as:

$$a_c = \omega^2 R$$

The total test input ($\vec{a}_T$) applied at the ECM is centripetal acceleration plus local gravity ($\vec{g}_L$):

$$\vec{a}_T = \vec{a}_c + \vec{g}_L$$

The component of $\vec{a}_T$ along IA is a_i .

The primary unit of these quantities is usually normalized to local g units (see 3.3), whereby g_L becomes unity.

This simplified model may be satisfactory for some applications. For more precise applications, a detailed model equation of the centrifuge with higher-order terms resulting from temperature, mechanical interactions, and instrumentation errors, may be required.

These errors are different for every centrifuge and measurement system and must be individually evaluated for significance. An individual model equation containing only the significant error terms must be developed for each setup. In order to develop a custom model equation, typical error equations for each error source identified are listed in the Section 4. so that they can be evaluated and significant terms combined in cookbook fashion to provide a correct equation for each test.

3.3 Simplified Gravity Model

The term “gravity” (g_L) as used in this recommended practice refers to “plumb-bob gravity,” which is the force per unit mass exerted by the earth on a mass that is at rest relative to the earth. Its direction defines the local vertical and its magnitude is that of the vector sum of Newtonian gravitational force per unit mass and the centripetal force arising from the earth's rotation, divided by the mass.

According to Newton's Law of Gravity, there exists a mutually attractive force F between any two masses m_1 and m_2 at a distance d between their effective centers such that:

$$F = G m_1 m_2 / d^2$$

where G is the gravitational constant:

$$G = 6.670 \times 10^{-8} \text{ cm}^3/\text{gm s}^2$$

In the case where one of the masses is the earth (5.975×10^{27} gm), a gravitational field may be defined at the surface such that the force on a test mass is:

$$F = m g_n$$

where

$$g_n = \text{Newtonian gravitation}$$

Since this has the same form as the inertial law:

$$F = ma$$

and the Theory of Relativity states that, in principle, the effects of gravitation and acceleration are indistinguishable, g_n is defined to be gravitational acceleration and has the units of length per unit time squared.

The downward force of gravity acting on the proof mass of an accelerometer at rest is balanced by an upward restoring force of the accelerometer. Since an upward acceleration requires an additional restoring force of the same polarity, the direction of the acceleration of gravity is sensed to be upward. An accelerometer at rest on earth reacts as if it were therefore experiencing an acceleration of g_L upward.

The centripetal acceleration due to the earth's rotation in inertial space is perpendicular to the earth's rotation axis and is nominally:

$$a_b = R_e \Omega^2 \cos \lambda \text{ in magnitude,}$$

where:

$$\begin{aligned} \Omega &= \text{earth rate} \\ R_e &= \text{earth radius} \\ \lambda &= \text{latitude of the mass} \end{aligned}$$

At the equator, this amounts to 3.392 cm/s^2 and decreases to zero at the poles.

The acceleration of gravity also varies because the earth is not spherical and because of density variations in the earth's crust. The acceleration of gravity is further affected by elevation. A typical equation for the variation of g_L with latitude λ and altitude h (in meters) is approximated by:

$$g_L = 978.039 (1 + 0.005295 \sin^2 \lambda) - 0.000307 h \text{ cm/s}^2$$

By international agreement, the standard value of gravity is defined to be:

$$g_0 = 980.665 \text{ cm/s}^2 \text{ or } 32.1740 \text{ ft/s}^2 \text{ or } 386.089 \text{ in/s}^2$$

This value corresponds closely to the formula value at 45 degrees latitude and sea level elevation.

In the calibration of an accelerometer scale factor, the local value of g_L is normally used as a reference. Since this may deviate from the International Standard by as much as $0.003\ g$ depending on latitude, and by $0.3\ \mu g$ per meter of altitude, a normalization to it or to units of length per unit time squared should be made when an absolute determination of scale factor is required.

Survey data for specific locations may be obtained from the Defense Mapping Agency at the following addresses:

Defense Mapping Agency
Headquarters
8613 Lee Highway
Fairfax, VA 22031-2137

Defense Mapping Agency
Hydrographic-Topographic Center
Geodetic Survey Group
P.O. Box 9617
F. E. Warren Air Force Base
Cheyenne, WY 82005
(Gravity Survey Teams, Gravity Data Library)

Defense Mapping Agency
Aerospace Center
2nd and Arsenal Street
St. Louis, MO 63118
(Gravity Data Library)

4. Test Error Sources

This section endeavors to identify many frequently encountered error sources, and to provide a means to evaluate their significance to the test planned. This section is organized in the fashion of an expansion in partial derivatives or sensitivity coefficients. Each subsection examines one error source and evaluates its contribution to total error as though it were the only error source acting. Section 4.5.2 considers those few cases where error sources interact sufficiently that their combined effects may need to be examined as a separate issue. To the extent possible, the forms of the errors are described as an aid to their identification in test data. Error effects are accordingly described in terms of their ability to masquerade as test unit errors when not properly identified and corrected. In particular, they are described in terms of errors in evaluation of the coefficients of a model equation, such as that described in Section 5.

Measures must be taken to minimize or compensate for significant errors that would be based on the level of precision required in the particular application. These measures can take the form of instrumentation added to a basic centrifuge, or special test procedures, such as multiple-sensor testing to reject common mode errors, or both.

4.1 Radius Uncertainty

A major problem of centrifuge testing is radius uncertainty. Factors contributing to this uncertainty are:

- a) uncertainty in the static radius;
- b) dynamic changes in radius; and
- c) changes in radius due to the environment.

Each contributor to radius uncertainty will be discussed and examples given to show the magnitude of the errors they may cause.

4.1.1 Uncertainty in Static Radius

To determine the static radius to the ECM of the test accelerometer, it is necessary to know the location of the center of the arm, the location of the ECM relative to the reference surfaces of the accelerometer, and the dimensions and interfaces of all the mechanical components between these points, including test fixtures. For high-precision applications, it may be necessary to know this stack-up of dimensions to an overall accuracy on the order of 0.0001 inch. On a 30-inch nominal radius machine, for example, 0.0001 inch introduces an error in applied acceleration of 3 ppm.

Few, if any, centrifuges provide a direct means to measure static radius to useful accuracies, even assuming that the position of the ECM inside the accelerometer is accurately known. Therefore, the static radius must be estimated from the output of the instrument under test.

Many estimation techniques have been used to determine static radius, and the most popular of these are described in Section 7. and Appendix C. In 7.3.3, this document introduces an algorithm that for the first time puts this estimation on a statistically rigorous footing.

A necessary condition for these estimates to be accurate is that the radius must be fixed during the test, or that changes in radius during the test are compensated for in the input data.

4.1.2 Arm Stretch

Arm stretch (ΔR_{AS}) is the elongation of the mechanical structure connecting the accelerometer to the centrifuge spin axis beyond the static value (R_0), and is due to centrifugal loading. If the radius change is due only to arm stretch, the equation for radius is:

$$R = R_0 + \Delta R_{AS}$$

or:

$$R = R_0(1 + \Delta R_{AS}/R_0)$$

Define the normalized equations:

$$a_0 = R_0\omega^2/g$$

and

$$a_c = R\omega^2/g$$

where:

$$a_c = \text{true centripetal acceleration of centrifuge.}$$

Because the arm stretch is proportional to load (hence acceleration), one can write:

$$R = R_0(1 + C_{AS}a_0)$$

where C_{AS} is a constant

then:

$$R\omega^2 = R_0(1 + C_{AS}a_0)\omega^2$$

Dividing both sides by g , we get:

$$a_c = a_0(1 + C_{AS}a_0)$$

resulting in an acceleration-squared error.

This error increases the magnitude of the applied acceleration for either polarity and is therefore an odd-quadratic term (K_{oq}) in the accelerometer output data. In testing precision accelerometers, every effort should be made to estimate the effect of arm stretch and, if significant, correct the input acceleration data.

The magnitude of this error can be estimated by calculating its value for the simple case of an arm with constant cross-section by integrating the elastic strain over its length. For the component due to loading of the arm by its own mass:

$$S(x) = 1/A \int_0^x \omega^2(R-x)dm = 1/A \int_0^x \omega^2(R-x)\rho A/g dx = \rho\omega^2(Rx - x^2/2)/g$$

where:

$S(x)$ = stress at x
 R = test radius (arm length)
 x = distance inward from stress free end
 A = cross-sectional area
 dm = increment of mass
 ρ = density (weight units)

Then, strain = S/Y

$$\Delta R/R = 1/R \int_0^R S/Y dx = \rho\omega^2 R^2/(3Yg) = (\rho/Y)\omega^2 R^2/(3g)$$

where

Y = Young's Modulus

It should be noted that the strain is independent of the area A . It is also nearly independent of the arm material. The inverse of the factor ρ/Y is the specific stiffness (K_s), which for steel or aluminum is 1×10^8 inch.

Replacing $\omega^2 R^2/g$ with $R_0 a_0$ gives:

$$\Delta R/R = R_0 a_0/(3K_s) = C_{AS} a_0$$

The magnitude of C_{AS} is the nonlinearity coefficient caused by stretch of the bare arm. For a 30-inch radius, its value is $0.1 \mu g/g^2$.

The arm stretch due to the test-object weight will add to that of the bare arm. The tensile load is the test-object weight, w , multiplied by the normalized acceleration. The corresponding tensile stress is:

$$S = wa_0/A$$

giving:

$$\Delta R/R = 1/R \int_0^R S/Y dx = wa_0/(AY)$$

In this case, both area and arm material are clearly significant. As an example, if the 30-inch arm is of aluminum with a cross-sectional area of 10 square inches, a 5-pound test object will produce an additional stretch equivalent to $0.05 \mu\text{g}/g^2$.

4.1.3 Accelerometer Proof Mass Deflection

The effects of proof mass deflection under applied acceleration are indistinguishable from those of arm stretch, since both result in a change of radius to the ECM proportional to applied centripetal acceleration and both will produce an apparent odd quadratic term (K_{od}) in the accelerometer output data. It differs only in that it is produced by an interaction between test unit and test bed characteristics and cannot be characterized in the same way that a fixed test bed error might be. The magnitude of the deflection can vary from near-zero to as much as $100 \mu\text{inch}/g$, depending on sensor design. Accelerometer packages that contain internal isolators may experience large deflections. Since the deflection is internal to the accelerometer or sensor package, physical measurements of the effect cannot be made on the centrifuge. However, the deflection can be estimated and used to correct the input data if the static compliance of the constraint is known.

For example, if the accelerometer being tested has a proof mass compliance such that the natural frequency is 1000 Hz (equivalent to a translational mass-spring system with a deflection of $10 \mu\text{inch}/g$), then with a 30-inch distance to the center of rotation, the increase in distance per g is 0.33 ppm. This results in an apparent $0.33 \mu\text{g}/g^2$ odd quadratic error due to gradient in acceleration applied by the centrifuge. Note that this error is comparable in magnitude to that in the arm stretch example of 4.1.2.

4.1.4 Arm Bending

Since the arm of a centrifuge has a finite stiffness, it will tend to sag due to the effects of gravity. Centrifugal forces acting on imbalances of the arm may cause bending in the vertical and/or horizontal plane.

The output of an ideal accelerometer (see 3.1) consists of a bias term (K_0) and a linear term proportional to acceleration along the input axis (K_1). When testing an accelerometer on a centrifuge, the bias term will include a component of local gravity if the input axis is not perfectly horizontal. Arm bending may also cause this misalignment to change as a function of a_c .

A secondary effect of arm bending is the resulting radius change due to the change of end slope during the test. This has the same form of error as arm stretch and will appear as an acceleration-squared term. If a high degree of precision is required, it is important to locate the ECM of the accelerometer as close as possible to the neutral axis of the arm, thereby minimizing the effects of arm bending. For typical centrifuges, deflections are on the order of a fraction of a milliradian, and the resulting radius change due only to beam curvature is less than 1 ppm. However, for a 30-inch radius centrifuge where the ECM of the test accelerometer is mounted 6 inches above the arm neutral axis, a beam deflection of 1 milliradian will produce a radius error of 200 ppm.

4.1.5 Dynamic Center of Rotation

The centrifuge axis of rotation is defined by a set of bearings that may be ball, roller, hydrodynamic, or other. Good quality bearings typically control the axis of rotation within a few microinches at slow speeds. If the arm is balanced along its axis and in the vertical plane, that accuracy will be maintained at the higher speeds required for accelerometer tests. If the centrifuge arm with the accelerometer and its mounting fixture is unbalanced in a vertical plane, the resulting torque will cause the axis of rotation to tilt. If the arm is balanced in the vertical plane but unbalanced radially, the axis of rotation will shift radially and may also tilt depending on the location of the radial bearings and on their individual stiffnesses. Thus, in general, the axis of rotation will move in some orbital fashion that differs from that defined by the bearings at slow speed.

The simplest case to consider is that of a planar approximation in which the arm imbalance is static only—that is, the arm is loaded symmetrically above and below its neutral axis, but one end is slightly heavier than the other so that the

center of mass is shifted slightly along the arm axis by a distance R_{cm} . Then as the arm rotates, it will shift in the direction of the initial offset due to the centrifugal force on the arm. The offset is given approximately by:

$$\Delta R_{\text{dcr}} = (R_{\text{cm}} + \Delta R_{\text{dcr}})m_a\omega^2/k$$

where:

ΔR_{dcr} = shift in dynamic center of rotation
 R_{cm} = initial center of mass offset due to imbalance
 m_a = arm mass
 ω = rotation speed
 k = radial stiffness

The term “radial stiffness” is a direct measure of the resistance of the centrifuge axis to deflection due to a horizontal force at the center of rotation, and must include the effects of all compliances of the structure, including the bearings, connection to the floor, and the foundation on which the machine is mounted.

Then:

$$\Delta R_{\text{dcr}} = \frac{R_{\text{cm}}(m_a\omega^2/k)}{1 - m_a\omega^2/k} = R_{\text{cm}}m_a\omega^2/k$$

This approximation corresponds to assuming $m_a\omega^2/k \ll 1$, or $(\omega/\omega_n)^2 \ll 1$, where $\omega_n^2 = k/m_a$; that is, assuming that the rotational frequency is much smaller than the resonant frequency of the arm on its bearings and support structure. Since ω , the rotational speed, rarely exceeds five revolutions per second, the assumption is usually true.

In this case, ΔR_{dcr} is proportional to ω^2 and therefore to the nominal centripetal acceleration a_0 . Substituting the proportionality constant C_{dcr} :

$$R = R_0 + \Delta R_{\text{dcr}} = R_0(1 + C_{\text{dcr}} |a_0|)$$

The centripetal acceleration then is:

$$a_c = \omega^2 R_0(1 + C_{\text{dcr}} |a_0|)/g = a_0(1 + C_{\text{dcr}} |a_0|)$$

The effect of an imbalance in the centrifuge arm is to introduce a false second-order term. If C_{dcr} remains unchanged when IA is reversed, then only the odd quadratic nonlinearity coefficient K_{oq} will be affected. If C_{dcr} changes sign but not magnitude when IA is reversed, then only the quadratic coefficient K_2 will be affected. In either of these cases, the magnitude of the coefficient error will be C_{dcr} .

In general, C_{dcr} will be different for the two polarities, so both K_2 and K_{oq} will be affected.

The significance of this term is most readily appreciated by an example. Assume:

$$\begin{aligned} \Delta R_{\text{dcr}} &= 0.005 \text{ inches} \\ R_0 &= 30 \text{ inches} \\ a_0 &= 30 \text{ g} \end{aligned}$$

Then:

$$C_{\text{dcr}} = 5.6 \mu\text{g/g}^2$$

The 5-mil motion is unlikely to be noticed without sensitive instrumentation and $5.6 \mu\text{g/g}^2$ can be quite significant.

The assumptions used in this simple analysis are valid in a great many cases. Sometimes the signature of imbalance may be more complicated. For example, it may not be true that $\omega < \omega_n$, in which case a significant fourth-order term appears and the structure may even pass through resonance where phase effects become significant. In addition, the bearing structure may not be isoelastic and its compliance will then vary cyclically with arm rotation.

4.1.6 Thermal Expansion

Since the acceleration produced by the centrifuge is directly proportional to the arm length, any change of length caused by thermal expansion represents an error source. In its simplest form, where the entire centrifuge arm is operating at a temperature different from that where the arm length was measured, the arm length can be computed as:

$$R = R_0(1 + \alpha\Delta T)$$

where:

ΔT = temperature rise above calibration temperature
 α = coefficient of thermal expansion of the arm

It should be noted that a number of difficult complications can arise in situations where this error source is significant, where the temperature of the arm is a function of time as a result of heating or cooling during the centrifuge run itself, or where there is a significant heat flow along the arm causing a temperature gradient to exist. In these cases, the arm temperature must be monitored and the input acceleration data corrected for the changes in R_0 .

As a quantitative example, when the arm is made of cast iron with $\alpha = 13$ ppm per degree Celsius, and the arm temperature changes five degrees from the calibration temperature, a change in arm length of 65 ppm results.

4.1.7 Radial Asymmetry With Acceleration Polarity

The radius errors described in 4.1.1 acquire a special importance when the test unit IA is reversed to test both the positive and negative parts of the input range. Since the location of the ECM is typically not known within 0.03 inch, there is almost always a significant change in radius when the input axis is reversed. If this change is not compensated for, the resulting output data will appear to have scale factor asymmetry, which can easily corrupt estimates of linearity coefficients.

Even-order coefficients are strongly affected by such asymmetry, and radius estimates based on approximations are frequently not accurate enough to avoid gross errors in these coefficients. The best-known way to minimize this effect is to use the algorithm of 7.3.3, with separate measurements of positive and negative scale factor where needed.

For example, if the ECM location is in error by 0.03 inch on a 30-inch radius centrifuge, the error will be 1000 ppm. At the 50 g level this amounts to $50\ g \times 1000\ \text{ppm} = 50,000\ \mu g$, the same error produced by a K_2 of $20\ \mu g/g^2$ at 50 g .

4.1.8 Instrumentation Methods and Errors

The determination of centrifuge radius can be divided into two areas: determination of the nominal or static radius and the determination of dynamic changes in radius. The static radius can be determined several ways, depending on the accuracy of the test to be performed. Measurements of the radius may be possible with a mechanical arrangement such as an Invar rod and a micrometer. However, the accuracy of measurements by this method is typically limited by endpoint determination to about 1000 ppm. For greater accuracy, it is usually preferred to let the test item measure the static radius. This is covered in depth in Section 7, Data Reduction.

Several devices and methods are available for measuring dynamic radius changes. Each device must not only measure the stretch of the centrifuge arm, but must also measure any changes in the dynamic center of rotation. If the device itself cannot do this, it must be supplemented with other devices.

A laser interferometer is an optical device that may be mounted either on- or off-board of the centrifuge arm. A major advantage of optical systems is that, assuming provisions for optical access have been made, the radius growth can be measured right at the test item. Another advantage is that the output of the device, analog or digital, is continuously available for monitoring. The major disadvantages of this system are its sensitivities to temperature and air density, typically producing errors of several ppm under normal laboratory conditions. If more precise measurements are required, the optical path should be evacuated and temperature controlled.

Proximity detectors are analog voltage output devices that are usually mounted off-board. They do not use any centrifuge sliprings and they are not exposed to forced convection heat transfer currents. They are reliable, easy to use, and inexpensive. However, they do have two major disadvantages. Their output is valid only as the arm or the test item swings by, so the data must be sampled by some kind of fast-sampling analog to digital converter, since it is valid for only a few milliseconds. Second, the proximity detectors cannot measure the stretch of the arm at the test package, but must instead look at the surrounding structure, which may not be indicative of that at the test package.

Radius measurement devices cannot be used to compensate for the uncertainty in the location of the ECM or for asymmetry with acceleration polarity. These problems are most readily handled during the data reduction and are discussed in Section 7.

4.2 Alignment Uncertainty

In order to properly define the accelerations along the principal accelerometer axes, it is necessary to know the misalignments between those axes and the centrifuge arm, the axis of rotation, and the gravity vector. In some cases, dynamic terms that cause deflections or changes in the alignment due to centripetal loading or temperature changes must be considered. These error sources must be considered whenever appropriate to achieve the level of precision required.

4.2.1 Static Leveling Error

Static leveling error refers to errors in the acceleration seen by a test item due to misalignments of the accelerometer IA to the centrifuge and gravity vector. A static error is one that is present when the centrifuge is not rotating, and may change with arm position. Typical misalignments are between an accelerometer IA and its mounting surface, the mounting surface and the centrifuge rotation axis, and the rotation axis relative to gravity. As long as the misalignments are truly static (i.e., do not change as a function of the centrifuge g level), they affect the apparent bias (zero-order term in the data) but have little or no effect on the higher-order coefficients (K_2 and K_3). For this reason, a centrifuge test cannot be used to accurately determine the accelerometer bias, but as long as the misalignments are less than about one degree, their effects on the K_2 and K_3 coefficients are negligible.

Tilting of the main centrifuge rotation axis is an error source that requires special consideration in that the acceleration input has a component that varies sinusoidally with each revolution but is independent of arm speed. This error can be eliminated by averaging the accelerometer output over complete revolutions of the arm. At zero rate, a number of readings must be taken and averaged, with the arm stopped at equally spaced intervals through 360 degrees.

4.2.2 Dynamic Leveling Error

For an accelerometer mounted with its IA nominally parallel to the centrifuge centripetal acceleration vector, any angular deflections of the mounting fixture about a horizontal line perpendicular to the acceleration vector results in a change in the component of gravitational acceleration along the accelerometer IA. A change in the component of centripetal acceleration along the IA also results. Considering this misalignment, the acceleration along the IA can be written as:

$$a_i = a_c \cos\phi_T + g_L \sin\phi_T$$

where:

a_i = acceleration along sensor IA
 a_c = centripetal acceleration of the centrifuge
 ϕ_T = mount deflection angle
 g_L = local value of gravitational acceleration unit.

For most applications, small angle approximations can be used for $\sin\phi_T$ and $\cos\phi_T$, giving:

$$a_i = a_c + g_L \phi_T$$

If ϕ_T varies linearly with centripetal acceleration, it can be written as:

$$\phi_T = \phi_{T0} + C_d a_c$$

where:

ϕ_{T0} = initial mount misalignment
 C_d = deflection coefficient (angle/ a_c)

The acceleration along the sensor IA becomes:

$$a_i = a_c(1 + g_L C_d) + g_L \phi_{T0} = \omega^2[R(1 + g_L C_d)] + g_L \phi_{T0}$$

The proportional term, $a_c g_L C_d$, produces additional acceleration in the test unit input axis, which is indistinguishable from that which would be caused by a small change in the test radius, as shown in the second part of the equation. Since the true radius is never known exactly in a centrifuge test and must be estimated by means of the separately measured scale factor, this change produces no error in the indicated nonlinearity. A coefficient of one arc-second per g is equivalent to a radius change of only 5 ppm.

The constant term, $g_L \phi_{T0}$, is similar to a change in accelerometer bias in that it produces a small change in indicated acceleration, which is added to all data points. For example, one arc-second is equivalent to $5 \mu g$. Angles in excess of 0.5 degrees are required to produce significant errors in indicated nonlinearity even in precision testing.

However, when the sensor IA is not approximately parallel to the arm, small deflections can strongly affect recovery of the nonlinearity coefficients. For example, when the IA is vertical, the acceleration along its IA is:

$$a_i = a_c \sin\phi_T + g_L \cos\phi_T$$

or, using small angle approximations:

$$a_i = a_c \phi_T + g_L$$

If ϕ_T varies linearly with centripetal acceleration, this becomes:

$$a_i = C_d a_c^2 + \phi_{T0} a_c + g_L$$

If not compensated for, this results in errors in determining accelerometer cross-axis sensitivities to the square of acceleration. For example, a deflection of one arc-second per g results in a $5 \mu g/g^2$ error in the determination of the coefficients K_{00} or K_{pp} .

A common source of dynamic leveling error is the mode of motion called "coning." When a centrifuge turns very slowly, its axis of rotation defines a line that is fixed in the rotating structure. The line perpendicular to this rotating structure axis through the ECM of the accelerometer under test defines the centrifuge arm axis. As the centrifuge speed is increased, forces due to imbalance can drive the elastic compliance of the bearings and their support structure to

cause the structure axis to trace out a cone about the rotation axis as shown in Fig 2. This motion is synchronous with the basic rotation rate, ω .

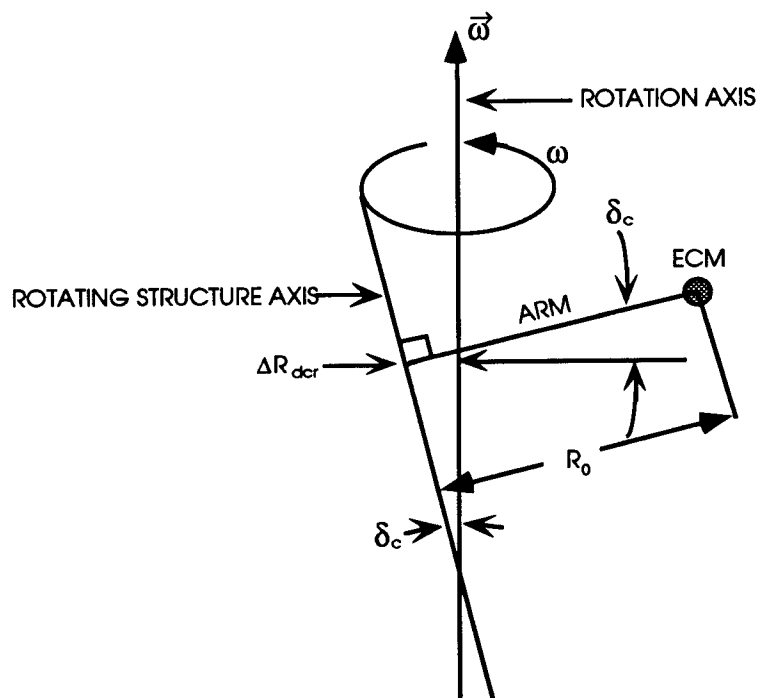


Figure 2—Centrifuge Coning

The radius of the cone as measured at the level of the centrifuge arm is the radius change due to a shift in the dynamic center of rotation, R_{dcr} , which was introduced in 4.1.5. The cone angle δ_c is a contributor to dynamic leveling error. Coning is a prominent feature of many centrifuge analyses for two reasons. First, the displaced structure axis/arm coordinate system is the one to which test fixtures are typically related. Second, the geometry of the coning motion is one of the features commonly measured by auxiliary instrumentation, such as bearing support motion detectors.

4.2.3 Sensor Misalignment About a Vertical Axis

Misalignments and changes of the IA about a vertical axis have no effect on the coupling of gravity, but they do affect the component of a_0 that lies along the sensor IA. Static misalignment creates only a scaling error, which is indistinguishable from radius uncertainty. Changes in misalignment that are a function of applied acceleration due, for example, to arm and fixture compliances, may produce linearity errors in the input acceleration that can masquerade as linearity errors in the sensor output. These linearity effects generally can be identified and compensated for by means of multiple-orientation testing.

Multiple-orientation testing may require specification of nominal angles with respect to the centripetal acceleration vector that are too large to be treated by small angle approximations. The format of the rotation angle ϕ_v , accordingly, is somewhat different than in the previous section:

$$\phi_V = \phi_{V0} + C_d a_c$$

$$a_i = a_c \cos \phi_V$$

where

ϕ_{V0} = initial alignment angle
 $C_d a_c$ = variation in ϕ_V due to a_c

Since $C_d a_c$ is assumed to be a small angle, trigonometric approximations may be used in the expansion of $\cos\phi_V$:

$$\cos\phi_V = \cos\phi_{V0} \cos(C_d a_c) - \sin\phi_{V0} \sin(C_d a_c) = \cos\phi_{V0} - C_d a_c \sin\phi_{V0}$$

$$a_i = a_c \cos\phi_{V0} - C_d a_c^2 \sin\phi_{V0}$$

The first a_i term, which contains only static components of ϕ_V , shows only a small error in apparent radius due to uncertainties in ϕ_{V0} , generally within the uncertainty band for radius. The second term adds a quadratic linearity error.

If the test sensor is assumed to have linearity errors of the form:

$$a_s = a_i + K_2 a_i^2 + K_{ip} a_i a_p + K_{pp} a_p^2 + \text{terms containing } a_0, a_0 a_i, \text{ or } a_0 a_p$$

and a_0 is small, then to second order in a_c :

$$a_s = a_c \cos\phi_{V0} + K_2 a_c^2 \cos^2\phi_{V0} + K_{ip} a_c^2 \cos\phi_{V0} \sin\phi_{V0} + K_{pp} a_c^2 \sin^2\phi_{V0}$$

More than one orientation will be required to separate all the input and output terms that contain a_c^2 . When $\phi_{V0} = 0^\circ$, there is no input error due to the effects of this section, so K_2 can be determined unambiguously. When $\phi_{V0} = 90^\circ$, the C_d input error can be confused with the K_{pp} output error. If the test is repeated with $\phi_{V0} = -90^\circ$, however, and the fixture design is such that C_d does not change, the input error will change sign, allowing the two effects to be separated. Similarly, if $\phi_{V0} = 45^\circ$, even after the K_2 and K_{pp} terms are accounted for, there remains a C_d term that can masquerade as K_{ip} . Once again, if the test is repeated at 225° , the input error will change sign while the output error remains unchanged.

The magnitude of the effect depends, of course, on the accuracy and compliance of the fixture. If the uncertainty in ϕ_{V0} is 0.001 radian, and $C_d a_c = 0.001$ radian at $a_c = 20 g$, then $C_d = 50 \mu\text{rad}/g$. The apparent error varies from zero at $\phi_{V0} = 0^\circ$ to 0.1% at $\phi_{V0} = 90^\circ$. The K_{pp} error, if uncorrected, is $50 \mu g/g^2$ and the K_{ip} error is $70 \mu g/g^2$.

4.2.4 Misalignment About a Radial Axis

Misalignment of the test item about a radial centrifuge axis will have no effect on tests conducted with the accelerometer IA along the centrifuge arm. For orientations in which the accelerometer IA is perpendicular to the centrifuge arm, this misalignment will result in a component of gravitational acceleration being sensed by the accelerometer. This misalignment, if not compensated for, results in an apparent bias error but does not affect the determination of accelerometer nonlinearities, the primary purpose of most centrifuge tests.

4.2.5 Instrumentation Methods and Errors

The measurement of angular deflections of the test item about any of three orthogonal axes is best accomplished by some on-board device, as the nature of the rotating centrifuge environment makes the detection by some stationary off-board device nearly impossible. The most practical on-board devices are the same ones that are used for dynamic radius measurements (see 4.1.8). The same arguments as before apply for the optical and proximity detector devices, so the accuracy, readout resolution, slip ring requirements, etc., for the device must be selected commensurate with the test requirements.

The reference with which these measurements are taken must be chosen with care. The measurement should be made with respect to some fixed reference (i.e., gravity). However, since the device is mounted on the centrifuge arm, it can move relative to the reference. Movements of the measurement device itself must either be minimized by careful placement on the centrifuge or measured and compensated for.