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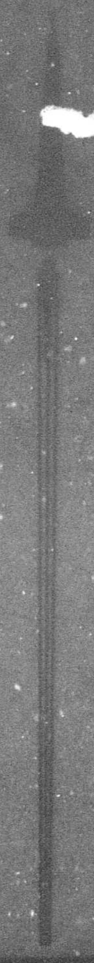

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CENTRIFUGE LINEARITY INTERPRETATION OF ANALOG AND DIGITAL ACCELEROMETERS

by

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U S ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA

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CENTRIFUGE LINEARITY VERIFICATION OF ANALOG AND DIGITAL ACCELEROMETERS

by

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ABSTRACT

This report discusses recent changes in the Army's method of inertial guidance accelerometer applications in order to correlate performance with system cost and accuracy requirements. A recent study of revised test requirements, methods, and techniques in actual test performances are explained, and the results evaluated and depicted using graphs. The major areas covered are: test instruments, calculation techniques, centrifuge errors, digital test methods, and linearity requirement background.

The Army has devised a practical, rapid, and low cost system of evaluating analog accelerometer linearity performance.

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ILLUSTRATIONS

SYMBOLS

ω_1 = Speed of centrifuge at reference g level

ω_2 = Speed of centrifuge at high g level

t_1 = Time required for one revolution of the centrifuge arm at reference g level

t_2 = Time required for one revolution of the centrifuge arm at high g level

R = Nominal radius from center of rotation of centrifuge to accelerometer

ΔR = Centrifuge arm change from reference g level to high g level

E_o = Accelerometer bias and vertical misalignment gravity component (measured at zero centripetal acceleration)

E_1 = Actual output of accelerometer at reference g level

E_2 = Output obtained by projecting a line determined by the zero g and reference g points to a higher g level at which the linearity is to be determined

E_2' = Actual output of accelerometer at high g level

K = The product of the nominal accelerometer scale factor (volts per g) and the cosine of the angle of misalignment of the accelerometer sensing axis with the centrifuge radius

1. Introduction

It is interesting to note that inertial guidance accelerometer applications in the Army have drastically changed within the past year. With missiles like the REDSTONE, JUPITER, SERGEANT, and PERSHING, accelerometer applications have been on stabilized platforms with low acceleration profiles and with sufficient funding to permit the use of high quality gyroscopic-type accelerometers. Accelerometers on the new Army missiles, such as LANCE and others yet to come, however, do not ride on stabilized platforms; they may be body-mounted without shock pads; they may be spinning or even swinging on a pendulum; the instrument compartment is not temperature-controlled; and the g level is high.

2. Linearity Requirement Background

A study of the changing Army applications was made to help correlate accelerometer performance with system cost and accuracy requirements. It was felt that generally an optimum system cost would result if accelerometer error contributions were approximately equal to gyroscope error contributions. The outstanding error sources of accelerometer nonlinearity and gyro drift rate were the parameters selected for this trade-off study. Usually other accelerometer and gyroscope errors make lesser system error contributions, and experience has taught us that the two parameters of nonlinearity and drift rate are almost proportional to the quality and cost of the instruments.

The results of this study can be seen in Figure 1. As an example, it can be seen in Figure 1 that a ballistic missile application using a 0.01 percent nonlinear accelerometer requires a gyro drift rate from about 0.1 to 20 degrees per hour, which is well within the state-of-the-art today. It is only for navigation applications that gyro requirements press the state-of-the-art when used with 0.01 percent nonlinear accelerometers.

Even if accelerometers better than 0.01 percent nonlinear were available for higher than 20 g applications, the added costs of both gyro and accelerometer would restrict usage.

The 0.01 percent nonlinear accelerometer selected for the above example is about the limit of the state-of-the-art today.

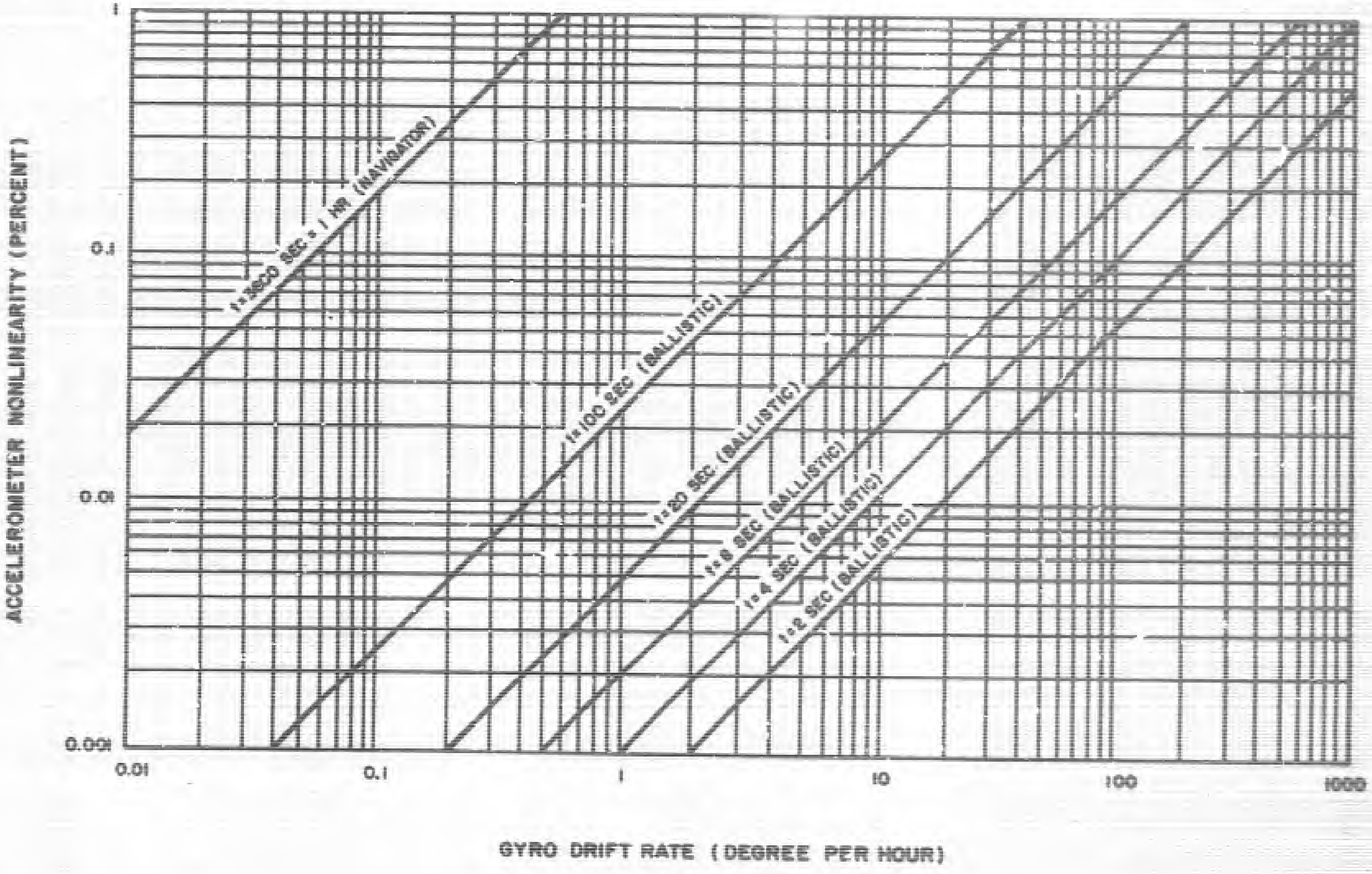


Figure 1. Equal Error Plots for Fixed Time Durations

Another study was made to determine the approximate system mil error caused by an accelerometer nonlinearity on a ballistic missile application. The derivation part of this study is given in Appendix A. This study concludes that a given percent nonlinearity in acceleration measure results in a mil error approximately equal to 20 times the given percent nonlinearity. As an example, 20 times the 0.01 percent nonlinearity of the state-of-the-art accelerometer results in 0.2 mil error for any ballistic missile application. This 0.2 mil error is a reasonable error contribution to most missile error budgets.

In summary, because of the above reasons, matching gyro performance, cost, availability, and error budget contributions, the 0.01 percent nonlinear accelerometer has turned out to be the basic standard required for new Army applications.

Of course, it is possible to use an accelerometer which is highly nonlinear, but repeatable to 0.01 percent from unit to unit, and make a computer or firing table correction to 0.01 percent. For reasons not pertinent to this report, no such computer or firing table correction has been pursued by the Army.

3. Calculation Techniques

After determination of the standard 0.01 percent nonlinearity Army requirement, the next step was to select or develop appropriate techniques to be used in reducing linearity test data. Curve fitting was the first method to be investigated, and since an accelerometer output can be expressed as a series function of the input, curve fitting of input-output data is an accepted method of evaluating the series constants and computing deviations from linearity at different input levels. The advantages of the above method are the ease of computing linearity deviations at different acceleration levels once the series constants are known, and by knowing which constants in the series predominate, it is easier to identify design points of strength and weakness. The disadvantages of the series reduction method are the high cost of such a program, and since inherently equal weight is given to all data points, it tends to distort all data points a like amount instead of accentuating the low-g points as is the case in any application where a scale factor is determined strictly from a 1-g input.

All Army accelerometer linearity verifications have been based on deviation measurements from the 1-g scale factor line, because all Army accelerometer applications depend on scale factors determined from output measurements for 1-g inputs or less and not on scale factors determined from curvilinear fits of input-output data points to mathematical models of abbreviated series functions. It is to be noted that deviation measurements from the 1-g line do not yield prime design information; the series constants are not evaluated, but it does measure actual performance and it can be done relatively inexpensively. It is for the above reasons that the Army has developed and used a three point linearity data reduction method for rapid verification of accelerometer performance. For development and design verification testing, of course, the Army utilizes the curve-fitting series method.

4. Test Instruments and Instructions

The establishment of Army accuracy requirements and test techniques still left the question of which test instruments should be used. To answer this question many different methods of generating input-output data for the three point and series data reduction techniques were investigated with the following conclusions and results:

1) The dividing head is an accurate instrument, but the effect of second and third order series constants are reduced by ratios of 100 and 1000, respectively, at 1g from the effects produced by the same constants at a 10-g level. It is beyond the ability of presently available instrumentation to measure deviations on 0.01 percent instruments which are reduced by factors of 100 or more.

2) Vertical accelerators or pogo sticks produce step inputs which are impossible to measure accurately, and step inputs contain frequencies beyond the response of most accelerometers. It is true that a perfect accelerometer on a perfect vertical accelerator could be integrated at 1-g for the time of operation, but this is not useful information.

3) Some very close correlations have been obtained between centrifuge and vibrator tests for K_2 values, but this requires an extremely accurate eccentric type vibrator with high g capacity at low frequencies and yields no information on the odd order terms.

4) Counter rotating heads on rate tables are similar to vibrator tests. They have accuracy and high g at low frequency, but the unwanted oscillating cross axis inputs eliminate most instruments from this type of testing.

5) Excellent results are obtainable from sled tests on digital accelerometers, but it is extremely expensive and requires a stabilized platform mounting. Analog instruments cannot be evaluated on sled tests because of telemetry accuracy limitations.

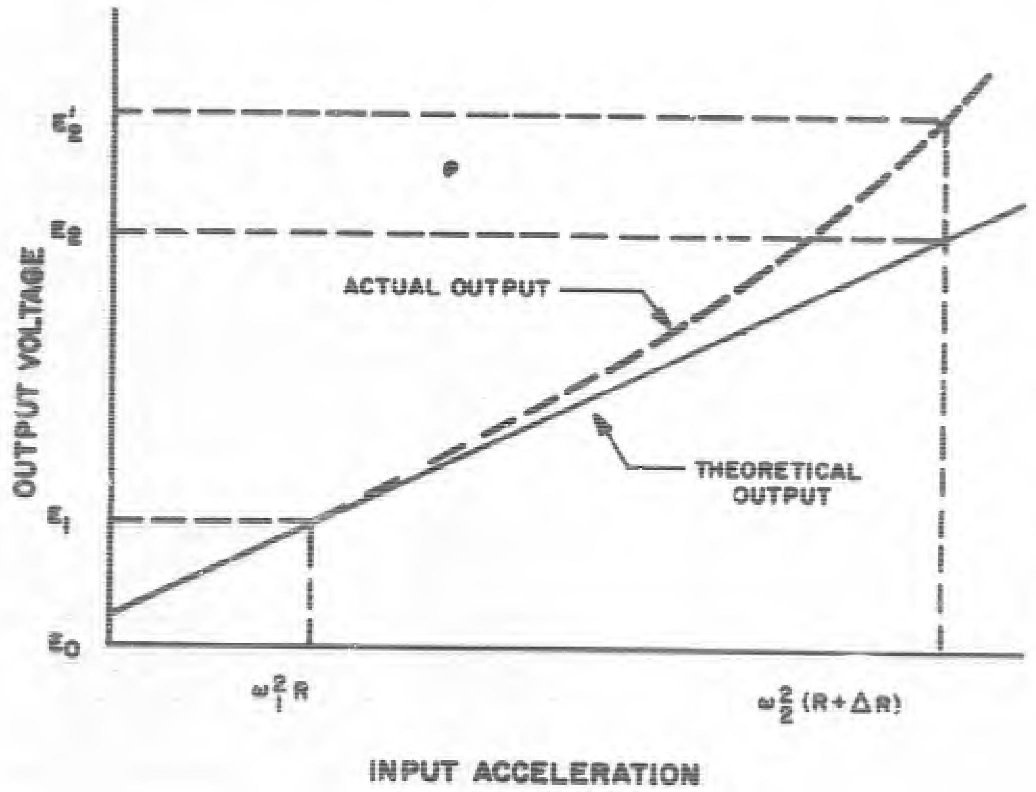
6) Actual flight tests have the same objections as sled tests except that they have the added objection of not knowing displacement as accurately as on sled tests and the test is not usually repeatable.

7) Centrifuge tests were found to be possible of generating sufficiently accurate inputs.

The previous discussions pertained to all types of accelerometers; however, there is a method called current torque insertion which can be used on force-balance accelerometers where current is inserted in the balance coil which simulates a g level input requiring an equivalent amplifier output to balance out the inserted current. Under these conditions, no current is flowing in the balance force coil and little information is available since the prime source of nonlinearity in a force balance instrument is the torquer or balance coil.

Based on the above, centrifuge testing was selected as the best method for generating input-output data, primarily because it is the only available method which has uncertainties less than the accuracy being checked. A centrifuge can be used equally well for any type of data reduction. When design information is needed, the Army utilizes the standard method of curvilinear regression of centrifuge input-output data to fit a mathematical model of the test accelerometer. When evaluation of accelerometer performance is required, the Army uses a three-point method. Since the three-point method is the "something new" in the Army picture, its derivation for centrifuge data reduction will be explained in some detail at this point, together with the centrifuge and measurement uncertainties encountered.

Stated in its simplest form, the three-point method is the percent of output deviation from a straight line constructed through the outputs for a zero and a low g input as can be seen in Figure 2. The zero point (E_o) is the accelerometer output when the centrifuge is not running and the accelerometer sensitive axis is alined horizontally along the centrifuge radius. The low g point (E_1) is the accelerometer output on the centrifuge which corresponds to the calibration point. The low g point is usually 1g or less, but under special conditions, covered later, it may be a point higher than 1g. The high g point (E_2) is any point higher in acceleration than the low g point at which linearity is to be checked.



$$E_1 = K\omega_1^2 R + E_0 \text{ or } R = \frac{E_1 - E_0}{K\omega_1^2}$$

$$E_2 = K\omega_2^2 (R+\Delta R) + E_0 \text{ or } E_2 = K\omega_2^2 R \left(1 + \frac{\Delta R}{R}\right) + E_0$$

$$E_2 = K\omega_2^2 \left(\frac{E_1 - E_0}{K\omega_1^2}\right)\left(1 + \frac{\Delta R}{R}\right) + E_0$$

$$E_2 = \left(\frac{\omega_2}{\omega_1}\right)^2 \left(E_1 - E_0\right)\left(1 + \frac{\Delta R}{R}\right) + E_0$$

$$E_2 = \left(\frac{f_1}{f_2}\right)^2 \left(E_1 - E_0\right)\left(1 + \frac{\Delta R}{R}\right) + E_0$$

$$\% \text{ NONLINEARITY} = \left(\frac{E_2' - E_2}{E_2}\right) 100$$

Figure 2. Linearity Results with Calculations

From Figure 2, the theoretical output of a perfect accelerometer with a fixed bias (E_0) will have outputs proportional to the product of the rotation rate squared and the radius in addition to the fixed bias at any point. From the mathematical equations in Figure 2, it can be seen that accelerometer scale factor, accelerometer vertical and centrifuge misalinements, and centrifuge radius cancel out of the equation E_2 when it is expressed in terms of E_1. It is true that the term $\Delta R/R$ does not disappear, but ΔR can be measured very accurately and small errors in the nominal radius will not have an appreciable effect on this term. $\Delta R/R$ is never more than 0.01 percent on any precision centrifuge and even a 10 percent error in the radius length would make only a total error contribution in the final percent nonlinearity of 0.001 percent. It is also true that a change in the accelerometer alinement in the process of the test would distort the results. Some precision centrifuges do have a method of continuous alinement readout, but most centrifuges have a "droop" measurement which shows vertical movement. The vertical "droop" measurement could be caused by either arm bending or change in the vertical height of the arm of both. When a uniform centrifuge arm is used, it can be shown that a uniform arm bending causing all the droop measurement would be of no consequence on most centrifuges.

In the Figure 2 derivation, the period of revolution was used instead of the rotation rate in the final equation. This is important because rotation rate readout depends on centrifuge encoder pulses for a unit of time and the resolution of the pulse count is a sizable error.

5. Digital Test Methods

The preceding has pertained to analog testing; for digital testing, the period of some number of accelerometer or centrifuge pulses would be used as a time base to count a sufficient number of pulses to minimize the resolution error. The proper technique would be to select the slowest rate of pulsing either accelerometer or centrifuge and use it to gate a timer and a counter to accumulate the fast pulses.

6. Centrifuge Errors

The most difficult centrifuge parameters to control is the "wow", or speed deviation of the machine. It can be seen in Appendix B that a 0.45 percent cyclic speed deviation results in an acceleration error of only 0.001 percent. Most precision centrifuges have a wow considerably less than 0.45 percent. For digital or analog integrating type accelerometers the centrifuge wow is not a problem on most machines. For analog nonintegrating accelerometers the centrifuge wow is an almost impossible problem. The difficulty is in determining the accelerometer output. In attempting to read a DC voltage level within 0.001 percent about 0.002 percent is the maximum deviation that can be tolerated and yet retain a 0.001 percent confidence in the indicated reading. A 0.002 percent acceleration corresponds approximately with a 0.001 percent speed deviation which is four hundred and fifty times less than the 0.45 percent wow that generated the 0.001 percent error in the input to the integrating type instrument.

There are only four ways to solve the analog wow problem: a 0.001 percent integrator, a combination 0.001 percent bucking voltage reference and integrator, a 0.001 percent recorder, or a 0.001 percent wow centrifuge. At the present time, the 0.001 percent wow centrifuge seems to be the best approach.

The fact that about 0.002 percent wow is the best available today may be partially due to small user demand and insufficient interest of competent control groups.

7. Discussion

Many factors affect an accelerometer's performance and every effort must be made in the process of conducting a linearity test to obtain linearity alone without combining unwanted conditions. Test specimens should be held at a constant temperature and loading time minimized. In applications requiring short flight times, it is desirable to stabilize the centrifuge and energize the accelerometer only long enough for a reading. If an accelerometer has a null uncertainty, it should be considered as an uncertainty in the bias voltage used in the nonlinearity computations. The actual movement of the sesmic mass of the accelerometer must make an insignificant error contribution for the selected centrifuge radius. If test results vary for different radius lengths then allowance must be made for spin sensitivity or g gradients in the plane of the sensitive axis. Extreme care should be used with split sesmic mass sensors when each sesmic mass half does not see the same force. If a unit is so noisy that test results are not repeatable within expected limits, it may be necessary to increase the low g point to minimize the noise contribution when using the three point method. Increase of the low g point over the application calibrating point can never be done without some sacrifice of possible error in the application, but it is sometimes advisable to allow a small precent of possible error to go unmeasured if large test deviations due to noise can be greatly reduced. In addition to the above factors, there are factors which affect gyroscopic accelerometers only such as input-output axis misalinement effects on the zero g reading, servo loop strain due to outer case rotation of the spin motor housing, and spin sensitivity of the output gimbal due to its own precession.

8. Conclusions

In conclusion, it can be stated that the Army has devised what seems to be a practical method of evaluating analog accelerometer linearity performance rapidly and at low cost. Use of the simple three-point method now makes possible fast and widespread evaluation of new types of analog instruments on the market as well as cheap and fast acceptance testing on the various Army projects. If Army accuracy requirements tighten in the future, it is anticipated that it will be on digital or integrating accelerometer type applications which are well within the Army's ability to handle today.

Appendix A

APPROXIMATE EFFECT OF A KNOWN ACCELERATION NONLINEARITY VECTOR MEASUREMENT ON A FREE-FALL SYSTEM

1. Assumptions

The following items were assumed:

1) The given percent acceleration non-linearity measurement yields the same percent velocity error at cutoff.

2) Flat earth.

3) Boost distance covered is considered negligible.

4) No other error sources.

5) Gravity constant.

6) A mil is equal to one part in a thousand.

2. Definitions

V = Desired cutoff velocity

ΔV = Velocity error[1]

V_y = Vertical velocity component

V_x = Horizontal velocity component

S = Desired distance (range)

ΔS = Distance error[1]

θ = Firing angle

T = Desired flight time

ΔT = Time error[1]

---

[1] Error resulting from nonlinearity in acceleration measurement.

NL = Nonlinearity percent error in acceleration measurement

G = Gravity constant

A = Desired acceleration

ΔA = Acceleration error[2]

3. Solution for System Error in Mils for a Given Percent Nonlinearity Acceleration Measurement

$$V_y = V \sin\theta \tag{1}$$

$$V_x = V \cos\theta \tag{2}$$

$$T = \frac{2V \sin\theta}{G} \tag{3}$$

$$S = TV_x \tag{4}$$

$$S = \frac{2V^2 \sin\theta \cos\theta}{G} \tag{5}$$

Equation (5) represents the range distance without any errors.

$$S + \Delta S = \frac{2}{G} (V + \Delta V)^2 \sin\theta \cos\theta \tag{6}$$

$$\% \text{ change in } S = \frac{(S + \Delta S) - S}{S} (100) = \frac{\Delta S}{S} (100)$$

$$\% \text{ change in } S = \frac{\dfrac{[(V^2 + 2V\Delta V + \Delta V^2) - V^2]\ 2 \sin\theta \cos\theta\ (100)}{G}}{\dfrac{2V^2 \sin\theta \cos\theta}{G}}$$

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[2] Error resulting from nonlinearity in acceleration measurement.

$$\% \text{ change in } S = \frac{2V\Delta V + \Delta V^2 (100)}{V^2} \qquad (7)$$

Equation (7) can be approximated by neglecting the ΔV^2 term which is very small.

$$\frac{\Delta S}{S}(100) \approx \frac{2\Delta V}{V} 100 \qquad (8)$$

$$\frac{\Delta V}{V}(100) = \frac{\Delta A}{A} 100 = \text{NL (by definition)} \qquad (9)$$

$$\% \text{ range error} = \frac{\Delta S}{S}(100) = 2\,(\text{NL}) \qquad (10)$$

$$\text{Mils range error} = \frac{\Delta S}{S}(1000) = 20\,(\text{NL}) \qquad (11)$$

Equation (11) states that a percent nonlinearity in acceleration measure results in a CPE error in mils approximately equal to 20 times the percent nonlinearity.

Appendix B

CENTRIFUGE WOW RESULTING IN A 0.001 PERCENT ACCELERATION ERROR

GIVEN: Centrifuge speed W is a combination of a constant ω and a sine function $\sin \alpha t$ with a maximum value B.

$$[\,W = \omega + B \sin \alpha t\,] \tag{12}$$

FIND: The percent value that B is of ω that results in a 0.001 percent average deviation in the centrifuge radial acceleration vector a at radius R.

$$[\,a = W^2 R\,] \tag{13}$$

SOLUTION:

$$\left(\frac{W^2R - \omega^2 R}{\omega^2 R}\right)100 = 0.001 \text{ by definition}$$

$$\frac{W^2 - \omega^2}{\omega^2} = 0.00001$$

$$\frac{(\omega^2 + 2\omega B \sin \alpha t + B^2 \sin^2 \alpha t) - \omega^2}{\omega^2} = 0.00001$$

For an average deviation the cyclic parts are omitted and the above equation reduces as follows:

$$\frac{B^2}{2\omega^2} = 0.00001$$

$$B^2 = 0.00002\ \omega^2$$

$$B = 0.0045\ \omega = 0.45 \text{ percent } \omega$$

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