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METHODS FOR CALIBRATING MOTION MEASURING TRANSDUCERS AT LOW FREQUENCIES

(Zero to 20 Hz)

By Otis C. Ingebritsen

NASA Langley Research Center
Langley Station, Hampton, Va.

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METHODS FOR CALIBRATING MOTION MEASURING TRANSDUCERS AT LOW FREQUENCIES

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Aerospace Technologist
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ABSTRACT

The discrete point method and the continuous comparison method of calibrating accelerometers on a centrifuge are discussed. The discrete point method uses an integrating technique to average an accelerometer's output over the same time interval as a counter averages the centrifuge angular velocity. The continuous comparison method produces a linearity correction curve of an accelerometer by a simultaneous comparison with a reference accelerometer. This latter system is accurate, saves time, and is more likely to detect anomalous dispersion characteristics.

The three-dimensional rotator method for the calibration of inertial angular transducers is also discussed. An angular transducer is mounted in a two-gimbal frame with its sensitive axis perpendicular to the axis of the inner gimbal. The two gimbals are simultaneously rotated about their mutually perpendicular axes at angular velocities of ω_1 (outer gimbal) and ω_2 (inner gimbal). A sinusoidal variation of angular displacement, velocity, and acceleration results with $\phi_{max} = \frac{\omega_1}{\omega_2}$, $\omega_{max} = \omega_1$, and $\alpha_{max} = \omega_1 \omega_2$. Speed of rotation can be measured very accurately and the calibration is basic.

INTRODUCTION

Many rectilinear and angular motion transducers are employed in the flight and space research facilities at the Langley Research Center; consequently, development of accurate and reliable calibration methods was required. The centrifuge discrete point method and the centrifuge continuous comparison method for the calibration of rectilinear accelerometers and the three-dimensional (3-D) rotation method for the calibration of angular transducers are methods which were developed to fulfill some of these needs.

The rectilinear and angular motion transducers used here have wide range but medium accuracy (0.1 to 1 percent), and are used in making motion measurements on equipment, vehicles, or structures. The advanced techniques used in the precision calibration of guidance and control transducers are not within the scope of this paper.

Many transducers exhibit problems such as: gas bubbles or trash in damping fluid, excessive friction or hysteresis, poor linearity, zero shifts, and "oil canning" springs. Because of the transient nature of some of these anomalies, a calibration method which overcomes certain limitations of the discrete point technique was sought.

In 1956, with a servo accelerometer for a reference accelerometer and an early X-Y discrete point plotter, our first centrifuge comparison method was developed. Over the years we made improvements in the method and our confidence in the resulting calibrations grew.

At present, not only does the centrifuge continuous comparison method show up discrepancies in transducer performance, but the calibrations can be performed more quickly, are relatively free of human error, and are extremely repeatable.

With the advent of the integrating voltmeter, the centrifuge discrete point method was improved and for each calibration is incorporated with the centrifuge continuous comparison method for the basic two-point sensitivity measurement of the reference accelerometer.

The 3-D rotator was conceived at LRC in 1951 as a means to calibrate angular accelerometers. This method has been used since then with reliable results over the range 1 to 10 Hz to an uncertainty of ±1 percent up to $1000 r/s^2$. Other methods such as the angular vibration calibrator and the torsion pendulum can yield good results, but are limited by the difficulties of making precise measurements of the frequency and dynamic angular amplitude. The 3-D rotator method is basic and requires only the measurement of two constant angular velocities. These can be very accurately measured.

Since these techniques have proven extremely valuable in standardizing calibrations and in troubleshooting malfunctioning accelerometers, they are described in this report with the hope that other agencies will adopt them and thus provide good correlation between users.

CENTRIFUGE CALIBRATOR, GENERAL

The centrifuge calibrator is described in ASA S-2.2.(1) Although the centrifuge is employed to

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[1] Superior numbers refer to similarly-numbered references at the end of this paper.

calibrate accelerometers, it is also used to measure the effects of linear acceleration on other kinds of transducers. When corrections for acceleration effects are to be made on these other transducers, an acceleration sensitivity calibration is performed.

The acceleration a imposed on the accelerometer seismic mass by a centrifuge is,

$$a = \frac{\omega^2 R_o}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]} \tag{1}$$

where ω is the angular velocity of the centrifuge, ω_n is 2π times the undamped natural frequency of the accelerometer, and R_o is the radial distance from axis of rotation of the centrifuge to the center of the accelerometer's seismic mass at its zero measurand (input) position.

The undamped natural frequency is determined from a sinusoidal vibration measurement and is the frequency at which the accelerometer output lags the input acceleration by 90°.

The centrifuge calibration accuracy is affected by many factors(2,3) and the effects of these factors must be controlled to a level consistent with accuracy required of the overall calibration. Some of these factors are:

1. Centrifuge angular velocity measurement.

2. Radius of gyration of the accelerometer seismic mass with seismic mass deflection considerations.

3. Alinement of the accelerometer sensitive axis along a radius of the centrifuge.

4. Orientation of a pendulous accelerometer.

5. Centrifuge static and dynamic balance.

6. Centrifuge speed variations, short term (wow) and long term (drift).

7. Alinement of the centrifuge spin axis to the earth's gravitational field.

8. Vibration of the centrifuge giving rise to possible accelerometer or readout rectification errors and the tendency to relieve friction in the accelerometer.

9. Thermal effects on the accelerometer due to centrifuge windage (forced air circulation) and heat-sink conditions.

10. Centrifuge slip-ring quality: Insulation resistance, self-generated emfs, or brush noise.

11. Actual input and output voltage at the accelerometer terminals.

12. Lead resistance, insulation resistance, and shielding.

Some of these factors are discussed below:

Centrifuge Angular Velocity Measurement

Centrifuge speed may be measured in several ways. A few methods are listed here:

1. dc generator and voltmeter technique.

2. Electronic counter or frequency meter technique using for frequency detection either a coded disk with optical pickoff, ac voltage generator, or a multitoothed wheel with proximity pickup.

3. Photographic method.

4. Rate gyro technique.

With either the toothed wheel or coded disks, it is important that these be mounted concentrically with the centrifuge spin axis. It is also important that the teeth or the coded disk marks be accurately spaced as this and/or poor concentricity will produce "wow" in the readout of speed even though the centrifuge may be relatively free of wow. The effect of such an error can be minimized by measuring over a sufficient number of revolutions of the centrifuge.

Radius of Gyration of Accelerometer

The radius of gyration of the accelerometer seismic mass must be known with an accuracy consistent with the required accuracy of the overall calibration. The radius of gyration determination requires the measurement of the distance from the center of rotation to a point on the accelerometer and a measurement from this point to the center of the accelerometer's seismic mass. The center of the seismic mass along the sensitive axis can be found by testing the accelerometer on a high-speed table and finding the position of the accelerometer, relative to the center of rotation, where there is no output change with high angular rate. Where the centrifuge radius is very large, the dimension from the mounting base to the seismic mass from drawings of the transducer may be sufficient.

The measurement of the seismic mass deflection per g-unit of applied acceleration must be known. The deflection of the seismic mass adds to the initial radius of gyration of the mass as the centripetal acceleration is applied to the accelerometer. The expression above (eq. (1)) for acceleration can be rewritten

$$a = \omega^2 R_o (C) \tag{2}$$

where

$$C = \frac{1}{1 - \left(\frac{\omega}{\omega_n}\right)^2}$$

A graph such as figure 1 can be constructed to yield the value of C for easy reference in order to determine the magnitude of the correction required for each angular velocity. It can be seen that if ω_n is high and R_o is large, then the centrifuge angular velocity ω will be small and the correction C will approach unity.

All calibrations must include consideration of this correction. It must be remembered that the correction may be appreciable if the accelerometer natural frequency is low or the accelerometer radius of gyration is small. Neglecting this correction will produce apparent nonlinearity and a sensitivity error in the accelerometer calibration, since the correction has a different value for each acceleration level (centrifuge speed) (figure 1).

Orientation of a Pendulous Accelerometer

If the accelerometer is pendulous, a decision must be made whether to orient the pivot or hinge axis parallel to the axis of centrifuge rotation (so as to minimize earth's gravitational field effects) or to orient the pivot or hinge parallel to the plane of rotation (minimize the angular accelerations of the centrifuge). This consideration is important for accurate work, and is particularly critical for low range accelerometers with low natural frequencies.

Where zero frequency (static) accelerations are imposed and the centrifuge is free from wow and drift, one can orient the pivot or hinge axis parallel to the axis of rotation. If, however, the centrifuge has appreciable short-term speed variations (wow) it is better to orient with the pivot or hinge axis of the accelerometer parallel to the plane of the axis of centrifuge rotation. For the latter case, the pendulum up or down orientation of the accelerometer results in an error due to a component of earth's field depending on the angular displacement of the pendulous mass at each level of sensitive axis acceleration applied. By making two calibration runs, pendulum up and pendulum down (pendulum free end up and then free end down), the calibration can be derived by averaging the two sets of data.

The calibration presented in terms of g-units must state whether the data is corrected to standard g or is in units of local value of g.

Also any centrifuge calibration should include (±1g) field of gravity test outputs (while still wired in the centrifuge circuit) for correlation with the centrifuge data.

THE CENTRIFUGE DISCRETE POINT METHOD

Two data acquisition techniques are considered here in performing the discrete point accelerometer calibration employing a centrifuge:

(1) Manually adjusting to the exact speed settings, and reading the accelerometer output voltage, or,

(2) Manually adjusting to approximate speed settings, then measuring the actual speed and accelerometer output voltage by integrating each over the same period of time.

In the widely used first technique the operator acts as a human servo dividing his time between setting an exact centrifuge speed and adjusting the reading of (nulling) a differential voltmeter. This is a tedious and time-consuming procedure and the quality of the calibration is much dependent on the setability of the equipment and the skill of the operator. Now consider the second technique where the operator simply sets the centrifuge to an approximate speed then pushes a button on an electronic counter to initiate a READ command to the integrating instruments. As the electronic counter starts to count, it triggers an integrating digital voltmeter. These integrating instruments then average the actual values of speed and voltage over the same time period.

Advantages of the Integration Technique

The integration technique, described above, saves operator time and tedium and improves accuracy by eliminating operator errors through automating the measurement process. Also, without the need to set exact speeds, there is less chance of overshooting the setting during the speed adjustment. Overshooting gives rise to an error in measuring the friction and repeatability of an accelerometer.

The simultaneous integration of the speed and voltage yields the average of the actual values and virtually eliminates the effects of wow and drift in the measurement. This added precision can be realized in the calibration of the friction-free accelerometers available today.

Disadvantages

Of course, using approximate settings will require each point to be separately calculated which can be time consuming and a source for human error. To relieve that situation at LRC, a small computer program handles the data reduction yielding the sensitivity, zero balance, and deviations from the best straight line.

Where friction is inherent in the accelerometer, wow and drift of the centrifuge may limit the precision of the calibration. A better method for detection of friction and anomalous behavior is the centrifuge continuous comparison method using a friction-free reference accelerometer (to be discussed later in this paper).

Results on a Friction-Free Accelerometer

The results of a (±50g) calibration using the integration technique is shown in figure 2. The accelerometer used was a servo type and the centrifuge employed had ±0.05 percent of wow and drift. The smallest division on the linearity correction plot represents 0.01 percent of the accelerometer full-scale output. Experience at LRC has shown that the deviations using the integration technique were about 1/5 the deviations using the former technique (set and read) even with an experienced operator performing the calibration.

THE CENTRIFUGE CONTINUOUS COMPARISON METHOD

The accelerometer to be calibrated and a reference accelerometer are mounted on a centrifuge. The difference in output voltage between the reference accelerometer and the test accelerometer is plotted on one axis of an X-Y recorder (plotter) simultaneously with the reference accelerometer output on the other axis as shown in the wiring diagram (figure 3). A transfer function is written which permits the resulting X-Y plot to be used as a linearity correction to the accelerometer output as shown in figure 4:

Transfer function,

$$G = \frac{1}{S}\left(E_o - E_b + C\right)$$

where

G	multiple of g units, in standard g (standard g is 9.80665 m/sec^2)
S	reference accelerometer sensitivity in volts/g unit (standard g)
E_o	test accelerometer output, volts
E_b	test accelerometer zero balance output fitted to the correction curve, volts
C	linearity correction from the mean curve of the plotted data, volts

The zero balance E_b is derived by finding the midpoint voltage, E_o at zero g, between the test accelerometer output at +1g and -1g and then substituting this value in the transfer function and solving for E_b:

$$E_b = E_o + C$$

where C is the Y-axis deviation at the reference accelerometer zero output along the X-axis (labeled $E_o - E_b$, figure 4).

Essential to the method is a reference accelerometer with very low values of hysteresis, friction, nonlinearity, and nonrepeatability. The reference accelerometer should allow rapid and very fine ranging from 1g to the highest range accelerometer that must be calibrated. The reference accelerometer with a high natural frequency can be mounted on the centrifuge at a fraction of the radius of the test accelerometer to extend the range of the calibration system. For example, a 250g accelerometer may be calibrated using a 50g range reference accelerometer mounted at 1/5 the radius of the test accelerometer. The reference accelerometer sensitivity S is determined from measurements of the reference accelerometer output by discrete point readings at zero and full range acceleration on the test accelerometer. Since the imposed acceleration is calculated for the test accelerometer radius of gyration, it matters little whether the reference accelerometer is at the same radius. The reference accelerometer linear output is used much like a straight edge to connect the discrete point measured values. In the comparison method the following conditions are required:

1. The natural frequency of the reference and test accelerometers must be high and the centrifuge should provide a radius of gyration large enough so that the seismic mass deflections may be neglected, or corrections may be applied (figure 1).

2. A detailed calibration by the centrifuge discrete point method must be performed on the reference accelerometer (figure 2).

3. The reference accelerometer should have a self-test capability (acceleration simulation by current insertion).

The reference accelerometer must be recalibrated at intervals depending on its long-term stability. The calibration will establish the reference accelerometer sensitivity, linearity, repeatability, and short-term stability. Repeated calibration at intervals of time will establish its long-term stability, reliability, and confidence level.

A continuous plotting current insertion technique as shown in figures 5 and 6 can be applied to some servo accelerometers to verify the linearity, hysteresis, friction, and resolution. Although these characteristics may appear different with current insertion than with acceleration applied, the test results strongly imply the continuity, linearity, and precision of the accelerometer between the discrete points at which it was calibrated on the centrifuge.

Commercially available servo accelerometers suitable for use as reference accelerometers are relatively inexpensive.

The Centrifuge Continuous Comparison Circuit

The circuit of figure 3 allows the reference accelerometer sensitivity to be adjusted to any value from less than 0.5 millivolt per g to 5.0 volt per g. The force coil sensitivity of one type of servo accelerometer is 0.2 ma per g. The force coil current passes through the centrifuge slip rings to the calibration panel where the reference accelerometer range resistors are located. The reference accelerometer can be balanced to zero output in its mount on the centrifuge. Its output can be switched to provide either a positive or negative output to "buck out" the test accelerometer. A battery source for the plotter zero adjust is provided to buck out the test accelerometers zero unbalance voltage where the zero unbalance is great. If the accelerometer output resistance is small compared to the plotter input resistance, the calibration of the accelerometer is virtually potentiometric since only the difference voltage is affected by the one megohm input resistance of the plotter. The reference accelerometer output also drives the plotter X-axis and is labeled $E_o - E_b$ (figure 4).

The Continuous Comparison Plot

After the required warmup, the output of the accelerometer at +1g and -1g in the field of gravity is measured while on the centrifuge. A suitable arrangement must be provided on the centrifuge for this purpose. (In the circuit of figure 3 the plot switch must be in the Off position when making these measurements or an error due to loading will result.)

From the preceding data, the polarity and approximate sensitivity of the test accelerometer are determined. The sensitivity of the reference accelerometer is set initially to this approximate sensitivity of the test accelerometer. Refinement of this sensitivity setting is made after an initial run.

With the accelerometers mounted and the plotter controls adjusted, the speed of the centrifuge is slowly varied to full range of the test accelerometer and back to zero. If the test accelerometer has a bi-directional range, it is reversed on the radius, the output of the reference accelerometer is reversed, and the plot through this range is made. If the position of the record is not accurately oriented on the axes of the graph, refinements are made to the settings and another plot is made. When the position of the plot is satisfactorily alined on the axes of the graph, the zero and full-scale outputs of both accelerometers are measured using the discrete point method. During the excursion to and from full scale to take this data, another comparison plot can be generated. This plot should be almost identical to the former plot if the accelerometer is stable and repeatable.

Precautions

The procedure requires that the seismic mass of the test accelerometer be at the same radius for both plus and minus acceleration. If this is not done it will be necessary to adjust the reference accelerometer sensitivity between the + and - accelerations to compensate for the radius difference.

The rate of change of angular velocity is generally not critical, except that the rate should be slow enough so that there is no apparent dynamic lag in the plot. With some pendulous accelerometers or even a misalined rectilinear accelerometer, the centrifuge angular acceleration may appear as additional hysteresis or friction on the plot. In general, with high natural frequency accelerometers, well alined, and a slow rate of change of angular velocity (about 1 minute to full range), little trouble of this nature is encountered. The centrifuge control must allow the speed to be controlled slowly and smoothly.

Advantages of the Continuous Comparison Method

An important benefit of the continuous comparison method is the infinite-point nature of the calibration. The plot documents the detailed linearity of the accelerometer with no assumptions required between the points on a curve. Often in the discrete point calibration many points are required to adequately determine the true calibration over the entire range. The time saved using the comparison method can be very great, indeed, if a large number of discrete point data are required.

The comparison method details the anomalies that would escape attention with the discrete point calibration method. Air bubbles or foreign particles often present in a damping medium may be discovered (figure 7(a)). A minor obstruction (figure 7(b)) may be revealed that could cause gross errors if the accelerometer was used without this kind of calibration. "Oil canning" of the seismic mass suspension spring(s) could remain undetected with the limited discrete point calibration (figure 7(c)).

The comparison method is rapid and lends itself to precision production calibration. The perturbations that occur during a single calibration, caused by gas bubbles or trash in the accelerometer, may not be repeatable. The detailed plot obtained with this method captures this kind of transient malfunction and provides the record necessary to better communicate the nature of such malfunctions to others. Many times "a continuous comparison record" is worth a thousand words (or a hundred discrete points).

This quasi-static calibration method records the accelerometer friction and hysteresis with less chance for centrifuge wow to affect the detection and measurement of friction although centrifuge vibration may relieve friction somewhat. It should be noted that when both accelerometers are mounted on the centrifuge near each other, some vibration effects tend to cancel on the plot.

THE THREE-DIMENSIONAL ROTATOR METHOD

The tilted centrifuge(1) has its counterpart in the angular motion domain in the three-dimensional rotator.(4) The tilted centrifuge turns a rectilinear inertial transducer over in the earth's gravitational field; whereas the three-dimensional (3-D) rotator turns an angular inertial transducer over in an angular rate field as shown in figure 8. As with the rectilinear transducer, the angular transducer should be insensitive to angular accelerations about other axes. This can be true only where the inertial element of the angular transducer is kinetically symmetrical about the axes orthogonal to the sensitive axis. That is, where the inertias about any axis drawn perpendicular to the sensitive axis through the mass center of the inertial mass are everywhere equal as shown in figure 9.

The equations that describe the 3-D rotator angular accelerations generated on the inertial mass (figure 10) are, in the cross axis:

$$\alpha_x = \frac{I_x + I_y - I_z}{I_x} \omega_1 \omega_2 \cos \omega_2 t$$

$$\alpha_y = - \frac{\left(I_x - I_z\right)}{I_y} \frac{\omega_1^{\,2}}{2} \sin 2\omega_2 t$$

in the sensitive axis:

$$\alpha_z = \frac{I_x - I_y - I_z}{I_z} \omega_1 \omega_2 \sin \omega_2 t$$

If the inertial element of the transducer is a sphere, or the inertial equivalent, $I_x = I_y = I_z$, then the equations become

$$\alpha_x = \omega_1\omega_2 \cos \omega_2 t$$

$$\alpha_y = 0$$

$$\alpha_z = -\omega_1\omega_2 \sin \omega_2 t$$

With such a spherical inertial element, the transverse and sensitive axis angular accelerations are equal but displaced in time.

As is more often the case, the inertial element is designed as a ring, or disk. For a very thin disk, of mass M, and radius r,

$$I_z = \frac{Mr^2}{2}$$

$$I_x = I_y = \frac{Mr^2}{4} = \frac{I_z}{2}$$

then,

$$\alpha_x = 0$$

$$\alpha_y = \frac{\omega_1{}^2}{2} \sin 2\omega_2 t$$

$$\alpha_z = -\omega_1\omega_2 \sin \omega_2 t$$

The double frequency cross-axis acceleration α_y is a maximum when I_x and I_y approach $\frac{1}{2} I_z$ and is zero when $I_x = I_y = I_z$. In general, with a kinetically symmetrical inertial element in a properly designed angular accelerometer, the angular deflection of the inertial element about the sensitive axis does not cause interactions due to the existing cross-axis accelerations.

Advantages of the 3-D Rotator Method

1. Large angular amplitudes in the low-frequency range can be readily obtained.

2. The input angular acceleration is generated by simply setting the axes velocities ω_1 and ω_2 (figure 10).

3. An accuracy of better than 0.1 percent is feasible, depending on design.

4. A measurement of the kinetic symmetry of the inertial mass can be made by repositioning the transducer about the sensitive axis on the 3-D rotator (figure 10).

5. The calibration may more nearly simulate use conditions, say, in a spinning, coning space vehicle.

Precautions

For the least distortion in the waveform, the careful adjustment of static and dynamic balance of each of the 3-D rotator axes and adjustment of equality of the 3-D rotator X- and Z-axes inertias are required. This helps to attain a constant speed on both 3-D rotator axes.

Since the 3-D method also produces dynamic tilting in the field of gravity, an imperfect balance of the transducer's inertial element may cause a superimposed output due to this unbalance. To determine the true angular acceleration sensitivity, the direction of ω_1 may be reversed and an average of the sensitivities will minimize the error introduced by the earth's field of gravity. Also, in fluid damped or fluid inertial element transducers, gas bubbles in the fluid can cause serious perturbations in the transducer output. This technique may reveal such potential errors in the use of the transducer.

Because of the transverse accelerations generated on the 3-D rotator, care must be exercised to prevent overload of the transducer. This requires a knowledge of the transducer construction to predict, from the above equations, the magnitude of the transverse accelerations.

SUMMARY

It has been shown how the centrifuge discrete point method using the integration technique yields improved data compared with usual (set and read) technique. The centrifuge continuous comparison method has many advantages which recommend it for adoption as a standard method. Consider the benefits if the manufacturers would present their customers with NBS referenced linearity correction curves such as illustrated here! I should like to see them take up this challenge.

The 3-D rotator method has been described and shown to be basic and, potentially, very accurate. It is certainly worthy of consideration as a standard technique.

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4. "Three-Dimensional Rotation Method for the Dynamic Calibration of Angular Displacement, Velocity, and Acceleration Transducers." Paper presented to the Instrument Society of America, Los Angeles, California, Sept. 11, 1961; Author Otis C. Ingebritsen, NASA Langley Research Center.

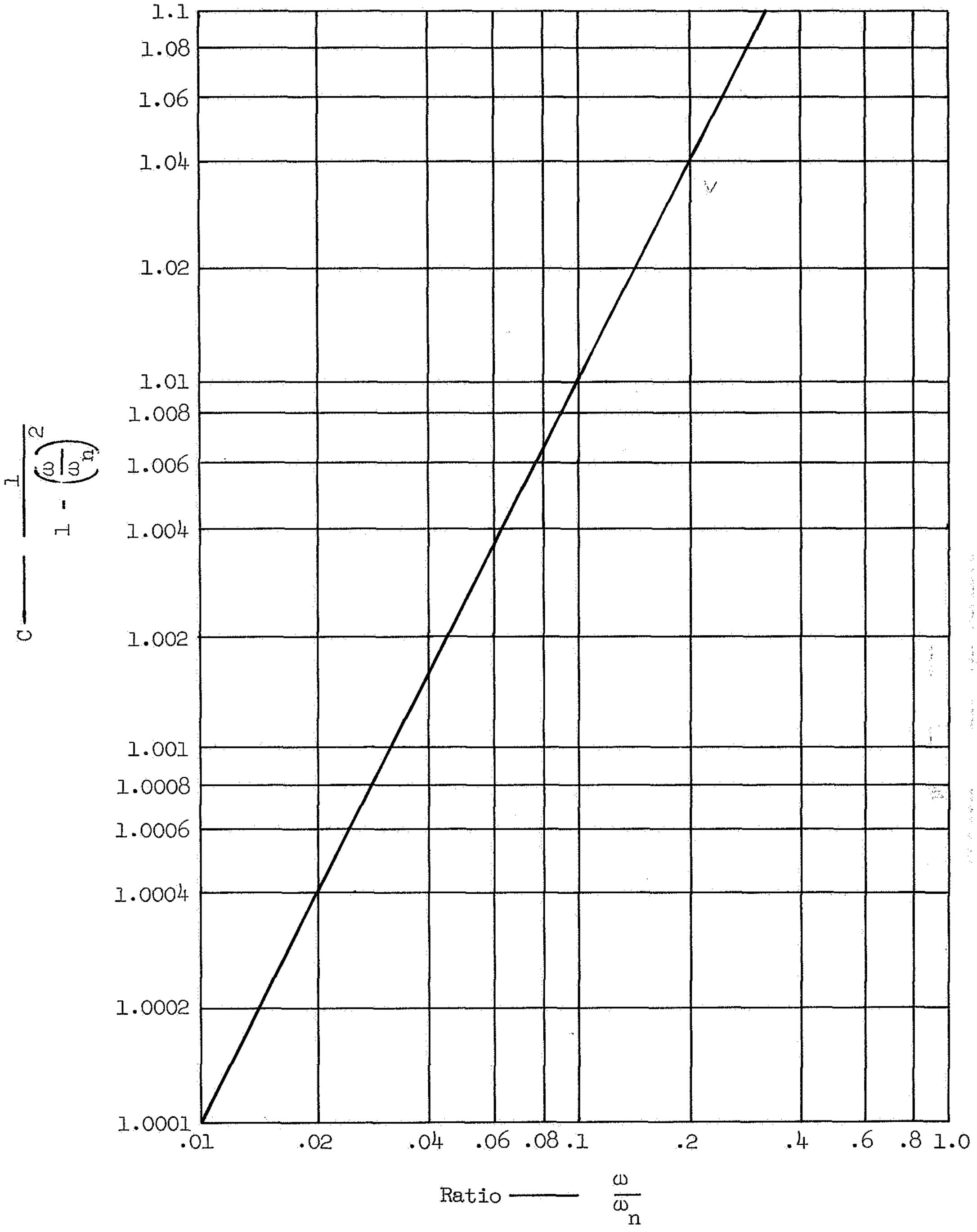


Figure 1.- Centrifuge radius correction for seismic mass deflection.

NASA-LRC STANDARDS SECTION

Sheet ____ of ____

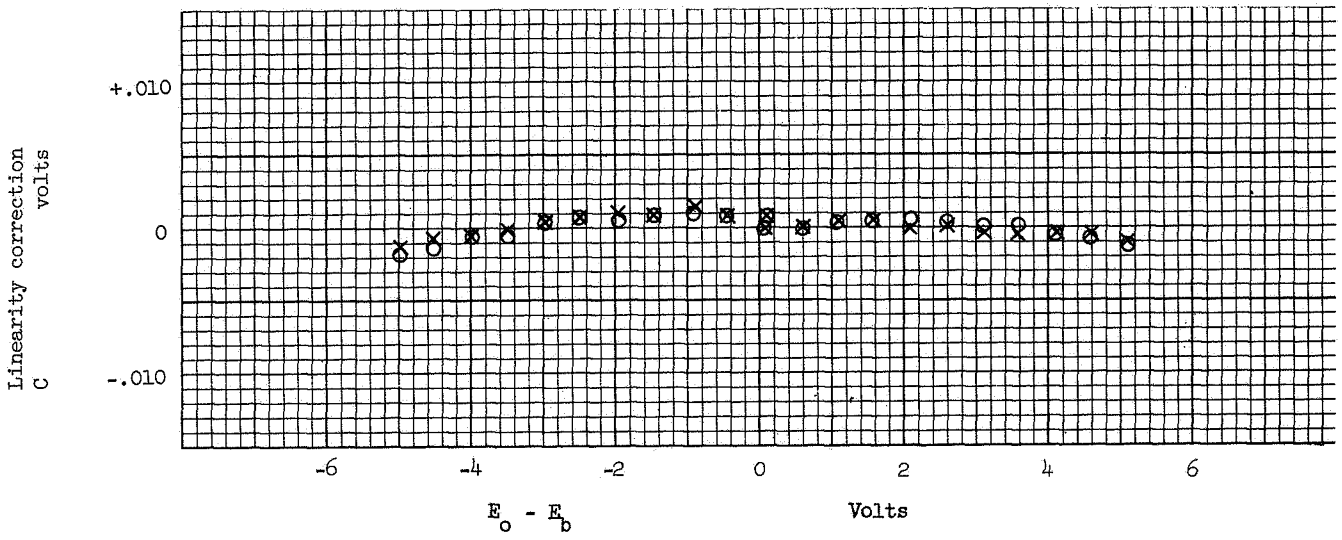
REPORT ON Accelerometer

Mfg. XYZ Model ABC Inv. No. 123456 Ser. No. 1731 Range ±50 G

Terminals & polarity: Input (+) 1 (-) 3 Output (+) 2 (-) 5 Output impedance 500 ohms

Calibration: Excitation 28.0 VDC External load O.C.

Amb. temp. 76° Inst. temp. 83° Amb. press. 29.92 Amb. R.H. 47 percent



Transfer function:

$$G = \frac{1}{S}(E_o - E_b + C)$$

$$= 9.9625(E_o + .00023 + C)$$

S is sensitivity .10037 volts/g

E_o is output

E_b is zero balance -.00023 volts

C is linearity correction (from curve)

Linearity ±0.015%

Hysteresis 0.01%

Date 3-27-67

Date for recal. 9-27-67

Cal. by LSW

Approved TDF

Figure 2.

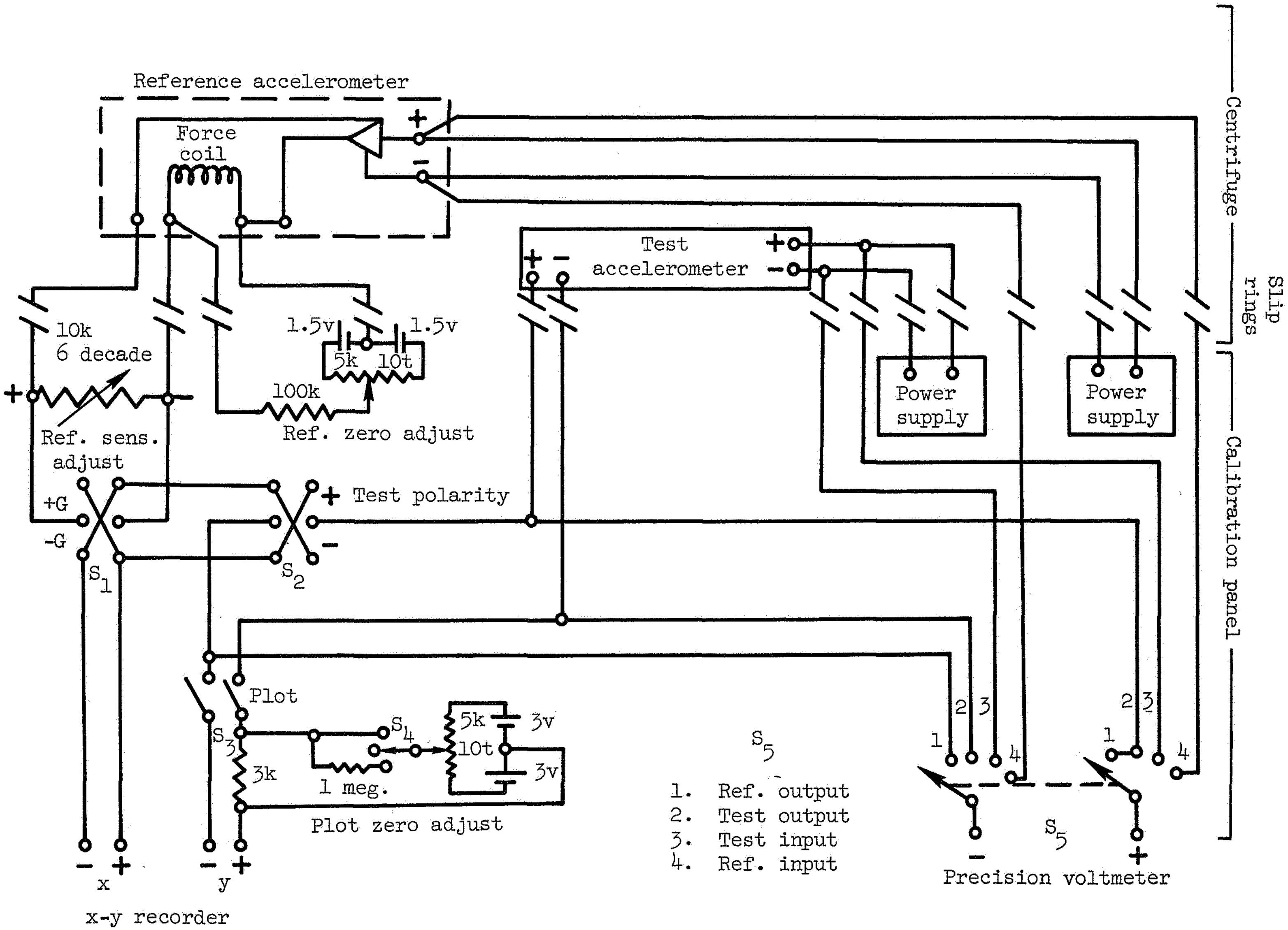


Figure 3.- Centrifuge continuous comparison circuit.

Sheet ____ of ____

NASA-LRC STANDARDS SECTION

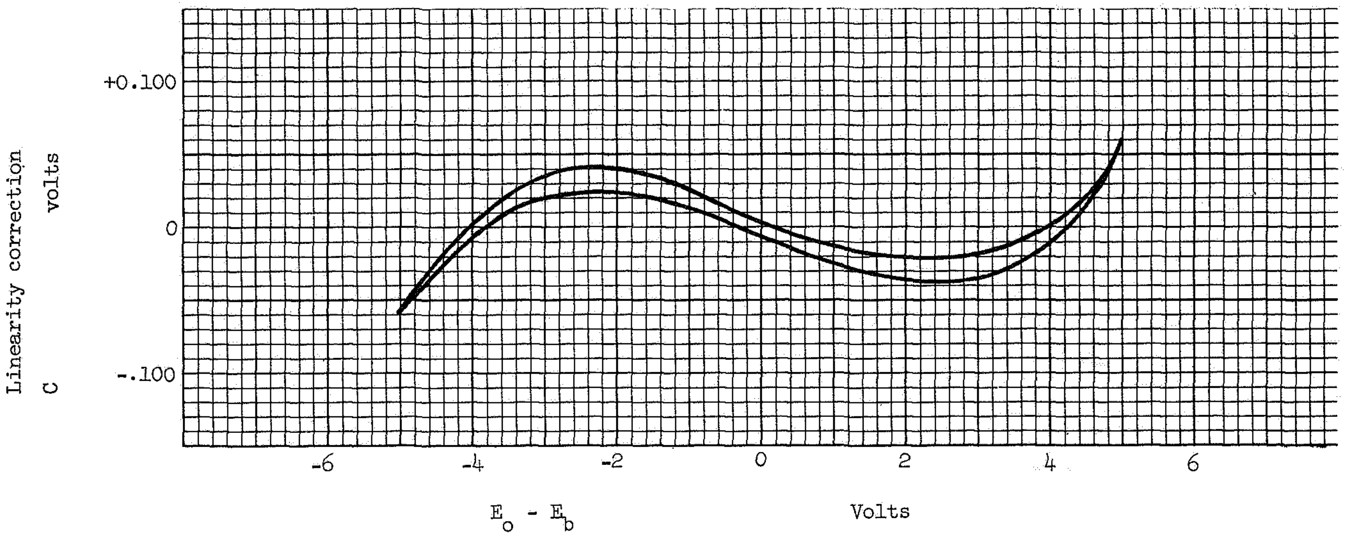
REPORT ON Accelerometer

Mfg. XYZ Model ABC Inv. No. 123456 Ser. No. 757 Range ±10 G

Terminals & polarity: Input (+) 2 (-) 1 Output (+) 6 (-) 4 Output impedance 5.36K

Calibration: Excitation 28.0 VDC External load O.C.

Amb. temp. 72° Inst. temp. 83° Amb. press. 29.92 Amb. R.H. 47 percent



Transfer function:

$$G = \frac{1}{S}\left(E_o - E_b + C\right)$$

$$= 1.984\,(E_o - 0.012 + C)$$

S is sensitivity 0.5041 v/g

E_o is output

E_b is zero balance -0.012 volts

C is linearity correction (from curve)

Linearity ±0.6 percent

Hysteresis 0.25 percent

Date 11-26-66

Date for recal. 5-26-67

Cal. by H-39

Approved ______

Figure 4.

NASA-LRC STANDARDS SECTION

Sheet ____ of ____

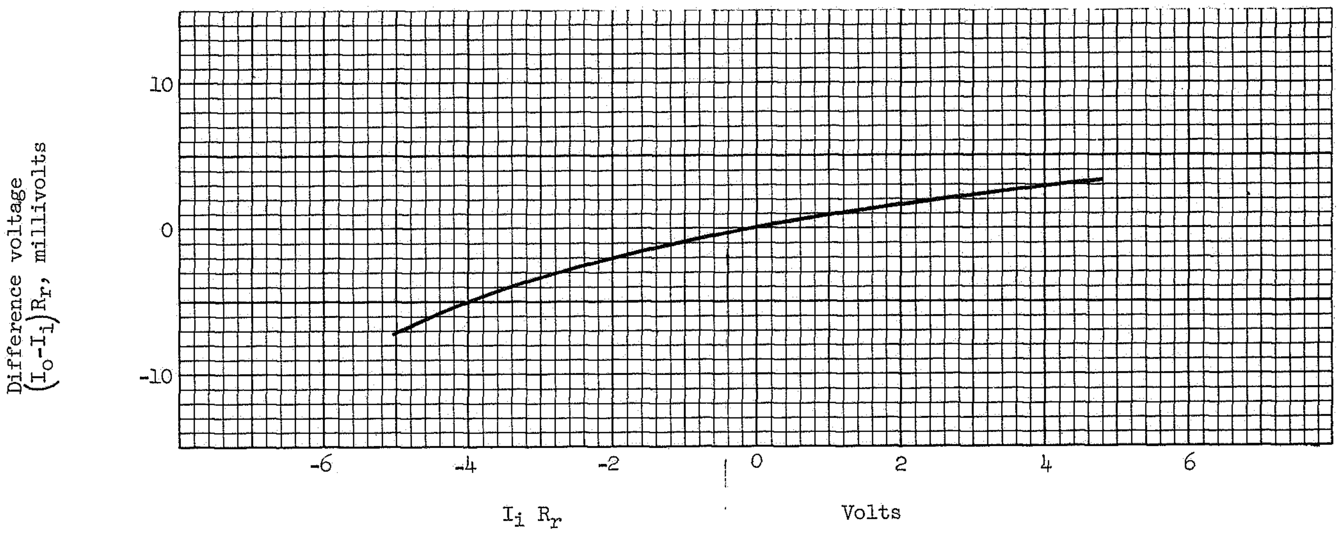
REPORT ON Accelerometer

Mfg. XYZ Model ABC Inv. No. 123456 Ser. No. 1731 Range ±50g

Terminals & polarity: Input (+) 1 (-) 3 Output (+) 2 (-) 5 Output impedance 500 ohms

Calibration: Excitation 28.0 VDC External load O.C.

Amb. temp. 76° Inst. temp. 83° Amb. press. 29.92 Amb. R.H. 47 percent



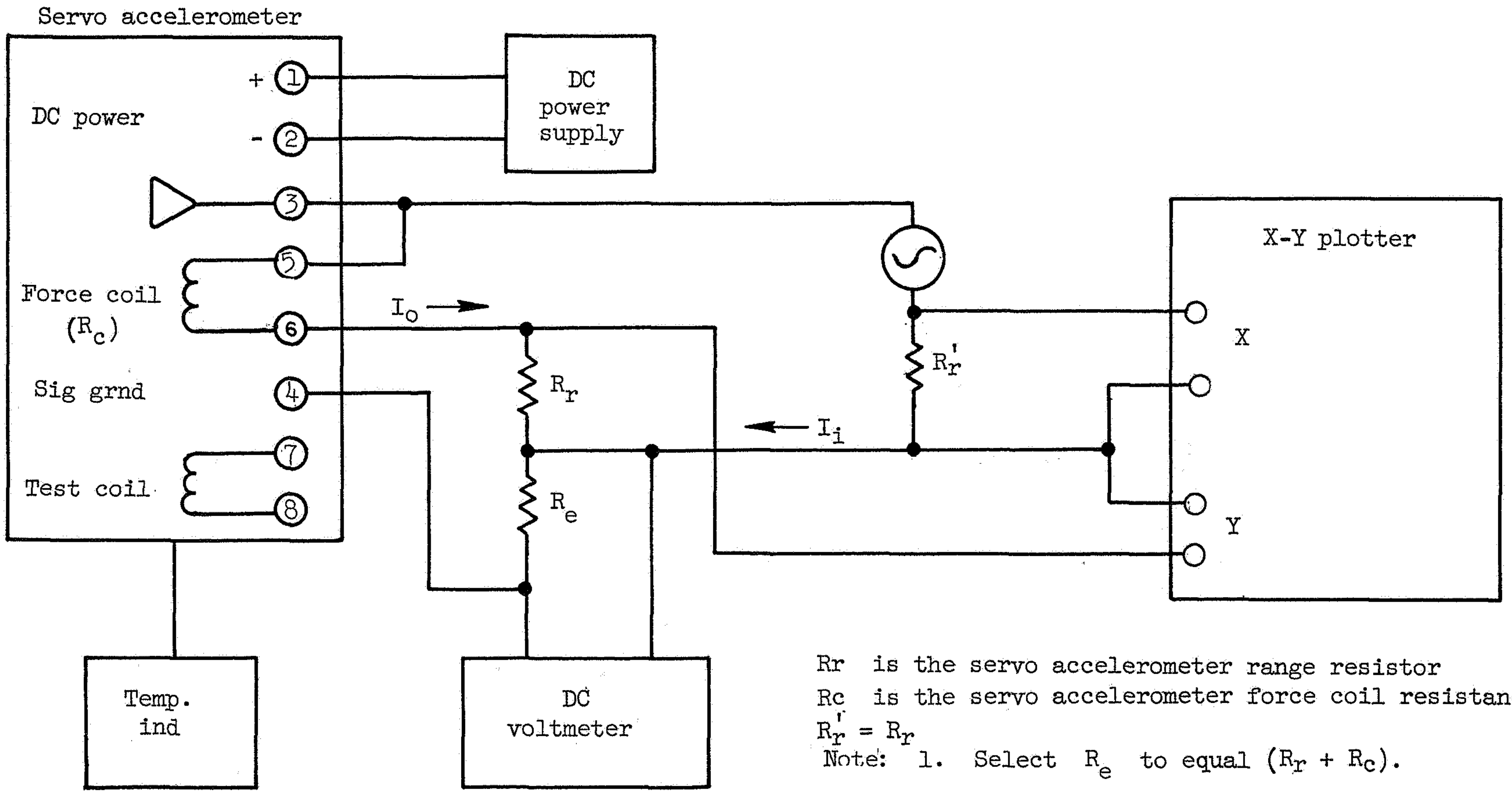
where,

I_o is the accelerometer output current
R_r is the accelerometer range resistance, ohms
I_i is the insertion current
(see figure 6)

Linearity ±0.01 percent
Hysteresis < 0.001 percent

Date 6-5-67
Date for recal. 12-5-67
Cal. by TDF
Approved OCI

Figure 5.- Continuous plotting-current insertion.



Rr is the servo accelerometer range resistor
Rc is the servo accelerometer force coil resistance
$R_r' = R_r$
Note: 1. Select R_e to equal $(R_r + R_c)$.

Figure 6.- Typical circuit for continuous plotting using current insertion.

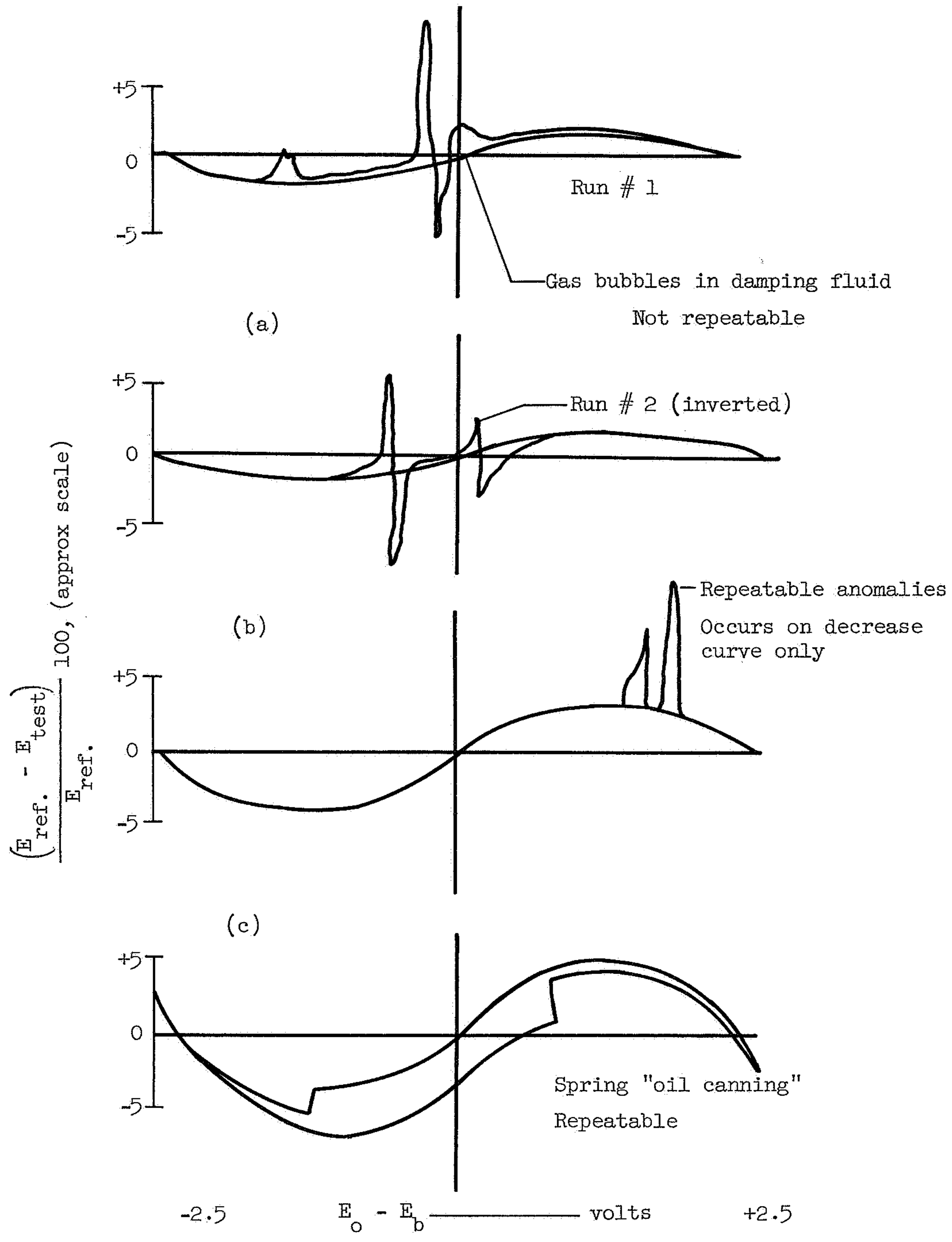


Figure 7.- Continuous comparison calibration plots revealing accelerometer anomalous behavior.

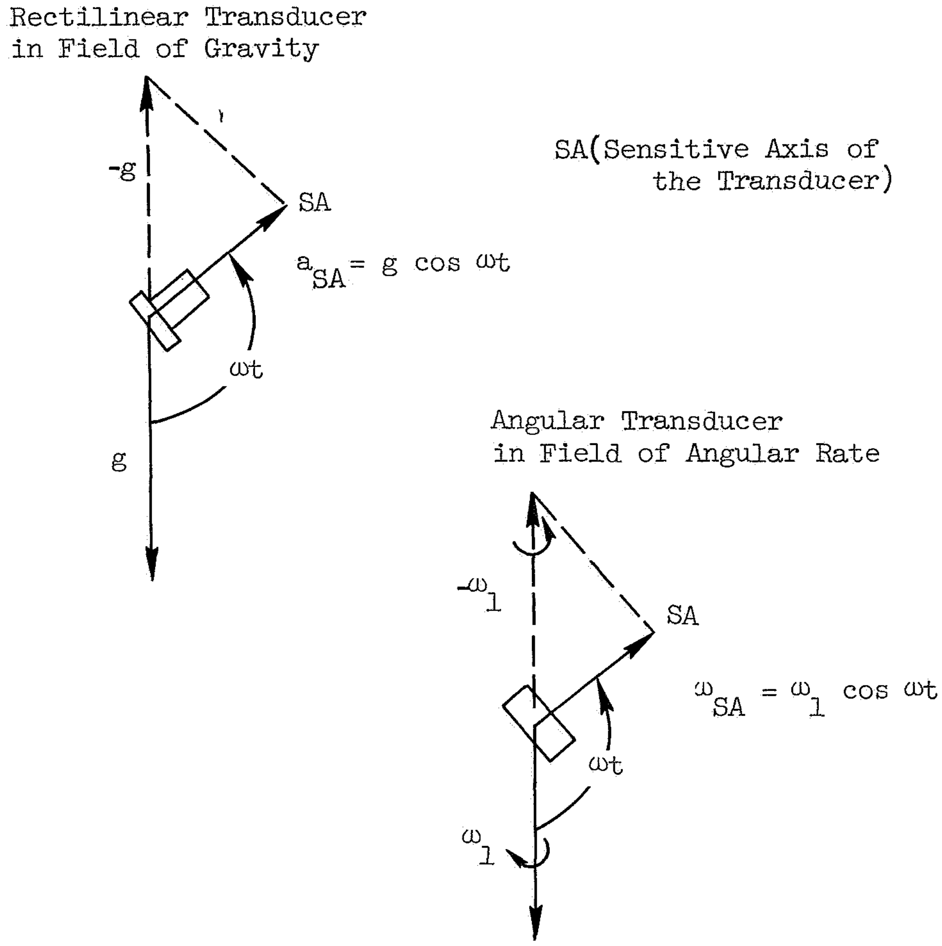
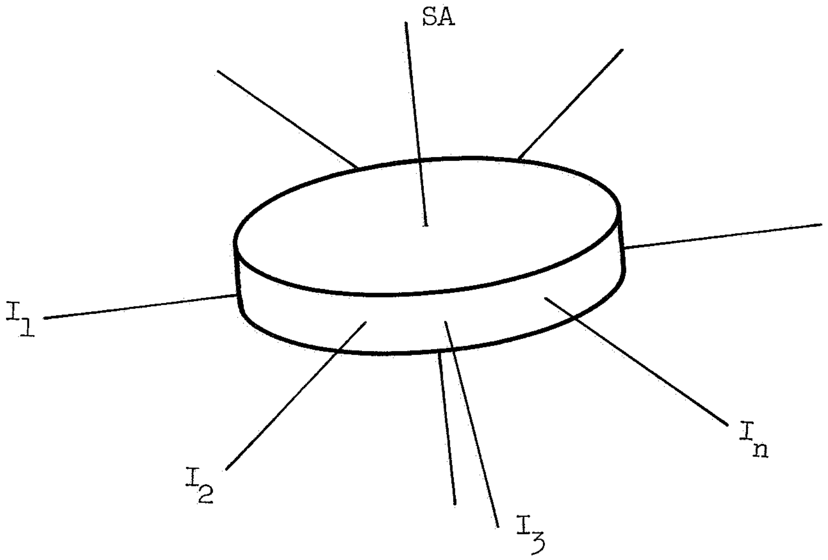


Figure 8.- 3-D rotator analogy to the tilted centrifuge at low rate of tilt.



$$I_1 = I_2 = I_3 \cdot \cdot \cdot \cdot \cdot \cdot = I_n$$

Figure 9.- Kinetically symmetrical inertial mass for an angular accelerometer.

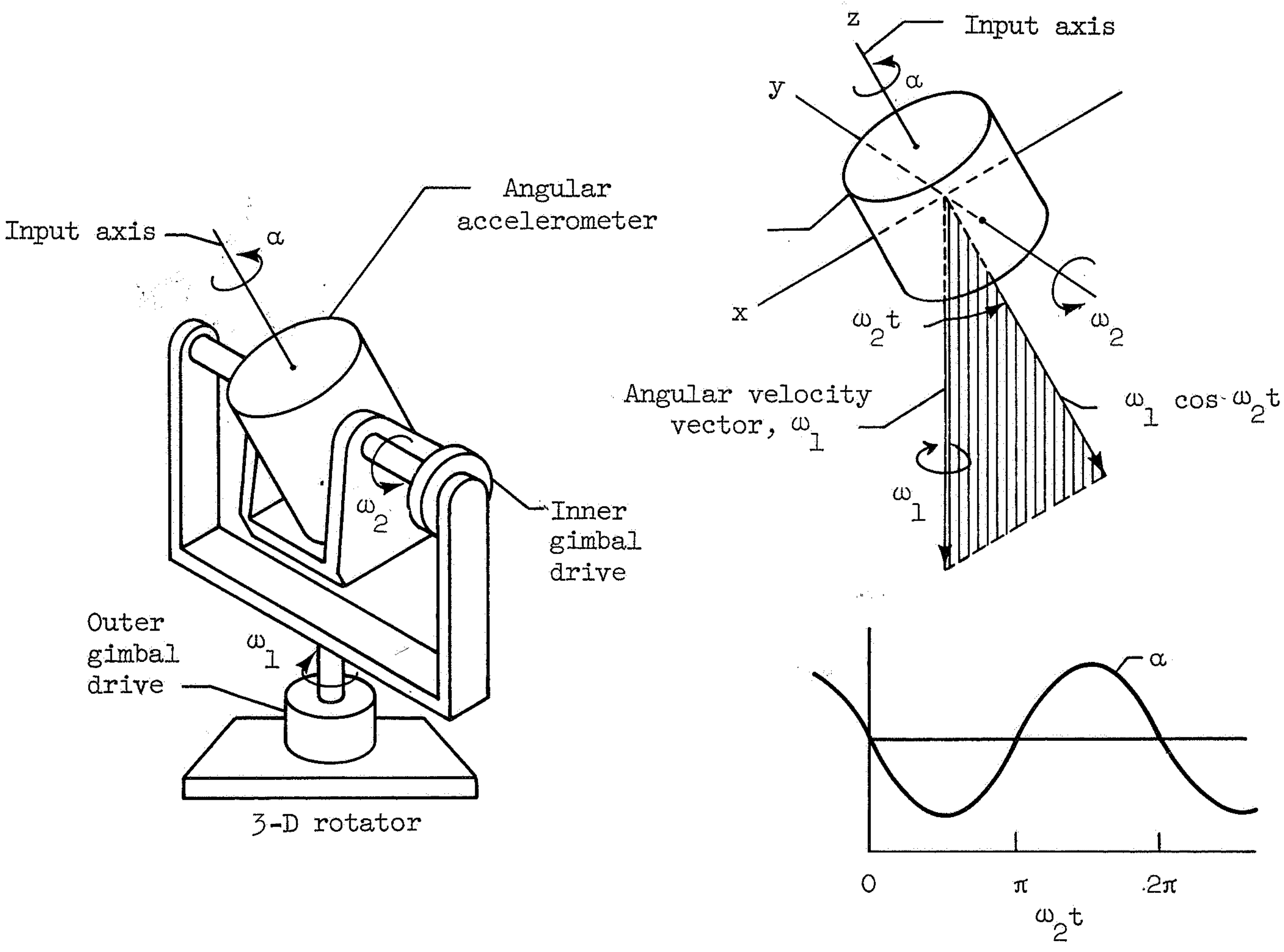


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Figure 10.- The three-dimensional rotator.

NASA-Langley, 1967