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Technical Note 269

EARTH'S FIELD STATIC CALIBRATOR FOR ACCELEROMETERS

P. S. LEDERER AND J. S. HILTEN

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Electronic Instrumentation Division
Institute for Applied Technology

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Earth's Field Static Calibrator for Accelerometers

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This paper describes a simple, relatively inexpensive system for the precise static calibration of accelerometers in the earth's gravitational field with an estimated limit of error of ±0.0004 *g*. The system consists of a precision machinists dividing head on a surface plate and a precision level. Experimental results obtained during the calibration of three types of accelerometers are shown to indicate the capabilities and usefulness of the system.

KEY WORDS: Calibrator, Earth's Field Static Calibrator, Accelerometer, Dividing Head, and ±1*g* Calibrator.

1. Introduction

There are two common methods for the static calibration of accelerometers: The centrifuge method and the "tilting support" method.[1] The centrifuge method is applicable to all ranges of accelerometers, but may not be as convenient or as accurate as the "tilting support" method for the calibration of accelerometers with ranges from a fraction of 1 *g* to several *g*'s.

With the increasing use of more precise devices such as "servo" accelerometers (frequently used as plant or transfer standards) the need exists for correspondingly precise calibration equipment. It is desirable in all calibration equipment that, in addition to meeting the stated requirements for accuracy, it be relatively simple, rugged, and inexpensive.

A static calibrator for accelerometers using the "tilting support" method appears to meet these requirements. The "tilting support" method utilizes the earth's gravitational field to provide a force simulating the inertial force due to an acceleration. The term "applied acceleration" is used here for brevity. By tilting the accelerometer in a vertical plane, the component of the gravitational field acting on the instrument can be varied. This permits the static calibration of accelerometers at fractional values of the local value of gravitation acceleration up to ±1*g*. This is necessary to establish instrument characteristics like hysteresis, linearity, repeatability, and possible misalignment of the sensitive axis. If the orientation of the accelerometer in the vertical plane can be changed in sufficiently small increments, the resolution of the instrument can also be determined. The component of the gravitational field acting along the sensitive axis of the accelerometer is equal to the local value of gravitational acceleration multiplied by the cosine of the angle between the sensitive axis and the vertical. The possible error in applied acceleration due to an error in the determination of this angle is least at 0° at $\pm 1\ g$. For this reason, the calibrations at $\pm 1\ g$ made in the earth's field are frequently the most precise ones that can be made. For instruments with ranges greater than $\pm 1\ g$ and very good repeatability, it is frequently most satisfactory to extrapolate the calibration between these two points to several times 1 *g* rather than depend on direct calibration alone at the higher level of input by less accurate means. It should be noted, however, that accuracy of measurement of this angle is rarely the limiting factor in making the 1 *g* calibration. It may be difficult to provide a mount for the equipment which will not contribute a vibratory input several times the error due to the angle.

An earth's field calibrator of the "tilting support" type was assembled and tested as part of a program now carried out in the Basic Instrumentation Section, Electronic Instrumentation Division, Institute for Applied Technology of the National Bureau of Standards. The objectives of this program include the development of testing techniques and apparatus for the determination of the characteristics of electromechanical telemetering transducers required for making meaningful measurements in aero-space development and industrial uses. The capabilities of the calibrator are described and shown below, as are test results obtained during the calibration of three accelerometers.

2. Description of calibrator

The earth's field static calibrator for accelerometers is shown in Fig. 1. The two components shown are a machinists precision dividing head and surface plate. The dividing head described as having an indexing accuracy of one minute in 360 degrees and equipped with an index plate which can be rotated with the spindle locked in position rests on the precision ground surface plate. The three feet of the surface plate rest in three cup-shaped brass supports. Each of the cups is threaded for a cap-screw which serves as an adjustable height leg. The heads of the three cap screws rest on a 1/4 inch thick flat brass plate on the top of a heavy work bench.

A precision ground steel right angle bracket is attached to a blank face plate on the spindle of the dividing head. The accelerometer to be calibrated is mounted on the arm of the bracket which forms a right angle with the face plate. When the calibrator is properly leveled, the bracket can be rotated in the vertical plane.

The surface plate is leveled with the aid of a six-inch precision machinists level equipped with a ground and graduated main vial with a sensitivity of 1 minute of arc per one-tenth inch graduation interval. The same level is also used to level the right angle bracket on the dividing head. The "floating index plate" feature of the dividing head chosen for the calibrator permits subsequent rotation of the index plate so that the level position of the bracket plate corresponds to the 0° setting on the index plate. The dividing head was ordered with one crank index plate containing 6 circles with equally spaced holes dividing the circle into 15, 16, 17, 18, 19, and 20 divisions. The circle used for accelerometer calibration was the one with 18 divisions. This, in conjunction with the 40: 1 wormgear reduction, permits rotation of the face plate (and accelerometer mounting bracket) in precise 0.5° steps. Other index plates are available from the manufacturer including one with a 99 division circle which permits increments of angular rotation of 5.45 minutes of arc.

3. Error analysis of earth's field static calibrator

3.1. Angular setting errors and misalignment

For an accelerometer calibrated by the "tilting support" method, the component of the gravitational field acting along the sensitive axis of the accelerometer is a function of the angle between the sensitive axis and the vertical. Since the actual orientation of the sensitive axis within the accelerometer is not precisely known, calibrations are usually referred to the mounting base of the instrument and thereby to the plane surface to which it is attached. For this calibrator it is the mounting plane of the right angle bracket on the face plate. The component of gravity acting in the direction perpendicular to that plane is equal to the value of local gravity multiplied by the cosine of the angle between that perpendicular and the vertical.

Thus the accuracy with which the value of applied acceleration is known is a function of the accurate knowledge of this angle. The following procedure was employed in leveling the calibrator in order to establish the proper relationship.

With a leveled surface plate, the crank arm of the divider was turned until the bracket plane was also horizontal as indicated by the precision level when placed on the bracket along a line parallel to the plane of the face plate. Since the sensitivity of this level is 0.1 inch for one minute of arc, closeness to a perfectly horizontal position in the direction indicated could be established to better than one minute of arc. Without disturbing the bracket position, the index plate was loosened and rotated until one of its holes fully engaged the crankarm pin. The index plate was tightened in this position which is the zero degree angular reference position. The level was then placed at right angles to the previous position. This time it indicated that the plane of the bracket was inclined toward the face plate at an angle of 4 minutes.

The crankarm was then rotated the correct number of holes until the face plate had rotated exactly one half revolution (180°).

The level of (now bottom side of) the bracket plane was checked again in the two directions previously used. The 4 minute inclination toward the face plate was confirmed and the error of less than one minute in the other direction was also confirmed. The top and bottom surfaces of the bracket arm had been precision ground to be flat and parallel within better than ±0.001 inch over the entire 5 3/4 inch by 6 inch area. This established parallelism of these surfaces of the arm to within ± 1 minute.

To confirm this latter value and to establish the accuracies of other angle setting, the dividing head was calibrated by the Engineering Metrology Section of NBS. The calibration data are listed in the appendix but may be summarized briefly as follows: Three calibrations were performed at each of 24 angle settings and the results averaged. These averages showed maximum deviations from the nominal angle settings of -22 seconds and +79 seconds. Only three of the settings showed deviations of more than one minute of arc. Thus an overall limit of error for <u>all setting</u> of ±1.3 minutes is a conservative working figure.

Although most accelerometers are designed to have their sensitive axes at right angles to the mounting base, there are some with the sensitive axis parallel to the base. For the latter type an additional reference plane must be assumed which is generally an outside surface of the instrument at right angles to the mounting base and parallel to the plane of the face plate.

For the former instrument, an acceleration of 1 *g* acts on the accelerometer at the 0° setting of the dividing head, for the latter this occurs at the 90° setting.

The two sources of error are the uncertainty of the angular setting of the dividing head and the 4 minute inclination of the mounting bracket. The latter calls for a maximum correction factor for all settings equal to the cosine of 4 minutes = 0.999999, or effectively no correction is required at all.

For accelerometers whose axis of sensitivity is perpendicular to the plane of the mounting bracket, at the 0° setting of the dividing head, even with the above correction for bracket inclination, the applied acceleration is 1 *g* (local) within better than 0.001% (all values of applied acceleration in this paper refer to <u>local</u> values of gravitational acceleration) for such accelerometers.

The error is largest at the 90° setting; with the limit of error of ±1.3 minutes, the applied acceleration may differ from 0 *g* by as much ±.0004 *g*. At the 180° setting, the limit of error of ±1.3 minutes changes the value of applied acceleration of 1 *g* (with opposite sign to that at 0 degrees) by less than .001%. For instruments with less than 1 *g* range, the percentage errors are larger. As an example, an angle setting of 84° results in an applied acceleration of 0.10453 *g* with possible limit of error of ±.0004 *g*, resulting in limit of error of ±0.38% of that range.

For accelerometers whose axis of sensitivity is parallel to the plane of the mounting bracket, at the 0° setting of the dividing head, the applied acceleration is 0 *g* with an estimated error of less than ±.0001 *g*. At the 90° setting and 270° settings the acceleration applied to this instrument is 1 *g* with respect to the plane of the bracket and parallel to the plane of the face plate with an estimated error of up to ±0.0004 *g* (±0.04% of 1 *g*). At the 180° setting, the limit of error of ±1.3 minutes produces a possible error of ±.0001 *g*.

3.2. Error due to building vibration

In addition to the calibration errors caused by the uncertainties of angle setting, building vibration may also cause errors. Such errors result because fluctuations of the output of the accelerometer due to building vibration may make it difficult to balance the precision potentiometer used to measure the output.

The earth's field static calibrator was set up on a heavy workbench inside a shielded room which is located on the concrete floor of the building. No particular attempt was made to vibration isolate the calibrator. Measurements of building vibration were made by means of a servo accelerometer with a sensitivity of 1.09 volts/*g* and a flat frequency response to beyond 200 Hz. Figs. 2 A,B,C show photographs of the accelerometer output as displayed on an oscilloscope. Fig. 2A shows that the building vibration is composed of a number of frequencies of semi-random nature with a lowest repetition rate of about 3 Hz, with a peak-to-peak amplitude of about .0022 *g*. Fig. 2B with an expanded time base shows a very distinct vibration at 55 Hz and about the same amplitude as before. Both pictures show vibration levels in a vertical direction. Fig. 2C shows vibration levels in a horizontal direction, indicating the presence of additional higher frequencies than in Fig. 2B. Fig. 2D, showing vertical vibrations with the accelerometer on a thick sponge rubber pad directly on the workbench, indicates that some of output fluctuation observed may originate within the accelerometer fluctuation observed may originate within the accelerometer itself.

The galvanometer used to balance the precision potentiometer used during the static calibrations has a free period of 3.6 seconds. The response of this galvanometer to a frequency of 3 Hz, (approximately the lowest vibration frequency observed) is about 0.4% of its response to DC, consequently the observed vibration level of .0022 *g* peak-to-peak should result in a galvanometer balance uncertainty in order of .00001 *g* peak-to-peak, less than uncertainties due to angle setting. The effects of higher frequency vibrations on balance should be even less. These considerations appear confirmed by the calibrations of the servo accelerometer, Figs. 3A,B,C where experimental data deviate by less than ±0.0005 *g* from the computed best straight line.

3.3.2. Electrical measurement errors

In the static calibration of accelerometers, whether they are strain-gage types, potentiometer types, or servo-devices, it is necessary to measure excitation and output voltages. A precision potentiometer is used to measure output voltage, and also, in conjunction with a volt-box, the excitation voltage which is provided by an electronically regulated power supply. The limit of error of measuring the excitation voltage is estimated at ±0.027% of the voltage, that of measuring athe output voltage is estimated at ±0.016% of the voltage (for voltages below 0.16 volt) and ±0.011% of the voltage (for voltages from 0.16 volt to 1.6 volts).

Results of accelerometer calibrations by means of Earth's Field Static Calibration

4.1. Servo Accelerometer

A linear, transistorized servo accelerometer was calibrated over the full ±1 *g* range. The instrument is cylindrical with the sensitive axis along the longitudinal axis of the cylinder. The accelerometer flange mounted to a flat plate on the mounting bracket of the dividing head. The dividing head was set so that this plate was horizontal at the 0° setting. The acceleration acting on the sensitive axis of the instrument in this position was ±1 *g*. The positive sign was chosen since the output voltage of the instrument was positive. For this accelerometer the calibration was a 40 point one at 9° intervals from 0° (±1 *g*) to 90° (0 *g*) to 180° (-1 *g*) to 270° (0 *g*) ending at 360° (±1 *g*). The best straight line through all points was computed by method of least squares and the calibration data are shown in Fig. 3A in terms of deviations from this straight line. As may be seen, none of the points deviate by more than ±0.00035 *g* from the computed best straight line, well within the estimated limit of error of ±0.0005 *g* (composed of uncertainty of 0 *g* value of ±0.0004 *g* and possible voltage error equivalent to ±0.00012 *g*.) Thus, combined hysteresis and non-linearity for this instrument are less than 0.018% of the full 2*g* range.

Another calibration of the servo accelerometer, over the dividing head range of 0 to 12-1/2° (corresponding to acceleration values from 1.000 *g* to 0.976 *g*) is shown in Fig. 3B. Deviation from the best fit straight line in this case do not exceed ±0.00008*g* (within the estimated limit of error of ±0.00014 *g*).

Finally, Fig. 3C shows a calibration of this servo accelerometer over the range of 78-1/2 to 90° (corresponding to acceleration values from 0.2 to 0 *g*). Deviations form the best fit straight line do not exceed ±0.00025 *g* (within the estimated limit of error of ±0.0005 *g*).

The data indicate how effective the calibrator may be in investigating transducer performance over small portions of its range. The computed slope of the straight line through the calibration points from 0 to 0.2 (fig. 3C) differs from the slope of the ±1 *g* calibration (Fig. 3A by only 0.16%. The computed slope in Fig. 3B (0.976 *g* to 1.000 *g*, a range of 0.024) or (1.2% of the full ±1 *g* range) differs from the ±1 *g* calibration slope by only 2.2%.

4.2. Unbonded strain gage accelerometers

A pair of linear, undonded strain gage accelerometers with built-in transistor amplifiers and full scale range of ±5 *g* was calibrated over the ±1 *g* range and one of them also over smaller sections of the range. The sensitive axis of this instrument is perpendicular to its base and to the mounting bracket. An acceleration level of ±1 *g* acts on the instrument in the 0° position of the dividing head. A 40-point calibration was made on one of the instruments and its results are shown in Fig. 4 in terms of deviation from the computed best fit straight line through all the points. Non linearity and hysteresis are well within ±0.04% full scale range (considerably better than the manufacturers specifications). One noteworthy feature is the fact that the output for decreasing accelerations appears to be less than that for corresponding values of increasing accelerations. This characteristic which appears to be "negative" hysteresis, since it is opposite in direction to the more generally found hysteresis effect, is even more apparent in Fig. 5 which shows the same calibration for the other accelerometer. The combined "non-linearity and hysteresis" is still less than ±0.2% full scale (well within the manufacturers specification for these instruments). One cause of such apparent "negative" hysteresis is misalignment of the sensitive axis of the accelerometer. For this accelerometer with its sensitive axis perpendicular to the mounting base; misalignment of the axis would produce a relatively small error at ±1 *g*. This is due to the fact that the cosine of an angle near 0° say 1° differs from the cosine of 0° by only 0.015%. However, at the 90° setting of the dividing head, when this particular accelerometer would see a nominal acceleration of 0 *g*, a 1° error (due to axis misalignment) would cause an error in applied acceleration of 0.017 *g* or 1.7% of 1 *g*. Thus, for the accelerometer whose calibration is shown in Fig. 5, an axis misalignment of about 20 minutes of arc could account for the apparent "negative" hysteresis shown.

It can be shown for an instrument with axis misalignment that a "positive" or "negative" hysteresis loop may be traced depending on the calibration sequence. For the dividing head set up with the calibration starting at ±1 *g* (0°) and rotating the accelerometer through increasing angular position (90°, 180°, 270°, 0) if the sensitive axis is at a small positive angle at the ±1 *g* starting point, a "negative" hysteresis loop results. If the direction of rotation is reversed (0°, 270°, 180°, 90°, 0°). A "positive" loop will result for the same instrument. The magnitude of the loop will be the same and its value at 0 *g* will be a measure of the axis misalignment.

Two additional calibrations of this instrument over ranges from

0 to 0.2 *g* and from 0.976 *g* to 1.000 *g*, are shown in Figs. 6A and 6B respectively. In both cases, all calibration points are within ±0.04% of full scale from the computed best straight lines. The slopes of these straight lines show the variations expected from the appearance of Fig. 5. In that Figure, the deviations of points near 0 *g* should be close to the slope through all the points over the ±1 *g* range. Computed values are 0.2505 v/*g* for the range 0 to 0.2 *g* (Fig. 6A) and 0.2523 v/*g* for the 1 *g* calibration, a difference of 0.7%. On the other hand, the slope through all the points near 1.0 *g* should be somewhat greater than that through all points as indicated by the increasing deviation of calibration points as the acceleration decreases from ±1.0 *g* shown in Fig. 5. The computed slope for the calibration from 0.976 *g* to 1.000 *g* (fig. 6B) is 0.2732 v/*g*, about 8.3% greater than that for the 1 *g* calibration. The values given for the slopes refer to the output voltage across a voltage divider used to keep voltages measured within the range of the precision potentiometer. The actual output voltage of the accelerometer was approximately twice that indicated.

4.3. Potentiometer accelerometer

A linear potentiometer accelerometer with full scale range of ±10*g* was calibrated on the earth's field static calibrator over the ±1 *g* range. The sensitive axis of this instrument is parallel to its base and the side closest to and parallel to the faceplate of the dividing head was used as the second required reference plane for this instrument. The accelerometer was mounted so that the side was in contact with the side of the mounting bracket which is attached to the face plate.

Results of a calibration over the ±1 *g* range are shown in Fig. 7. The output of the accelerometer was measured by means of a precision ratio set with a resolution of 0.01%. The manufacturer stated that the resolution of the accelerometer was 0.25% of full scale and the static error band ±1.0% of full scale. The graph in Fig. 7 indicates that about half of the changes in accelerometer output, either between successive values of acceleration or between the same acceleration input in increasing or decreasing directions, appear as multiples of 0.012 *g*. Apparently this represents the effective resolution of this instrument, or about 0.06% of full scale. Smaller changes than this are thought to be due to variations in contact resistance. Larger changes (multiples of resolution) are thought to be due to friction effects between slider and resistance element, since no dithering was used.

5. Conclusion

The Earth's Field Static Calibrator described is a simple relatively inexpensive and rugged device for the static calibration of electromechanical accelerometers over a ±1 *g* range with an estimated limit of error of ±0.04% of 1 *g*. It may also be used to investigate other characteristics of accelerometers such as resolution over small fractions of the ±1 *g* range. In addition, the device may be used for the precise

±1 *g* calibration for accelerometers of good repeatability and a range of several *g*'s. For such devices it may be more desirable to extrapolate the ±1 *g* calibration to the full range rather than depend on direct calibration alone at the full range by less accurate means.

6. REFERENCE

(1) "American Standard Methods for the Calibration of Shock and Vibration Pickups"
S 2.2-1959
American Standards Association November 1959

7. APPENDIX

Calibration of Dividing Head
Engineering Metrology Section
National Bureau of Standards
June, 1964

Nominal Angle Degrees	Deviation from Nominal Angle Seconds
1	-11
2	-21
3	+14
4	- 7
5	-10
6	+ 2
7	+ 1
8	-20
9	- 2
10	-16
20	-22
30	0
40	-20
45	+11
50	-19
60	+17
70	- 6
80	+16
90	+40
135	+65
180	+79
225	+77
270	+50
315	+20

Values represent average of three determination and represent corrections to be made to nominal values. Precision of making single angular settings is represented by standard deviation of 10 seconds. Angular settings were approached in clockwise direction to eliminate backlash, which was found to be about 40 seconds.

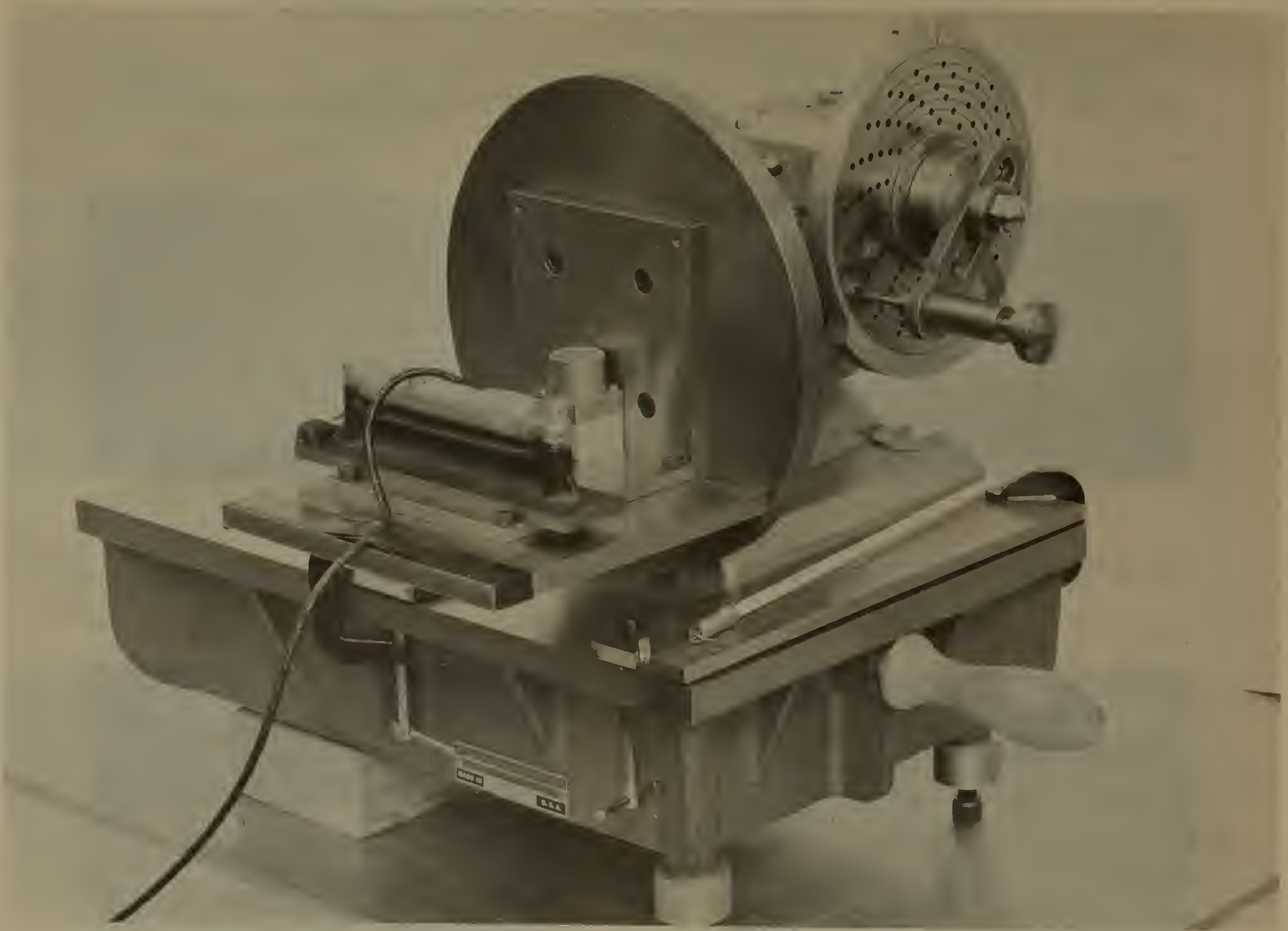
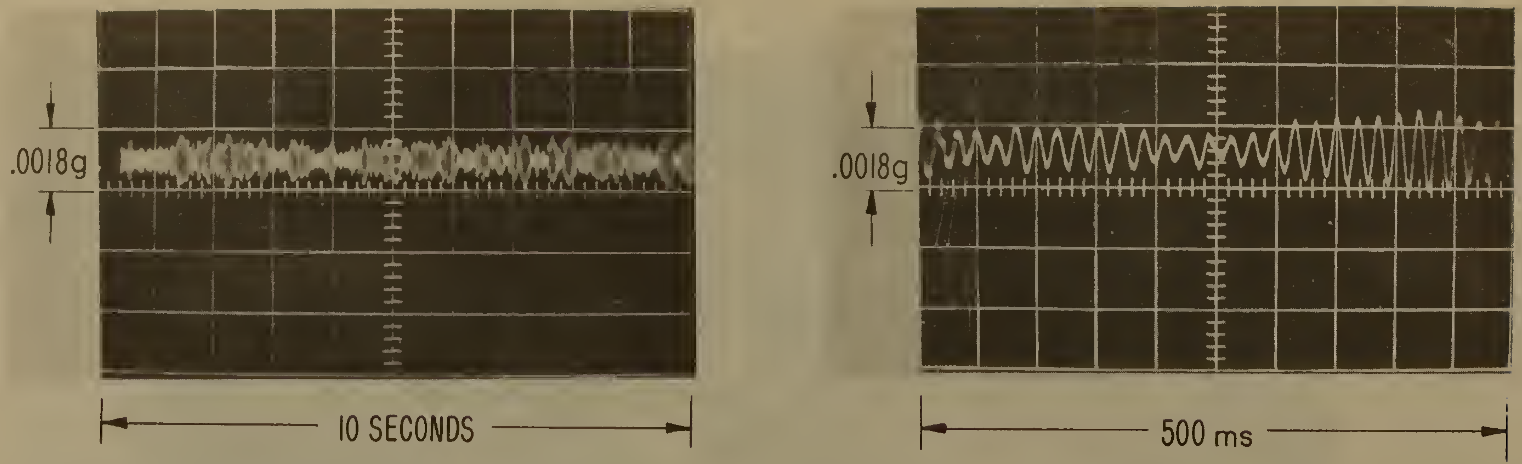
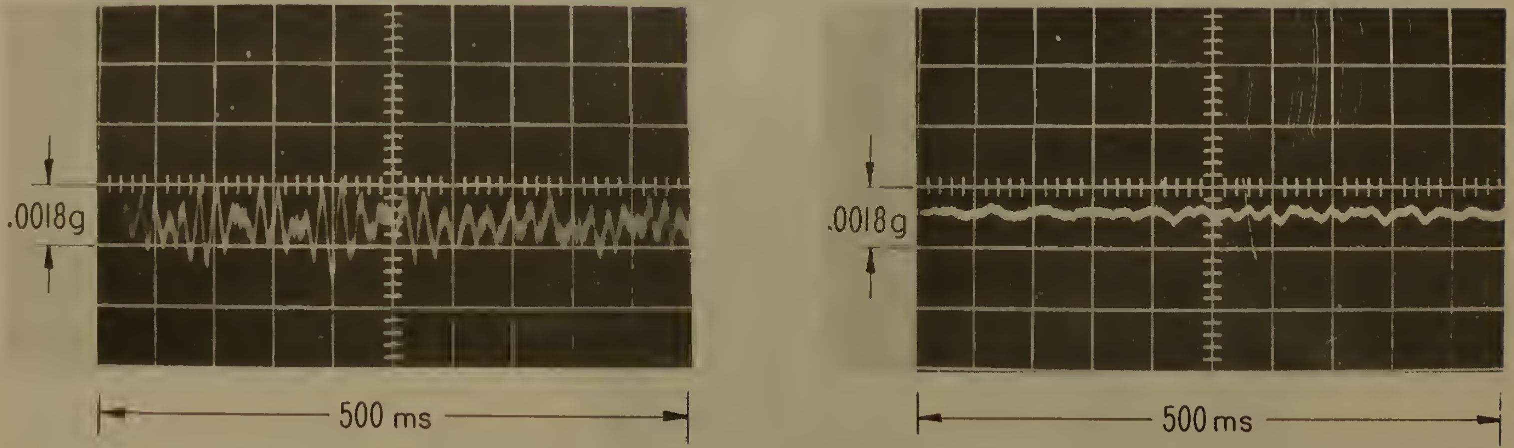


FIG I EARTH'S FIELD STATIC CALIBRATOR



A – ACCELEROMETER ON CALIBRATOR, VERTICAL VIBRATION

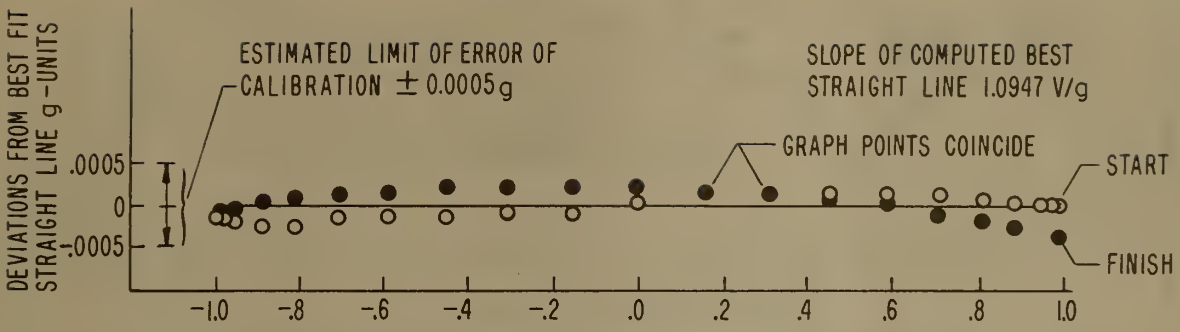
B – ACCELEROMETER ON CALIBRATOR, VERTICAL VIBRATION



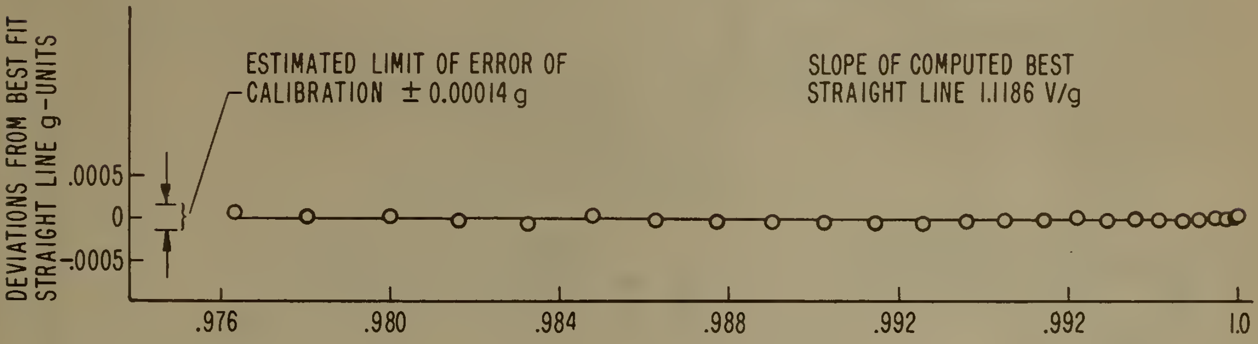
C – ACCELEROMETER ON CALIBRATOR, HORIZONTAL VIBRATION

D – ACCELEROMETER ON SPONGE RUBBER PAD ON WORK BENCH, VERTICAL VIBRATION

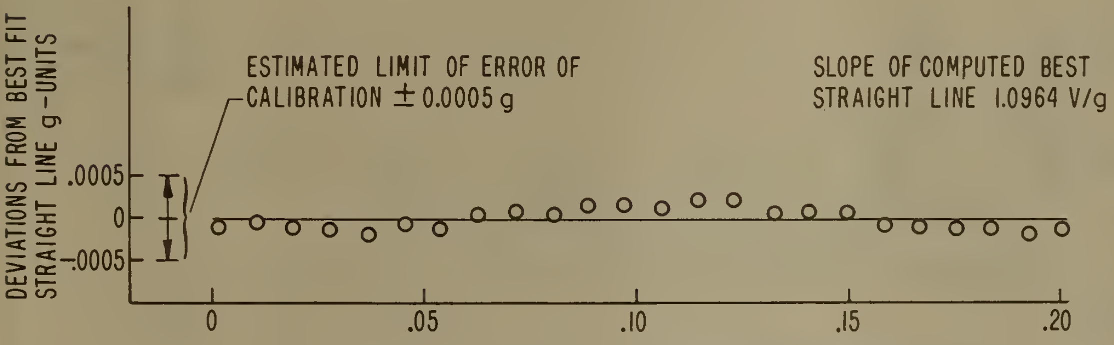
FIG 2 BUILDING VIBRATION INDICATED BY SERVO ACCELEROMETER



(a) APPLIED ACCELERATION, g-UNITS (RANGE ± 1g)



(b) APPLIED ACCELERATION, g-UNITS (RANGE 0.976 g TO 1.000 g)



(c) APPLIED ACCELERATION, g-UNITS (RANGE 0g TO 0.2g)

FIG 3 STATIC CALIBRATION OF LINEAR SERVO ACCELEROMETER

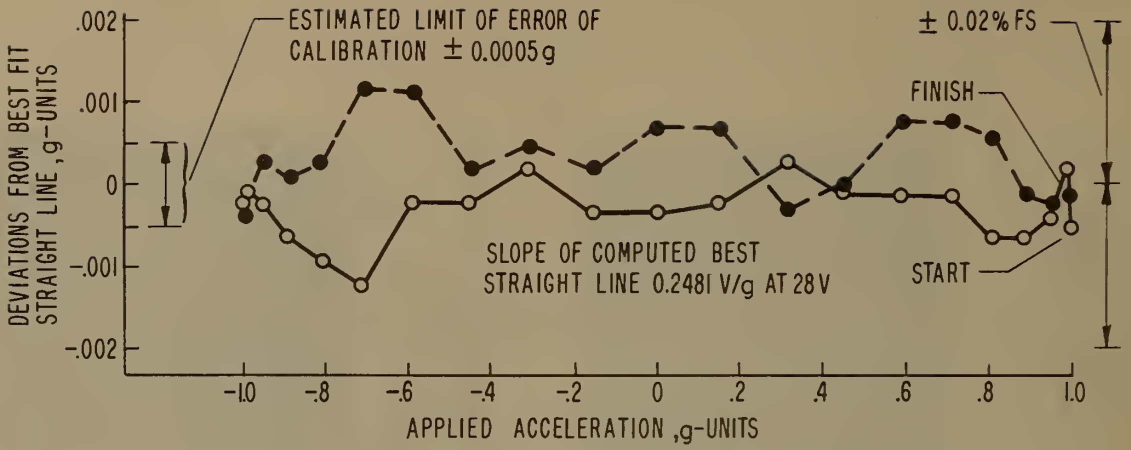


FIG 4 CALIBRATION OF FIRST UNBONDED STRAIN GAGE ACCELEROMETER OVER ± 1g RANGE

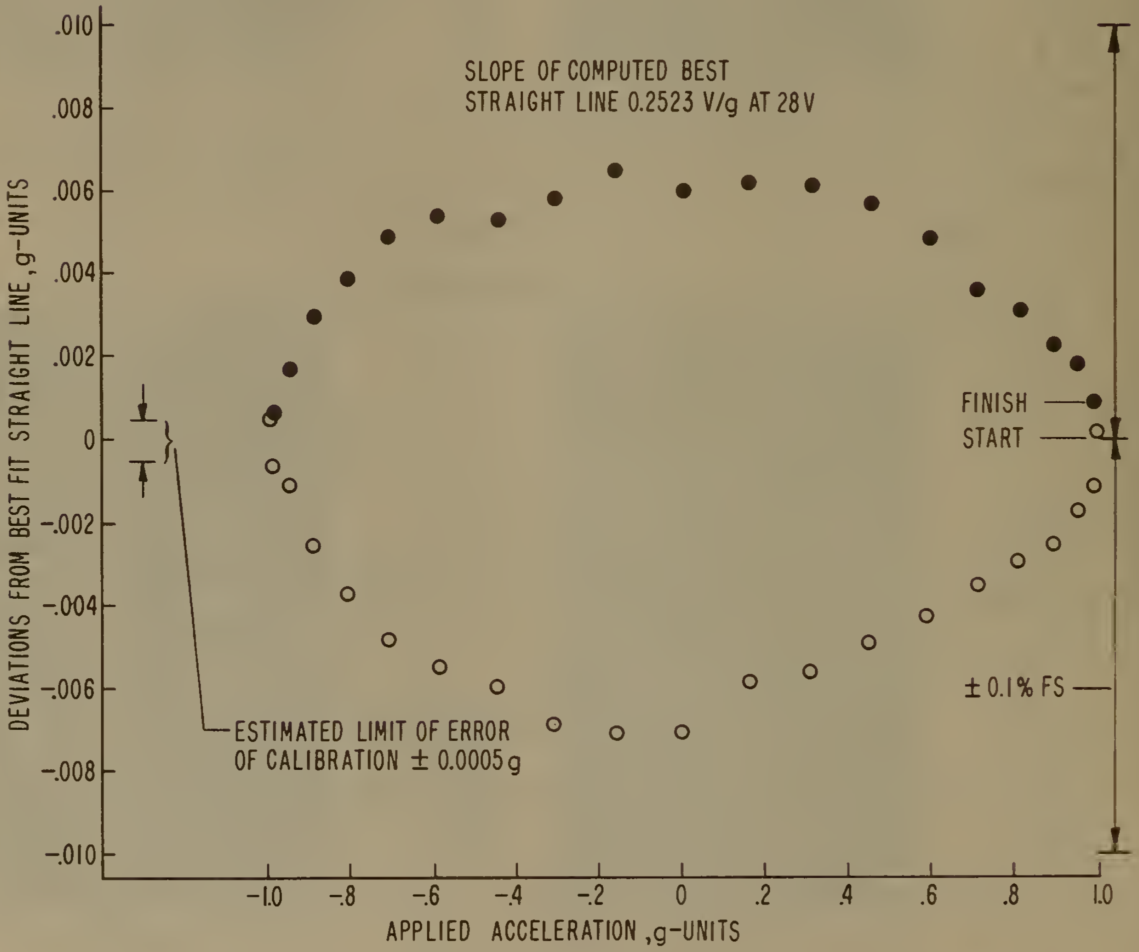
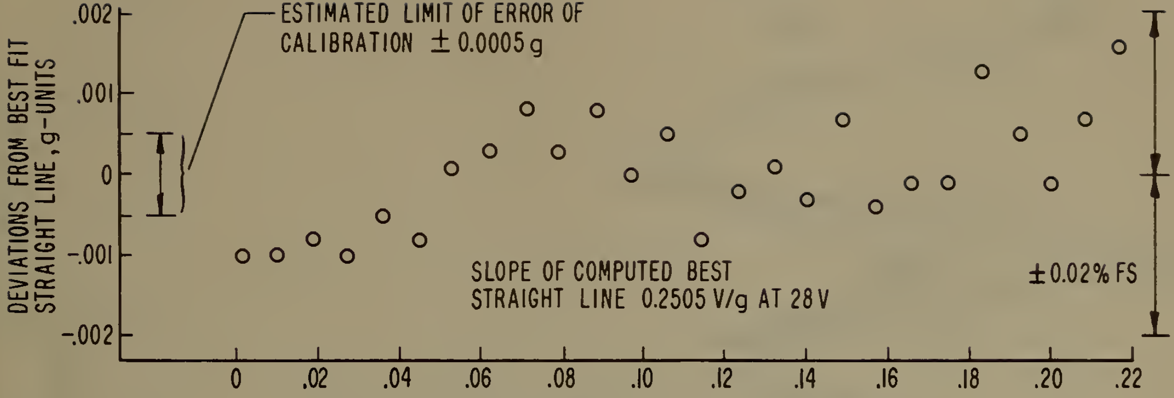
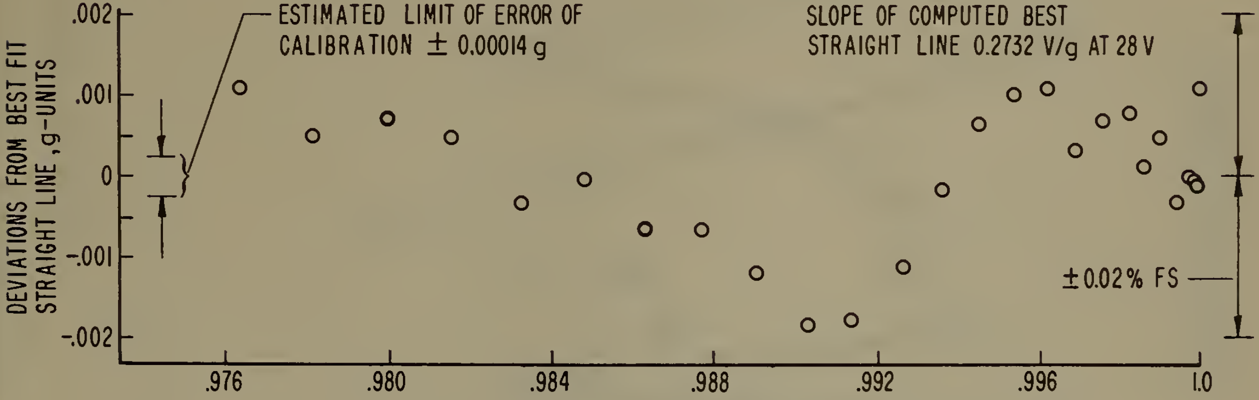


FIG 5 CALIBRATION OF SECOND UNBONDED STRAIN GAGE ACCELEROMETER OVER ± 1g RANGE



(a) APPLIED ACCELERATION, g-UNITS (RANGE 0 TO 0.2g)



(b) APPLIED ACCELERATION, g-UNITS (RANGE 0.976 g TO 1.0 g)

FIG 6 CALIBRATION OF SECOND UNBONDED STRAIN GAGE ACCELEROMETER

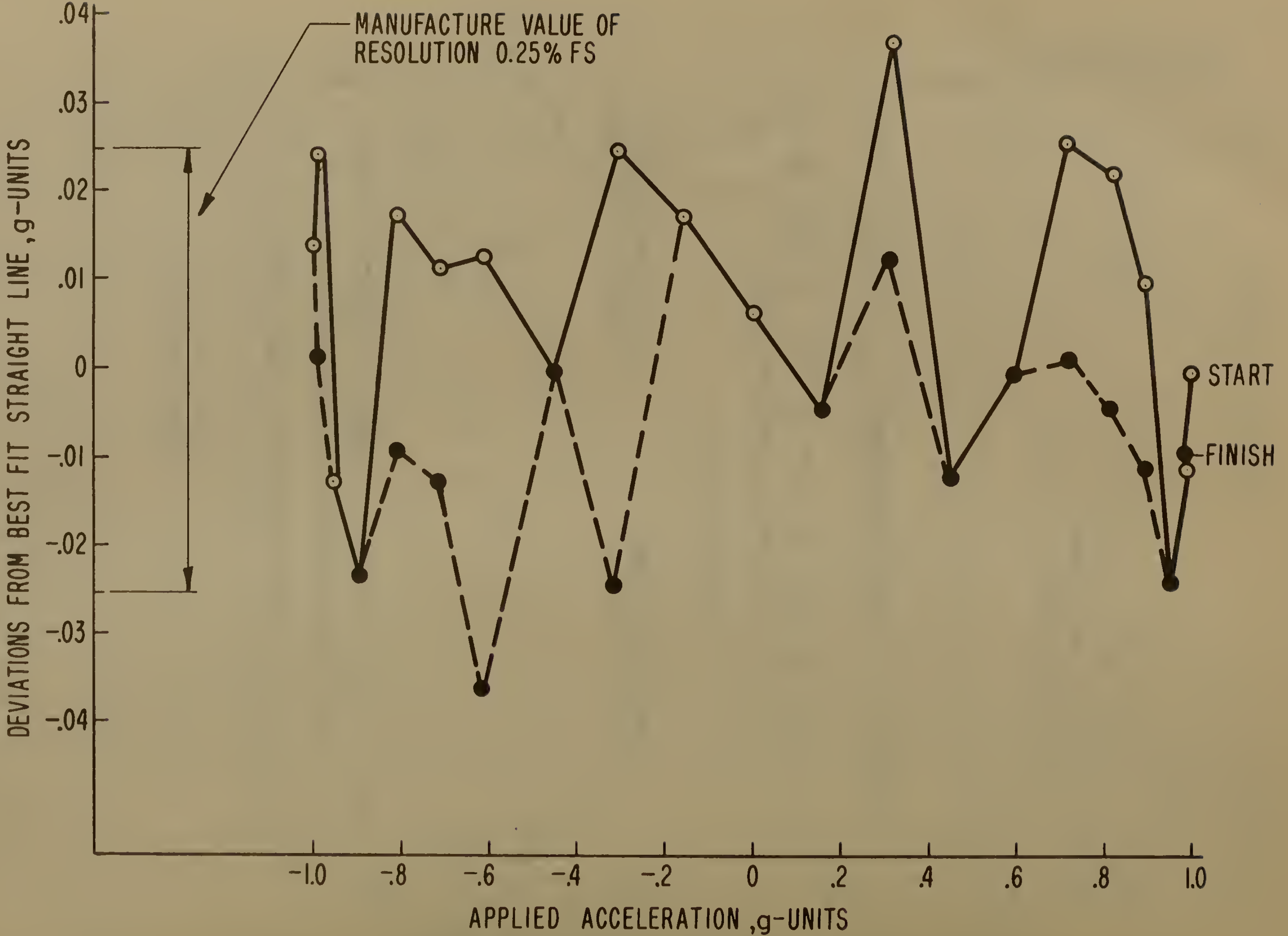


FIG 7 CALIBRATION OF POTENTIOMETER ACCELEROMETER

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