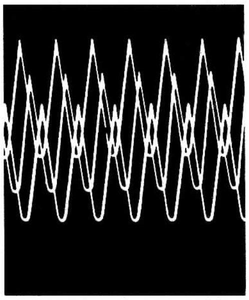

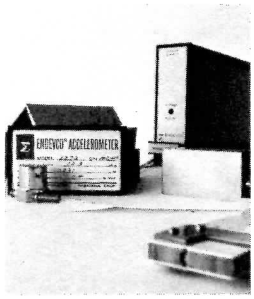

COMPARISON SHOCK MOTION CALIBRATIONS

ABSTRACT

Experimental work on improvements in making shock motion calibrations by the comparison method has been completed. The comparison calibrations are performed with the Endevco® Model 2270 Acceleration Standard using a drop ball shock calibrator similar to the type used for absolute calibrations. The advantage is that the comparison method eliminates error sources which are present in absolute calibrations. In addition to improved accuracy, the comparison calibrations are less tedious and less time consuming and thus can be performed routinely.

1.0 INTRODUCTION

The development of the Endevco® Model 2270 shock and vibration standard resulted in significant improvement in the accuracy and acceleration range which it is possible to achieve when performing shock motion calibration of accelerometers by the comparison method. These improvements have been verified by extensive evaluation tests and calibrations performed on the Model 2270 shock standard. These tests verified experimentally the amplitude linearity of the standard at accelerations equivalent to 50,000 g. Other important tests necessary for evaluating shock motion standards included determining the effect of mass loading and the strain sensitivity of the standard. With the standard fully evaluated, an error analysis was made which included all of the error sources and all of the instruments used to perform the comparison shock motion calibration on test accelerometers.

Shock motion calibrations are performed on test accelerometers with one of several different purposes being considered. The most important purpose is to experimentally verify the amplitude linearity and zero shift characteristics of accelerometers. It is also important to determine the shock motion environmental rating for positive and negative shock pulses; as well as the effects of transverse shock motions on all accelerometers. Shock calibrations are very useful for verifying overall system characteristics including accelerometer, amplifier, filter and oscillographic recorders. For example, the calibration can be used to verify that the system has adequate frequency response and phase angle characteristics for making accurate shock motion measurements. Shock motion calibrations are used also to calibrate impact fuses which are set to actuate at certain prescribed accelerations.

As indicated above, shock motion calibrations provide certain definite information concerning the characteristics of accelerometers. However, they do not eliminate the necessity for performing sinusoidal motion calibrations. The most important calibrations performed on all accelerometers include sensitivity calibration, transverse sensitivity and resonant frequency. Due to the greater accuracy, the sinusoidal sensitivity generally should be used to establish the acceleration sensitivity even when the accelerometers are to be used only for shock measurements. The shock motion sensitivity calibrations are used to verify that the amplitude linearity deviations at high accelerations are less than certain prescribed limits. For example, the sensitivity increase at high accelerations should be significantly less than 10 percent; since, if the deviation is larger the accelerometer is not considered to be suitable for

Reprinted from the 1968 Proceedings of the Institute of Environmental Sciences.

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making shock motion measurements at that acceleration. Sinusoidal transverse sensitivity and resonant frequency calibrations are the most definite means for determining that an accelerometer is in good operating condition and has not suffered internal damage. However, shock motion calibrations are useful for detecting certain malfunctions which ordinarily are not discovered when performing sinusoidal calibrations at accelerations up to 100 g.

2.0 EVALUATION OF ACCELEROMETER STANDARD

Extensive evaluation tests and calibrations must be performed on accelerometer standards used for performing comparison shock calibrations.

2.1 Amplitude Linearity of Accelerometer Standard

The most important of these tests is the determination of the amplitude linearity of the standard. It has been demonstrated[1] that the sensitivity of piezoelectric accelerometers increases linearly with applied acceleration. To provide useful accuracy in shock motion standards, this sensitivity increase should not exceed a few percent at the highest acceleration of intended use. It would even be better if the sensitivity increase were as small as 1 percent throughout the rated acceleration range. It is a difficult task to prove experimentally that the sensitivity increase is only 1 percent at high accelerations such as 10,000 g. This task is difficult because shock motion calibration errors can be as large as 5 percent. Accordingly, to prove that the amplitude linearity deviations of a shock standard are less than 1 percent, it is necessary to perform calibrations on the standard at accelerations five times the maximum acceleration of intended use. For example, a shock calibration with errors up to 5 percent performed at accelerations up to 50,000 g is adequate to acquire confidence in the linearity of the standard for use at accelerations up to 10,000 g. Similarly, shock calibrations performed on standards up to 10,000 g provide confidence of adequate linearity in the standard at accelerations up to only 2,000 g.

Facilities for performing calibrations at 50,000 g are available only in a small number of laboratories. Another disadvantage is that absolute calibration methods are frequently used at these facilities. Present day absolute shock methods require extreme care to consistently achieve errors of 5 percent or less.

In the case of the Model 2270 shock and vibration standard, it is necessary to perform shock amplitude linearity calibrations on the standard at accelerations equivalent to 50,000 g. These high acceleration calibrations are performed by building a special accelerometer standard having an extra heavy mass element. By this means, the same stress is applied to the crystals at low accelerations that would be present at high accelerations if a light mass element were used. The heavy mass element used produces crystal stresses that would be present at 23.3 times the actual applied accelerations. Consequently, applied accelerations at 2,500 g on the heavy mass accelerometers produce the same amplitude linearity deviations that are present in the 2270 standard at accelerations over 58,000 g.

The special 2270 accelerometer is built with a conventional accelerometer base. It is mounted on the 2270 accelerometer standard in the normal way for performing comparison calibrations. The comparison calibrations are performed on the Endevco® Model 2965C calibrator with the special 2270 and the 2270 standard mounted on one-piece anvils. The results of these comparison shock motion calibrations are shown in Figure 1. Each point in Figure 1 is obtained from an oscillogram such as that shown in Figure 2. These oscillograms are computed following the procedure described in Section 3 below. The data points processed with the General Electric computer program LINREG give the least squares line shown in Figure 1. As expected, the sensitivity of the standard increases linearly with applied acceleration. The sensitivity increase is 5 percent at 50,000 g and 1 percent at 10,000 g. It is concluded that the nominal sensitivity increase of the Model 2270 shock and vibration standard is 0.1 percent at 1,000 g. With such good performance, it frequently would be unnecessary to perform corrections to calibration results when using the 2270 standard. However, improved accuracy would be obtained if a correction of +0.5 percent were made at 5,000 g and +1 percent at 10,000 g.

The least squares fit of the line in Figure 1 resulted in an intercept value of 50.5 pC/g. This agrees closely with sinusoidal calibrations performed on the special 2270 which show that the sensitivity at low accelerations is 50.7 pC/g. The difference between these two values is 0.4 percent which is significantly less than the calibration errors present in sinusoidal and shock motion calibrations.

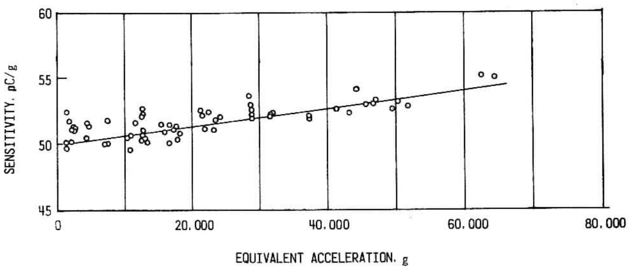
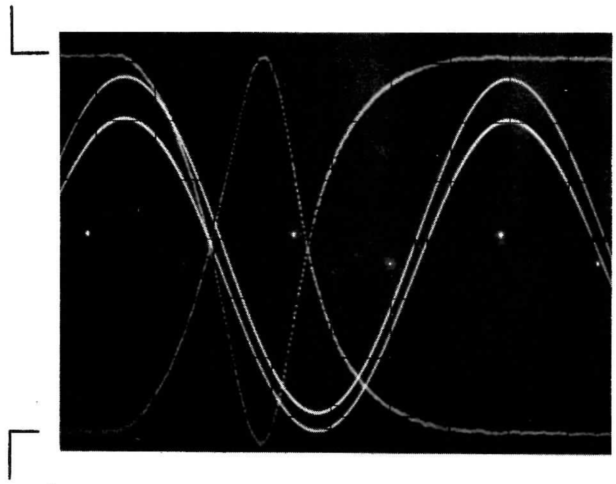


Figure 1. Amplitude linearity calibration on the Endevco® Model 2270 accelerometer standard.

2270
Standard



Special
2270

Figure 2. Typical oscillogram of shock calibration on special 2270 accelerometer at 936 g which produces a crystal stress equivalent to 21,800 g. The sinusoidal voltage signals are used to calibrate the oscilloscope.

2.2 Other Characteristics of Standards

It is important to evaluate other performance characteristics of accelerometer standards used for performing comparison shock calibrations. These characteristics and the specification limits are given in Table 1. In addition to establishing the sensitivity, frequency response and other usual calibrations, it is necessary to demonstrate that the sensitivity of the standard will not change when subjected to various external forces. For example, the standard is subjected to axial inertia forces due to the presence of the test accelerometer and also it is subjected to transverse inertia forces if the applied acceleration is not exactly parallel to the sensitive axis of the standard. These characteristics are evaluated by performing relative motion and strain sensitivity tests on the standard.

The relative motion is evaluated by frequency response calibrations performed with different masses attached externally to the mounting surface of the standard. The results of these evaluation tests are shown in Figure 3 and in Table 1. The relative motion tests show that the sensitivity changes less than 4 percent at frequencies up to 10,000 Hz when masses up to 50 grams are attached to the standard. For sinusoidal motion calibrations, corrections are applied to the calibration results by using Figure 3. Only small errors occur when ignoring these corrections for shock motion calibrations because the predominant frequencies present are significantly less than 10,000 Hz[2].

Also, it is necessary to evaluate sensitivity changes at low frequencies caused by inertia forces produced by the externally attached masses. These forces transmit finite stresses to the crystal which affect the accuracy of the standard. Finally, the strain sensitivity is evaluated on a beam[3] which subjects the standard to bending stresses. Table 1 indicates that the effect of mass on the sensitivity of the standard is less than ±0.2 percent for test accelerometers weighing up to 100 grams and that the strain sensitivity of the standard is less than 0.001 g/μ in/in.

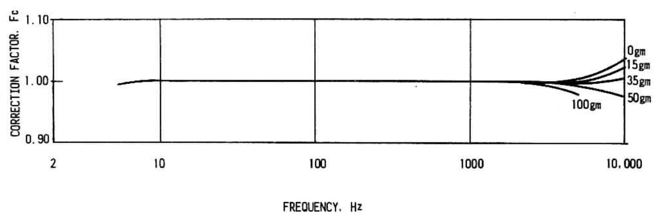


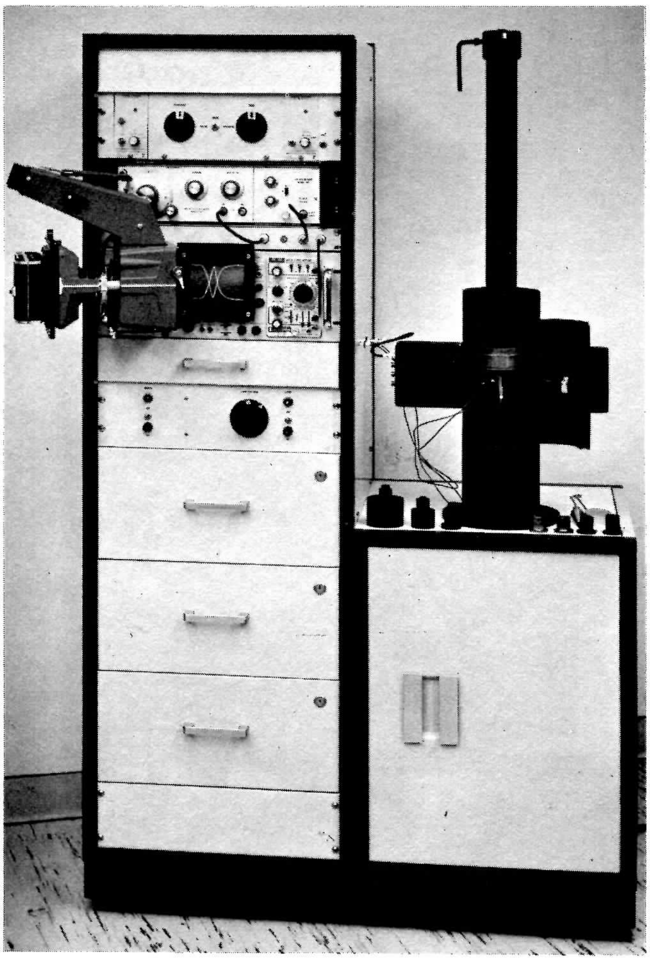
Figure 3. Correction factor indicates the sensitivity change of accelerometer standard at high frequencies as a function of the total mass for various test accelerometers.

TABLE 1

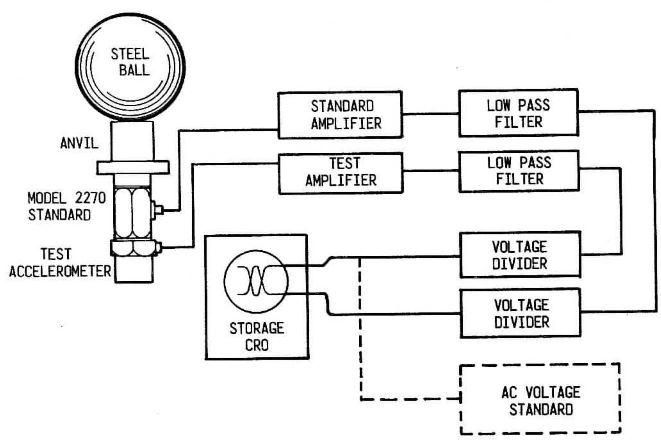
Shock and Vibration Standard Endevco® Model 2270

Performance Characteristic	Specification
Sensitivity error	±0.5 percent
Sensitivity stability at 100 Hz	±0.5 percent/year
Mass effect on Sensitivity at 100 Hz	±0.2 percent/100 grams
Frequency Response and Relative Motion	
Sensitivity change, 5 Hz-5000 Hz with up to 100 grams attached mass	-2 percent*
Sensitivity change, 5 Hz-10,000 Hz with up to 50 grams attached mass	±4 percent*
Amplitude linearity sensitivity change	+0.1 percent/1000 g
Transverse sensitivity ratio	±3 percent
Temperature response charge sensitivity	±0.5 percent/10°C
Strain sensitivity	0.001 g/μ in/in

*Estimated maximum error of correction made from curves showing nominal response is ±1 percent.



(a)



(b)

Figure 4. (a) Instrumentation system for performing shock calibrations by the comparison method

(b) Block diagram illustrating shock pulses obtained when ball strikes anvil.

3.0 COMPARISON CALIBRATION PROCEDURE

Comparison shock calibrations are performed with the Endevco® Model 2965C calibrator and other instruments shown in Figure 4. A steel ball is allowed to fall and impact a cylindrical anvil to which the standard and test accelerometers are attached. The accelerometers are connected to amplifiers equipped with low pass filters. The filter cutoff frequency is 15 kHz. Voltage dividers are used to produce approximately equal signals at the oscilloscope input and to make the pulse heights approximately 6 cm. The oscilloscope is dual trace to record both accelerometer outputs simultaneously. A common calibration voltage standard signal is subsequently applied simultaneously to both oscilloscope channels.

The formula for calculating the sensitivity of the test accelerometer is:

$$Q_t = \frac{H_t}{H_s} \; \frac{D_s}{D_t} \; \frac{C_t}{C_s} \; \frac{K_s}{K_t} \; A_s$$

where

Q_t = Sensitivity of test accelerometer, pC/g

H_t = Pulse height of test accelerometer, cm

H_s = Pulse height of accelerometer standard, cm

D_t = Divider setting on test accelerometer

D_s = Divider setting on accelerometer standard

C_t = Calibration signal on test channel, mV/cm

C_s = Calibration signal on standard channel, mV/cm

K_t = Gain of test amplifier, mV/pC

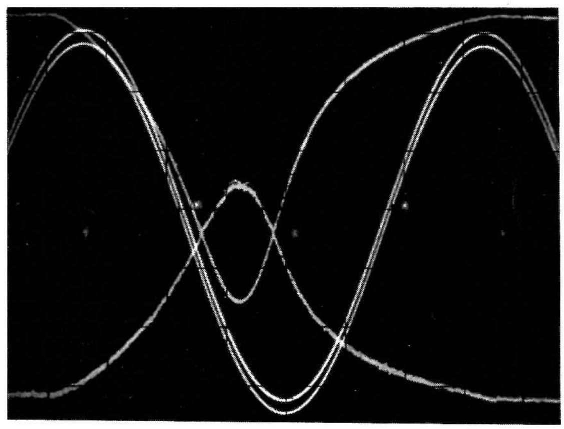
K_s = Scale range of standard amplifier, mV/g

A_s = Amplitude linearity correction for accelerometer standard.

Typical oscillograms obtained during a comparison shock calibration are illustrated in Figure 5. The shock pulse outputs from the standard and test accelerometers are inverted for ease in separating the traces. The sinusoidal traces are the calibration signals; the upper signal is for the standard channel and the lower signal is for the test channel. The gain and scale ranges used in the equation are selected on the test and standard amplifiers. The amplitude linearity correction, A_s, determined from the special calibration discussed above, is one percent per 10,000 g or 0.1 percent per 1,000 g.

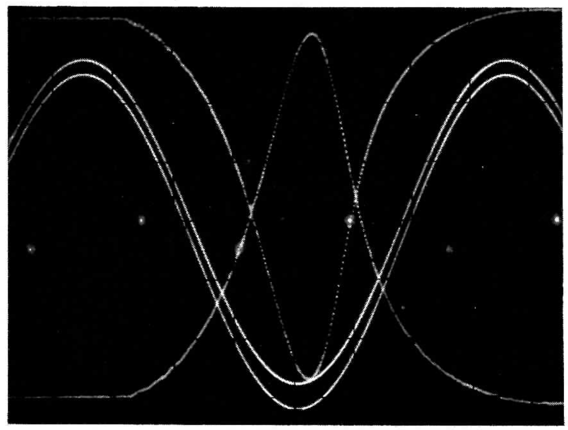
The results of the calibrations illustrated in Figure 5 are given in Table 2. The results show that the charge sensitivity of the 2225 accelerometer increases at high accelerations. The nominal response is that the charge sensitivity increases linearly with applied acceleration with a value of 4.5 percent at 10,000 g. The deviations from the nominal response are less than the calibration errors of ±5 percent, which are discussed below.

2270 Standard

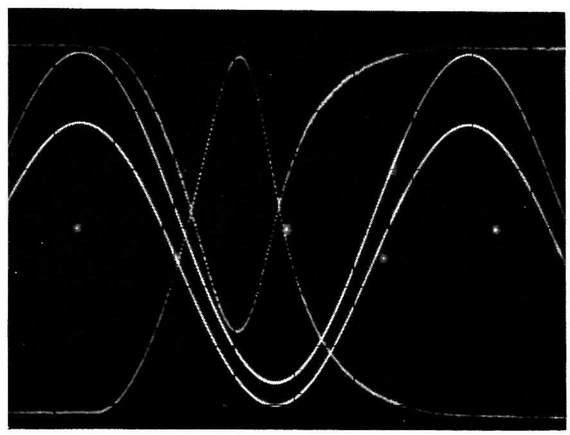


Test Accelerometer

(a) 99g

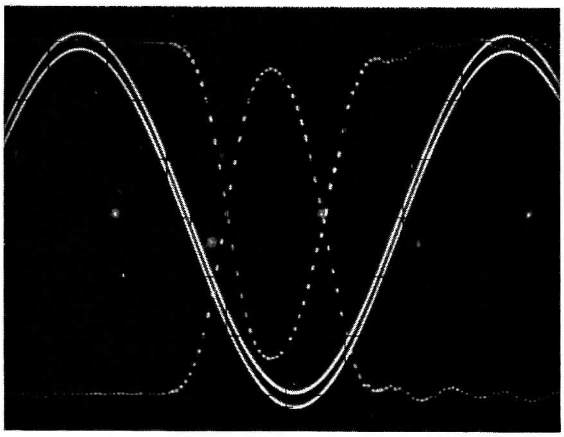


(b) 533 g



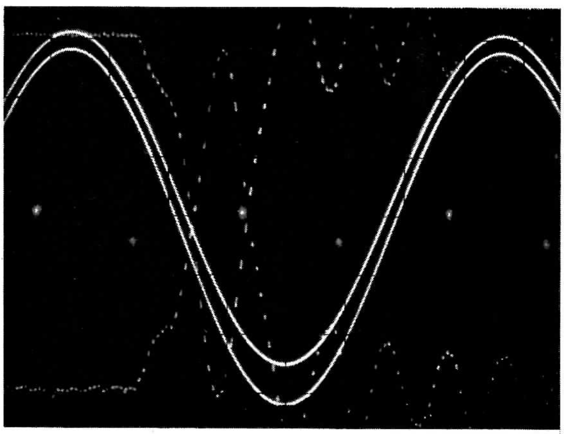
(c) 982 g

2270
Standard



Test
Accelerometer

(d) 4567 g



(e) 10,164 g

Figure 5. Oscillograms obtained during the comparison shock calibration of an Endevco® Model 2225 test accelerometer.

4.0 ERROR ANALYSIS

The error analysis must include estimated errors for the applicable performance characteristics of all of the instruments used to perform the comparison shock calibration on test accelerometers. The instruments for the Endevco® Model 28701 Shock Motion Calibrator include the Model 2270 standard, Models 2710FM13 and 2710FM14 charge amplifiers with low pass filters, resistance decade dividers and dual beam oscilloscope. The error analysis must include those characteristics of the test accelerometer which could produce error signals or change the sensitivity of the test accelerometer during the time that the calibration is being performed.

The procedures for performing the error analysis are described by Beers[4]. The actual error used for certain performance characteristics is sometimes less than the maximum limits stated for the instrument. This is an accepted practice because the nominal performance of the instruments in most cases is less than the limit established to determine acceptance or rejection of a particular instrument during manufacture. Furthermore, the specific errors used in the analysis are sometimes less than the nominal performance of the instrument. This is done to account for the fact that the conditions present during calibration are usually not at the operating extremes for the instrument. However, care is taken in assigning errors so that the maximum possible errors under extreme conditions never exceed 1.5 times the nominal error used in the analysis. This ratio of maximum to nominal errors is suggested by Beers in reference 4.

The results of the error analysis are shown in Table 3. Experience shows that the errors of the reciprocity calibration of the 2270 standard are usually less than the ±0.5 percent listed in Table 1. Therefore, the estimated error in Table 2 is given as 0.35 percent. The accelerometer standard could be calibrated by the sinusoidal comparison method rather than by the absolute reciprocity method when using the standard only for shock motion calibrations. However, the reciprocity calibrations have sufficient accuracy to demonstrate the stability of the standard with time. The other possible errors in the accelerometer standard include 2.1 percent for the

TABLE 2

Calibration of Endevco® Model 2225 Accelerometer, Serial No. JC62

Fig. No.	Applied Acceleration	Pulse Duration	D_t	D_s	C_t	C_s	K_t	K_s	A_s	Q_t
	g	ms			mV/cm	mV/cm	mV/pC	mV/g		pC/g
5(a)	99	2.6	1.0	1.0	202	203	10	10	1.000	.732
5(b)	533	.85	0.4	0.3	247	256	10	10	1.000	.729
5(c)	982	.75	0.2	1.0	236	201	10	1.0	1.001	.733
5(d)	4567	.15	0.8	0.6	510	507	1.0	1.0	1.005	.786
5(e)	10,164	.10	0.8	0.7	108	115	0.1	0.1	1.010	.778

TABLE 3

Analysis of Errors in the Sensitivity
of
Test Accelerometers Calibrated On
Endevco® Shock Motion Calibrator Model 28701

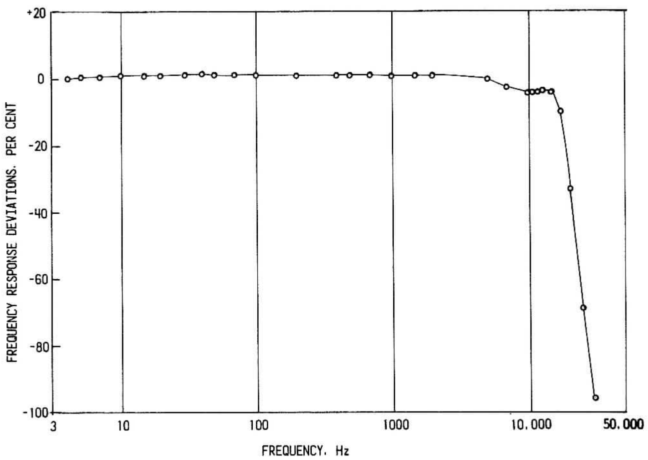
Measurement	Sensitivity Error
	Percent
1.0 Accelerometer Standard	
1.1 Reciprocity Calibration at 100 Hz	0.35
1.2 Stability of Sensitivity	0.35
1.3 Mass Effect on Sensitivity at 100 Hz	0.14
1.4 Comparison Frequency Response Calibration Error for Standard	2.1
1.5 Relative Motion up to 10,000 Hz	1.0
1.6 Amplitude Linearity Corrections up to 10,000 g	0.5
2.0 Charge Amplifiers	
2.1 Range Tracking of Standard Amplifier	0.7
2.2 Gain of Test Amplifier	0.35
2.3 Range Tracking of Test Amplifier	0.2
2.4 Relative Frequency Response	0.1
2.5 Gain Stability, Source Capacity, Etc.	0.2
3.0 Low Pass Filters	
3.1 Relative Gain	1.0
3.2 Relative Frequency Response to 10,000 Hz	1.0
3.3 Phase Angle Linearity	1.0
4.0 Voltage Ratio Measurement	
4.1 Decade Voltage Divider	0.05
4.2 Height of Standard Pulse	2.0
4.3 Height of Test Pulse	2.0
4.4 Calibration of Oscilloscope	2.0
5.0 Environmental Effects on Amplifiers and Accelerometers Including Transverse Sensitivity, Strain Effects, Temperature, Distortion, Etc.	1.0
6.0 Estimated Errors in Test Accelerometer Sensitivity	4.8*

*Determined from the square root of the sum of the squares of the individual errors.

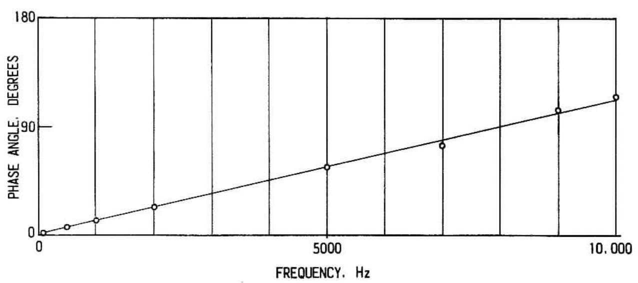
frequency response calibration of the standard. This error includes the errors in the National Bureau of Standards calibration of the reference standard used to calibrate the 2270 standard. The errors in Table 3 for the charge amplifiers apply for the Models 2710FM13 and 2710FM14. The errors for the low pass filters in the charge amplifiers are listed separately. Calibration of the low pass filters is shown in Figure 6. Identical filters are used in both amplifiers and the errors, due to gain and frequency response, tend to cancel. Therefore, the errors of 1 percent in 3.1 and 3.2 in Table 3 should be more than adequate. The phase angle of the filters changes linearly with frequency, Figure 6, which is the requirement for avoiding distortion in the shock pulse wave form. The proportional phase response extends to 10,000 Hz which is adequate for the frequency components produced by the shock motion calibrator as indicated by the Bode diagrams given in reference 2. Therefore, the errors, due to phase angle characteristics of the filters, are estimated to be less than 1 percent.

The comparison calibration is performed by simultaneously recording the outputs from the standard and test accelerometers on a dual beam oscilloscope. Decade voltage dividers are used so that the height of the shock pulses and sinusoidal calibration signals on the oscilloscope can be adjusted in the range of 5-8 cm. Following this procedure, the pulse height can be measured with errors less than 2 percent. The oscilloscope is also calibrated to allow for differences between the voltage scales. An error of up to 2 percent is allowed for this calibration.

An error of 1 percent is allowed for environmental effects on the standard and test accelerometer and amplifiers. These include errors due to transverse sensitivity, strain effect, temperature, distortion, etc. In order to minimize distortion errors it is necessary to use anvils which produce pulse durations at least 5 times the natural period of the test accelerometer. This requirement is usually met because most accelerometers having a low resonant frequency are limited



(a)



(b)

Figure 6. (a) Frequency response and
(b) Phase angle calibration on charge amplifiers equipped with a 15 kHz low pass filter.

to use at low accelerations and the low acceleration anvils produce long pulse durations. Some distortion is also produced due to exciting the resonant frequency of the outer case and base portion of the standard. The errors due to this distortion tend to cancel because it occurs equally in both the test and standard outputs.

The estimated error in the test accelerometer sensitivity is determined by the square root of the sum of the squares of the individual errors listed in Table 3. This error in the shock motion comparison calibration of the test accelerometer sensitivity is 4.8 percent. However, actual practice in performing numerous shock motion calibrations on accelerometers having known characteristics, indicate that the error is usually significantly less than 4.8 percent. Errors of less than 3 percent are achievable when some skill is used to acurately measure the pulse heights and calibration signals.

Some experimental verification of the calibration errors is demonstrated by analyzing the calibration points in Figure 1. A total of 63 calibration points indicate a normal distribution with a standard deviation of 1.43 percent from the nominal response given by the least squares straight line. There is 95 percent confidence that the errors are less than ±3 percent. These statistics are another indication that the actual errors are usually significantly less than those predicted in the error analysis in Table 3.

5.0 SIGNIFICANCE OF ABSOLUTE SHOCK MOTION CALIBRATIONS

Prior to the development of improved instrumentation for performing comparison shock motion calibrations, it was necessary to perform absolute calibrations in order to calibrate accelerometers up to 10,000 g. The absolute calibration method has a number of operational disadvantages. It requires the measurement of the velocity change applied to the accelerometer and the measurement of the area of the shock motion pulse from the accelerometer output. To maintain calibration errors of less than 5 percent requires constant attention to these measurements. Care must be taken to assure that all parts of the calibrator are in good working order. Even when following extreme care in the laboratory, it is sometimes difficult to eliminate completely sporadic errors in the velocity measurement, particularly when calibrating in the 5,000 to 10,000 g range. An inherent error is present in the absolute calibration for accelerometers having non-linear characteristics. The error occurs in the method of integration used in the area measurement and becomes significant if the test accelerometer nonlinearity is greater than about 5 percent. Another disadvantage of absolute calibrations is that they are tedious and time consuming to perform.

Comparison shock motion calibrations, on the other hand, greatly simplify the measurements necessary to perform calibrations throughout the acceleration range from 100 g to 10,000 g. Comparison calibrations eliminate the critical error sources present in absolute calibrations. It is no longer necessary to perform absolute calibrations in most calibration laboratories. Absolute calibrations should be limited to those laboratories performing primary standard calibrations. Now that comparison calibrations are fully developed, the sole purpose of performing absolute calibrations should be restricted to the calibration of accelerometer standards used to perform comparison shock motion calibrations on various test accelerometers. However, since the accuracy of absolute calibrations is ±5 percent at the present time, it is necessary to perform the absolute calibrations on the standards at accelerations five times the maximum acceleration for which it is necessary to certify the standard. These high acceleration calibrations are required in order to verify the amplitude linearity of the standard with a certainty of ±1 percent. Accordingly, to demonstrate the linearity of a standard to 10,000 g would require absolute calibrations to 50,000 g. Until further developmental work is accomplished in performing absolute calibrations up to 50,000 g or reducing absolute calibration errors to significantly less than 5 percent, it will be necessary to use the methods described earlier for verifying the amplitude linearity of shock acceleration standards. Also, absolute shock motion calibrations to 10,000 g with ±5 percent errors is only useful for demonstrating the linearity of acceleration standards to 2,000 g. These considerations indicate that most laboratories will have the need to perform only comparison shock motion calibrations up to 10,000 g.

6.0 CHANGES IN ENDEVCO SHOCK CALIBRATION SERVICES

Absolute shock motion calibrations have been performed for a number of years. Because of the recent development work on comparison calibrations the absolute calibrations are now performed only by special request. Since few laboratories will require absolute calibrations, most of the calibration services provided by Endevco will be performed by the comparison method. The comparison shock calibrator is similar to the absolute calibrator except that the means to measure velocity are removed and one-piece anvils are used to accomodate the Endevco® Model 2270 standard.

7.0 SUMMARY

Comparison shock motion calibrations up to 10,000 g are performed with consistent accuracy. The errors present in the comparison calibrations are equal to or less than those present in performing absolute calibrations over the same acceleration range. The accuracy of comparison calibrations is established by performing an error analysis on all of the instruments used during the calibrations. This analysis was made possible after performing calibrations which demonstrate the amplitude linearity of the accelerometer standard at accelerations equivalent to 50,000 g.

The development of comparison shock motion calibrations using accelerometer standards eliminates the need to perform absolute calibrations except in laboratories performing primary calibrations. It is expected that most laboratories will discontinue performing absolute calibrations because of the simplicity and accuracy by which comparison calibrations can be performed.

It is necessary to perform shock calibrations in order to verify the characteristics of accelerometers and amplifiers at high accelerations and short pulse durations. However, shock calibrations do not eliminate the need to perform sinusoidal calibrations. Sinusoidal calibration is the most accurate means for measuring sensitivity, resonant frequencies and other characteristics of accelerometers.

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