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Accurate Accelerometer Calibrations by Absolute and Comparison Methods

Technical Paper 233

By Dr. R. R. Bouche

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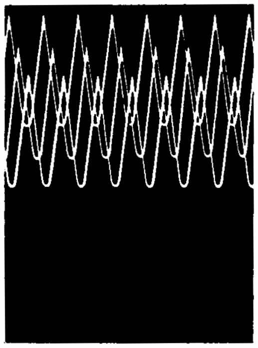

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Accurate Accelerometer Calibrations by Absolute and Comparison Methods

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INTRODUCTION

Absolute and comparison methods are used for calibrating vibration transducers. A decade ago, most laboratories used the direct viewing optical calibration method. In the past several years comparison calibration methods have become fully developed and good quality accelerometer standards have become available. As a result, hundreds of calibration laboratories now use the comparison method for the calibration of velocity pickups and accelerometers. However, primary calibration laboratories use absolute methods to establish the sensitivity of vibration standards.

After reviewing various absolute calibration methods, this paper describes an accelerometer standard designed for reciprocity and comparison calibrations. At the present time, the reciprocity calibration of this standard is performed only at the frequency of 100 Hz. For this reason, the comparison calibration method is used to prove experimentally the characteristics of the standard at frequencies up to 10,000 Hz. Once the reciprocity and comparison calibrations are performed on the standard, it is used to perform comparison calibrations on other vibration transducers.

ABSOLUTE CALIBRATIONS

The purpose of the absolute calibration is to establish the sensitivity of the vibration standard. The sensitivity is defined as the ratio of the electrical output of the standard to the applied

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ABSOLUTE CALIBRATIONS (continued)

motion. Absolute calibration methods approved by the American Standards Association[1] are included in Table 1. The errors listed in Table 1 include all error sources present in establishing the sensitivity of the standard. Accordingly, the error reflects the uncertainty in the electrical output of the standard and includes the error in the applied motion. The error in the reciprocity calibration of an accelerometer standard at 100 Hz is ±0.5%. An analysis for establishing this error is given in a later section of this paper. The error for the reciprocity calibration of a velocity standard is ±1% up to 900 Hz and ±2% up to 2000 Hz. These errors are taken from Reference 1. The error of the direct viewing optical method using a microscope is ±1% to 50 Hz. The optical method error includes the following error sources: measurement of displacement amplitude, error in the computation of acceleration amplitude resulting from distortion in the motion wave form, frequency error, and error in measuring the electrical output from the vibration standard. The error in using the fringe-disappearance interferometer method[2, 3] is ±2%. Although this error is not found in the literature, it is stated frequently in calibration reports issued by the National Bureau of Standards.

TABLE 1
Errors of Vibration Standards Calibrated by Absolute Methods

Method	Amplitude	Frequency	Standard Sensitivity Error
		Hz	per cent
Reciprocity, accelerometer standard	0 - 10 g	100	±0.5
Reciprocity, velocity standard	0 - 10 g	10 - 900 900 - 2000	±1* ±2*
Optical, direct viewing	0.1 in.	5 - 50	±1
Interferometer	4 μin.	1000 - 10,000	±2

*These errors include the voltage ratio measurement error present when performing comparison calibrations with the velocity standard. The errors attributable to the reciprocity calibration of the velocity standard are slightly less than the values listed.

[1] American Standard Methods for the Calibration of Shock and Vibration Pickups, S2.2-1959, American Standards Association, Inc., 10 East 40 Street, New York, New York.

[2] Edelman, S., Jones, E., and Smith, E. R., Some Developments in Vibration Measurements, Journal of the Acoustical Society of America, Vol. 27, No. 4, July 1955, pp. 728-734.

[3] Schmidt, V. A., Edelman, S., Smith, E. R., and Pierce, E. T., Modulated Photoelectric Measurement of Vibration, Journal of the Acoustical Society of America, Vol. 34, No. 4, 1962, pp. 455-458.

ABSOLUTE CALIBRATIONS (continued)

Having these various absolute calibration methods available, it becomes necessary to select at least one of the methods to establish a primary vibration standard. One of the factors that determines the selection is the accuracy of the vibration transducers for which the standard is being established. The stability of good quality piezoelectric accelerometers in every day use is better than ±1%. To prove this stability, it is necessary that the error in the absolute calibration of the standard be significantly less than 1%. In addition, it has become necessary for the accelerometer manufacturer to have very accurate standards in order to meet the requirements of many users of accelerometers. For these reasons, the reciprocity method with an error of ±0.5% has been selected for establishing the sensitivity of accelerometer standards.

RECIPROCITY ACCELEROMETER STANDARD

To achieve the 0.5% error of the reciprocity method, it is necessary for the accelerometer standard to have certain performance characteristics. The standard must be unaffected by mechanical strains when the standard and test accelerometer are attached to each other or to the vibration exciter, when masses are attached for the reciprocity calibration, and when the vibration exciter experiences transverse motion. Extreme care must be followed in the design of an accelerometer standard in order to keep these strain sensitivity errors within acceptable limits. The sensitivity change in the standard should be insignificant for the temperature range present in various calibration laboratories. The accelerometer standard must be structurally rigid in order to minimize relative motion between the standard and mounting surface to which test accelerometers are attached. Although it is helpful for the transverse sensitivity of the standard to be reasonably small, the errors due to this characteristic are usually smaller than the errors caused by the characteristics already mentioned. The other performance characteristics of an accelerometer standard are similar to the characteristics of most piezoelectric accelerometers.

Once it is determined that the accelerometer standard has all the above characteristics, it can be calibrated by the reciprocity method. In addition to the reciprocity calibration, the following discussion describes comparison calibrations performed on the standard to demonstrate its suitability for use at frequencies up to 10,000 Hz.

Reciprocity Calibration

Figure 1 illustrates a vibration exciter equipped with two driving coils which are required for reciprocity calibrations. The accelerometer standard is attached to the exciter together with one of the masses used for the reciprocity calibration. The other masses used in the calibration are also illustrated in Figure 1. The other equipment required for the reciprocity calibration includes a precision variable resistance decade voltage divider, an AC vacuum tube voltmeter, a precision resistor in series with one of the driving coils, frequency counter, power amplifier and oscilloscope.

Reciprocity Calibration (continued)

The reciprocity calibration consists of transfer admittance, voltage ratio, frequency and mass measurements.[4, 5, 6] The transfer admittance (ratio of current in one driving coil to standard voltage output) is measured with each of the known masses attached. One of the requirements of the reciprocity calibration is to use this driving coil as a velocity pickup. For this reason, this driving coil is open circuited and current is applied to the second driving coil in the vibration exciter to produce sinusoidal motion. The ratio of accelerometer standard output to the voltage output of the open circuit driving coil is measured with the exciter vibrating at exactly the same frequency used in the transfer admittance measurement. These measurements are used in the reciprocity equation[4] to determine the sensitivity of the accelerometer standard. The estimated error in this sensitivity is ±0.5% at frequencies at which there is no relative motion between the accelerometer standard and the driving coil used as the velocity pickup. An analysis of all the errors present in performing the reciprocity calibration is given in the left half of Table 2.

In addition to the reciprocity calibration, the following comparison calibration is performed on the standard.

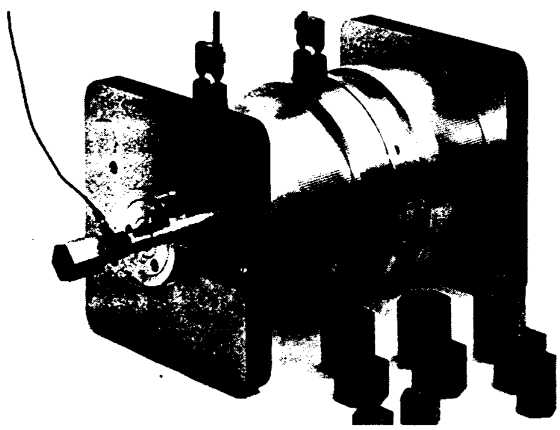

FIGURE 1

Reciprocity Calibration is performed with accelerometer standard attached to an electrodynamic vibration exciter equipped with two driving coils. One coil is used open circuit for the voltage ratio measurement. The masses are attached to the standard for the transfer admittance measurements.

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[4] Bouche, R. R., and Ensor, L. C., Use of Reciprocity Calibrated Accelerometer Standards for Performing Routine Laboratory Comparison Calibrations, The Shock & Vibration Bulletin No. 34, Part 4, 1965, pp. 21-29.

[5] Levy, S., and Bouche, R. R., Calibration of Vibration Pickups by the Reciprocity Method, Journal of Research of the National Bureau of Standards, Vol. 57, No. 4, October 1956, pp. 227-243.

[6] Dimoff, T., and Payne, B. F., Application of Air Bearings to an Electrodynamic Vibration Standard, Journal of Research of the National Bureau of Standards, Vol. 67C, No. 4, 1963, pp. 327-333.

Frequency Response Comparison Calibration

The accelerometer standard is designed with a high resonant frequency to assure that its sensitivity is constant throughout the operating frequency range. This performance is verified by a frequency response calibration performed by the comparison method using an accelerometer previously calibrated up to 10,000 Hz at the National Bureau of Standards, and also previously calibrated by the optical method at 5 Hz. This accelerometer is attached directly to the accelerometer standard and the ratio of their outputs is measured. The equipment for the comparison calibration is the same as the equipment listed above for the reciprocity calibration except that the precision series resistor and frequency counter are no longer required.

The results of this frequency response calibration are shown in Figure 2. The estimated errors in performing this frequency response calibration are shown in the right half of Table 2. The errors include the NBS errors on the accelerometer used to perform this frequency response calibration. As a result, the estimated error is as high as 2.1% at 10,000 Hz.

The sensitivity at 10,000 Hz in Figure 2 is about 1.5% higher than the sensitivity at lower frequencies. The mass of the accelerometer used to perform the calibration in Figure 2 is 20 grams. This demonstrates that there is little or no relative motion in the standard when an accelerometer with a mass of 20 grams is attached to it. It remains to be demonstrated whether or not relative motion is present when attaching test accelerometers having a mass lighter or heavier than 20 grams.

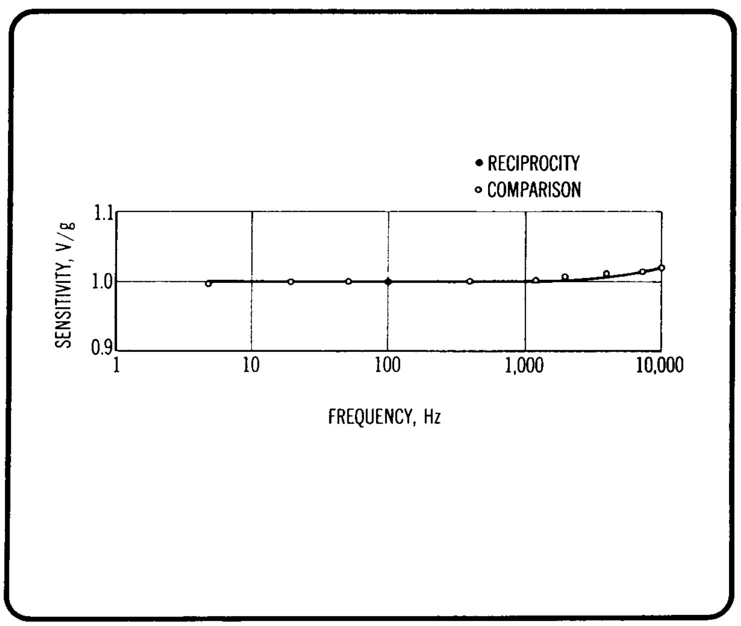

FIGURE 2

Calibration of a Model 2270 Accelerometer standard and charge amplifier. The reciprocity calibration performed at 100 Hz and comparison calibration to 10,000 Hz are traceable to the National Bureau of Standards.

TABLE 2

Analysis of Calibration Errors in Determining the Sensitivity
of the
Model 2270 Accelerometer Standard at Various Frequencies

Reciprocity Calibration 100 Hz		Comparison Calibration 5-10,000 Hz	
Measurement	Error	Measurement	Error
	per cent		per cent
Mass	0.05	Optical Calibration, 5 Hz	1.0
Transfer Admittance Intercept	0.2*	NBS Calibration, 10-900 Hz	1.0
Voltage Ratio	0.2*	NBS Calibration, 900-10,000 Hz	2.0
Distortion	0.1	Distortion	0.2
Frequency	0.05	Accelerometer Effects, Transverse Sensitivity, Strain, etc.	0.2
Accelerometer Effects, Transverse Sensitivity, Strain, Temperature, etc.	0.2	Amplifier Effects, Frequency Response, etc.	0.1
Amplifier Effects, Gain, Stability, Source Capacitance, etc.	0.3	Relative Motion, 900-10,000 Hz	0.5
		Voltage Ratio	0.2
Estimated Error, at 100 Hz	0.5**	Estimated Error, 5-900 Hz	1.1**
		Estimated Error, 900-10,000 Hz	2.1**

* Assume 0° and 90° phase shifts for transfer admittance and voltage ratio measurements, respectively.

**Determined from the root-mean-square of the applicable individual errors.

Relative Motion

The effect of test accelerometer mass on the accelerometer standard is determined by performing additional comparison calibrations using various accelerometers of known frequency response characteristics. The frequency response characteristics of these various accelerometers are known from resonant frequency measurements and from previous comparison calibrations traceable to the National Bureau of Standards. These comparison calibrations are performed using the same equipment and procedure described above for frequency response comparison calibration.

Relative Motion (continued)

The results of the comparison calibrations performed on the accelerometer standard are shown in Figure 3. The relative motion between the acceleration standard and test accelerometer attached to it depends upon the mass of the test accelerometer. To simplify the use of Figure 3, the relative motion is expressed in terms of a sensitivity change of the standard. This is similar to the method used to illustrate the relative motion in the reciprocity velocity standard used at the National Bureau of Standards.[5] To be precise, the relative motion indicates that the velocity standard at NBS and the accelerometer standard in Figure 3 change their sensitivity at high frequencies and the amount of this change depends on the dynamic mass (or mass) of the object (or accelerometer) attached to the standard. This should be expected because the sensitivity of the standard is defined as its electrical output divided by the motion present at the mounting surface where test accelerometers are attached. At high frequencies, this motion depends on the mass of the test accelerometer attached.

Figure 3 indicates the sensitivity change of the accelerometer standard is less than about 0.5% up to 5000 Hz for piezoelectric accelerometers having a total mass up to 35 grams. The highest calibration frequency used in most calibration laboratories does not exceed 5000 Hz. Therefore, for most routine calibrations, the standard is used without making relative motion corrections to the results.

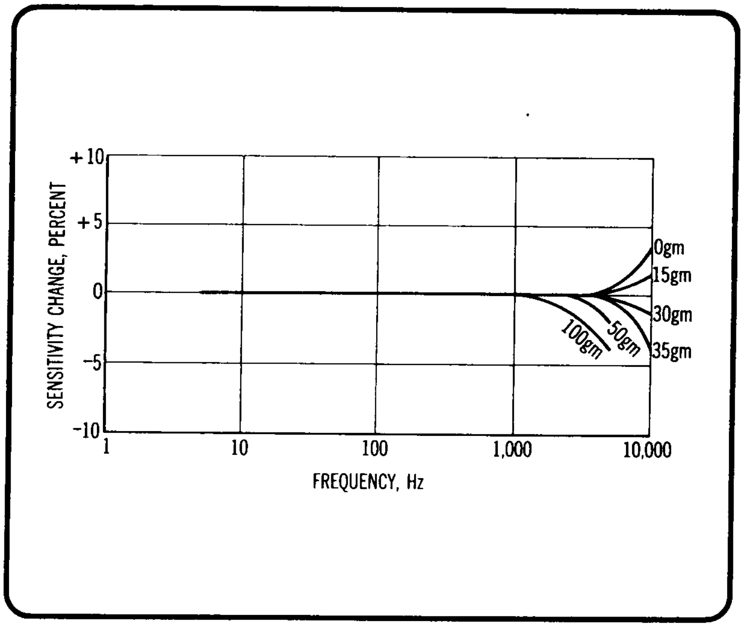

FIGURE 3

Comparison Calibrations performed to determine the relative motion present in the 2270 accelerometer standard as a function of test accelerometer mass.

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[5] Levy, S., and Bouche, R. R., Calibration of Vibration Pickups by the Reciprocity Method, Journal of Research of the National Bureau of Standards, Vol. 57, No. 4, October 1956, pp. 227-243.

Relative Motion (continued)

All the above calibrations are performed by the manufacturer of the accelerometer standard. The rather extensive comparison calibrations just described need not be repeated on each accelerometer standard manufactured. Each standard of the same design will have the same high frequency characteristics. To demonstrate this to the user, each standard manufactured is subjected to a frequency response calibration. In addition, the sensitivity of the standard is established by a reciprocity calibration at 100 Hz. The question is often asked, how frequently should these calibrations on the standard be repeated? The accelerometer standard is extremely stable. Like similar standards,[4] sensitivity changes are only about 0.5% per year. Therefore, the practice of repeating the reciprocity calibration at 100 Hz and the frequency response comparison calibration at yearly intervals is quite acceptable. The calibration laboratory accumulates a history on the standard by following this practice.

The whole purpose of the above work is to demonstrate that the standard is suitable for making accurate comparison calibrations on various accelerometers. The remainder of this paper describes these routine comparison calibrations and the vibration exciter performance required to achieve accurate results.

ROUTINE COMPARISON CALIBRATIONS

A typical setup for performing routine comparison calibrations on piezoelectric accelerometers is illustrated in Figure 4. The accelerometer standard is connected to the charge amplifier installed in the left side of the portable cabinet. The test accelerometer mounted on top of the standard is connected to the charge amplifier in the right side of the cabinet. The charge amplifiers are designed to indicate the charge acceleration sensitivity of the test accelerometer in units of pC/g. The ratio of the outputs of the two charge amplifiers, Figure 4, is measured with suitable equipment, such as an AC-DC converter with digital ratiometer or digital voltmeter, an AC vacuum tube voltmeter with precision resistance decade box for measuring voltage ratios, or a chart recorder which accurately measures voltage ratios. An audio oscillator and good quality power amplifier is used with the electrodynamic vibration exciter. A dual beam oscilloscope is useful for monitoring the acceleration wave form at the charge amplifier outputs.

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[4] Bouche, R. R., and Ensor, L. C. Use of Reciprocity Calibrated Accelerometer Standards for Performing Routine Laboratory Comparison Calibrations, The Shock and Vibration Bulletin No. 34, Part 4, 1965, pp. 21-29.

ROUTINE COMPARISON CALIBRATIONS (continued)

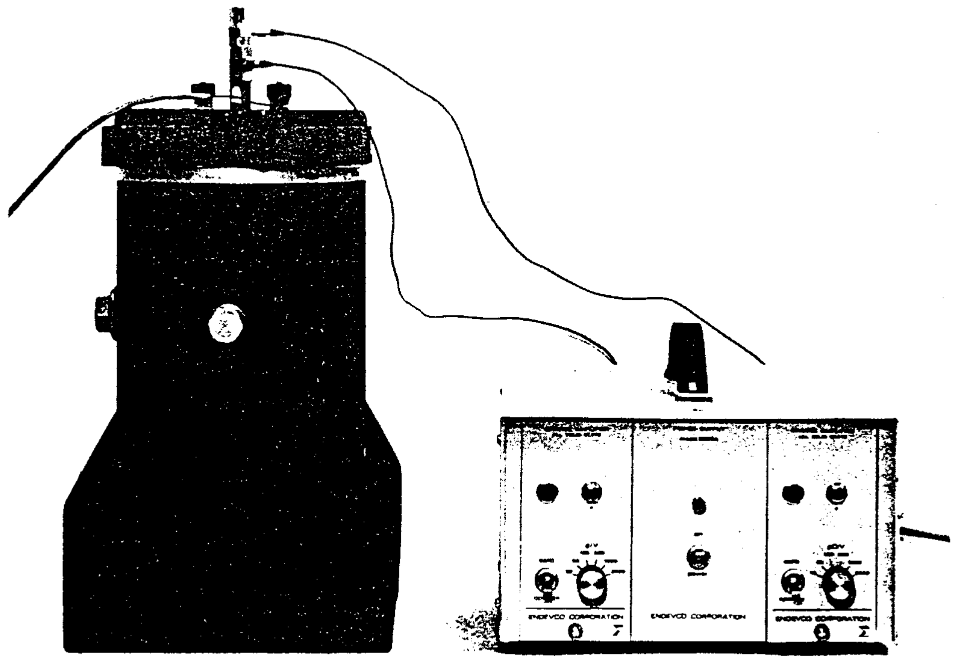

FIGURE 4

Setup used for the comparison calibration of a test accelerometer using an accelerometer standard previously calibrated by the reciprocity method.

Typical calibration results obtained on test accelerometers are shown in Figure 5. The charge sensitivity of the accelerometers using P-6 and P-8 ceramic materials decreases about 1% for each octave increase in frequency. This characteristic is typical of lead-zirconate-titanate accelerometers. It happens that the capacitance of these accelerometers has the same frequency characteristic. Therefore, if the voltage sensitivity of the accelerometer is desired, the charge sensitivity at the frequency of the capacitance measurement is divided by the sum of the accelerometer capacitance, cable capacitance, and other capacitances that will be connected across the accelerometer. The use of charge amplifiers eliminates the need for this computation. Accelerometers built with P-10 ceramic material do not have this frequency characteristic; both the charge and voltage sensitivities are constant at all frequencies up to about one-fifth the resonant frequency. Like all accelerometers, the increase in sensitivity[1] at high frequencies is due to their resonant frequency. The lines in Figure 5 are faired through the points.

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[1] American Standard Methods for the Calibration of Shock and Vibration Pickups, S2.2-1959, American Standards Association, Inc., 10 East 40 Street, New York, New York.

ROUTINE COMPARISON CALIBRATIONS (continued)

For accelerometers known to have a flat frequency response, a horizontal line is drawn at the average of the sensitivities obtained at frequencies up to one-tenth the resonant frequency.[8] The deviation of the points from the drawn line indicates the order of magnitude of the calibration errors.

The estimated errors of the sensitivities indicated by the points in Figure 5 are listed in Table 3. The error analysis in Table 3 includes the errors from Table 2 for the sensitivity calibration of the accelerometer standard itself, that is, 0.5% for the reciprocity calibration at 100 Hz and up to 2.1% for the comparison calibration of the standard at 10,000 Hz. In addition, a stability error of 0.5% is allowed for the possibility of a sensitivity change in the standard. All other possible sources of error in the accelerometers and amplifiers are included in Table 3. Finally, the estimated error in the test accelerometer sensitivity, last three lines in Table 3, is determined from the square root of the sum of the squares of the individual errors. Except at 100 Hz, the estimated error is between 1.5% and 2.5% because the NBS errors are included in the calibration of the standard. The error at 100 Hz is 1%. The 1% error is achieved because the standard is calibrated at 100 Hz by the reciprocity method which does not depend on the NBS absolute and comparison calibration errors.

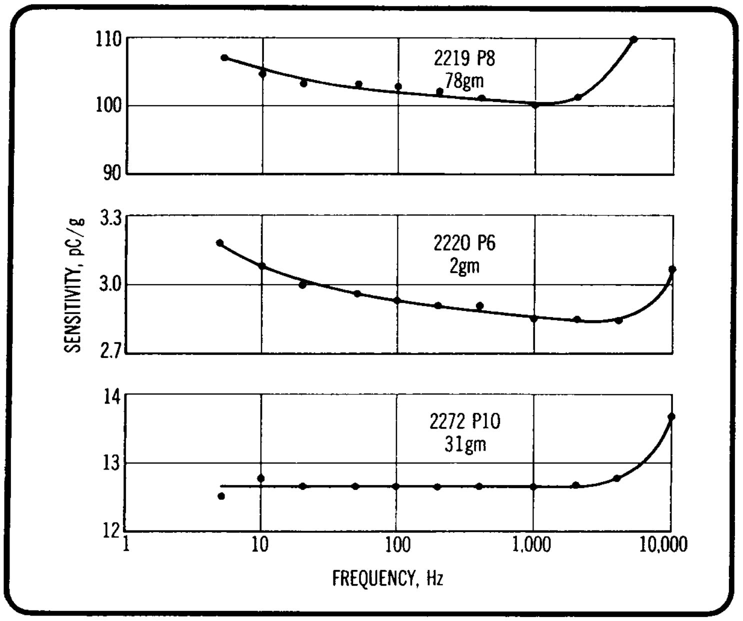

FIGURE 5

Comparison calibration results on three accelerometers using the setup shown in Figure 4.

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[8] Bouche, R. R., Instrumentation for Shock and Vibration Measurements, Colloquim on Experimental Techniques in Shock and Vibration, American Society of Mechanical Engineers, 1962, pp. 71-80.

ROUTINE COMPARISON CALIBRATIONS (continued)

The accelerometer standard and associated charge amplifiers are designed to meet the errors listed in Table 3. Some of the errors depend on temperature and line voltage variations usually present in most calibration laboratories. Other precautions to be followed when performing calibrations concern the vibration exciter.

TABLE 3

Analysis of Errors in the Sensitivity of Test Accelerometers Calibrated by the Comparison Method

Measurement		Sensitivity Error
		per cent
Reciprocity Calibration Error for Standard, 100 Hz		0.5
Stability of Standard		0.5
Comparison Frequency Response Calibration Error for Standard		
	5 Hz - 900 Hz	1.1
	900 Hz - 10,000 Hz	2.1
Relative Motion, 900 - 10,000 Hz+		1.0
Distortion		0.2
Voltage Ratio		0.2
Amplitude Linearity - 0.2 g to 100 g		0.2
Range Tracking, Standard Amplifier - 1, 10, and 100 g/V Ranges		0.2
Range Tracking, Test Amplifier		0.2
Amplifier Relative Frequency Response		0.1
Amplifier Gain Stability, Source Capacity, etc.		0.2
Environmental Effects on Accelerometers, Transverse Sensitivity, Strain, Temperature, etc.		0.5*
Environmental Effects on Amplifiers, Residual Noise, etc.		0.2**
Estimated Error - 100 Hz		1.0***
Estimated Error - 5 to 900 Hz		1.5***
Estimated Error - 900 to 10,000 Hz+		2.5***

* The error varies from 0% to 0.5% for most accelerometers operated under controlled laboratory conditions.

** Applies for controlled laboratory conditions.

***Determined from the root-mean square of the applicable individual errors.

\+ Highest frequency is 5000 Hz for test accelerometers with a total mass exceeding 35 grams.

VIBRATION EXCITER REQUIREMENTS

The vibration exciter is used at frequencies at which the motion is sinusoidal. The distortion in the motion can be measured by connecting a distortion meter or harmonic analyzer to the output of the accelerometer standard at the amplifier output. The vibration exciter should be used for comparison calibrations only at frequencies at which the distortion is less than 5%. For reciprocity calibrations, the distortion should be less than about 1%. There are two typical causes for excessive distortion in the acceleration wave form. Distortion occurs at frequencies below the rigid body resonance of the shaker. This resonance is determined by the moving element acting as a rigid mass and the support system attaching the moving element to the exciter acting like a massless spring. The vibration exciter also produces distortion at frequencies which are sub-harmonic to the axial elastic body resonances of the moving element. For example, if the moving element has a resonance at 4500 Hz, distortion should be expected at 900 Hz and 1500 Hz. This happens because the power amplifier used with the vibration exciter produces significant third and fifth harmonic distortions and the magnification factor of the moving element at resonance can be as high as 50 or 100. For this reason, it is good practice to operate the power amplifier at a fraction of its rated power and avoid exciting resonances in the exciter.

Vibration exciters should not be used at frequencies at which excessive transverse motion is present. The transverse motion of the exciter can be measured by using a triaxial accelerometer. The output of the three accelerometers is measured throughout the operating frequency range. Care is taken to identify all resonant peaks as indicated by the outputs of the two transverse accelerometers divided by the output of the axial accelerometer. The exciter should be used only at frequencies at which the transverse motion is less than 25%. At these frequencies, accurate calibrations can be performed even if the maximum transverse sensitivity of the standard and test accelerometers is as large as about 3%. This happens because it is probable that the direction of maximum transverse sensitivity[7] does not coincide with the direction of transverse motion. Accordingly, the errors due to transverse sensitivity are usually insignificant.

SUMMARY

Absolute calibration methods are used in primary calibration laboratories for determining the sensitivity of vibration standards. The error in the sensitivity of the accelerometer standard calibrated by the reciprocity method is 0.5%. Once the standard is calibrated by the reciprocity method, it is sent to any calibration laboratory for the purposes of performing routine comparison calibrations on other vibration transducers. The accelerometer vibration standard described is suitable for performing these comparison calibrations at

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[7] Bouche, R. R., Ensuring the Accuracy of Shock and Vibration Measurements, Institute of Evironmental Sciences Proceedings, 1965, pp. 409-415.

SUMMARY (continued)

frequencies between 5 Hz and 10,000 Hz. The estimated error in the sensitivity of accelerometers calibrated by the comparison method at 100 Hz is 1%. The error is somewhat larger at other frequencies. The maximum error is 2.5% which occurs at 10,000 Hz.

ACKNOWLEDGMENT

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