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Vibration Standards for Performing Comparison Calibrations

Technical Paper 241

By Dr. R. R. Bouche

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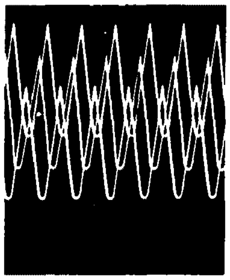

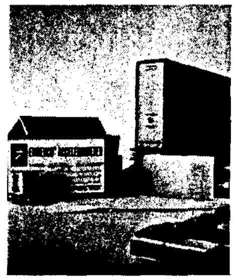

TP 241

VIBRATION STANDARDS FOR PERFORMING COMPARISON CALIBRATIONS

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ABSTRACT

Early vibration standards used a velocity coil. The absolute reciprocity calibration showed that these standards have excessive relative motion. Improved accelerometer standards have less relative motion as determined from comparison calibrations.

REVIEW OF VIBRATION STANDARDS

The velocity vibration standard consisted of a coil built into an electrodynamic shaker. The coil was located at a point about two inches beneath the mounting table of the shaker. The standard was used to perform comparison calibrations on test accelerometers and other vibration transducers. These transducers were attached to the mounting table on the shaker and accurate calibrations were performed up to 2000 Hz. The sensitivity of the test transducer was obtained by comparing its output to the output of the velocity vibration standard.

The vibration standard was calibrated by the reciprocity method prior to using it for comparison calibrations on test transducers. A significant advantage of this calibration method was that it experimentally determined sensitivity changes and the amount of relative motion present at high frequencies. The calibrations showed that the sensitivity of the velocity vibration standard changed at frequencies above 1000 Hz(1). The sensitivity was reduced approximately 25 percent at 5000 Hz for an attached mass of 0.5 lb. This sensitivity change was excessive and the velocity vibration standard could be used for comparison calibrations only up to 2000 Hz. The sensitivity change is due to relative motion between the standard and the base of the test transducer on the mounting table. The relative motion present increases depending upon the total mass attached to the mounting table. In order to minimize relative motion errors at high frequencies, it is necessary to avoid the use of external fixtures to attach test transducers.

Definition of Sensitivity

The sensitivity of a vibration standard is defined as the ratio of its electrical output divided by the motion at the mounting surface of the test transducer. This definition of sensitivity takes into account the relative motion between the vibration standard and the surface of the mounting table to which test transducers are attached. It should be expected that relative motion and sensitivity changes will be present in all vibration standards at high frequencies. The amount of sensitivity change will depend upon the type of sensing element used in the standard and on the materials and dimensions used between the standard and surface to which test transducers are attached. The changes in sensitivity are reduced if small devices such as piezoelectric accelerometers are used as standards and if stiff materials and small dimensions are used in designing the standard.

Early Calibrations on Accelerometer Vibration Standards

The early calibrations on accelerometer type vibration standards were performed by the reciprocity method. One of the advantages of the reciprocity calibrations is that the procedure of attaching masses detects sensitivity changes which usually are not observed by other methods employed to calibrate vibration standards. These sensitivity changes occur at all frequencies due to strain effects and, as mentioned above, occur at high frequencies due to relative motion. The procedures for reciprocity calibrations on accelerometer type(2) standards are nearly the same as the reciprocity procedure for velocity type vibration standards(1).

The results of these calibrations on various standards are shown in Table 1. The numerous calibrations on the velocity standard were helpful in establishing confidence in the accuracy of the other standards as indicated by the standard deviations in Table 1. The various

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piezoelectric vibration standards were based upon designs of piezoelectric accelerometers in common use. Modifications were made in these accelerometers in order to improve their strain characteristics so that the sensitivity of the standard could be determined with errors less than 0.5 percent. Furthermore, the reciprocity calibrations demonstrate that the sensitivity of the standard will remain unchanged when using the standard for comparison calibrations on test accelerometers. The sensitivity of the piezoelectric vibration standard is adjusted to a multiple of 10 as indicated in Table 1. These sensitivities make it convenient to perform comparison calibrations on test transducers. The sensitivity is adjusted by changing the gain or input circuitry of the charge amplifier used with the vibration standard. Charge amplifiers are superior to voltage amplifiers because they are unaffected by changes in input capacitance and have excellent gain stability and other desirable characteristics. The complete vibration standard consists of a system including the piezoelectric accelerometer standard and a charge amplifier.

The history of the development of piezoelectric vibration standards, listed in Table 1, reflects a tremendous improvement from the original velocity vibration standard. The piezoelectric vibration standards are much smaller in size and the sensitivity changes due to relative motion at high frequencies should be much less than indicated in reference (1) for the velocity vibration standard. Most of the standards in Table 1 are intended for use in back-to-back fixtures or are permanently mounted in a shaker beneath the mounting table. In the case of the Model 2270, the piezoelectric standard is built permanently into a fixture to permit easy use on various shakers and facilitate return to primary calibration laboratories for periodic recalibration.

IMPROVED VIBRATION STANDARDS

An improved piezoelectric vibration standard is illustrated in Figure 1 and described in reference [3]. The vibration standard consists of a fixture with a built-in piezoelectric accelerometer. The standard is constructed with stiff materials and has small dimensions to minimize relative motion effects and sensitivity changes at high frequencies. The mounting surface of the standard contains a 1/4 - 28 threaded hole that is 1/2 inch deep. These dimensions permit the use of internal adapter studs to permit attaching test accelerometers flush with the mounting surface on the standard for all screw sizes in common use. With this flush mounting, additional errors are avoided which would otherwise be present if external fixtures were used between the vibration standard and test accelerometer mounting surfaces.

The standard must be calibrated to determine the sensitivity applicable at all frequencies up to 10,000 Hz for attached masses up to 100 grams, which correspond to the mass of various test accelerometers. These calibrations are done prior to using the standard to perform routine comparison calibrations on the test accelerometers. The calibrations are repeated at yearly intervals or more frequently if it is desired to establish a calibration history on the standard.

Reciprocity Calibration of Standard

The piezoelectric vibration standard is calibrated by the reciprocity method at 100 Hz. The calibration is performed with a charge amplifier which is adjusted to provide a system sensitivity of exactly 1000 mV/g. The sensitivity determined at 100 Hz can be used at all frequencies up to 10,000 Hz. However, correction factors are used between 5000 Hz and 10,000 Hz to account for changes due to relative motion.

Comparison Calibrations on the Standard

Comparison calibrations are performed on the piezoelectric vibration standard at high frequencies to determine sensitivity changes. These comparison calibrations are performed with several reference accelerometers having masses up to 100 grams. The frequency response of each reference accelerometer is previously determined by performing comparison calibrations traceable to the National Bureau of Standards. The results of these comparison calibrations are shown in Figure 2. These results show that the sensitivity changes at high frequencies for the piezoelectric standard are much less than the changes in the velocity standard[1]. The sensitivity changes near and above 5000 Hz in Figure 2 are used to apply correction factors when performing comparison calibrations on test accelerometers at high frequencies.

Error Analysis on the Standard

In order to use a vibration standard accurately, it is necessary to perform an analysis to establish the errors present in the sensitivity of the standard[3]. This analysis is given in Table 2. The errors for the reciprocity calibration are applicable at 100 Hz. The comparison calibration errors apply throughout the operating range from 5 Hz to 10,000 Hz. The analysis includes all error sources in the piezoelectric standard and its associated charge amplifier. These errors include accelerometer effects such as transverse sensitivity, strain sensitivity and temperature response of the standard. The error of 0.2 percent for these effects is achievable as a result of the mechanical design of the standard and by taking care to select the piezoelectric material that has the best characteristics for use in a standard. Similarly, the amplifier is carefully designed to minimize errors due to range tracking, gain stability and other effects. The comparison calibration errors include errors stated by the National Bureau of Standards for the calibration of the reference accelerometers used to determine sensitivity changes in the piezoelectric standard at high frequencies.

ROUTINE COMPARISON CALIBRATIONS

Comparison Calibration Procedure

Comparison calibrations are performed by attaching both the test accelerometer and standard to a sinusoidal motion shaker, as indicated in Figure 3. The charge amplifiers are shown; one for the standard and the other used with the test accelerometer mounted on top of the standard. The ratio of the test output to the standard output is measured throughout the operating frequency range of the test accelerometer. The sensitivity of the test accelerometer is given by the following equation.

$$S_t = S_s \, R \, F_c$$

where S_t = Sensitivity of the test accelerometer

S_s = Sensitivity of the vibration standard

R = Ratio of test accelerometer to standard outputs

F_c = Correction factor for sensitivity changes in the standard at high frequencies.

The sensitivity of the vibration standard is 1000 mV/g which is previously determined by the reciprocity calibration described above. Additional standard sensitivities of 100 mV/g, 10 mV/g, etc., are obtained by adjusting the control knob on the standard amplifier. Similarly, ranges in multiples of 10 are provided on the test amplifier so that the sensitivity of the test accelerometer is indicated in pC/g directly by the value of the ratio R. The correction factor F_c is obtained from Figure 2 and is used only at high frequencies where relative motion occurs. Typical comparison calibrations performed by this procedure on three different piezoelectric test accelerometers are shown in Figure 4.

Errors in Test Accelerometer Sensitivity

The probable error in each of the calibration points illustrated in Figure 4 is determined by performing an analysis which includes all error sources in the vibration standard, in the test accelerometer, in the charge amplifiers and read-out instruments used to measure the ratio of the test transducer output and standard output. The analysis of these errors is given in Table 3. The error in the reciprocity calibration performed previously on the standard is 0.5 percent. Also, 0.5 percent is allowed for the stability of the standard to account for possible sensitivity changes since the last reciprocity calibration. The estimated error in the charge sensitivity of the test accelerometer at 100 Hz is ± 1 percent. The errors at other frequencies include errors for the frequency response calibration of the vibration standard and also errors in making corrections for relative motion at high frequencies when using the curves in Figure 2. The errors in Table 1 apply when using accurate read-out instruments such as a voltage divider and vacuum tube voltmeter.

SUMMARY

The reciprocity calibrations on the velocity vibration standard indicate that the changes in sensitivity of the standard are excessive at high frequencies. These changes occur because the velocity standard is built into the shaker and located some distance from the mounting table to which test transducers are attached. The velocity standard can be used to perform comparison calibrations on various test transducers but is limited to frequencies up to 2000 Hz.

Reciprocity calibrated accelerometer standards are also built in shakers and others are used in two-piece fixtures. The sensitivity changes due to relative motion at high frequencies are significantly less than those present in the velocity standard.

A recent design of an accelerometer vibration standard consists of the portable fixture with a built-in piezoelectric standard. This standard, previously calibrated by the reciprocity method, is used to perform comparison calibrations on various test accelerometers at frequencies up to 10,000 Hz. Only a small correction is required to account for sensitivity changes due to relative motion present above 5000 Hz. Good quality accelerometer standards are obtained by using care in the design of the standard and associated charge amplifiers to minimize all error sources as determined by performing careful evaluations and error analyses on their performance characteristics.

REFERENCES

(1) Levy, S. and Bouche, R.R., Calibration of Vibration Pickups by the Reciprocity Method, Journal of Research of the National Bureau of Standards, 57, 4, pp 227-243, 1956.

(2) Bouche, R.R., and Ensor, L.C., Use of Reciprocity Calibration Standards for Performing Routine Laboratory Comparison Calibrations, Shock, Vibration and Associated Environments, Bulletin No. 34, Part IV, Dept. of Defense, pp 21-29, Feb. 1965.

(3) Bouche, R.R., Accurate Accelerometer Calibrations by Absolute and Comparison Methods, Society of Environmental Engineers Publications (London), vol 2, April 1966.

TABLE 1

SUMMARY OF RECIPROCITY CALIBRATION RESULTS ON VIBRATION STANDARDS

Type of Standard	Calibration History, years	Number of Reciprocity Calibrations	Average Sensitivity*	Standard Deviation, percent
Velocity #1	3	10	99.8	0.5
Accelerometer P6SP31#1	1	4	100.2	0.4
Accelerometer P6SP31#2	1	2	99.9	0.1
Accelerometer P10SP46#3	4	8	10.00	0.4
Accelerometer P10SP46#4	4	6	9.98	0.5
Accelerometer P10SP31#5	2	7	101.0	0.8
Accelerometer P10SP46#10	2	2	10.01**	0.0
Accelerometer P10SP46#11	2	2	10.05	0.0
Accelerometer P10SP46#12	2	2	10.04	0.3
Accelerometer P10SP46#14	2	3	9.97	0.2
Accelerometer 2270/NA09	1	11	1001	0.3
Accelerometer 2270/NA21	1	2	1000	0.0
Accelerometer 2270/MA01	1	2	1000	0.2

* Units are pC/g or mV/g; for the electrodynamic velocity standard the units are applicable at 50 Hz only.

** Standard #10 was also calibrated at NBS; 10.02 mV/g was the average sensitivity reported up to 4 kHz with a standard deviation of 0.5 percent.

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 percent	Measurement	Error percent
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
Estimated Error, at 100 Hz	0.5**	Voltage Ratio	0.2
		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 square root of the sum of the squares of the applicable individual errors.

TABLE 3

ANALYSIS OF ERRORS IN THE SENSITIVITY OF TEST ACCELEROMETERS
CALIBRATED BY THE COMPARISON METHOD

Measurement	Sensitivity Error Percent
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, 2000 - 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 Amplifier, 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 is less than 0.5% for most accelerometers operated under controlled laboratory conditions.

** Applies for controlled laboratory conditions.

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

\+ Highest frequency is 5000 Hz for test accelerometers with a total mass exceeding 50 grams.

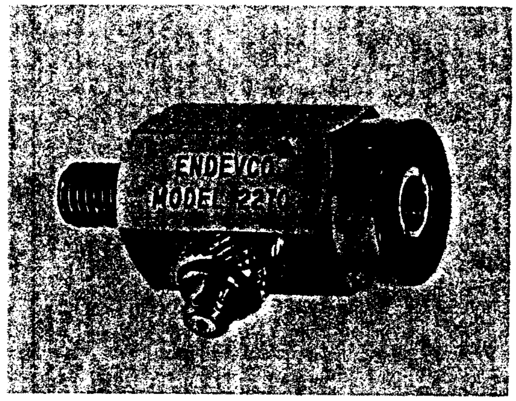


Figure 1 - Reciprocity calibrated vibration standard is used to perform routine comparison calibrations on various test accelerometers.

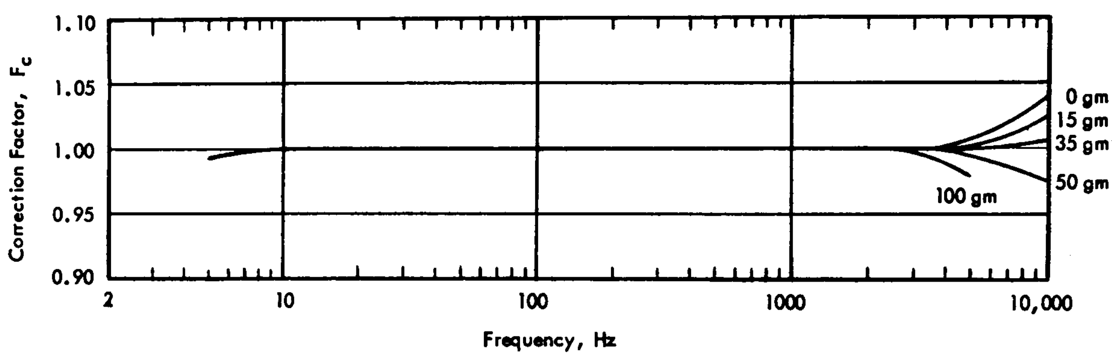


Figure 2 - Calibrations performed on piezoelectric vibration standard show nearly constant sensitivity up to 5000 Hz. Nominal sensitivity changes due to relative motion at higher frequencies are dependent on the mass of the test accelerometer as indicated.

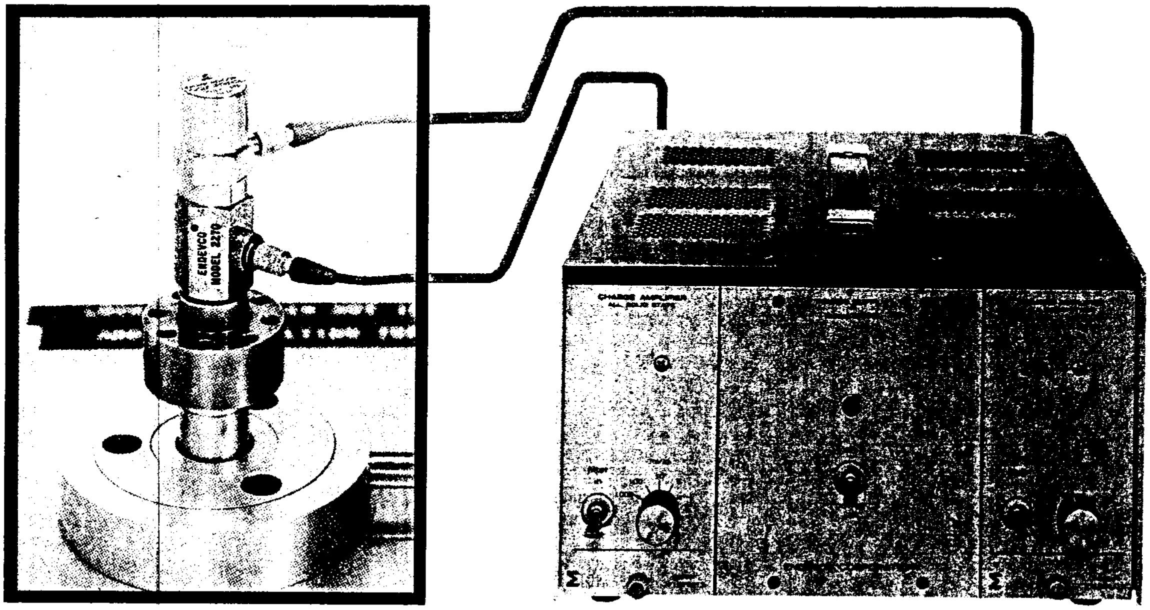


Figure 3 - Comparison calibrations are performed with the test accelerometer and piezoelectric vibration standard mounted on a shaker. Amplifiers are provided to permit direct reading of the test accelerometer sensitivity in units of pC/g.

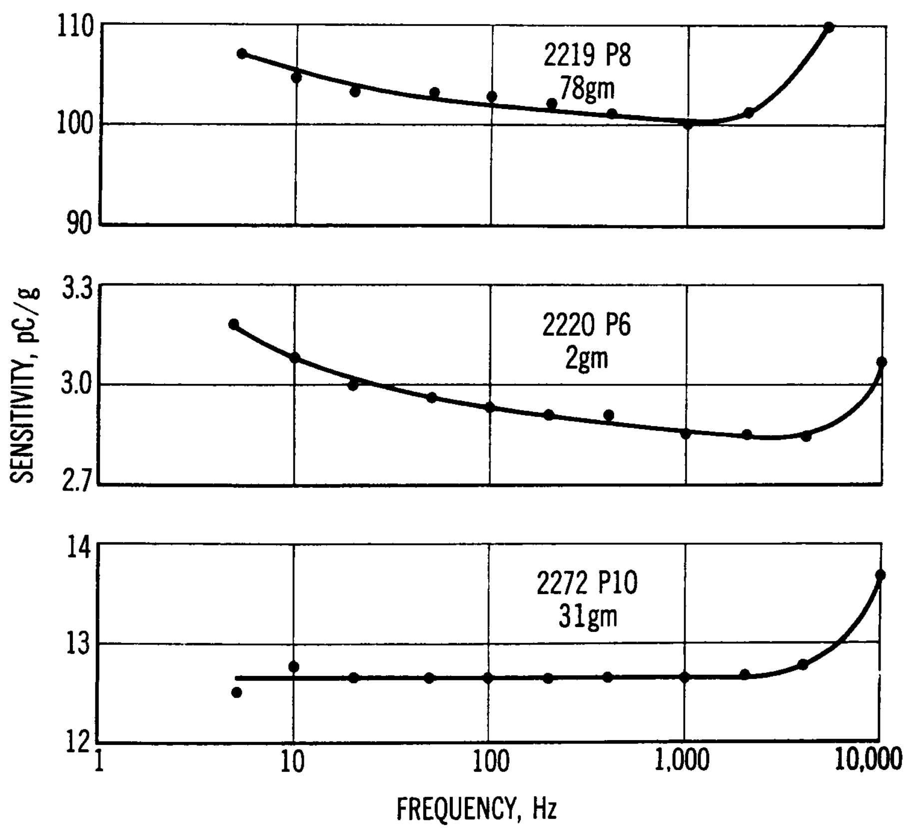
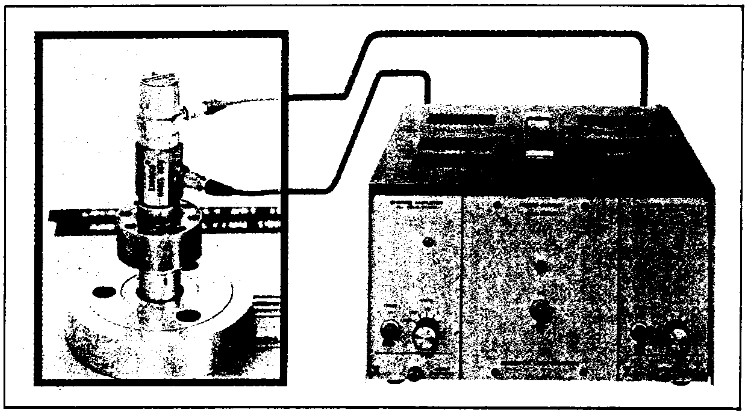
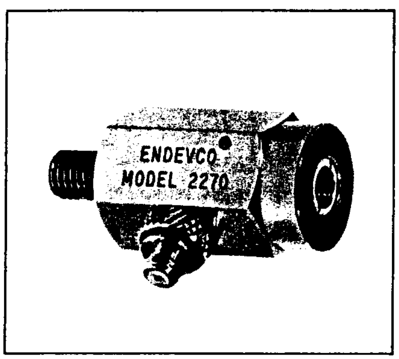


Figure 4 - Comparison calibration results on three accelerometers using the setup shown in Figure 3.

ENDEVCO PRODUCTS RELATED TO THIS ARTICLE



Model 28350F
Reciprocity Calibration Systems
Designed for use as a primary standard, traceable to NBS, the Model 28350F includes a Model 2270 Primary Standard Accelerometer, a Model 2710FM13 Standard Amplifier, a Model 2710FM14 Test Accelerometer Amplifier, and a Model 2629B Portable Power Supply. The system is supplied with an absolute reciprocity calibration at 100 Hz (sensitivity error less than ±0.5%), and a frequency response calibration from 5 Hz to 10,000 Hz.



Model 2270
Primary Standard Accelerometer
The Model 2270 Accelerometer Standard is a combination accelerometer and calibration fixture for performing comparison calibration on other accelerometers. Extremely high stability is achieved by use of Piezite® Type P-10 crystal element. When calibrated by the reciprocity method, an absolute calibration, the error in sensitivity of the Model 2270 is ±0.5% at 100 Hz. Adapters provide for mounting test accelerometers with a variety of stud sizes. Calibration ranges are 5 Hz to 10,000 Hz and 0.2 g to 10,000 g.

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