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A PRACTICAL APPLICATION OF ACCELEROMETER CALIBRATIONS

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Recent advances in calibration techniques and instrumentation now make it possible to perform complete calibrations on accelerometers. High frequency shakers which are virtually free of distortion and transverse motion are used to perform calibrations depicting the true performance of accelerometers. A recently published standard is most useful as a guideline in performing calibrations. This standard describes which calibrations need to be performed and how to use the results. The sensitivity, frequency response, and resonance frequency are the most important calibrations.

The sensitivity calibration is performed at 100 Hz on accelerometers intended for ordinary use in shock and vibration measurements. However, it is also important to obtain a continuous plot of frequency response and resonance frequencies to detect any undesirable characteristics and unwanted resonances in the accelerometer. Good performance is indicated by a calibration which demonstrates that the accelerometer operates as a single-degree-of-freedom mechanical system. Some accelerometers have irregular frequency response characteristics and possess several resonances. By performing these calibrations the accelerometers with marginal performance are detected and judgments can be made regarding possible effects when making shock and vibration measurements.

Another use of resonance frequency calibrations is to detect damaged accelerometers. It is practical to cull out these accelerometers before any serious problems are encountered in their use.

INTRODUCTION

The recently published American National Standard for the Selection of Calibrations and Tests for Electrical Transducers Used for Measuring Shock and Vibration, S2.11-1969 [1], is useful for determining which calibrations to perform and how to put calibration results to practical use. Many of the calibrations and tests specified in S2.11-1969 are used to verify the performance characteristics of accelerometers. Some of these calibrations and tests are performed at the time of design and manufacture and need not be repeated thereafter. Other calibrations should be performed at time intervals ranging from three months to one year, depending upon usage. These important calibrations include sensitivity, frequency response, and resonance frequency. The sensitivity calibration must be performed in order to use the accelerometer accurately. The frequency response calibration is useful for detecting unusual performance characteristics and the resonance frequency calibration is the most accurate means for determining the operating condition of accelerometers.

SENSITIVITY AND FREQUENCY RESPONSE

Primary accelerometer standards previously calibrated by the reciprocity method and recently developed shakers are required for performing accurate sensitivity and frequency response calibrations routinely. With these instruments it is practical to detect unusual performance characteristics. The use of inferior accelerometer standards and shakers makes it difficult to determine whether unusual results are a characteristic of the accelerometer or are errors caused by the instruments on which the calibration is being performed.

Accelerometer Standard

In order to establish the performance characteristics of accelerometer standards, it is necessary to perform the calibrations and tests listed in S2.11-1969. These calibrations and tests determine that the standard will perform accurately under all conditions of use. The performance characteristics of an accelerometer standard now in use in many laboratories are listed in Table 1. This standard is used

TABLE 1

SHOCK AND VIBRATION STANDARD ENDEVCO® MODEL 2270

Performance Characteristic	Specification
Sensitivity Error	±0.5 per cent
Sensitivity Stability at 100 Hz	±0.5 per cent/year
Mass Effect on Sensitivity at 100 Hz	±0.2 per cent/100 grams
Frequency Response and Relative Motion	
Sensitivity Change, 5 Hz - 5000 Hz with up to 100 grams attached mass	-2 per cent*
Sensitivity Change, 5 Hz - 10,000 Hz with up to 50 grams attached mass	±4 per cent*
Amplitude Linearity Sensitivity Change	+0.1 per cent/1000 g
Transverse Sensitivity Ratio	±3 per cent
Temperature Response Charge Sensitivity	±0.5 per cent/10° C
Strain Sensitivity	0.001 g/μ in/in

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

for both shock motion and vibration calibrations. It is necessary for an accelerometer standard to have low strain sensitivity and certain other characteristics in order to perform accurate calibrations on the standard and demonstrate that the sensitivity of the standard remains unchanged for long periods of time [2]. These high quality standards are calibrated by the reciprocity method. This absolute calibration method has a unique advantage in establishing the sensitivity of the standard with an error not exceeding ±0.5 per cent. First of all the standard must possess good performance characteristics to make small errors achievable and the reciprocity method must be used to obtain small errors. Consequently, the use of the reciprocity method helps to establish that the standard possesses good performance characteristics and, therefore, can be used to accurately calibrate other accelerometers.

Sensitivity Calibrations

The sensitivity calibration of most accelerometers is usually performed at 100 Hz. This calibration is very important because it is impossible to use an accelerometer accurately without it. The sensitivity calibration is performed routinely at periodic intervals as specified in S2.11-1969. The calibration result is used to determine the required gain setting on accessory amplifiers and to compute the accelerations being measured during test applications. The sensitivity calibration basically serves this sole purpose. It is not very useful for determining other characteristics or the operating condition of accelerometers.

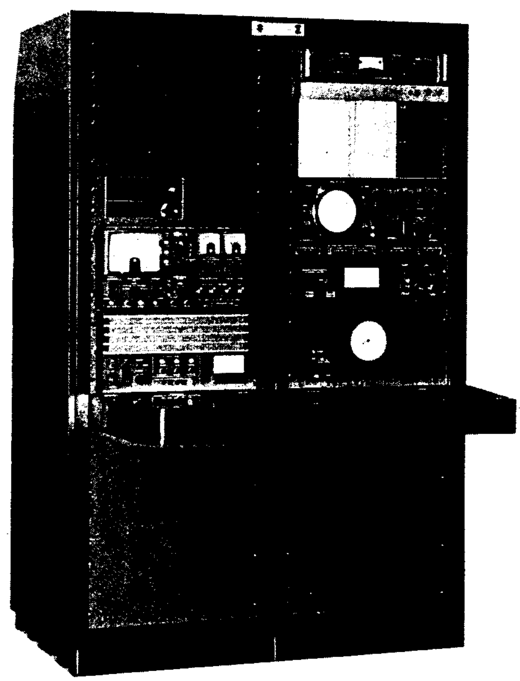

Fig. 1 - High frequency shaker and instrumentation used for automatically plotting the frequency response and resonance frequencies of accelerometers

Shaker Requirements

Almost any shaker can be used to perform accurate sensitivity calibrations on most accelerometers at a single frequency. However, it is important to perform a frequency response calibration throughout the range of intended use. Accurate frequency response calibrations can only be performed on shakers having low acceleration distortion, and little transverse motion, Fig. 1. If the shaker used does not have these characteristics, it is necessary to previously determine the frequencies of excessive distortion and transverse motions and avoid these frequencies during the calibration. Since improved shakers have been developed [3, 4], it is good practice to avoid the use of other shakers. The use of good shakers is necessary to determine the true performance of accelerometers such as detecting abnormalities in frequency response.

Frequency Response Calibrations

Frequency response calibrations serve two useful purposes. One is to establish the operating frequency range. The second and perhaps more important practical use of frequency response calibration is to determine that the accelerometer is free from abnormal response. Does the accelerometer have erratic response at any frequency within the operating range? This question is answered through the use of calibration shakers having the above mentioned characteristics. Normally, the frequency response of accelerometers is as shown in Fig. 2. Most of the accelerometers calibrated have the characteristic of no minor resonances and increasing sensitivity at the high frequencies. However, there are a number of accelerometers which have responses similar to those given in Fig. 3. The irregular response in Fig. 3(a) is due to the performance characteristics of this particular accelerometer. The minor resonance at 7300 Hz may be due to a resonance in the accelerometer case. Another accelerometer, Fig. 3(b), has a minor resonance with unusually high sensitivity between 8000 Hz and 9400 Hz. Fig. 3(c) shows an erratic frequency response which sometimes occurs in accelerometers having very small size. The frequency response of an accelerometer having damaged mounting threads is shown in Fig. 3(d). These results are extreme examples of certain accelerometers.

It is important to know that the frequency response is normal throughout most, if not all, of the operating frequency range. The presence of large sensitivity changes in narrow frequency bands might be overlooked or mistakenly attributed to shaker characteristics if the calibration is performed on shakers having excessive transverse motion or acceleration distortion. It is also important to use standards having low relative motion [5] in order to be sure that unusual response at the higher frequencies is due to the accelerometer rather than being caused by excessive calibration error. In some test applications it may be important to avoid the use of accelerometers having poor frequency response such as those given in Fig. 3. It is easy to cull out these accelerometers when performing routine frequency response calibrations. Abnormal frequency response in accelerometers may be due to internal damage, internal lead wire resonances, connector resonances, accelerometer case resonances, cable effects, etc.

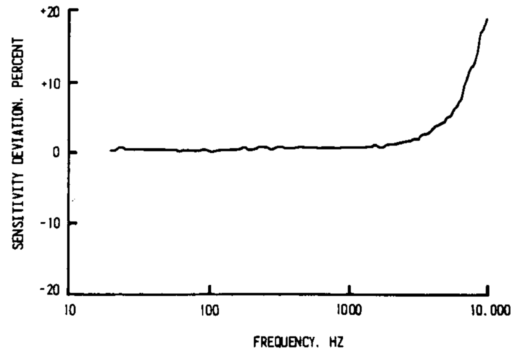

Fig. 2 - Frequency response calibration performed on an accelerometer having the characteristics of a single-degree-of-freedom mechanical system with no minor resonances

RESONANCE FREQUENCY CALIBRATIONS

Although sensitivity and frequency response calibrations are required for the accurate use of accelerometers, the plot of resonance frequencies is a very important and definitive calibration. The resonance frequency calibration is the only method for evaluating the basic performance characteristic of accelerometers and their operating condition. The resonance frequency calibration determines whether or not the accelerometer operates as a single-degree-of-freedom mechanical system. Perhaps even more important is its use for detecting internal damage. In order to perform resonance frequency calibrations it is necessary to use a high frequency shaker, Fig. 1, in which the resonance frequencies [1, 3] of the shaker moving element exceeds the resonance frequencies of the accelerometers being calibrated. The resonance frequency of most accelerometers is less than 50,000 Hz. However, some accelerometers used for shock measurements have their resonance frequency above 100,000 Hz. Even with these accelerometers it is useful to perform resonance frequency calibrations up to 50,000 Hz to detect any unusual performance characteristics at lower frequencies.

Ideal Accelerometers

Many accelerometers now being used operate as the ideal accelerometer shown in Fig. 4. It has a single resonance and few, if any, minor resonances. This ideal response is very similar to the theoretical response given in ANSI Standare S2.2-1959 [6]. It is good practice for the user to perform resonance frequency calibrations on accelerometers to establish their performance characteristics and to detect any changes in future years. This practice should be followed on accelerometers used for important and accurate measurements. The resonance frequency calibration should be repeated when there is evidence that the accelerometer was subjected to severe environments or rough handling. Although there may be no external indications, internal damage may occur.

Another reason for performing resonance frequency calibration is to determine if the response is like the ideal accelerometer. The use of accelerometers having a single resonance, Fig. 4, may be preferred for some applications where high accuracy and reliability are required. On the other hand accelerometers having multiple resonances, Fig. 5, are quite suitable for most applications and are used because of other desirable characteristics such as special size and shape.

Damaged Accelerometer

Although it is difficult to damage many piezoelectric accelerometers, the design of some accelerometers makes them vulnerable to extremely high shock motions. It is possible to apply high shock motions above the rated environmental limit by rough handling. Resonance frequency calibration is the most accurate method for determining accelerometer damage. Fig. 6(a) and 6(b) show the resonance frequency calibrations before and after an accelerometer was subjected to excessive shock motion. The resonance frequency of the accelerometer is decreased from 32,000 Hz to 29,500 Hz and a minor resonance is present at 9000 Hz, Fig. 6(b). The decrease in resonance frequency is a definite indication of internal damage. It is interesting to note that this is the same accelerometer used during the frequency response calibration in Fig. 3(b). On the basis of the frequency response calibration alone the minor resonance at 9000 Hz may have been overlooked

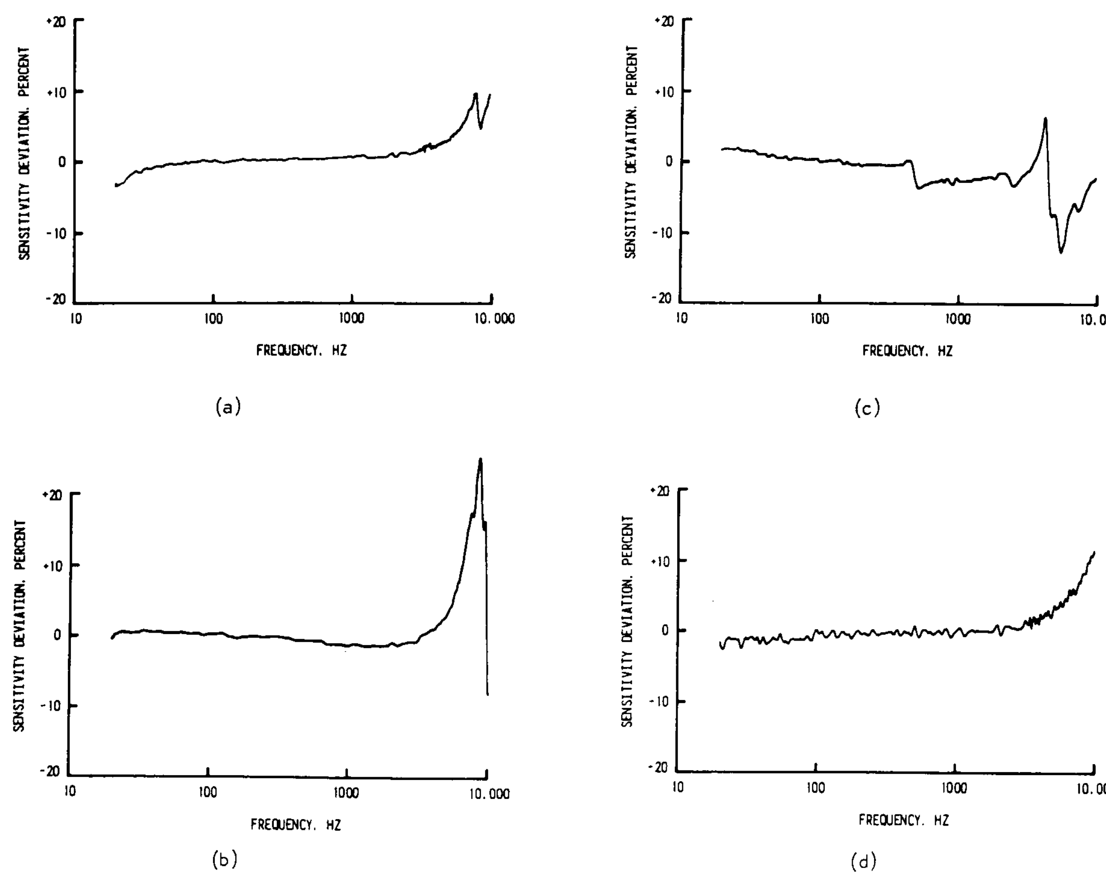

Fig. 3 - Frequency response calibrations performed on accelerometers having unusual characteristics

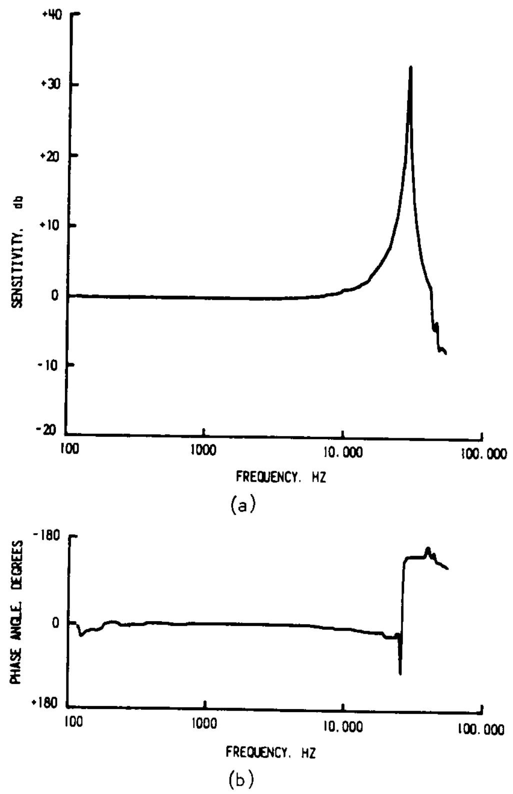

Fig. 4 - Typical resonance frequency calibration indicates performance characteristics of an ideal accelerometer. Phase angle calibration provides supplemental data at resonance

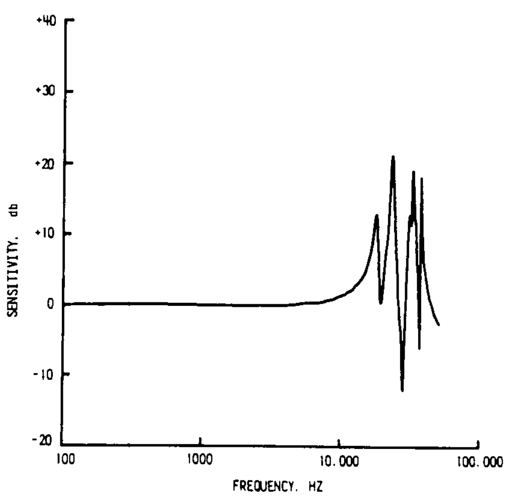

Fig. 5 - Calibration of an accelerometer having several resonances

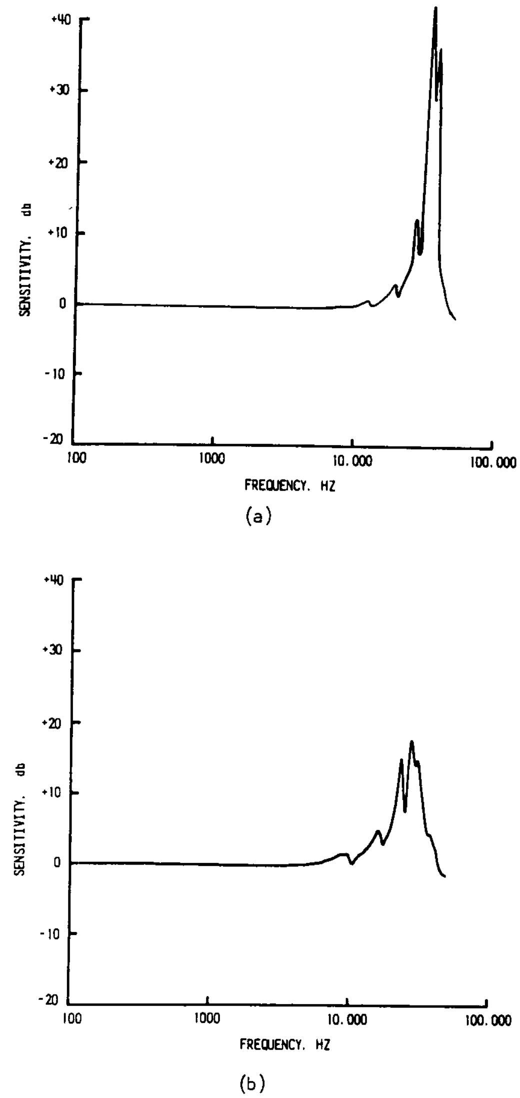

Fig. 6 - Calibrations performed on an accelerometer show a resonance frequency of (a) 32,000 Hz before damage and (b) 29,500 Hz after damage

because the response is acceptable at lower frequencies. However, the resonance frequency calibration in Fig. 6(b) establishes the fact that the accelerometer is damaged and probably should not be used in important tests.

It is becoming routine to perform resonance frequency calibrations as supplemental information during shock motion calibrations to detect any changes in the operating characteristics of the accelerometers. In most accelerometers no malfunction is detected. An exception to this is the accelerometer shown in Fig. 7. The result of the shock motion

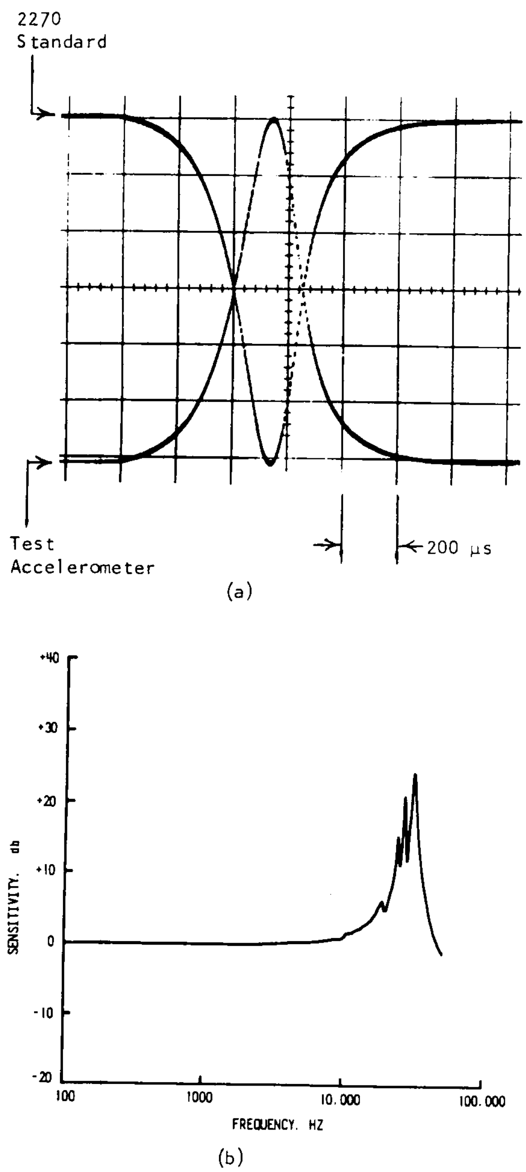

Fig. 7 - Calibrations performed on a damaged accelerometer show (a) normal response during 1000 g shock motion calibration and (b) unusually low resonance frequency which indicates the accelerometer has internal damage

calibration, Fig. 7(a), is perfectly normal. No unusual response is present in the oscillogram and the shock motion sensitivity agreed precisely with the sinusoidal calibration. However, the routine resonance frequency calibration, Fig. 7(b), shows multiple resonances and a resonance frequency of 28,500 Hz. The nominal resonance frequency of this accelerometer is 35,000 Hz. The low resonance frequency again is a definite indication of internal damage.

Failures in damaged accelerometers include such things as cracked piezoelectric elements and epoxy joints, plastic deformation in screws, defaced accelerometer mounting surface, deformed accelerometer case, etc.

Minor Resonances

Minor resonances detected during the frequency response calibration are the result of resonances in lead wires, accelerometer cases, etc. These resonances in some accelerometers occur at frequencies above 10,000 Hz which is the upper limit of most frequency response calibrations. The accelerometer in Fig. 8(a) has a minor resonance at 37,000 Hz. It is known that this is a minor resonance because the phase angle changes abruptly to 100 degrees at the resonance and returns to zero degrees above the resonance, and because the sensitivity changes only 20 db. Although this accelerometer is usually used for shock motion measurements, the presence of the minor resonance should have little effect in many test applications. However, it is desirable to be aware of the local resonance during the selection of accelerometers particularly in those instances where very high frequency characteristics are measured [7]. The calibration in Fig. 9 shows the response of a shock accelerometer having no minor resonances up to 50,000 Hz.

Accelerometer Effects on Structures

It is desirable to have resonance frequency data on accelerometers when considering the possible effects of the accelerometer on the motion of the structure. Neglecting the effects of rotary inertia, the motion of the sturcture with the accelerometer attached is given by the following equation: [1]

$$A = \frac{A_o M_s}{M_s + M_t}$$

where: A = amplitude of motion of the structure with accelerometer attached

A_o = amplitude of motion without accelerometer attached

M_s = point dynamic mass of the structure at the accelerometer mounting location in the sensitive direction of the accelerometer

M_t = dynamic mass of the accelerometer in its sensitive direction

The dynamic mass of the accelerometer at all frequencies below the lowest resonance is equal to the total mass of the accelerometer measured statically. However, it should be expected that the dynamic mass of the accel-

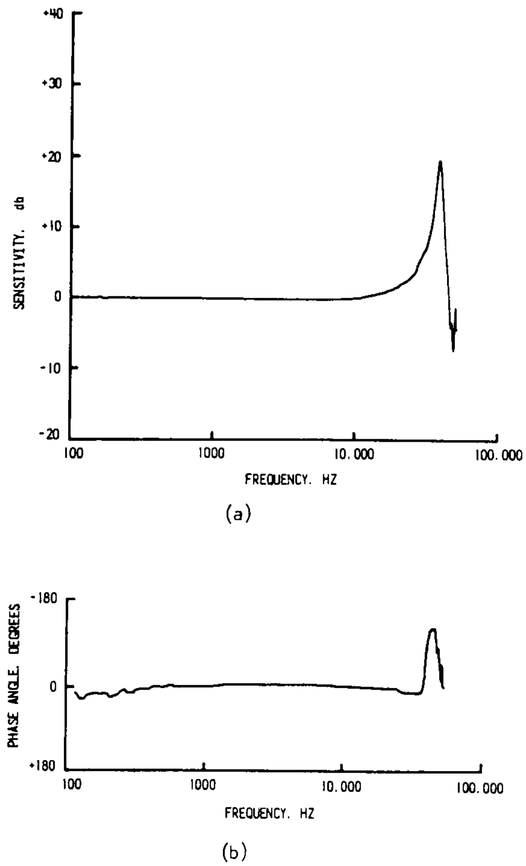

Fig. 8 - Calibration of shock motion accelerometer having a minor resonance below 50,000 Hz

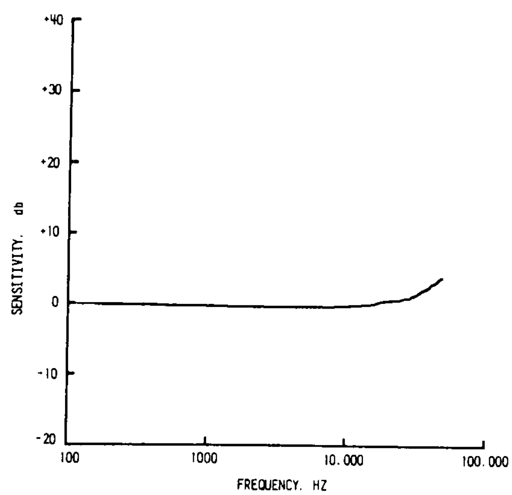

Fig. 9 - Calibration of shock motion accelerometer having no resonances below 50,000 Hz

erometer changes significantly at minor resonances particularly if the response has a rather large sensitivity change at the resonance [8]. The largest changes in dynamic mass should occur at the accelerometer resonance frequency. It is usually difficult to compute the change in response of the structure as a result of resonances in the accelerometer. However, a reasonable prediction of the effect can be obtained through the use of the above equation by knowing the resonance frequency of the accelerometer and the characteristics of the structure being tested.

Accelerometers With Damping

A resonance frequency calibration on a piezoresistive accelerometer with oil damping is shown in Fig. 10. During manufacture the damping is adjusted to approximately 0.7 of critical damping in order to assure that complex vibration and shock motions are measured

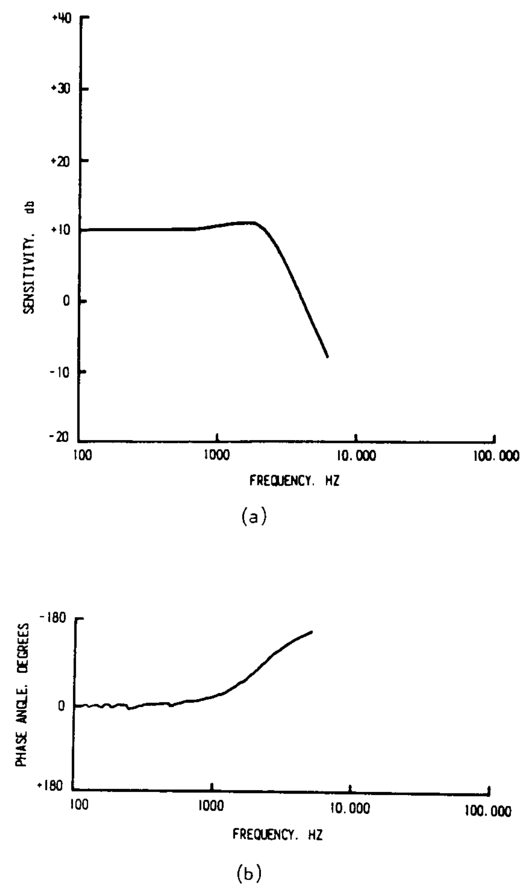

Fig. 10 - Frequency response calibration on a piezoresistive accelerometer using internal damping to produce proportionate phase response

accurately. In order to avoid distortion in the accelerometer output it is necessary for the phase angle to vary linearly with frequency which is indicated in Fig. 10 by taking into account the use of the logarithmic frequency scale. The waveform of the accelerometer output is identical to the waveform of the measured acceleration only when the phase angle response has this characteristic or is zero degrees as in the case of undamped accelerometers. The accelerometer is selected so that proportionate phase response is maintained at all significant frequency components of the motion to be measured. This usually requires that the proportionate phase response be maintained at frequencies up to about two-thirds of the natural frequency for damped accelerometers. Damped accelerometers are preferred in applications where it is desirable to filter out frequencies present near and above the natural frequency or resonance frequency of the accelerometer. However, if the damping changes significantly for any reason, the output will be distorted when the damping exceeds the range of about 0.5 to 0.85 of critical damping. Large changes in damping can occur at temperature extremes due to viscosity changes in oil damped accelerometers. It is important that no large changes in damping occur for unknown reasons, such as might be caused by damage or air leaks. Resonance frequency calibrations performed periodically should be useful for detecting changes in damping by comparing the response to that of an ideal accelerometer [6].

SUMMARY

With the introduction of new testing procedures using primary accelerometer standards and high frequency shakers, routine resonance frequency calibrations are performed in addition to sensitivity and frequency response calibrations. The sensitivity is obtained merely to determine the calibration factor for using the accelerometer in making shock and vibration measurements. The frequency response calibration determines the operating frequency range and is useful for evaluating certain performance characteristics.

The resonance frequency calibration is used to determine how closely the accelerometer operates as a single-degree-of-freedom system. It also identifies minor resonances which may affect the accuracy while making shock and vibration measurements at high frequencies. A very important use of the resonance frequency calibration is to detect changes in the accelerometer's operating condition and determine whether or not the accelerometer has suffered any internal damage. Resonance frequency calibrations should be used in laboratories responsible for verifying the operating condition of measuring instruments.

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Mr. Schell (Shock and Vibration Information Center): I noticed on a curve that the resonant frequency had shifted from about 35 down to 28 KHz., yet the calibration curve still looked pretty good. Is this still a useful accelerometer or is it damaged beyond use?

Mr. Bouche: It is still a very useful accelerometer. However, it is desirable to be aware of this situation since once an accelerometer is damaged, it can be further damaged more easily. It might have, for example, cracked ceramics inside the accelerometer. If you are aware that you have a damaged accelerometer, for important tests you might set that one aside. However, as long as it is not damaged further it will operate just as indicated by that response curve.

Mr. Peete (Naval Undersea R and D Center): After first determining the resonant frequency response of a given accelerometer dynamically under shock, does the effect of the sweep rate when applying a vibratory input signal cause any variation on the sensitivity when determining the resonant frequency under vibration?

Mr. Bouche: I think that you are asking whether the magnification factor might be affected by the rate of sweep when measuring the resonant frequency. It is. Frequently, when going up to 10 or 15 KHz, we slow down the sweep speed as we approach resonance.

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