
A New Solution for Shock and Vibration Calibration of Accelerometers

Marco Peres
The Modal Shop, Inc.

Robert D. Sill
PCB Piezotronics Inc.

Shock and vibration phenomena are present around us in everything that moves. The accelerometer is a class of instruments commonly used to measure that motion, producing an electrical output signal related to the applied motion. Accurate accelerometer calibration is a way to provide physical meaning to this electrical output and it is a prerequisite for quality motion measurements. Systems and standards on comparison methods for accelerometer calibration are discussed, providing an overview on current technology available for calibrating and testing accelerometer performance characteristics.

Introduction

The manufacturer of an accelerometer subjects the design to a wide variety of tests to determine output due to a large number of inputs. Output characteristics commonly measured include sensitivity, frequency and phase response, resonant frequency, amplitude linearity, transverse sensitivity, temperature response, time constant, capacitance, and environmental effects such as temperature response, base strain sensitivity, magnetic sensitivity, etc.

Often, when we talk about accelerometer calibration we are referring essentially to the measurement of sensitivity. The most common way to calibrate accelerometer sensitivity is by comparison to a reference transducer, generally another accelerometer designed to have stable low noise sensitivity in the conditions of calibration. Comparison methods are performed by back-to-back measurements. The sensor under test (SUT) is mounted in a back-to-back arrangement against a reference accelerometer and both sensors are subject to a common mechanical excitation. Since the motion input is the same for both devices, the ratio of their outputs is also the ratio of their sensitivities and the sensitivity can be expressed by the following equation:

$$S_{\text{sut}} = S_{\text{ref}} \cdot (V_{\text{sut}} / V_{\text{ref}}) \cdot (G_{\text{ref}} / G_{\text{sut}})$$

where:

S_{sut} is the SUT sensitivity (in mV/G, mV/(m/s²); pC/G, or pC/(m/s²))

S_{ref} is the reference transducer sensitivity (in mV/G, mV/(m/s²); pC/G, or pC/(m/s²))

V_{sut} is the SUT channel output (in mV)

V_{ref} is the reference channel output (in mV)

G_{sut} is the SUT conditioner gain (in mV/mV or mV/pC)

G_{ref} is the reference conditioner gain (in mV/mV or mV/pC).

Two calibration methods are available depending on the nature of the excitation, periodic (vibration calibration) or transient (shock calibration), and are described by the ISO-16063 Part 21 [1] and Part 22 [2]. A well-designed implementation of an accelerometer calibration system should not only follow the general guidelines provided by these standards, but also look carefully into the design and performance of each component of the system measurement chain, including the shock and vibration exciters, reference transducers, signal conditioner, digital data acquisition and controlling software.

Accelerometer Vibration Sensitivity Calibration

Vibration calibration uses oscillatory (sinusoidal) excitation normally provided by an electromechanical exciter or shaker (Figure 1) and the procedure for measurement of accelerometer sensitivity is described by the ISO 16063-21, "Methods for the calibration of vibration and shock transducers — Part 21: Vibration calibration by comparison to a reference transducer" [1]. The shaker is driven by a sinusoidal vibration signal and the sensitivity of the SUT is measured at that particular frequency. Sweeping through the desired range of frequencies then generates a frequency response curve of the SUT (Figure 2), while changing the level of excitation at a certain frequency allows a linearity curve of the SUT to be measured.

Vibration Exciter

Electromechanical flexure-based exciters (shakers) are commonly used for routine calibration of accelerometers and often are the "weak link" when calibrating accelerometers. Shakers are structures and have modes of vibration, just like any machine. Undesired shaker characteristics, such as excessive transverse motion and waveform distortion will adversely influence the accelerometer's response, resulting in degraded calibration accuracy.

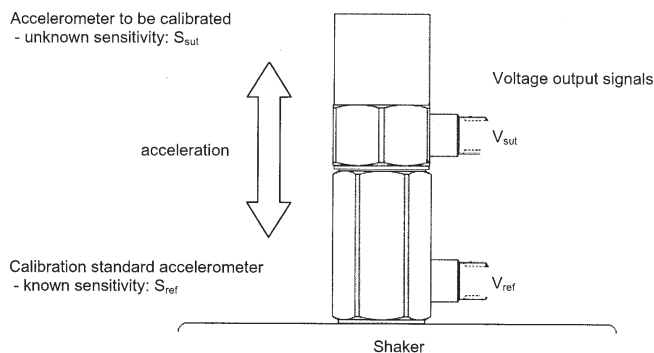


Figure 1. Back-to-back technique.

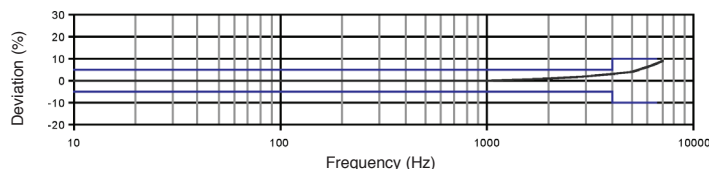


Figure 2. Typical frequency response of an accelerometer. Deviation values refer to calibrated sensitivity at the reference frequency (100Hz).

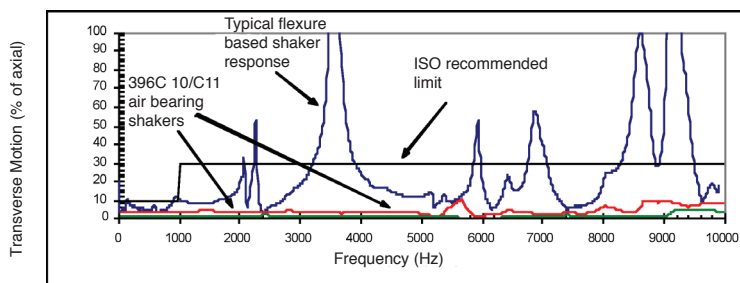


Figure 3. Transverse acceleration of a "50 lb shaker" compared to an air bearing shaker.

Transverse motion limits are required by the ISO 16063-21 to be less than 10% for frequencies below 1000Hz and less than 30% for frequencies greater than 1000 Hz. Undesired transverse motion, bending and rocking modes of traditional flexure-based shakers can easily be 100% (or greater) of the primary axis motion (Figure 3) at frequencies corresponding to a flexure or armature resonance.

This large cross-axis excitation motion, coupled with inherent transverse sensitivity found in any accelerometer, can cause increased measurement uncertainty and measurement errors at certain calibration frequencies in the frequency response curve. Taking the accelerometer's transverse sensitivity to be 5%, a worst-case calibration error due to the rse motion would be $1 \times 0.05 = 5\%$. It follows that when making high

accuracy measurements a reliable, high fidelity calibration shaker is one of the most important components in the entire measurement chain.

Because of that, air bearing shakers are now the preferable type of electrodynamic shakers to be used, as they can provide the best approximation to pure single degree of freedom vibration over the widest frequency range, while minimizing the transverse motion and distortion compared with traditional flexure-based electrodynamic shakers (Figure 3). The air-bearing assembly is composed of an armature fitted within a tight-tolerance porous air-bearing. The gap between the armature and air-bearing is extremely small, maintained at about 2 to 4 microns. Air film stiffness is inversely proportional to gap and this close fitting gap provides the armature with a high lateral stiffness [3].

An example of an air bearing shaker is shown in Figure 4. The armature assembly is composed of two pieces: the main body and a removable beryllium insert. The reference accelerometer is located within the insert and back-to-back calibration is performed by mounting the SUT on the insert. The armature insert is electrically isolated from the armature body providing means for the armature body to be isolated from the SUT signal ground. This eliminates any electrical noise contribution from the shaker drive signal on the transducer's measurement.

The armature body is fabricated from either aluminum or beryllium. Beryllium is used because its extremely low density and high stiffness combine to give unusually high speed of sound. Structural resonances are therefore very high, so rigid body motion is better approximated, allowing calibration up to 20 kHz. The light weight also means higher acceleration levels are possible with the given force.

Reference Accelerometer

A shear-mode quartz reference accelerometer is employed within a removable beryllium insert core,

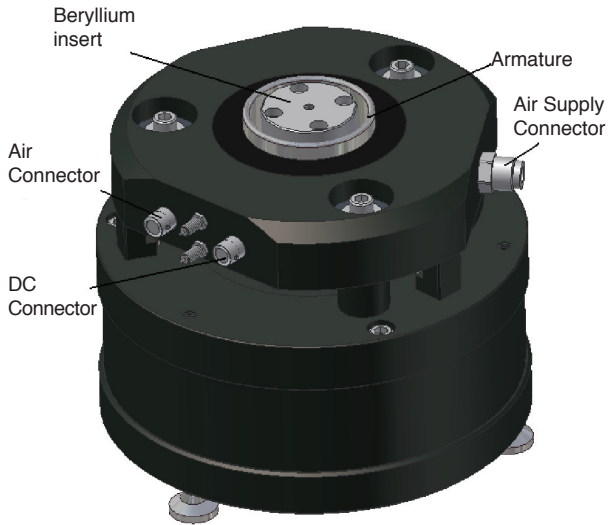


Figure 4. Air bearing shaker. [3]

providing long-term stability and isolation from case strains and thermal transients. Integral charge conversion electronics, using ICP® circuitry reduces the sources of cable-induced noise, relative to conventional charge mode standard transducers. Its nominal sensitivity is 10 mV/G and frequency calibration can be performed up to 20 kHz with resonant sweeps up to 50 kHz. The reference accelerometer is built in the beryllium insert for stiffness and maximized flat frequency response.

Resonance Test

The reference accelerometer resonance frequency is greater than 70 kHz which allows utilization of the reference for resonant search of the SUT up to at least 50 kHz.

Although accelerometers can generally withstand high shock limit levels, consider that a simple drop on a hard floor or an impact against a machine may create a shock of several thousands G's. If it is known that an accelerometer has been handled carelessly, it is advisable to recalibrate the accelerometer, preferably with a check of the frequency response and a resonance search test to indirectly verify the integrity of the piezoelectric crystal, seismic mass, and preload. Once built, an accelerometer resonance should remain constant and any measured difference is an indicator of sensor damage. Trending this parameter for a given accelerometer over time is an effective way for early determination of damage.

Data Acquisition

Computer-controlled accelerometer calibration workstations not only automate the monotonous calibration process but also help minimize human errors and enhance system repeatability and accuracy. Available

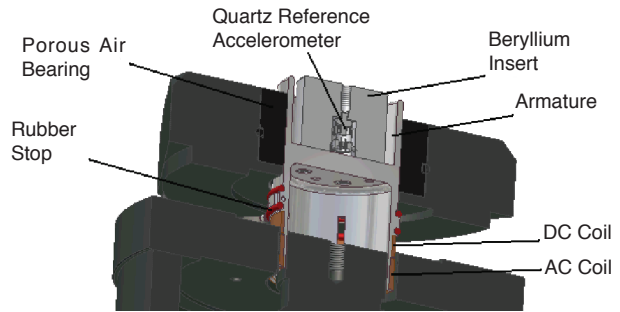


Figure 5. Cross section view of the air bearing shaker.

high-accuracy data acquisition boards with 24-bit delta-sigma analog-to-digital converters (118 dB dynamic range) and 24-bit analog output can be used for shock and vibration calibration applications. Variable anti-aliasing filters and simultaneously sampled analog inputs up to 204.8 kS/s allow for frequency calibrations up to 20 kHz and resonance search up to 50 kHz.

Frequency response analysis is implemented by using the Discrete Fourier Transform (DFT) method applied to the acquired digitally sampled data. Total harmonic distortion and excitation-measurement skewing over the calibration frequency range is negligible. The synchronously sampled dual channel 24 bit delta-sigma architecture provides significantly better measurement and accuracy when compared to broadband r.m.s. voltmeters which are sensitive to distortion and other signals at frequencies differing from the measurement frequency [1].

Precise frequency control of the calibration excitation signal and variable sampling frequencies are used for each single-sine excitation signal. Data acquisition sample rate is variable from 1 to 204.8 kS/s (kilo samples per second), in extremely fine increments, as small as 181.9 μ S/s (micro samples per second). Not being confined to a limited selection of fixed sample rates, brings accuracy and flexibility to the calibration system by allowing all measurements to be bin-centered and leakage free at any frequency within the system's range.

By fine tuning the data acquisition sample rate and the data window size to correspond to an integer number of periods of the user selected calibration frequencies, the DFT processing engine is able to accurately resolve each measurement point without introducing DSP (digital signal processing) leakage errors or amplitude errors inherent to fixed sampling rate and time windowing weighting commonly found on FFT (Fast Fourier Transform) based systems [5]. Unlike traditional FFT analyzers (that use windowing to somewhat reduce uncertainties caused by FFT leakage), the TMS 9155C [4] calibration system software eliminates leakage errors altogether. Eliminating the need for windowing also improves immunity to noise, because windowing increases the effective noise bandwidth by smearing noise signals into the frequency of the calibration signal.

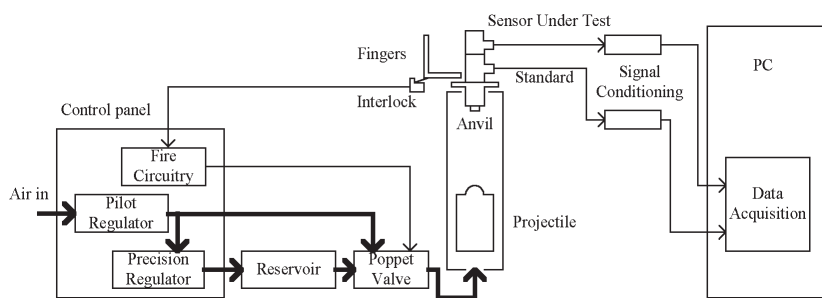


Figure 6. Schematic of a PneuShock® exciter [6].

A SUT signal conditioner correction is performed automatically during the channel calibration procedure. This procedure also measures the transfer function between each data acquisition channel, allowing for automatic compensation of any minute channel difference that may exist in the system. Ultimately, the only component in the calibration system that requires a traceable calibration is the standard reference accelerometer paired with its mating signal conditioner.

the standard reference accelerometer paired with its mating signal conditioner. Last but not least, the software closed-loop control algorithm automatically guarantees linear shaker performance over the calibration frequency range. It eliminates the need for prior calibration shaker characterization set up, shaker compensation, or manual adjustment of shaker response and shaker gain during the calibration process, making the calibration process smooth, fast and accurate.

Data Management

Printed calibration certificates fulfilling the requirements set forth by ISO 17025 can be easily generated, and calibration results are stored in open SQL compliant database format for ease of retrieval and data management. The database includes sensor specifications and test requirements to automate system setup and clearly define Pass/Fail calibration criteria for each sensor type.

Accelerometer Shock Sensitivity Calibration

Shock calibration uses transient excitation methods. A shock pulse of

0.05 ms to 8.0 ms duration is applied to the transducers and the measurement of the accelerometer shock sensitivity is performed according to the ISO 16063-22 "Methods for the calibration of vibration and shock transducers - Part 22: Shock calibration by comparison to a reference transducer" [2]. Different shock levels can be used to measure the amplitude linearity curve of the SUT at different high-acceleration levels.

Shown schematically in Figure 6, a shock calibration system may consist of an exciter using a pneumatically driven projectile, a back-to-back comparison standard (Figure 7), laboratory signal conditioning and PC-based data acquisition. This system can perform calibration and linearity checks from 20G's up to 10,000 G's and is the most versatile anvil shock type devices described by ISO 16063-22 for shock calibration (in terms of amplitude range, pulse duration, repeatability, and traceability to primary calibration methodologies).

In this exciter a regulated air pressure drives a projectile to impact an "anvil" upon which transducers are mounted as shown in Figure 8. A pilot-operated poppet valve is used to quickly release the controlled pressure, which controls the amount of linear momentum transfer in an impact. Pressure pulse duration and level can be finely tuned to provide precise control and ease of use adjustment of the projectile shock levels.

An assortment of anvils with different padding stiffness characteristics is available to adjust the acceleration and pulse duration resulting from the impact. The anvil assembly is inserted

into the guide at the end of the barrel in which a projectile is launched. A mechanism with "fingers" slides over the assembly, which catches the transducers during their upward flight. The finger mechanism has an interlock safety switch that disables the system if it is not in position. The pneumatic exciter also allows for quieter operation, more durable components, and greater range of input levels than other shock exciters.

Shock Reference Accelerometer

A new back-to-back comparison standard is shown in Figure 7 and was specifically designed for shock calibration. A quartz shear mode configuration provides long-term stability and isolation from case strains and thermal transients. The resonance frequency of the subassembly is nearly 100 kHz, giving essentially flat response to 10 kHz. Integral charge conversion using ICP® circuitry significantly reduces the sources of cable-induced noise, relative to the conventional charge mode transducers. Sensitivity was scaled to approximately 0.5 mV/G, to assure linear electrical conversion to well above 10 000G. Finally, the hermetic weld on the hardened 17-4 stainless steel housing gives true environmental immunity, whereas older reference transducer design used an epoxy seal [6].

Shock Data Acquisition

The accelerometer calibration workstation uses the same data acquisition card for both shock and vibration calibration methods.

A shock waveform is captured and displayed as shown in Figure 9 and allow for the closely monitoring of the shock pulse duration and shape. The pulse duration must be long enough compared to the period of resonance



Figure 7. Shock Reference Accelerometer.

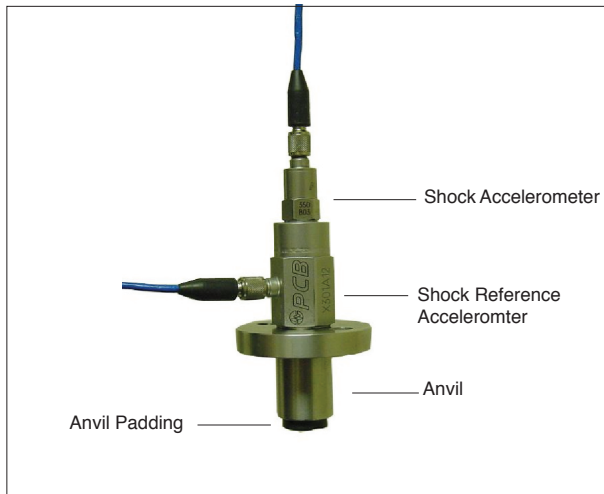


Figure 8. Reference accelerometer mounted on an anvil, with a test transducer mounted in the 1/4-28 tapped hole on the top surface. For size comparison, the length of the Standard (not including the integral stud) is about 29 mm.

of either transducer, so that the frequency content of the excitation falls in the lower more-linear region of their frequency response curves. A general guideline is that the duration be a factor of 5 larger than the resonance period, so for example, a transducer with a 20 kHz resonance would have natural period of 0.05 ms, and the shortest suggested pulse duration would be on the order of 0.25 ms [6].

The basis of the shock calibration is the comparison of two waveforms formed by the impact. Note that after the shock the two sensors are in free fall, with approximately zero acceleration after the event. Analysis of the flat regions before and after provides a measure of zero shift of the SUT. Note that 2 milliseconds after the peak a deceleration begins. This is caused by the anvils striking the padding of the fixture. The time duration between the positive and negative accelerations is adjusted by the spacing of the fingers above the anvils, defining the distance of free fall [6].

Multiple peak shock levels can be averaged and sensitivity values calculated. Through careful selection of drive pressure, pulse duration, anvil type material & padding, different shock levels over the 20G to 10,000G can be obtained and linearity measurement for the SUT is performed.

Conclusion

Although most people and companies perform accelerometer calibration on an annual basis, how a sensor is used and specific test requirements often dictate proper calibration interval. If the test object is safety critical or failure of the test object expensive, the calibration interval should be immediately before the test and immediately after the test. Such is the case with space flight hardware. On the other side, if the accelerometer is used only occasionally and

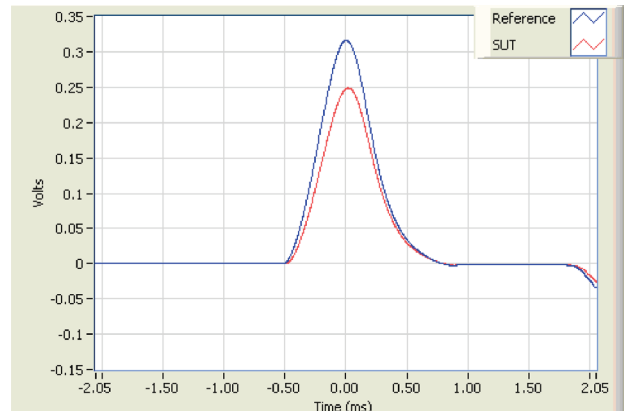


Figure 9. Typical transient data acquired with by the shock calibration system.

there is a documented history of stability, the calibration interval may be extended. Exceeding the accelerometer's high or low temperature specifications, or if it is dropped or abused, would also be cause for recalibration.

Vibration and Shock transducer calibrations can be accomplished by comparison to a reference transducer. The methods are covered recently published ISO-16063-21:2003 and ISO-16063-22:2005. Over the past few years a great deal of effort has been expended on developing and improving calibration systems to accomplish the requirements of the new standards. Careful system and component design through the measurement chain required by calibration systems have proven to be a key step for the successful implementation of such systems.

References

1. ISO 16063-21:2003, Methods for the calibration of vibration and shock transducers — Part 21: Vibration calibration by comparison to a reference transducer.
2. ISO 16063-22:2005 Methods for the calibration of vibration and shock transducers — Part 22: Shock calibration by comparison to a reference transducer.
3. Dosch, Jeffrey, Air Bearing Shaker for Precision Calibration of Accelerometers, IMAC 2006
4. <http://www.modalshop.com>
5. The Fundamentals of Signal Analysis – Application Note 243 – Agilent Technologies
6. Sill, Robert D., Kim, Sang H., Accelerometer Shock Sensitivity Calibration Using a Pneumatic Exciter, 77th Shock and Vibration Symposium, November 2006, Monterey, CA, USA.

Marco Peres, The Modal Shop, Inc., tel 513-351-9919, mperes@modalshop.com. Robert D. Sill, PCB Piezotronics Inc., tel 949-429-5259 x23, rsill@pcb.com.

This paper was originally presented at the Measurement Science Conference, February 2007. It is reprinted here by permission of the author and MSC.