# Calibration of Accelerometer Vibration Sensitivity by Reference

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## Abstract

Accelerometers are used to measure axial vibration that transmits through an object. In order to provide accurate data, accelerometers need to be calibrated to ensure they cover the correct frequency range and their sensitivity to acceleration is correctly rated. This note summarizes a common technique used to calibrate an accelerometer by referencing. It also includes suggestions for testing components as well as important points to consider during the calibration process. Users already familiar with hardware-software integration should find this document beneficial. Cases in which error in calibration can occur are also briefly examined.

## Introduction

In general, the calibration of an accelerometer refers to the sensitivity of the device in response to acceleration. A point to consider is the type of accelerometer data that is needed to be monitored. Accelerometers are typically purposed for vibration (periodic) measurement or shock (transient) measurement. This document will focus on vibration measurement calibration, which is applicable to our team’s design project.

### Objective

In many fields, calibration is thought of as the uncertainty or error in a measurement compared to a reference or known value that exists. There is an importance associated with sensors in removing structural errors in outputs. These errors can be identified as the differences between the expected and measured sensor readings. The inconsistencies that appear each time a measurement is taken can lead to false data, so it is of interest to remove these inconsistencies by calibrating sensors based on controlled experiment conditions. Therefore, the primary objective of calibration is to remove errors through consistent testing, comparison against known data and devices, and careful parameter calculation/estimation [4].

**Background**

An accelerometer is a device that measures acceleration (G-force). When stationary, it will measure the force of gravity, or 9.81 $m/s^2$. When vibration is detected, it will output a voltage based on its sensitivity rating. Some of the popular types of sensors include piezoelectric, piezoresistive, variable capacitance, and microelectromechanical (MEMS) accelerometers [5]. The accelerometer our team is using is a piezoelectric sensor rated 100 mV/G, so an applied force of 1 G triggers an output voltage of 100 mV.

It is important to note that our specific accelerometer was ordered directly from the manufacturer. This means that it has been previously calibrated prior to us receiving it. Therefore, we are not specifically going to be calibrating the accelerometer in terms of its sensitivity, but in relation to type of tool we are choosing to monitor and the data we receive from testing. This will be covered later in this note.

**Piezoelectric Accelerometers**

Piezoelectric sensors operate on Newton's Second Law, *Force = Mass X Acceleration*, and the Piezoelectric Effect (force on object generates charge) to measure the acceleration of an object. Pressure applied to the sensor compresses an internal crystal or man-made ceramic measuring element (**Figure 1**). This pressure displaces an electrical charge that is proportional to the applied force, which is also proportional to the acceleration of the measured object (F = ma). This output is a high-impedance signal that is measurable by electronic equipment such as an oscilloscope [3]. Piezoelectric accelerometers may contain internal signal conditioning, such as pre-amplification, to improve output signal quality [4]. From this acquired data, the transient and periodic responses of masses can be quantified and measured. Accelerometers, especially piezoelectric, are ideal for low frequency measurements, as visualized in **Figure 2**.

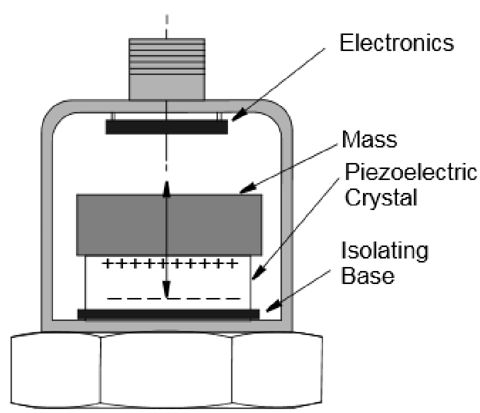


***Figure 1: Piezoelectric Compression Sensor [3]***

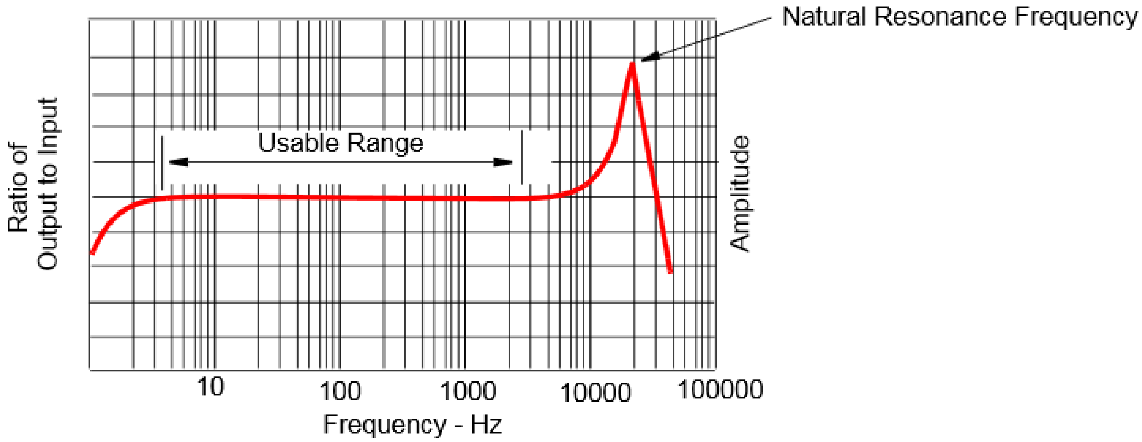


***Figure 2: Typical Response Curve of a Piezoelectric Vibration Sensor [3]***

The sensitivity and frequency range of a piezoelectric accelerometer is dependent on the crystals and materials used in construction. For example, natural crystals, such as quartz, have low charge sensitivity versus man-made ferroelectric materials. An advantage to using man-made materials is that they can be polarized to meet specifications [3].

## Vibration Calibration

This section covers the calibration of an accelerometer in regards to vibration sensitivity and frequency response. The device under test (DUT) is attached in what is known as a back-to-back method to a reference accelerometer with a known calibration (**Figure 3)**. This configuration is designed so that the standard accelerometer and DUT trigger an output in relation to the same surface [5].

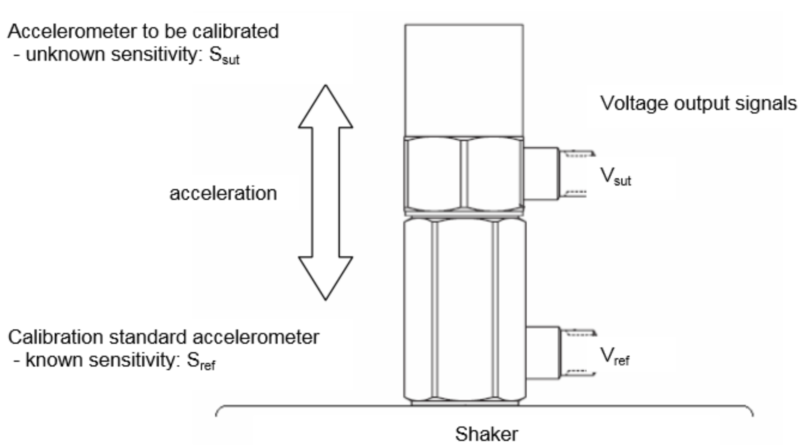


***Figure 3: Back-to-back Calibration Setup [5]***

This attachment is then excited by oscillatory vibration coming from an electromechanical or air bearing exciter/shaker. This shaker is set to oscillate at a sinusoidal frequency and the sensitivity of the DUT is measured at this frequency. This may be compared to a reference accelerometer (transducer) with a known calibration. A frequency response for the DUT can be created by sweeping the frequency of the shaker over a desired range.

The sensitivity of the DUT can be expressed as a ratio of the outputs of both devices. The following equation can be used to calculate the sensitivity:

$$S_{dut} = S_{ref} \bullet (V_{dut} / V_{ref}) \bullet (G_{ref} / G_{dut})$$

where:

$S_{dut}$ is the DUT sensitivity (in mV/G, mV/(m/s$^2$); pC/G or pC/(m/s$^2$))

$S_{ref}$ is the reference transducer sensitivity (in mV/G, mV/(m/s$^2$); pC/G or pC/(m/s$^2$))

$V_{dut}$ is the DUT channel output (in mV)

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

$G_{dut}$ is the DUT conditioner gain (in mV/mV or mV/pC)

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

***(equations adapted from [5])***

**Vibration Testing Equipment**

A vibration shaker is used to simulate high frequency sinusoidal oscillations. The combined mass of the armature, fixtures, standards of measurement, and the DUT will determine the maximum acceleration that is possible to test from the drive of the shaker. Sinusoidal inputs of 10 G and frequencies extending past 50 kHz are possible and common when testing. It is important to note that even the smallest distortions and transverse motion can have a significant effect on accelerometer readings [4]. If the distortion in a single harmonic becomes amplified, this can also be seen by the DUT. To solve this problem, signal processing and analysis methods such as the Fast Fourier Transform (FFT) can be used to filter, compare, and ultimately discard unwanted distortion frequency components caused by the shaker. To reduce and eliminate most of this transverse motion seen in traditional flexure-based, (electromechanical) shakers, air bearing shakers are the preferred type of dynamic vibration systems [5].

### Data Acquisition System

A computer-controlled accelerometer calibration workstation is preferred to minimize human errors and easily repeat test conditions with accuracy. It is best to have a high-accuracy data acquisition board with hardware that can support frequency calibrations of upwards of 20 kHz. To analyze the frequency response obtained from shaking, the Discrete Fourier Transform (DFT) is used. This algorithm provides a significantly more accurate response than using a root mean square (RMS) algorithm, which is sensitive to harmonic distortion and other signals at frequencies differing from the measuring frequency. To obtain the most precise calibration, extremely fine and adjustable sampling rates will be beneficial. This can consist of using sampling increments as small as 200 µS/s (micro samples per second). Another point to consider is using a DFT resolving method versus a traditional FFT algorithm. Common FFT systems with fixed sampling rates can introduce leakage errors or amplitude errors, while using a custom sampling rate can improve accuracy and eliminate these inconsistencies [5].

### Mounting and Loading

There are many sources that induce uncertainty in measurements. Although can be assumed that both the DUT and the reference accelerometer will experience the same acceleration during testing, there may be relative motion between the two sensors. This can be caused by masses and materials of test fixtures and other equipment relative to the accelerometers being tested. To ensure proper accuracy, the accelerometers should be mounted flush so to mate with a flat surface. If there are any nicks, scratches, or deformities on the mounting surface of the DUT, transverse waves can be induced and cause faulty measurements. Using proper torqueing techniques of all mounting hardware is also essential as to not cause pre-loading to the accelerometers. These forces could cause discrepancies in the calibration process as well as damage directly to the accelerometer itself [4].

**Accelerometer Damage**

It is important that during calibration, the accelerometer is not exposed to any high-shock conditions. While most models are manufactured with a robust mechanical design, sudden shock, such as a drop in a typical lab environment (3 to 5 feet), can induce shock amplitudes ranging from 3000 to 5000 g. This can easily be amplified if flat-to-flat contact occurs between the accelerometer and the opposing contact surface. If an accelerometer has been mishandled, it is recommended that it be recalibrated. This would involve a check of the frequency response as well as a resonance test to determine the integrity of the piezoelectric crystal and internal components [4].

**Thermal Calibration**

Thermal testing is also completed to measure the effect of temperature on the sensor that is being calibrated. These measurements are classified as measurements of uncertainty. This is due to the difficulty in determining the effect of temperature on the overall frequency response of the accelerometer. Chamber, device, and test equipment temperatures must be noted throughout test procedures. Corrections can be made to the overall calibration of the accelerometer where thermal performance of a previously tested system is known. However, the effect of temperature on the calibration uncertainty needs to be estimated. This takes into account some of possible fluctuations in variables such as the reference and test accelerometers and their capacitances, bias voltages, impedances, damping characteristics, and output gains [4].

## Further Reading

Specifications including standards, requirements, tests, and procedures as determined by the Institute of Electrical and Electronics Engineers (IEEE) for Linear, Single-Axis, Non-gyroscopic Accelerometers can be found by referencing document [1]. The International Organization for Standardization (ISO) has also published the document, Methods for the Calibration of Vibration and Shock Transducers [2], which also covers these specifications.

## Relation to Design Project

As previously noted, we will not be calibrating the accelerometer's sensing ability and sensitivity because this has already been completed by the manufacturer. Instead, for our task of monitoring tool condition on a six-spindle lathe, several steps will be taken to ensure the tool life is correctly mapped to the output signal. This section describes the general procedure to obtain a desirable calibration.

**Initial Data Acquisition**

First, data acquisition will occur at the engineering machine shop on an automated lathe. The speed and feed rate will be set as close as possible to actual operation performed on the machine of the sponsor. A spectrum analyzer will be used to map the Fast Fourier Transform (FFT) as a cut is being performed on a scrap piece of aluminum. This will allow us to visualize the frequency range of the vibrations picked up by the accelerometer. This data will be recorded for tests with new and dull cutting bits, and should provide a good operational range for the tool.

**Initial Filter Programming**

After sufficient data is taken, filtering of certain frequencies can occur via the MAX262 switched capacitor chip. Using the data acquired from the spectrum analyzer, the correct bandpass filter(s) can be determined and then calculated to correctly filter this useable data. The chip is programed to output the signal amplitudes over the frequency range that encompasses the lifetime of a tool. This filter output will be used in accordance with the microcontroller to further output a 0-10 V signal to the Programmable Logic Controller (PLC) being used with the lathe system. The most important step in this process will be interpreting the data to correctly assign frequencies that represent a new tool and a dull tool.

**Secondary Data Acquisition**

At this point the system should be calibrated enough to provide good performance on the six-spindle lathe at the real production facility. The team will travel and conduct the same spectrum analysis tests and data acquisition as first performed on the engineering machine shop lathe. The tests will need to be carried out for new tools and dull tools. It will be important to note if any additional hardware, such as amplification, is needed.

### Final Filter Programming & Testing

The final stages of calibration will involve tweaking the programmable filter frequencies to match those pertaining to the six-spindle lathe. This calibration will be specific to the tool being monitored and the machining operation being performed. If time permits, the team will make another trip to the production facility to test the final calibration on the lathe. Any minor changes to the calibration will be finalized in this step.

## Conclusion

Accelerometers are typically factory calibrated by the manufacturer, which is a careful process requiring an understanding of the underlying physics behind the device. In general, it is common practice to recalibrate once per year to ensure the highest level of accuracy in measurements. However, this period may be extended if the device is used infrequently and a documented of sensor stability exists. Most transducers do not show noticeable differences for a period of five or more years. The importance of the accelerometer data in relation to its measurement could prompt a recalibration before the test occurs.

## References

[1] IEEE-STD-1293-1998, IEEE Standard Specification Format Guide and Test Procedure for Linear, Single-Axis, Non-Gyroscopic Accelerometers

[2] ISO 16063: 2003, Methods for the calibration of vibration and shock transducers

[3] Judd, Bob. *Using Accelerometers in a Data Acquisition System*. 1st ed. Walpole, MA: United Electronic Industries, Inc., 2009. Print.

[4] *Minimizing Measurement Uncertainty In Calibration And Use Of Accelerometers*. 1st ed. Endevco Meggitt Sensing Systems, 2012. Print.

[5] Peres, Marco, and Robert D. Sill. *A New Solution For Shock And Vibration Calibration Of Accelerometers*. 1st ed. The Modal Shop, Inc., 2015. Print.