

Calibration of Accelerometers at Extended Frequencies Utilizing Piezoelectric Shakers

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Piezoelectric shakers are well suited to generate motion suitable for use with laser interferometric methods at frequencies of 3 kHz and above. One advantage of piezoelectric shakers is the higher achievable accelerations and displacement amplitudes as compared to electrodynamic (ED) shakers. Another advantage is the use of a solid ceramic construction rather than a compliant suspension system which results in much lower mechanical noise.

Piezoelectric shakers have been developed and used at NIST for many years for high frequency calibration of accelerometers. Previous papers have documented the performance of these shakers for the calibration of accelerometers over the range of 3 kHz to 25 kHz using interferometric calibration methods. Piezoelectric shakers with solid ceramic construction coupled with new high resolution data acquisition systems have made it possible to extend the calibration of accelerometers to smaller amplitudes and a broader range of frequencies. These factors have also allowed calibrations to be performed over a wide range of accelerations, rather than over a relatively limited range of accelerations. This paper presents these topics and gives examples of calibrations over a frequency range of 5 kHz to 100 kHz, using a piezoelectric shaker and a high resolution data acquisition system.

INTRODUCTION

Piezoelectric ceramic shakers are well suited to generate motion suitable for use with laser interferometric methods, especially at frequencies above 3 kHz. Electrodynamic (ED) shakers are also used, but a disadvantage is the shaker's mounting table can be agitated by low-frequency mechanical noise due to the use of a relatively compliant suspension. Piezoelectric shakers have a very stiff construction which tends to minimize this effect. This is a significant advantage for high frequency calibrations, above about 10 kHz.

In a previous paper [1] two small piezoelectric shakers designed and built at NIST were described in detail. The first shaker (P102) was shown to be capable of calibrations performed up to 20 kHz. A second smaller shaker (P103) was designed to extend the calibration of accelerometers in the range above 20 kHz. The small piezoelectric shaker, P103 provides accelerations necessary for higher frequency calibration and is the subject of this paper. A significant extension of the upper frequency range of calibration is possible with the use of new high-resolution digital sampling equipment together with the improved piezoelectric shaker to supply the motion.



Figure 1. Piezoelectric shaker P103.

PERFORMANCE OF PIEZOELECTRIC SHAKERS

Figure 1 shows the smaller NIST shaker P103 based on a design developed by Jones [2] for calibration of accelerometers at frequencies higher than 20 kHz.

Figure 2 gives the approximate accelerations obtainable over the frequency range of 3 kHz to 50 kHz when measured at the top center of the P102 and P103 shakers using a drive signal of 0.8 V. When used in performing calibrations, a power amplifier and step-up transformer are used to obtain the larger accelerations needed. The measurement results shown in Figure 2 were obtained using a small (0.5 g) accelerometer. As indicated in Figure 2, the P103 shaker has a large resonance near 25 kHz which provides enough acceleration amplitude to perform calibrations by fringe disappearance.

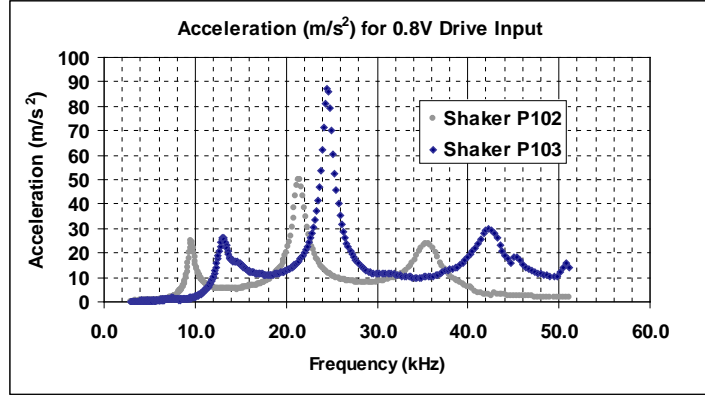


Figure 2. Accelerations obtainable for 0.8 V drive voltage.

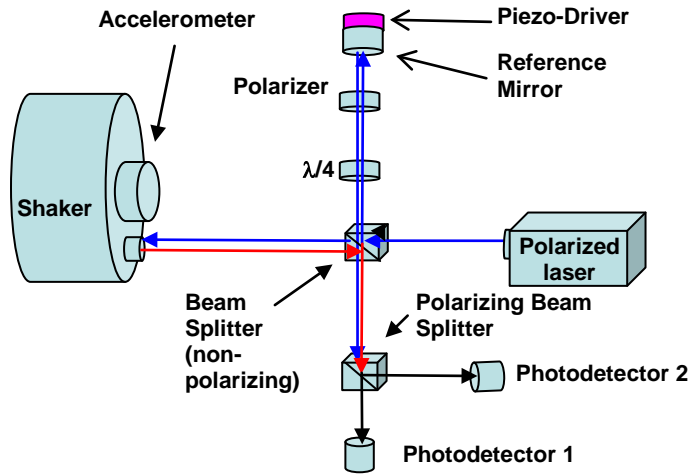


Figure 3. Setup using quadrature laser interferometer for sine-approximation and fringe disappearance methods.

The P103 shaker provides a substantial amount of acceleration between 40 kHz and 50 kHz which enables calibrations to be performed at frequencies higher than 25 kHz using the quadrature sine-approximation method.

Figure 3 shows a block diagram of the quadrature laser interferometer used to perform the calibrations. The small piezo-actuator attached to the reference mirror is typically driven at 1 kHz for modulation when performing calibrations at frequencies of 10 kHz and greater in order to ensure that just enough motion is applied so that a complete fringe is available for signal processing when using quadrature interferometry [3].

THE EQUIVALENCE OF FRINGE DISAPPEARANCE AND SINE APPROXIMATION INTERFEROMETRIC METHODS

FRINGE DISAPPEARANCE METHOD

The fringe disappearance (FD) method is similar to the minimum point method both of which are included in the ISO standard [4] as primary methods for accelerometer calibrations. The interferometer setup for the fringe disappearance method is the same as that shown in figure 3 but without the polarizer, $1/4 \lambda$ retardation plate, photodetector 2, and the polarized beam splitter. Also the interferometer does not need a polarized laser. The low frequency terms of the photodetector current produced in the photodetector is given by

$$I = A + B(\cos 4\pi \Delta / \lambda) J_0(4\pi d / \lambda) \quad (1)$$

A and B are constants, d is the displacement amplitude to be measured, λ is the wavelength of the laser light (632.82 nm), Δ is the optical path length difference of the two arms of the interferometer, and J_0 is the Bessel function of the first kind of order zero. Since the cosine function varies from -1 to +1, it may be observed that for any fixed value of d, the range of variation of I is

$$I(\max) - I(\min) = 2B J_0(4 \pi d/\lambda) = \Delta(I) . \quad (2)$$

This difference decreases as d approaches a value which makes

$$J_0(4 \pi d/\lambda) = 0 . \quad (3)$$

For a laser with $\lambda = 632.82$ nm, this value of d (displacement) is equal to 121.1 nm, or the fringe-disappearance condition. In practical use the fringes from a Michelson interferometer, if optically expanded by a lens for viewing, will appear to “disappear” so that a uniform pattern of light will replace the distinct fringes. In practical use, the light is detected by the photodetector and the “disappearance” will be detected by stepping through a series of displacements and measuring the change in light intensity between the dark and bright fringe lines as they impact the detector surface. This is fully documented in [5, 6].

QUADRATURE INTERFEROMETRIC METHOD

In this section, fringe disappearance (FD) calibration results are compared with quadrature laser interferometric calibration results. The FD data are taken at 121.1 nm which requires rather high accelerations at the higher frequencies. The quadrature calibrations can be performed over a wide range of accelerations and thereby permits calibrations at much higher frequencies.

Figure 4 shows calibration results of a widely used commercial, single-ended accelerometer over a wide range of accelerations at 10 kHz and 20 kHz using the quadrature interferometer as shown in Figure 3 above. Maximum differences in measured sensitivities due to differences in acceleration amplitude are on the order of 0.1 % to 0.2 % for this range of accelerations. Figure 5 shows calibration results of the same accelerometer obtained using piezoelectric shakers P102 and P103.

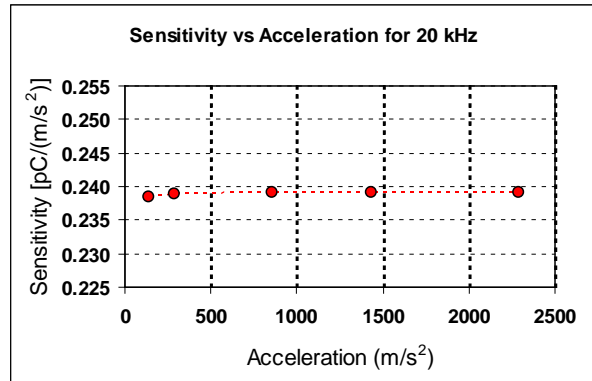
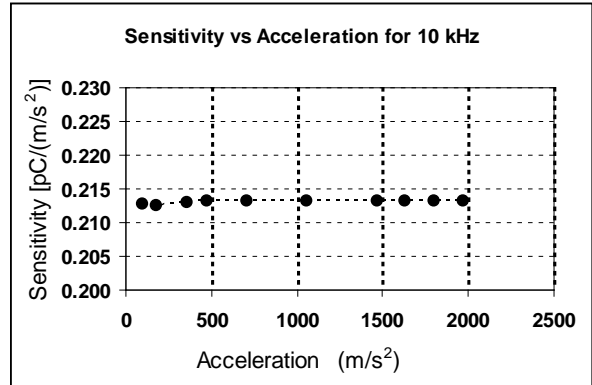


Figure 4. Calibration results of a single-ended accelerometer for a range of accelerations.

The data shown use the average displacement of three mirrors placed 120 degrees apart on the shaker top near the accelerometer. The smaller high-frequency shaker, P103, is capable of calibration by FD up to 25 kHz.

Both shakers have the capability for calibrations by quadrature interferometry in the frequency range of 5 kHz to 25 kHz. The FD calibrations were all performed at a constant displacement of 121.1 nm, and the quadrature interferometric calibrations were all performed at approximately 100 m/s² to 500 m/s².

The data shown in Figure 5 indicate that the two methods produce results that agree closely, usually less than 1 % difference. The quadrature method allows for calibration at even higher frequencies because it can be performed at lower amplitudes than is possible with fringe disappearance. Data shown is the average of three calibrations, one for each mirror as shown in the photograph below.

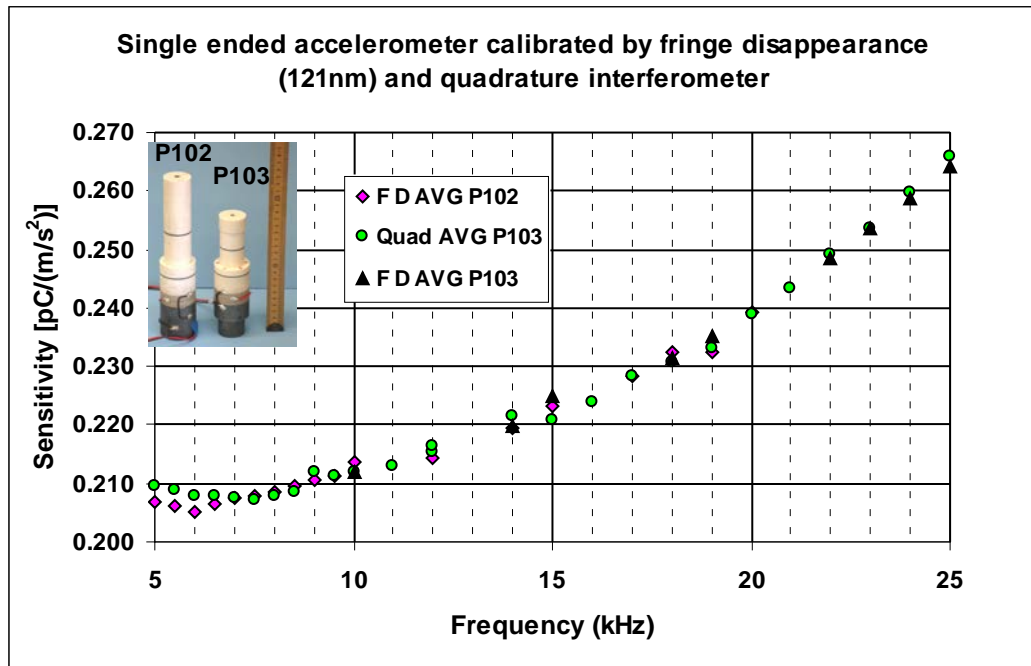


Figure 5. Accelerometer calibrated by two methods and two shakers.

For the test results shown in Figure 5, the combined relative uncertainty for the quadrature and fringe disappearance methods was calculated in accordance with methodologies described in the Guide to the Expression of Uncertainty in Measurement [7] using Type A and Type B evaluations of uncertainty components, including those contained in ISO 16063 Part 11 on the calibration of vibration and shock transducers [4]. Using a coverage factor of 2, the estimated expanded relative uncertainty, U , at 10 kHz is 1 %.

CALIBRATION OF ACCELEROMETERS AT EXTENDED FREQUENCIES

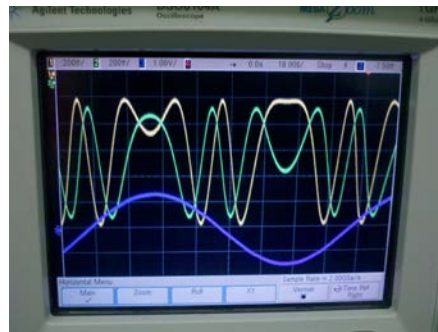


Figure 6 Photo-detector signals in quadrature (top), accelerometer signal (lower).

Shaker P103 has the capability of calibrations at frequencies above 25 kHz. Figure 2, above, shows that the shaker has motion in the region of 25 kHz to at least 50 kHz and later tests show sufficient motion for calibration up to about 100 kHz. Calibration at these higher frequencies must be performed at very low displacements due to limitations of the shaker. The amplitudes which the shaker can produce decrease rapidly as the frequency increases. Maximum amplitudes above 25 kHz are low (some less than 1 nm). Figure 6 shows the oscilloscope traces for the two photo-detectors in quadrature (top) and the accelerometer (lower) at a low calibration frequency (10 kHz, no modulation needed).

Figure 7a shows similar traces for 40 kHz calibration. For the 40 kHz trace the interferometer has a modulation frequency of 1 kHz. Figures 7b and 7c show traces of the two photo-detectors plotted as x and y voltages on the oscilloscope. Figure 7b shows the signals without the 1 kHz modulation and figure 7c shows the signals with the 1 kHz modulation. The condition shown in figure 7c (closed circle) is necessary for signal processing using sine approximation quadrature interferometry.



Figure 7a Photo-detector signals in quadrature with 1 kHz modulation on reference mirror.



Figure 7b Photo-detector signals plotted as x - y, no modulation

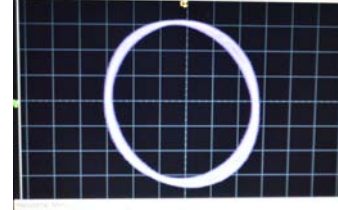


Figure 7c Photo-detector signals plotted as x - y, 1 kHz modulation.

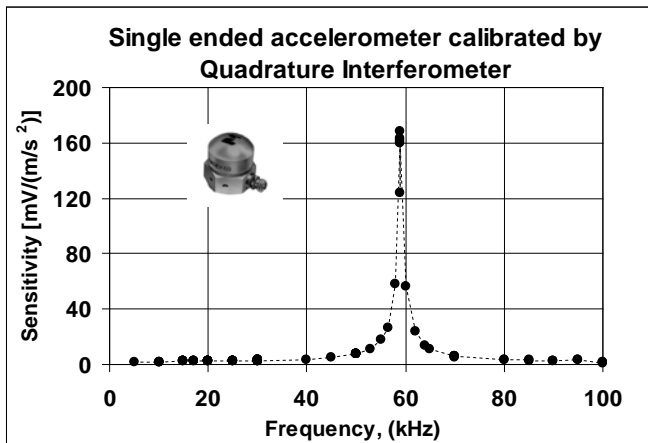


Figure 8a. Frequency response for a typical single-ended accelerometer.

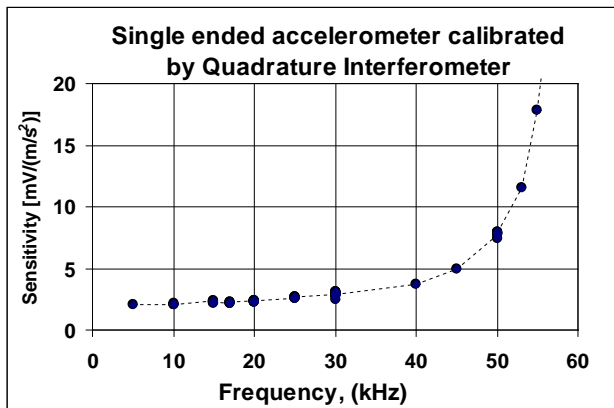


Figure 8b. Frequency response, 5 kHz to 60 kHz for a single-ended accelerometer.

Tests were performed to determine if the quality of motion produced by the shaker at higher frequencies was sufficient for use in performing calibrations. These tests are described below. Figures 8a and 8b show calibration results for the same single-ended accelerometer that was used to produce the measurement results shown in Figure 5. Figure 8c shows this accelerometer mounted at the center of the shaker and with mirrors mounted on the shaker to permit calibration at three positions.

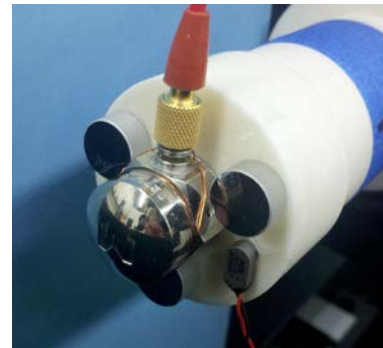


Figure 8c Shaker P103 with three mirrors.

The single-ended accelerometer positioned at the center of the mounting surface of shaker P103 as shown in Figure 8c has a nominal mounted resonance frequency of 55 kHz as specified by the manufacturer. The measured sensitivities shown Figure 8a indicate the mounted resonance frequency of the single-ended accelerometer tested to be about 59 kHz.

Tests were also performed on a single-ended miniature accelerometer, 0.3 g from a different manufacturer, as shown in Figure 8c. The manufacturer's specified nominal mounted resonance frequency is ≥ 70 kHz. Figures 9a and 9b show the results of the calibrations obtained using shaker P103. The test results indicate the mounted resonance of the transducer tested to be about 80 kHz. A common specification relating to accelerometer performance is the frequency range over which the transducer sensitivity is uniform within ± 3 dB. The measured sensitivities shown in figure 9b, indicate that the 3 dB increase in sensitivity for the transducer under test occurs just above 40 kHz which agrees with the nominal upper frequency limit of 40 kHz specified by the manufacturer.

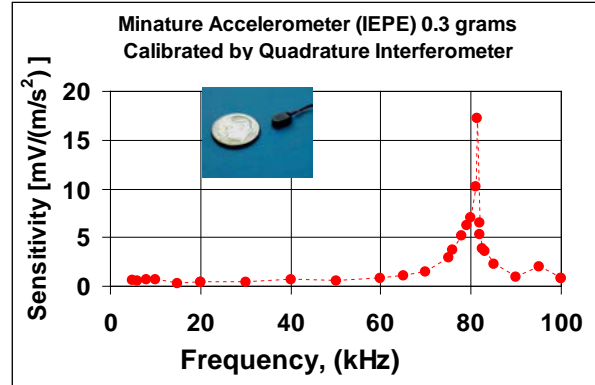


Figure 9a. Frequency response for 0.3 gram accelerometer

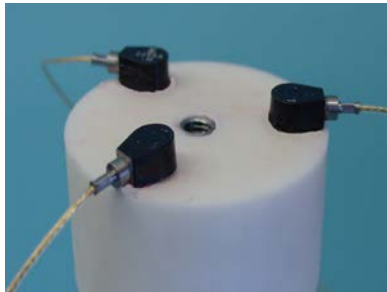


Figure 10. Small accelerometers mounted on P103 to check cross-axis

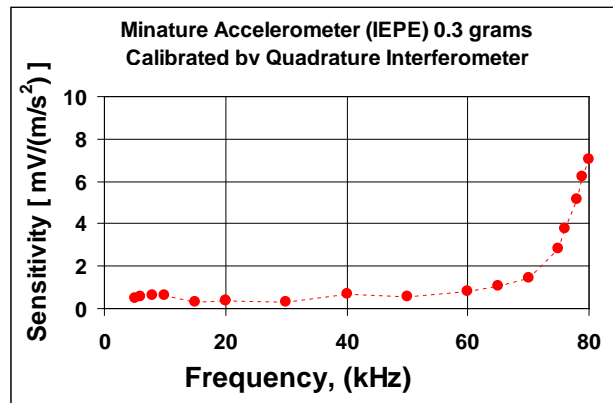


Figure 9b. Frequency response, 5 kHz to 80 kHz for 0.3 g accelerometer.

Waveform distortion at frequencies greater than 25 kHz is reasonably small [1]. However, additional work is needed in order to characterize the cross motion at these higher frequencies. Measurement of cross-axial motion at high frequencies always presents difficulties due to a number of factors. Tri-axial accelerometers often have high frequency limitations due to their resonances as well as axial crosstalk.

To estimate cross-axial motion at very high frequencies, three small uniaxial accelerometers were mounted on the shaker table in order to estimate cross-axial motion at very high frequencies as shown in Figure 10.

These accelerometers have high internal and mounted resonances, and a mass of about 0.4 g each. By measuring the phase difference of signals from any two accelerometers, one can get a good indication of the degree of piston-like motion of the shaker [2]. For frequencies above 15 kHz, this test should be performed as part of evaluating the uncertainties associated with the calibration process.

CONCLUSIONS

The progress made in piezoelectric shaker development and improvements in digital sampling make possible testing and calibration of accelerometers at higher frequencies. In addition to basic calibrations at higher frequencies, other tests can be more easily performed. These include the mounted resonance, frequency range, and amplitude linearity of accelerometers specified by their manufacturer.

Piezoelectric shakers can be custom designed and constructed for specific frequency ranges to produce motion with low harmonic distortion and low cross axis motion. Higher resolution digital sampling provides better amplitude resolution for measurements at higher frequencies than previously available.

Additional work needs to be done to improve shaker design for better high frequency performance, and to develop better techniques to measure critical factors influencing shaker performance.

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