Primary Calibration of Accelerometers at NIST Using a Dual Coil Shaker

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Until recently, the primary calibration of accelerometers at NIST over a frequency range of 50 Hz to 5 kHz utilized three different shakers with separate measurement systems. With the development of the NIST supershaker and associated calibration system, this frequency range can be covered in its entirety using one test setup. Three independent primary vibration calibration methods consisting of fringe counting, minimum point, and reciprocity can now all be used on one shaker system. There is an overlap in the range of frequencies over which each of these three methods can be used. The implementation of independent absolute calibration methods provides a physical means to verify estimates of uncertainty for each calibration method. Uncertainty estimates associated with the new system when using these methods show improvements in the estimated uncertainty of accelerometer calibrations performed at NIST. Examples of both single-ended and back-to-back accelerometer calibrations are given along with estimated uncertainties.

INTRODUCTION

A custom shaker was completed at NIST for the calibration of the sensitivity of accelerometers. This shaker features a dual-coil moving element[1]. A principal goal in the design of the shaker was to reduce uncertainties in the absolute determination of accelerometer sensitivity. Utilizing the design features of this shaker allows the implementation of three absolute (or primary) calibration methods for the determination of accelerometer sensitivity. The fringe-counting and the minimum-point methods use the wavelength of He-Ne laser light as the reference standard for displacement. Acceleration can be inferred from displacement by assuming ideal sinusoidal excitation and multiplying by an appropriate function of angular frequency. The fringe-counting method is used for frequencies up to and including 1 kHz and the minimum-point method is used for frequencies from 1 kHz to 5 kHz. The reciprocity method uses the application of the electromechanical theory of reciprocity and a set of masses as a mechanical reference standard to determine accelerometer sensitivity.

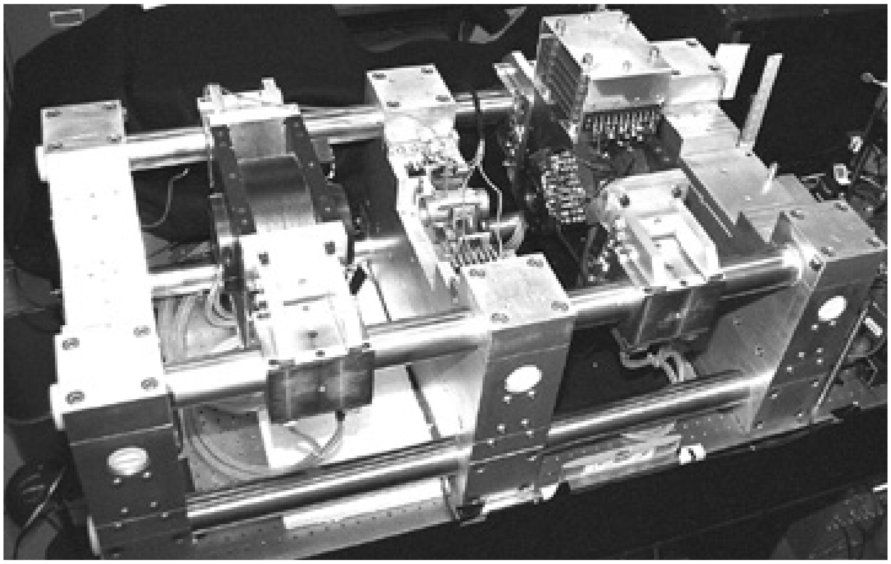

Figure 1. Dual-Coil Shaker.

FEATURES OF THE DUAL-COIL SHAKER

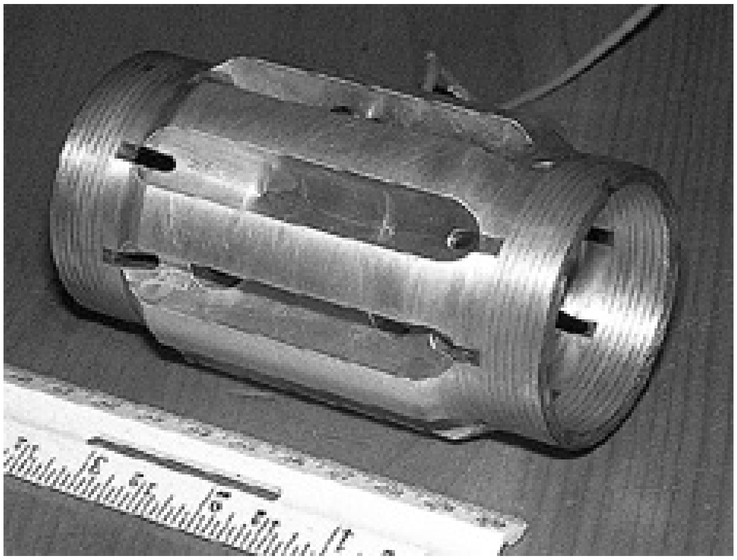

Figure 2a. Moving Element of the Dual-Coil Shaker.

The shaker, shown in Figure 1, has dual retractable magnets equipped with optical ports. These ports enable interferometric measurement of surface displacement by allowing a laser beam to access the surface upon which the accelerometer is mounted, or one 180° opposite to it. Physically compact for directional stability and high-frequency response, the moving element is equipped at each end with nominally identical coils and axially oriented mounting tables, Figure 2a. By allowing reciprocity calibrations to be done with the driving and sensing coils on the same moving element so that a separate shaker external to the calibration shaker is not needed, the new shaker design eliminates complications due to mutual mechanical coupling between two separate shakers. The implementation of independent absolute calibration methods provides a physical means to verify estimates of uncertainty for each calibration method.

Minimal distortion and cross-axis motion are essential to the validity of the inherent assumptions of the theory of electromechanical reciprocity. Therefore, the shaker was constructed with all critical dimensions held to close tolerances to minimize distortion and cross-axis motion. Dimensional tolerances for all subassemblies were specified to be no greater than ±25 μm (0.001). Total harmonic distortion for acceleration amplitudes of less than 20 m/s^2 is 1 percent or less and cross motion is less than 7 percent over the frequency of 40 Hz to 5 kHz.

CALIBRATIONS BY LASER FRINGE-COUNTING INTERFEROMETRY

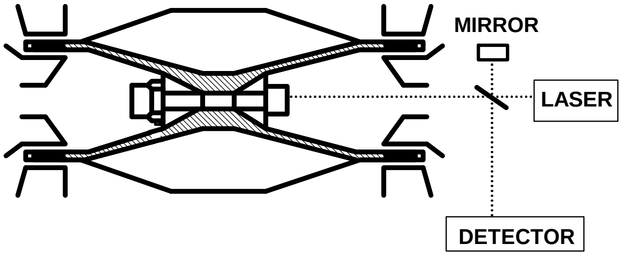

Figure 2b. Moving Element Configured for Fringe-Counting.

Figure 2b shows a schematic of the moving element of the shaker with the laser interferometer [2] located on the right side of the shaker. A flat mirror is mounted on the table located on the right side of the moving element opposite the table upon which the accelerometer is mounted. The shaker design allows optical access to the shaker mounting tables through a center hole in the magnet. The acceleration in meters per second squared is given by

$$A = \lambda \nu \pi^2 f^2 / 2, \qquad (1)$$

where λ is the wavelength of He-Ne laser light in meters, ν is the number of fringe counts per vibration cycle, and f is frequency in hertz. To provide additional displacement, both the right and left coils can be driven in a push-pull configuration.

In addition to distortion and cross-axis motion which are critical to reciprocity calibrations, the critical elements of interferometer operation include interferometer alignment and mechanical coupling between the shaker and the interferometer components. The shaker system was designed to minimize this coupling. The mass of the moving element (approximately 225 g) is very small compared to the mass of the magnet (approximately 68 kg) in order to minimize magnet movement. The shaker system is installed on an air isolation table to minimize the effects of floor movements. The magnets are moved into place on air-bearing guides and during operation the magnets are locked into place by turning off the air to the bearings.

The estimated combined relative uncertainty associated with the calibration results obtained by interferometry at 100 Hz is 0.14 % based on the current implementation of the measurement apparatus. This combined relative uncertainty was calculated in accordance with methodologies described in the Guide to the Expression of Uncertainty in Measurement [3] using Type A and Type B evaluations of uncertainty components, including those contained in ISO documents on the calibration of vibration and shock transducers. Using a coverage factor of 2, the estimated expanded relative uncertainty, *U*, at 100 Hz is: 0.3 %.

CALIBRATION BY RECIPROCITY

For reciprocity calibration, the test accelerometer is mounted on the left, as shown in Figure 2b; the mirror is removed from the right, and the right mounting table is used for attaching the calibration masses. At sufficiently low frequencies the magnitude of the accelerometer sensitivity (*S*) may be approximated by [2], [4]

$$S = [(JR)/(2\pi f)]^{1/2}, \qquad (2)$$

where:

J is the zero intercept (m=0) of a least-square-fit of the function $m/(Y_m-Y_0)$ vs. m with m the value of added mass and Y_m and Y_0 the measured transfer admittance with and without added mass. The transfer admittance is calculated by dividing the current of the driver coil by the output voltage of the accelerometer while the shaker is energized by the left coil.

R is the voltage ratio of the output voltage of the accelerometer to the output voltage across the left coil when used as a velocity sensor while the shaker is energized by the right coil. *f* is the test frequency.

It is critical that the coil of the reciprocal transducer remain in the same static position in the magnetic gap so that the magnetic field to which the coil is exposed will not vary as a function of mass loading. This position must remain stable so that changes in coil current for different masses can be measured accurately. Temperature should remain constant so that the physical dimensions of the shaker, the transduction characteristics of the reciprocal transducer, and the resistance used for current measurements will remain constant. For greater stability, the coil is driven at about 20 m/s^2 and allowed to remain energized throughout the measurements for all five masses. This results in measured voltages of typically 5 mV to 500 mV. The two digital voltmeters are placed close to the moving element so that the connecting cables can be kept short in order to reduce electrical noise. A thermocouple was attached to the accelerometer and the temperature was stabilized to about ±0.2 $^{\circ}$C.

The estimated combined relative uncertainty associated with the calibration results obtained by reciprocity at 100 Hz is 0.26 % based on the current implementation of the measurement apparatus. This combined relative uncertainty was calculated in accordance with methodologies described in the Guide to the Expression of Uncertainty in Measurement [3] using Type A and Type B evaluations of uncertainty components, including those contained in ISO documents on the calibration of vibration and shock transducers. Using a coverage factor of 2, the estimated expanded relative uncertainty, *U*, at 100 Hz is: 0.5 %.

CALIBRATION BY MINIMUM POINT METHOD LASER INTERFEROMETRY

The minimum-point method is based on the determination of displacement corresponding to the zero crossings of the Bessel function of the first kind and first order, J_1. This method utilizes the same setup as shown in Figure 2b for calibrations performed in the frequency range of 1 kHz to 5 kHz. In order to reject spectral components present in the output of the photo-detector except that corresponding to the fundamental frequency of vibration, the output of the photo-detector is filtered using a narrow band-pass filter centered at the fundamental frequency of vibration. The amplitude of vibration is then adjusted until the null corresponding to the desired zero crossing of J_1 is obtained. Peak displacement amplitudes of the first six zero crossings of J_1 for a He-Ne laser (λ=632.8 nm) are listed in Table 1. For the minimum-point calibrations, the number of the zero crossing was selected to obtain displacements corresponding to accelerations of approximately 50 m/s^2 or greater.

Table 1. Peak Displacement Amplitudes for the First Six Zero Crossings

Zero Crossing No.	Displacement (nm)
0	0.00
1	192.95
2	353.29
3	512.31
4	670.95
5	829.42

Once the displacement, *d*, is determined, the acceleration is calculated using the following equation:

$$A = (2\pi f)^2\, d. \tag{3}$$

The sensitivity of the accelerometer is then obtained by dividing the accelerometer output voltage by the acceleration, *A*.

The estimated combined relative uncertainty associated with the calibration results obtained by interferometry at 1 kHz is 0.22 % based on the current implementation of the measurement apparatus. This combined relative uncertainty was calculated in accordance with methodologies described in the Guide to the Expression of Uncertainty in Measurement [3] using Type A and Type B evaluations of uncertainty components, including those contained in ISO documents on the calibration of vibration and shock transducers. Using a coverage factor of 2, the estimated expanded relative uncertainty, *U*, for the minimum-point method at 1 kHz is: 0.5 %.

ACCELEROMETER CALIBRATION DATA BY THREE METHODS

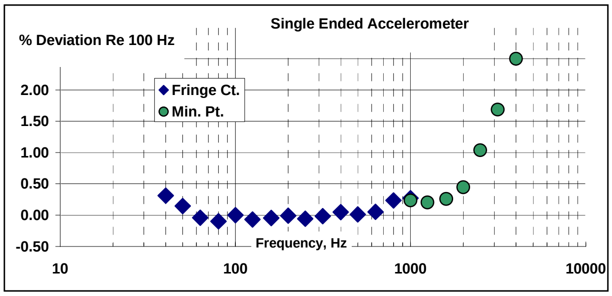

Figure 3. Calibration Data for Single-ended Accelerometer, Fringe-counting and Minimum-Point.

Calibration data for a single-ended accelerometer is shown in Figure 3. The accelerometer was calibrated by the fringe-counting method from 40 Hz to 1 kHz and by the minimum-point method from 1 kHz to 4 kHz. Data for the two calibration methods at the overlapping frequency of 1 kHz agree to within less than 0.1 %.

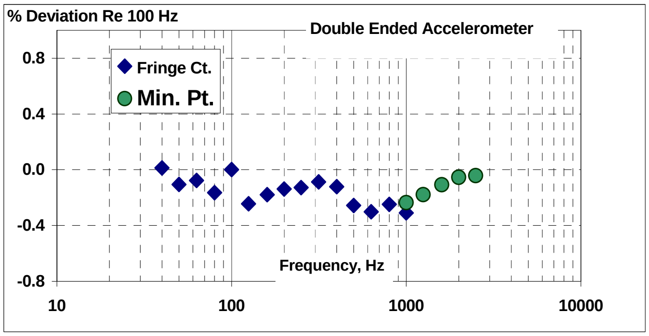

Figure 4. Calibration Data for Back-to-back Accelerometer, Fringe-counting and Minimum-Point.

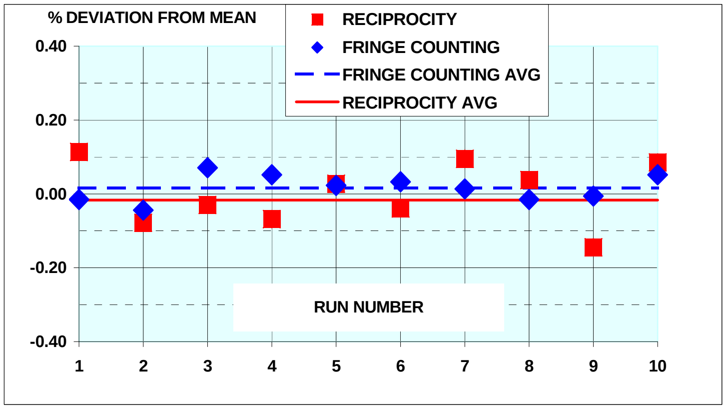

Figure 5. Calibration Data for Single-ended Accelerometer, Reciprocity and Fringe-counting.

Figure 4 shows similar data for a back-to-back accelerometer calibration using the same two methods. In this case, the accelerometer was positioned on the right mounting surface of the moving element and the polished top surface of the accelerometer was used as a reflecting surface for the interferometer. The overlapping frequency data at 1 kHz also agree to within less than 0.1 %.

Figure 5 shows data for reciprocity and fringe-counting calibrations on a single-ended accelerometer at 100 Hz. For a set of ten calibrations by each method, the maximum difference between any two data points of either of the two methods was never more than 0.3 percent, and the averages of the results obtained with the two methods agree within 0.04 percent.

SUMMARY

Primary calibrations of accelerometers over a frequency range of 50 Hz to 5 kHz can be accomplished using one shaker system. Three independent primary vibration calibration methods consisting of fringe counting, minimum point, and reciprocity with overlapping ranges of frequencies provides a physical means to verify estimates of uncertainty for each calibration method. Uncertainty estimates associated with the new system when using these methods show improvements of approximately a factor of 2 in the estimated uncertainty of accelerometer calibrations performed at NIST over previous calibration systems in these ranges. Both single-ended and back-to-back accelerometers can be calibrated.

REFERENCES

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3. "Guide to the Expression of Uncertainty in Measurement", 1993, International Organization for Standardization, 101.

4. Payne, B., Evans, D., "Comparison of Results of Calibrating the Magnitude of the Sensitivity of Accelerometers by laser Interferometry and Reciprocity", *Metrologia*, 1999, **36**, 391-394.