Comparison of results of calibrating the magnitude of the sensitivity of accelerometers by laser interferometry and reciprocity

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Abstract. The development of a new electrodynamic shaker permits the calibration of accelerometers by two independent and absolute methods using the same shaker. Minimizing the uncertainty in the calibration of accelerometers by the reciprocity method requires minimizing the cross-axis component of the induced motion, and the distortion of its waveform**.** Minimizing the uncertainty in the calibration of accelerometers by the laser interferometric fringe-counting method requires minimizing the mechanical coupling between the moving element of the shaker and the optical components of the interferometer. The design of the new shaker provides for minimal distortion and cross-axis motion in combination with a very large mechanical impedance between the moving element of the shaker and the optical components of the interferometer. The shaker is equipped with dual coils and two retractable magnets to provide for reciprocity measurements without having to attach a secondary source of vibration located external to the moving element. This paper presents a comparison of calibration results obtained using the two methods and describes the shaker and calibration systems.

Keywords: accelerometers, calibration, reciprocity, laser interferometer, fringe counting, uncertainty, shakers, exciters.

1. Introduction

A new shaker system for the calibration of the sensitivity of accelerometers at the National Institute of Standards and Technology was designed in 1993, and its initial testing was finished in 1995 [1]. A principal goal of this design is to reduce the inherent uncertainties of the absolute determination of accelerometer sensitivity. This paper gives the results of additional testing and a description of the implementation of two absolute calibration methods using the shaker. The fringe-counting method uses the wavelength of He-Ne laser light as the reference standard for displacement. The reciprocity method uses a set of masses as a mechanical reference standard, and the application of the electromechanical theory of reciprocity to determine accelerometer sensitivity. Acceleration can be inferred from the interferometric displacement measurement by assuming ideal sinusoidal excitation and multiplying by an appropriate function of angular frequency.

The shaker, shown in Figure 1, has dual retractable magnets equipped with optical ports to allow laser-beam access to the surface upon which the accelerometer is mounted, or one 180° opposed to it, to enable interferometric measurement of the surface displacement. 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. 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 two 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 in).

The moving element is supported by damped flexures which provide great axial stability, but also significantly limit the frequency range for reciprocity calibration. To allow data to be given for a typical accelerometer calibrated using both the reciprocity and fringe-counting methods, testing was conducted at 100 Hz. For this test frequency, typical total harmonic distortion is approximately 0.2 %, and cross-axis motion is less than 1 %.

2. Calibration by reciprocity

At sufficiently low frequencies the magnitude of the accelerometer sensitivity (S) may be approximated by [2]:

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

where:

J is the 0 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 measured transfer admittance with and without added mass;

R is the voltage ratio of the output of the accelerometer to the output of the reciprocal transducer used as a velocity sensor;

and f is the test frequency.

2.1 Critical factors

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 coil current changes for different masses can be measured accurately. The spring flexures tend to cause the axial position to change slowly after attachment of each mass. This problem is circumvented by allowing a few minutes for the axial position to stabilize after attaching or removing a mass and before the measurements are taken.

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 10 m/s^2 and allowed to remain energized throughout the measurements for all five masses. Thermocouples are attached to the accelerometer and the moving element close to the left coil. A small fan is attached to the end of the left magnet to draw air over the coil. After several minutes with the coil energized, the temperature of the moving element can be stabilized to about 0.2 $^{\mathrm{o}}$C.

For reciprocity measurements, circuit grounding is an important factor. It is necessary to ground the circuits at only one place. For transfer admittance measurements, a current-sensing resistor is interposed in the low-potential side of the circuit connecting the left coil to the power amplifier output.

Reciprocity calibrations are performed at small acceleration amplitudes, typically 10 m/s^2 to 20 m/s^2, in order to minimize heating effects. 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.

The estimated combined 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 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 contained in ISO documents under development on the calibration of vibration and shock transducers. Using a coverage factor of 2, the estimated expanded uncertainty, U, for these results is: 0.5 %.

3. Calibrations by laser interferometry

Figure 2 shows a schematic of the moving element of the shaker with the laser interferometer [2] located on the right side of the shaker. A corner cube retro-reflector 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 as shown in Figure 3. The acceleration in meters per second squared is given by:

$$a = \lambda \nu \pi^2 f^2 / 2 \,,$$

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 are driven in a push-pull configuration.

3.1 Critical factors

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.

Measurements made with the shaker operating at 10 m/s^2 at 100 Hz, and a seismic accelerometer installed on the air isolation table, indicate that only 0.05 % of the acceleration of the moving element is transmitted to the table.

The estimated combined uncertainty associated with the calibration results obtained by interferometry at 100 Hz is 0.22 % based on the current implementation of the measurement apparatus. This combined 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 contained in ISO documents under development on the calibration of vibration and shock transducers. Using a coverage factor of 2, the estimated expanded uncertainty, *U*, for these results is: 0.4 %.

4. Experimental procedures

Reciprocity and fringe-counting calibrations were performed on an accelerometer with a top-mounted cable connector and also an accelerometer with a side-mounted connector. The accelerometers are commercially available and commonly used as laboratory standards.

Experiments were conducted with the temperature and positioning stabilizing techniques described in 2.1. Calibrations were first performed using both the reciprocity and interferometry methods without removing the accelerometer in order to eliminate the possibility of differences in the calibration results being introduced by differences in mounting characteristics. The accelerometers were then removed and remounted, and the calibrations were repeated using both methods.

5. Experimental results

The results for the accelerometer with top-mounted-connector are shown in Figure 4. The 100 Hz calibration frequency is within the frequency range deemed to be that of minimal uncertainty. The maximum spread in all of the data is about 0.2 % while the largest difference in the data obtained for any given run is less than 0.2 % and the averages of the results obtained with the two methods agree within 0.04 %. Testing of the accelerometer with side-mounted-connector has not been completed, but preliminary results show similar agreement.

6. Summary and conclusions

A shaker system developed at NIST has capabilities for the calibration of the sensitivity of laboratory standard accelerometers by the methods of reciprocity and interferometric fringe counting. The system provides for both methods of calibration on the same shaker without remounting the accelerometer, or attaching or removing any hardware except the calibration masses needed for reciprocity, and the retro-reflector needed for the interferometer measurements. The setup provides for temperature monitoring and control within 0.2 °C for greater stability. The shaker has total harmonic distortion no greater than 0.2 % and cross-axis motion less than 1 %, at 100 Hz.

Data from a limited number of tests indicate that a calibration data point obtained at a frequency of 100 Hz by reciprocity agrees within about 0.2 % with a calibration data point obtained at the same frequency by interferometric fringe counting and that on average the methods agree conservatively to within less than 0.1 %. In the current implementation of the new shaker, it is expected, albeit not demonstrated, that similar results could be obtained over a frequency range of 100 Hz to 200 Hz. Prospects for improving the accuracy of the new electrodynamic shaker over a broad band of frequencies are limited by characteristics of the suspension flexure system. Because flexures allow much more cross axis motion than air bearing suspension systems, replacing the flexures with air bearings is expected to extend the frequency range for which greater accuracy can be obtained. The addition of multiple beam capability to the interferometer system will allow fringe counting and fringe disappearance measurements over a wider frequency range.

6. Acknowledgments

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7. References

1. Payne B. F., Booth G. B., *Proc. Metrologie 95*, 1995, 296-301.

2. A Description of NBS Calibration Services in Mechanical Vibration and Shock, 1987, NBS Tech. Note 1232, 26.

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

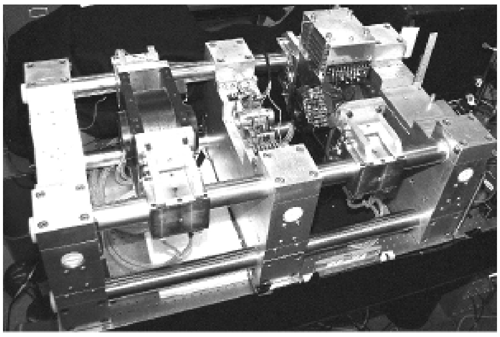

Figure 1. Dual Coil Shaker

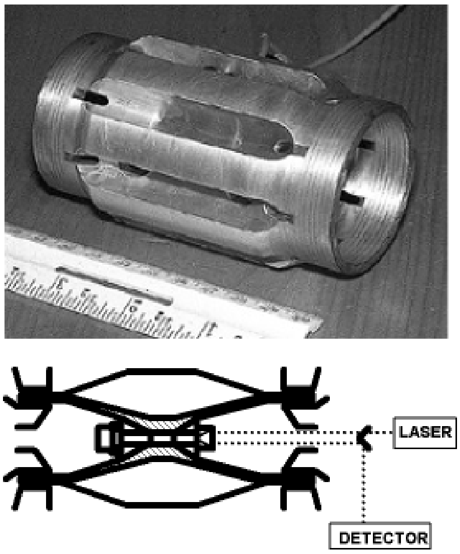

Figure 2 Moving element with fringe-counting test setup

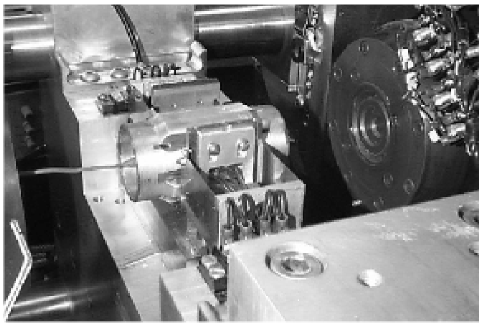

Figure 3. Shaker moving element and right magnet showing center port for laser beam access

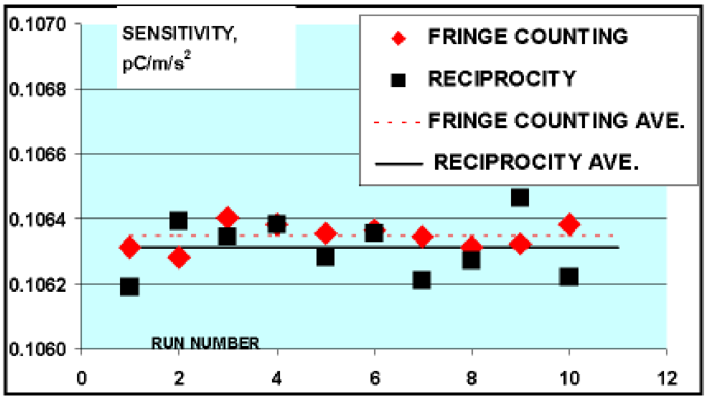

Figure 4. Fringe counting and reciprocity calibration of a single-ended accelerometer