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Laser Interferometer and Reciprocity Calibration of Accelerometers Using the NIST Super Shaker

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Abstract

The development of the NIST Super Shaker permits calibration of accelerometers by two independent and absolute methods on the same shaker. Minimizing the uncertainty of reciprocity calibrations imposes stringent requirements for distortion and cross-axis motion. Laser interferometer calibrations require very low coupling between the shaker and the interferometer components. The design of the Super Shaker provides for very low distortion and cross-motion with very low mechanical coupling between the shaker and optical components. The shaker is equipped with dual coils and two retractable magnets to provide for reciprocity measurements without attaching a driving shaker. These features enhance the convenience with which the Super Shaker can be used to perform both reciprocity and laser interferometer calibrations. This paper describes the shaker and calibration system and gives a comparison of calibration results from the two methods.

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

1. Introduction

A new Super Shaker system for calibration of accelerometers at NIST was designed in 1993, and its initial testing was finished in 1995[1]. A principal goal of this design is to reduce the uncertainties of accelerometer calibrations. This paper gives the results of additional testing and the implementation of two absolute calibration methods on the Super Shaker. The fringe-counting method uses the wavelength of a He-Ne laser light as a reference standard and the reciprocity method uses a set of standard masses as a reference standard.

The shaker, shown in figure 1, has dual retractable magnets equipped with optical ports for easy access of laser beams for interferometric measurement of accelerometer motion. Physically compact for purposes of directional stability and high-frequency response, the moving element is equipped at each end with 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 no additional driving shaker is needed, the Super Shaker design eliminates complications due to the coupling between two separate shakers that would otherwise be required. The implementation of two independent absolute calibration methods will provide a better indication of overall uncertainty.

Low distortion and low cross axis motion are essential for reciprocity measurements. The Super Shaker was designed 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 30 µm (0.001 inch.)

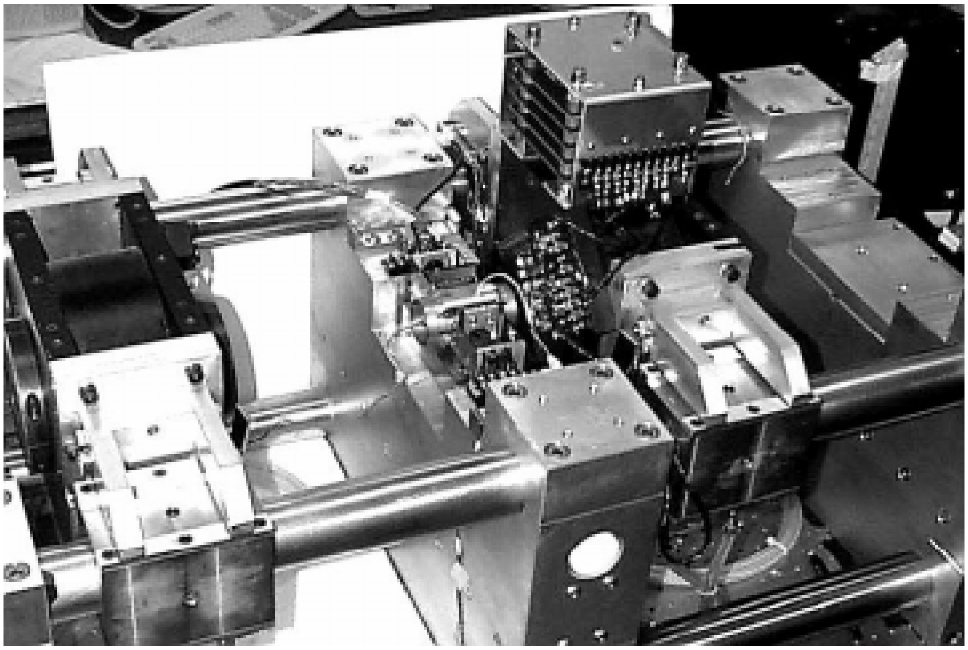

Figure 1. NIST Super Shaker

Among the other critical factors addressed in the design of the Super Shaker were:

- Magnet dimensions, especially the air gap size, roundness, symmetry, and finish.
- Moving element dimensions, including diameter, symmetry, and roundness.
- Position and repeatability of position of the moving element in the magnetic gap assembly.
- Symmetry of coil windings and uniformity of coil wire.
- Suspension system for the moving element in the magnetic gap assembly.
- Isolation of critical parts of the shaker to prevent cross coupling of various vibrating parts of the assembly.

The Super Shaker 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. Super Shaker Reciprocity Calibration

The accelerometer sensitivity (S) is given by[2]:

$$S = \left[\frac{JR}{2\pi\ f} \right]^{1/2}$$

where J and R are parameters derived from the results of two distinct measurements, and f is the test frequency in Hertz.

The first measurement is obtained by driving one coil and using the other coil as a velocity sensor. In Figure 2, the setup is configured to use the right coil as the driver and the left coil as the velocity coil. With no mass attached, the right coil is energized at a desired frequency and level of acceleration. The voltage ratio, R, is the result of dividing the accelerometer output voltage by the velocity coil output voltage at the frequency f.

The second measurement is obtained by using the left coil as a driver coil, as shown in figure 3,and measuring the transfer admittances, Y, between driver-coil current and accelerometer output voltage for six values of mass loading of the accelerometer and moving element. Each value of Y is calculated by dividing the driver-coil current by the accelerometer output voltage.

Zero mass admittance Y_0 is measured both before and after each mass is attached to one of the mounting tables of the shaker. Parameter J equals the zero intercept of a linear fit of mass/(Y_m-Y_0) vs. mass.

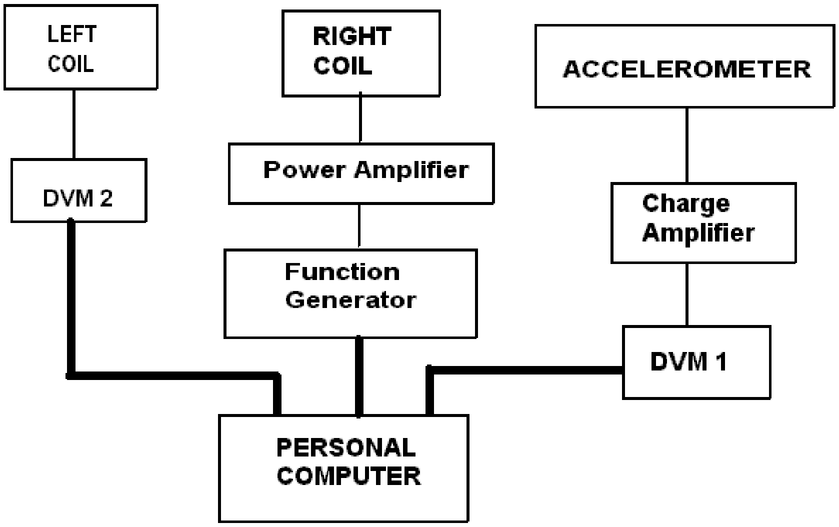

Figure 2. Diagram forReciprocityVoltage Ratio Measurements

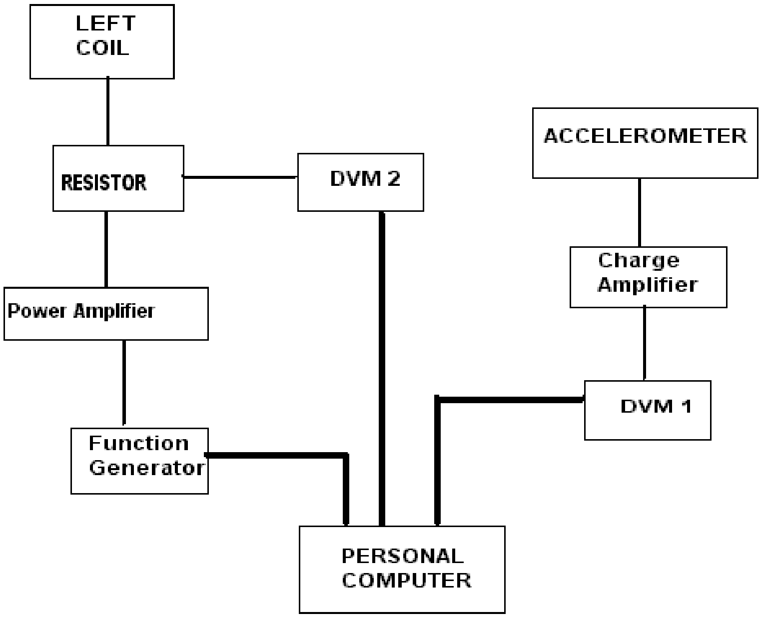

Figure 3. Diagram for Reciprocity Transfer Admittance Measurements

2.1 Critical Factors

1) One critical element is the position of the velocity coil in the magnetic field. 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 attaching each mass. This problem is circumvented by allowing a few minutes for the axial position to stabilize after changing a mass and before the measurement of the transfer admittance Y is taken.

2) Temperature should remain constant so that the physical dimensions of the shaker will remain constant and the resistor used for current measurements will not change resistance. For greater stability, the coil is energized at about 1g_n* 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 ^{o}C.

3) In the reciprocity measurements, the 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. Care must be taken to ground both reciprocity circuits at a single point. Both coils are electrically isolated from the shaker frame and each other, but the moving element frame has a common ground with the shaker frame. The shaker frame is electrically connected to the metal table top of the isolation table. The metal table top is connected to a conduit connected to to earth ground. The accelerometer case is grounded by attachment to the shaker moving element. For both transfer admittance and voltage ratio measurements, the function generator, power amplifier, computer, charge amplifier, and voltmeters are all isolated from ground.

In the voltage ratio measurements, the left coil is grounded to the chassis of the shaker frame, which is connected to the steel isolation table top. In the transfer admittance measurements, the series resistor is attached with a short lead close to the left coil. A very short metal link grounds the junction of resistor and the left coil to the shaker frame. This provides a single point ground to the shaker frame.

Reciprocity calibrations are performed at low accelerations, typically one to two g_n, in order to minimize heating effects. This results in measured voltages typically five to a few hundred mV. The two digital voltmeters are placed close to the moving element so that the connecting cables can be kept short.

3. Super Shaker Laser Interferometer Calibrations

Figure 4 shows the laser interferometer[2] utilized on the right side of the shaker. In this case a corner cube retro-reflector is mounted on the right shaker table. The Super Shaker design allows optical access to the shaker mounting tables through a center hole in the magnets as shown in figure 5.The acceleration in meters/s^2 is given by:

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

where λ= wavelength of He-Ne laser light in meters,
ν = number of fringe counts per vibration cycle

To provide additional displacement, both the right and left coils are energized.

* The unit g_n used in this paper refers to the standard value of acceleration due to gravity, $g_n = 9.80665$ m/s^2.

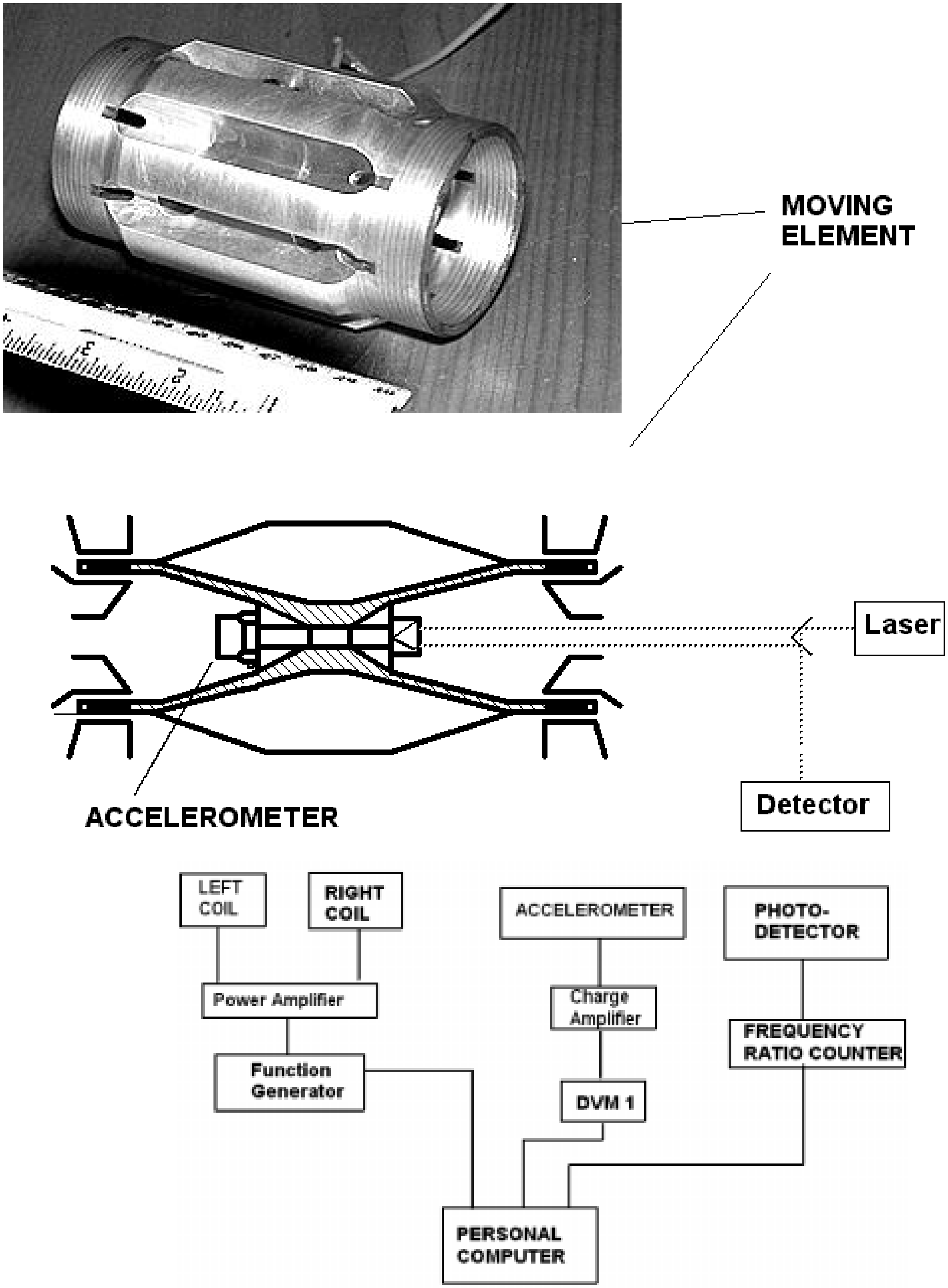

Figure 4. Fringe-Counting Test Setup

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 shaker and interferometer components. The shaker system was designed to minimize this coupling. The moving element of approximately 225 g is very small compared to the magnet mass of approximately 68 kg to minimize magnet movement. The shaker system is installed on an air isolation table to minimize the effects of floor movements.

Measurements made with a seismic accelerometer indicate the table horizontal movement is about 500 μg_n for a moving element movement of 1 g_n at 100 Hz. This is approximately 0.05 % transmission from moving element to the table.

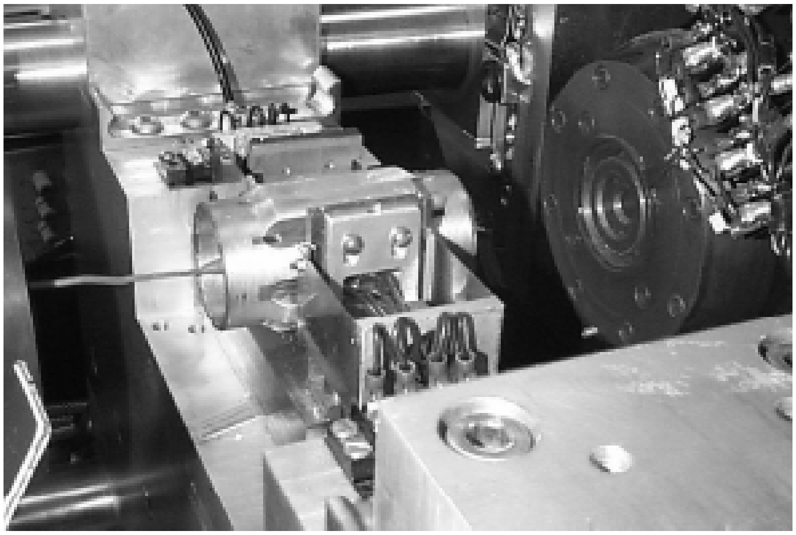

Figure 5. Super Shaker Moving Element and Right Magnet Showing Center Port for Laser Beam Access

4. Experiments

4.1 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 commercial ones commonly used as laboratory standards.

Experiments were conducted with the temperature and positioning stabilizing techniques described in 2.1. Interferometric calibrations were also performed on the same accelerometer before remounting, to get comparison results. The accelerometers were removed and remounted and both reciprocity and interferometric measurements repeated to reveal any effects due to mounting differences.

4.2 Results

The results from the top mounted connector unit at 100 Hz are shown in figure 6. The 100 Hz frequency was chosen to be within the best possible range of the shaker. The maximum spread in all data is about 0.2% and the averages for each of the two methods show that reciprocity and fringe-counting agree to within 0.1%. Testing the side mounted connector unit has not been completed, but the preliminary results show similar agreement.

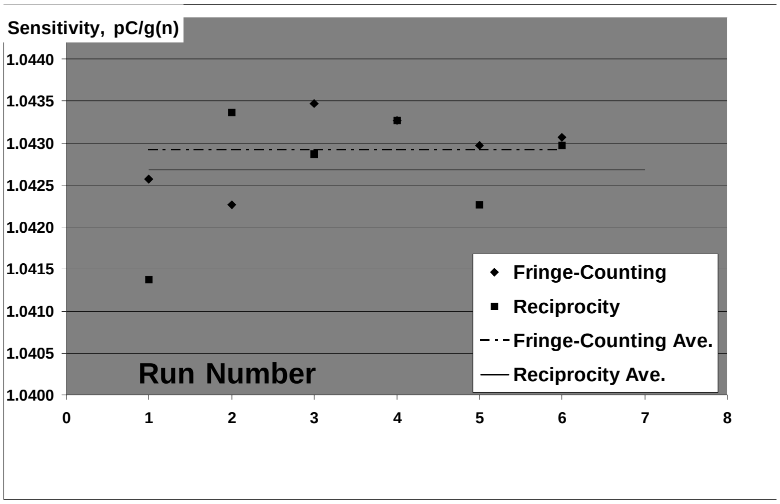

Figure 6. Results of Fringe Counting and Reciprocity Calibration of a Single-Ended Accelerometer on NIST Super Shaker

5. Summary and Conclusions

The Super Shaker system developed at NIST has capabilities for fringe-counting and reciprocity calibrations of laboratory standard accelerometers. 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 for reciprocity and the retro-reflector for the interferometer measurements. The setup provides for temperature monitoring and control within 0.2 degrees C for greater stability. The shaker has low harmonic distortion, with total harmonic distortion not greater than 0.2 % and cross-axis motion under 1%, at 100 Hz.

Data from a limited number of tests indicate that any given data point from reciprocity should agree within about 0.2 percent with the interferometer data. Repeated averaging over a period of days should produce results that give agreement within about 0.1 percent. Since the principal sources of error in the two calibration methods are significantly different, agreement between the two methods could indicate the overall uncertainty limits attainable using current hardware.

Prospects for improving the accuracy of the Super Shaker system are presently limited to a narrow band of frequencies. This is primarily due to 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

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