ACCELEROMETER CALIBRATION AT NBS/NIST:
THE LAST THIRTY YEARS

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This paper gives a short history of the development of the accelerometer calibration services at NBS/NIST from the mid-1950s to 1996. Many people were involved in the research and development that has led to the present calibration services. The references cited at the end of this article provide a listing of most of the significant results of this research and development.

INTRODUCTION

NBS/NIST has been involved in accelerometer calibration since the mid-1950s. Shakers with pure uniaxial sinusoidal motion are needed in order to accurately calibrate accelerometers. The development of the shakers occurred along with the development of calibration methods. Accurate reciprocity calibrations could not be performed until low distortion, low cross-axis shakers were developed. Likewise, accurate interferometer calibrations could not be performed on the piezoelectric shakers until new wide-band, low distortion shakers were developed. The development of shakers to provide good motion, and methods to measure the motion continues at NIST. The Super Shaker Project described at the end of this paper, is the latest project to improve the calibration services.

Figure 1. Dimoff air bearing shaker with ceramic moving element.

EARLY LOW FREQUENCY WORK

During the 1950s, Bouche and others developed a reciprocity method to calibrate shakers and vibration pickups. This development relied on a commercial shaker with a built in velocity coil and a mounting table for attaching pickups to be calibrated. By modifying the suspension system to replace metal flexure plates with steel wires in tension, he was able calibrate these commercial shakers by reciprocity over a frequency range of about 10 Hz to 2000 Hz. There were some frequency bands which had unacceptably large cross-axis motion. The basic design of these shakers limited their usefulness to frequencies up to about 2000 Hz [1].

In the early 1960s there was a major effort to improve the shaker performance and to extend the useful calibration frequency range. In 1963, Ted Dimoff retrofitted an existing commercial shaker with air bearings for the moving element. This resulted in greatly reduced cross-axis motion, and calibrations were possible for most frequencies in the range of 10 Hz-2000 Hz. Optical calibration by fringe disappearance [2] was also possible over a limited frequency range. By 1966, a new shaker, using the air bearing suspension, a ceramic moving element, and a permanent magnet had been developed at NBS by Dimoff . This new shaker, called the Dimoff 100, reduced cross-axis motion to less than 2 %, and harmonic distortion to 1 to 2 %, over the range of 20 Hz to 5000 Hz. This permitted reciprocity calibration over this frequency range. The new shaker used an internal accelerometer instead of a velocity coil. The internal accelerometer was better suited to accelerometer calibrations than the velocity coil, since most vibration pickup calibrations at NBS were for accelerometers. This shaker and the associated improvements in the reciprocity procedures provided a 1 to 2 % calibration uncertainty from 10 Hz to 5000 Hz, instead of the previous 10 Hz-2000 Hz (with some missing frequencies), using the old shakers [3]. By 1968, NBS had developed the Dimoff 200 series of shakers. These shakers extended the range to 10 Hz-10,000 Hz [4].

Until about 1964, the vibration work at NBS was performed by people in two distinct organizational units. The low frequency work (10 Hz-2000 Hz) was developed in the Engineering Mechanics Section and used electrodynamic shakers (coil and magnet). The higher frequency work (3000 Hz-10,000 Hz) had been developed in the Sound Section and used piezoelectric shakers. About 1964 the two groups were combined and became the Vibration Measurement Section, in the Mechanics Division. In 1968, the Vibration Section and the Sound Section moved into laboratories in the new Sound Building on the Gaithersburg campus.

Figure 2. Automated accelerometer calibration system (1971).

By 1967, the process of reading instruments was automated [5] so that numerical data was recorded directly on paper tape at the press of a button. All steps of the calibration procedures still required the direct control of a human operator. The data was processed on a remote-site computer and results transmitted back to the lab and recorded in printout form. The advent of time-shared computers made a tremendous impact upon the work of the laboratory. One person could now perform a reciprocity calibration (at a single frequency) and have the data processed in a few minutes. Previously the use of an electromechanical calculator required 4 to 6 hours for a single calibration point.

An even larger impact resulted from the availability, by 1968, of the on-site laboratory minicomputer. In 1971, NBS completed its first automated accelerometer calibration system (10 Hz to 10,000 Hz capability) [6]. No human intervention was required during the course of a calibration. The minicomputer used by this system was programmed in hexadecimal machine language. This comparison system was for high demand measurements. It was based on comparison to an internal accelerometer previously calibrated by reciprocity, and its full automation dramatically affected day to day operations. Further automation of calibration systems awaited the availability of high level languages, larger memories, the IEEE-488 bus, and software for graphics and printed reports.

EARLY HIGH FREQUENCY WORK

In the 1950s and early 1960s, piezoelectric shakers were developed at NBS. Also, calibration techniques were developed to measure displacement of vibration pickups using the new shakers. In 1955, Edelman, Jones, and Smith applied the fringe disappearance technique, using a Fizeau interferometer [7], to calibrate accelerometers at discrete amplitudes of vibration. They also constructed barium titanate accelerometers and used the new technique to obtain calibration data in the range of 50 Hz - 10 kHz. The human eye was used to determine fringe disappearance. By 1961, the human eye had been replaced by a photomultiplier tube [8]. The interferometer was improved in 1962 by adding modulation to the stationary glass plate of the interferometer [9], resulting in greatly improved resolution. Improvements in the shakers continued and in 1969, a shaker was developed for wide-frequency range calibrations. By using a combination of damped resonant ceramic cylindrical elements, the shaker had good motion up to 50 kHz [10].

Figure 3. Late 1950s setup for fringe-disappearance calibration using Fizeau interferometer

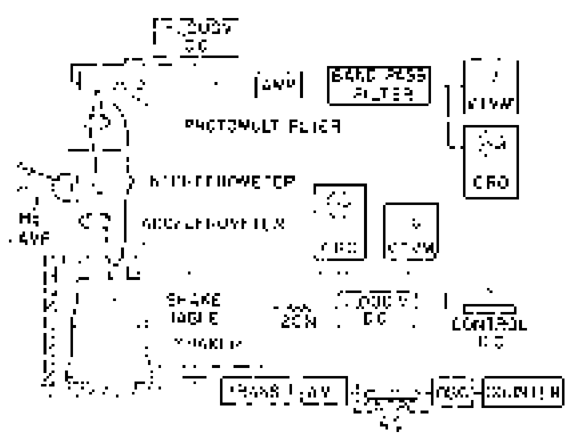

Figure 4. Block diagram of photometric calibrator (1961).

LATER HIGH FREQUENCY WORK

Figure 5. Wide-frequency range piezoelectric shaker

During the early 1970s, the mercury lamp for the interferometer was replaced by a helium neon laser, which gave more stable and well defined single-wavelength light. Because the laser could be positioned more remotely from the optics, its use allowed the Michelson interferometer configuration [11] to be more easily applied to vibration measurements than the Fizeau configuration. The new interferometer configuration was favored because it was compact and simpler to set up and align. The compact design eliminated the large supporting structures (figure 6) causing unwanted vibrations in the previous design. It also readily accommodated a small piezoelectric driver needed for modulation of the reference mirror, which was necessary for full automation of this measurement procedure.

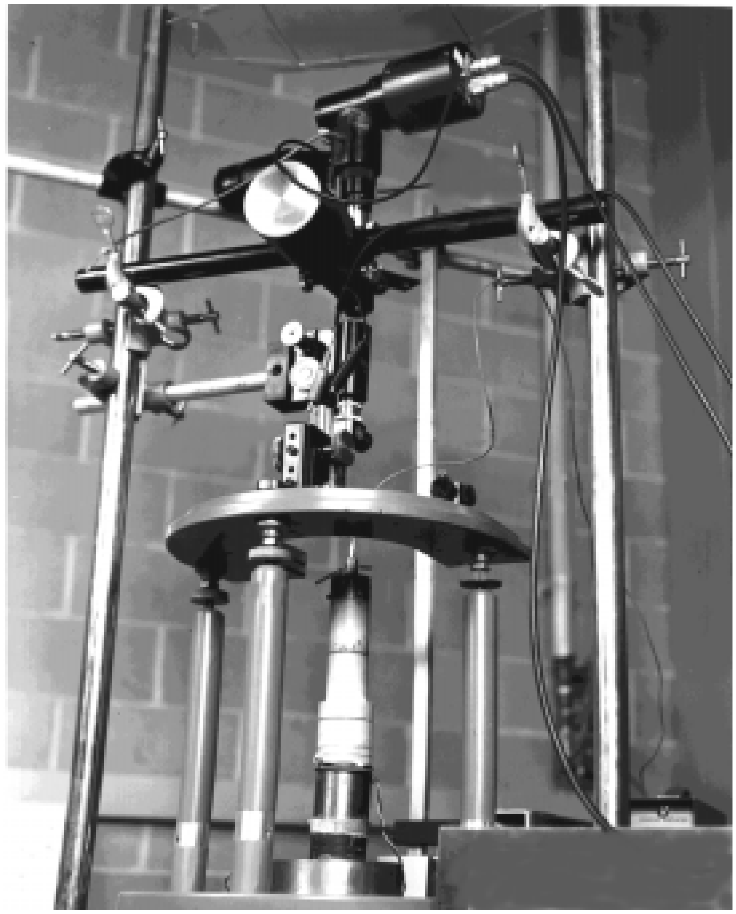

Figure 6. The Fizeau laser interferometer

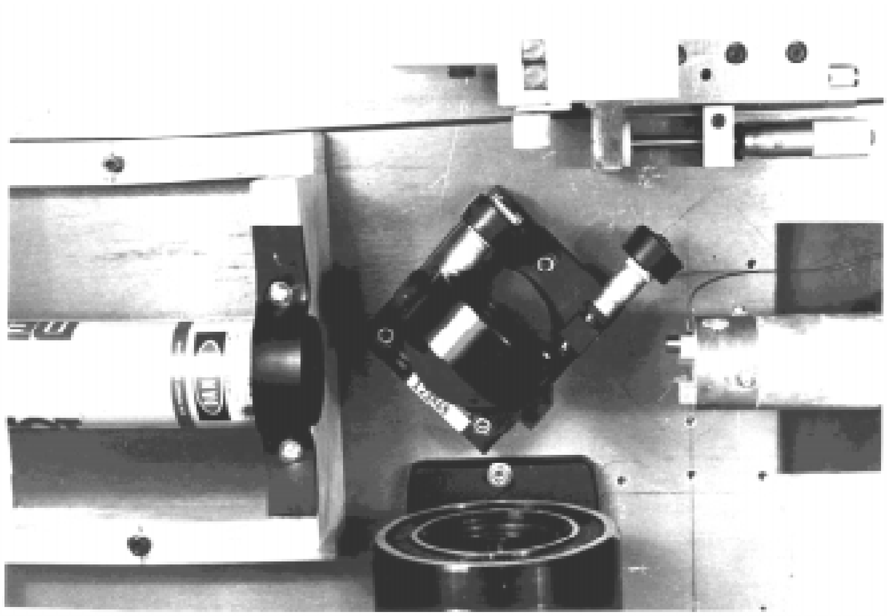

Figure 7. The modulated Michelson interferometer.

By the early 1980s laboratory computers could be programmed using BASIC, and were evolving into an important tool for the laboratory.

These computers were connected to equipment using the IEEE-488 bus, and experiments were readily automated. By 1984, a measurement technique had been developed to automate the fringe disappearance interferometer [12]. The system for determining the fringe disappearance condition used a reference mirror which was mounted on a small piezoelectric shaker. The small shaker was excited at a frequency of about 0.5 Hz and served as a modulation source to improve the resolution of the interferometer. The measurements no longer involved the use of a wave analyzer tuned to the driving frequency. Instead, the only measurement necessary for determining the disappearance condition is the rapid sampling of the voltage from the photo detector, as the fringes move past the detector. These fringe movements are caused by the motion of the reference mirror. Under computer control, 100 samples are obtained for each increment of the drive voltage. Fringe-disappearance is detected by the onset of minimum fringe contrast. This makes possible complete automation of the calibration process. The interferometer measures the disappearance at 121.1 nm (zero to peak), and calibrations of lightweight accelerometers (up to 10 g) are possible up to 25 kHz and calibrations up to 20 kHz are possible for heavier accelerometers (up to 25g).

LATER LOW FREQUENCY WORK

The comparison calibration first automated in 1971 was improved in the early 1980s by the use of a laboratory computer using BASIC. Although the computers then available provided a convenient tool for instrument control, their usefulness for data processing, graphical representations, and printing reports was subject to significant limitations. Documentation only came from the manufacturer, and third party software was not readily available. With the advent of the PC in the mid 1980s, many tools became available such as the spreadsheet, word processors, graphical tools, and data analysis programs. In 1990, NBS switched to a PC-based calibration system [13] for comparison calibrations and for the reciprocity calibration of shakers. This greatly increased the efficiency of the calibration process, primarily because of the spreadsheet and graphical capabilities of the PC.

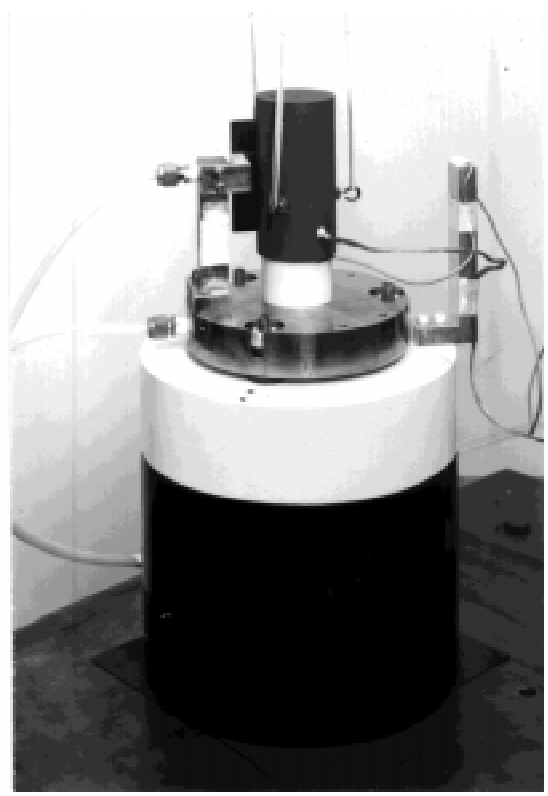

Figure 8. Low Frequency Shaker

By 1975, a low frequency (2 Hz - 50 Hz, later extended to 160 Hz) calibration shaker had been developed at NBS. An optical calibration system was developed using a laser interferometer and fringe counting [14]. This calibration system was a manually operated . The long-stroke shaker had an internal servo accelerometer. The servo accelerometer was calibrated by fringe counting, and test pickups were calibrated by comparison to the internal pickup. One of the problems encountered in the low frequency calibration was measurement of low amplitude, low frequency voltage from the test pickup. The use of analog differential voltmeters was time consuming, and was not conducive to automation. NBS did not offer a absolute low frequency calibration until a method for automation was developed. In 1986 an automated system [15] was completed, and in 1987 a software signal analysis technique using parameter estimation [16] made possible accurate voltage measurements at low frequencies and low amplitudes. Voltages as low as 1 mV (with a S/N ratio as low as 10) could be accurately measured by mathematically reconstructing the pickup voltage sampled by a digitizing voltmeter. This was only possible with the use of a high resolution digitizing voltmeter. These developments made possible an absolute calibration service at NBS for low frequency accelerometers.

BACK TO BACK CALIBRATION METHODS

Back-to-back accelerometers became widely used in the early 1980s, and required accurate calibrations. Methods were developed to calibrate these pickups by interferometry. This type of pickup is generally used to calibrate another pickup mounted on the top surface. Therefore, in calibrating these pickups, the other pickup is simulated by a loading mass mounted on the top surface of the back-to-back pickup. Holes in the mass were provided so that the laser light reflected from the top surface of the accelerometer. This is possible only with the laser light source, since the light source must be highly collimated. Back-to-back pickups were calibrated over the frequency range of 3kHz - 15 kHz using this arrangement [17-20]. Later measurements [21] were made for masses from zero to 58g and frequencies to 20 kHz, and mass loading coefficients were calculated.

SUPER SHAKER PROJECT

In an effort to improve the accuracy of the NIST calibration service, a project was started in 1991 with funds from the CCG (Calibration Coordination Group of the US defense agencies). The super shaker project is an effort to build a new shaker and calibration system using the best available technology. The new shaker is designed with a dual-coil moving element and dual permanent magnets, so that the reciprocity technique can be used to calibrate accelerometers. The shaker operates with the axis of motion horizontal. Conventional shakers with one coil and magnet were not suitable for direct reciprocity calibration of accelerometers. The Dimoff air bearing shakers use an internal accelerometer and require an external shaker to be attached each time a reciprocity calibration is performed.

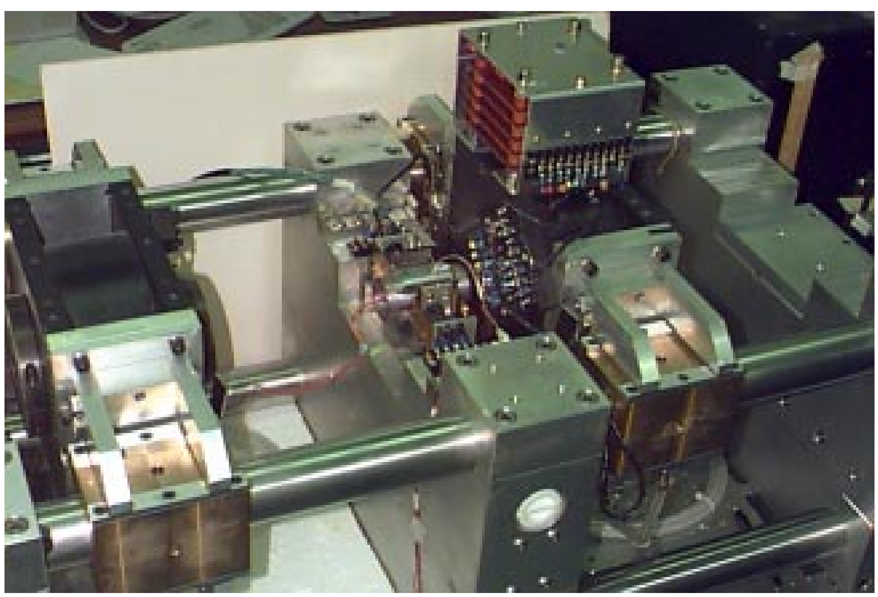

Figure 9. Dual coil super shaker

In the super shaker, the two magnets are permanently attached to an air bearing slide, and can be slid in and out from the coils without requiring realignment. Accelerometers can also be calibrated by laser interferometry by attaching a mirror to one of the mounting tables. The first phase of this three-phase project was completed in 1995, and calibrations were performed by reciprocity and laser interferometry. A polarized fringe-counting interferometer is being built, and will double the resolution of the conventional interferometer. The new shaker has very low harmonic distortion and cross-axis motion over most of its range [22]. For example at 100 Hz, a typical reference frequency, typical harmonic distortion and cross-axis motion are each less than 1% and coupling between moving element motion and pedestal holding the interferometer is less than 0.1%. The improvements in shaker design and calibrations techniques will result in improved calibration accuracy.

TIME LINE FOR NBS/NIST ACCELEROMETER CALIBRATION DEVELOPMENTS

1955 Fringe-disappearance calibration method developed

1956 Reciprocity calibration developed for electrodynamic shakers

1961 Photomultiplier used for interferometer calibration at small amplitudes

1962 Interferometer modulation developed with improved resolution

1966 Dimoff air-bearing shakers developed for 10 Hz-5000 Hz calibration

1968 Dimoff air-bearing shakers improved to extend range to 10 kHz.

1969 Piezoelectric shakers developed for high frequency calibration

1971 Comparison calibration first automated using dedicated lab computer

1975 (approx.) Helium-neon laser replaces mercury lamp in the interferometer

1975 Fringe-counting interferometer developed for low frequency (~2Hz) accelerometer calibration

1978 Michelson fringe-disappearance interferometer developed for high frequency accelerometer calibration

1982 Back-to-back laser interferometry calibration techniques developed

1984 Automated laser fringe-disappearnace interferometer developed

1986 Low frequency (~ 2 Hz) fringe-counting laser interferometer calibration automated

1987 Low frequency calibration uses parameter estimation for improved signal analysis.

1990 PC control of comparison calibration of accelerometers and reciprocity calibration of shakers

1991 Super Shaker project started

1995 Super Shaker Phase One completed, dual-coil reciprocity and fringe counting laser interferometer, higher accuracy calibrations

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