Improvements in Accelerometer Calibration at NIST Using Digital Vibrometry

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Improvements in shaker design and laser vibrometers have provided more precise calibration of accelerometers at NIST. Calibrations are performed at frequencies from less than 1 Hz to 20 kHz with improved uncertainty and improved efficiency compared to the former systems. The vibrometer mounting hardware is designed for easier and repeatable optical alignment at multiple unique reference positions on the shaker's mounting table. Calibrations using this system, which is now used for the NIST routine calibration service, show excellent agreement with traditional NIST calibrations obtained using the laser interferometer methods that were developed at NIST. The legacy NIST laser-interferometer system uses a shaker with a beryllium mounting table insert, while the vibrometer-based system uses multiple shakers to cover the desired frequency range. For high frequencies (10 Hz to 20 kHz), a shaker with a ceramic mounting table is used; this ceramic table is designed to reflect the laser beam without requiring a mirror. For low frequencies (< 10 Hz), a shaker with an aluminum mounting table is used. This system is described and compared with the previous calibration system. Comparison results for accelerometer measurements using the two measurement systems are presented.

INTRODUCTION

Recent improvements in shaker design and the introduction of the laser vibrometer have greatly improved the capacity for routine accelerometer calibrations with much lower uncertainties. This paper will show that the traditional NIST laser interferometer calibration systems are in good agreement with the newer laser vibrometer system at NIST. Both systems were independently used to calibrate two laboratory-type accelerometers and the measurements were found to be in excellent agreement over a range of 100 Hz to 10 kHz.

METHODS FOR PRIMARY ACCELEROMETER CALIBRATION

RECIPROCITY

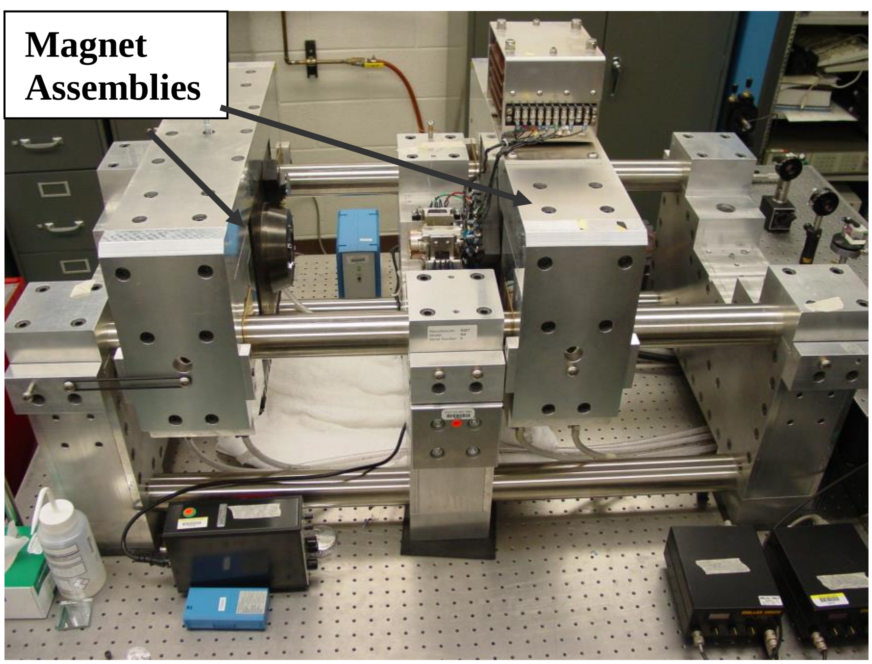


Figure 1a Dual coil shaker for reciprocity and laser interferometry calibrations; dual magnets mounted on air bearings, shown with left magnet retracted to allow access

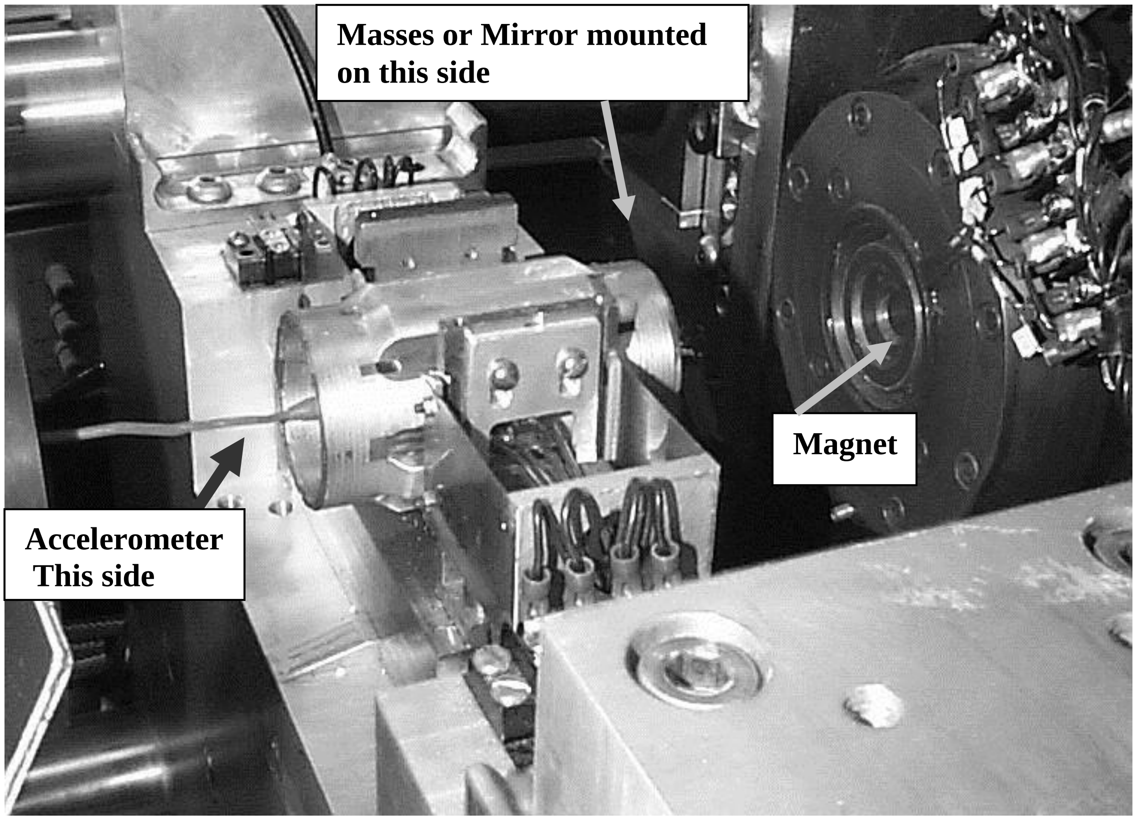


Figure 1b Shaker showing close-up of dual-coil moving element, both magnets retracted for access to the moving element

Reciprocity calibration is documented in ISO 16063-12 as a primary calibration method [1]. It does not involve the use of optical equipment of any kind. The unit of mass is recognized as the fundamental unit of reference for this method. A set of small, calibrated masses are placed (one at a time) on the shaker with the attached or imbedded accelerometer to be calibrated. Measurements of the transfer admittance between the primary drive coil (current) and the accelerometer (voltage) are made with each of the masses. The admittance is a function of the mass value. A second set of measurements is performed between the accelerometer and the driver coil of the shaker (now acting as a velocity coil) to determine the voltage ratio, while the shaker is excited with a secondary shaker (or a secondary coil if the shaker has two coils). With these two sets of data, accelerometer sensitivity can be calculated.

NIST has used a dual-coil shaker (Figure 1) for reciprocity calibrations to avoid the problems of connecting a secondary shaker to the primary shaker [2]. The dual-coil shaker is also designed to be compatible with laser interferometer calibrations for cross validation. Reciprocity requires shakers with very low distortion and cross-axis motion to provide quality accelerometer calibrations. Research has shown that reciprocity calibration is equivalent to optical calibration methods within limits based on the quality of the shakers. [3].

Figure 2 shows results from a comparison of reciprocity and fringe counting calibrations (described below) of an accelerometer at 100 Hz, ten data points for each method. By carefully holding the temperature of the reciprocity system constant, one can get lower than 0.1% difference in sensitivity for the two methods [3].

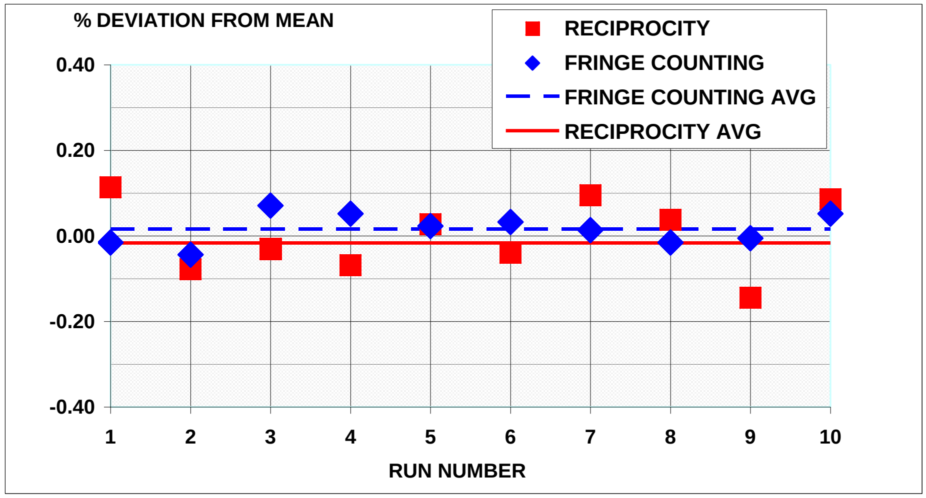


Figure 2. Reciprocity and fringe counting calibration differences

FRINGE COUNTING

Fringe-counting calibration is documented in ISO 16063-11, Method 1, as a primary calibration method [4]. It uses a laser interferometer as shown in Figure 3. Figure 3 shows the schematic for a simple single-coil shaker where the accelerometer is mounted in the center of the shaker table and the reflecting mirror is attached as close to the accelerometer as practical, without contacting the accelerometer.

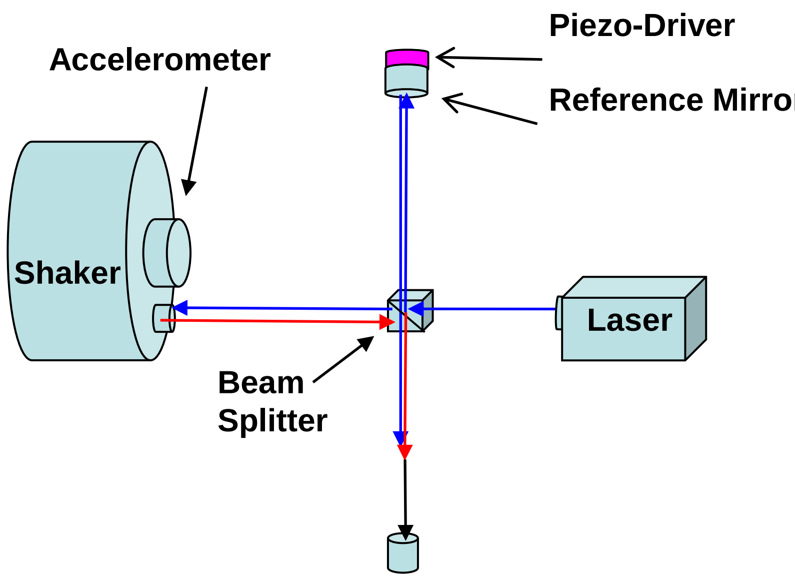


Figure 3. Laser interferometer for fringe-counting and minimum point calibrations

Some shakers now have mounting tables designed to reflect light from any point on the mounting table. For the dual-coil shaker shown in Figure 1, there are two mounting tables facing in opposite directions. A flat mirror is mounted on the shaker table located on the right side of the moving element, opposite the table upon which the accelerometer is mounted. This shaker design allows optical access to the shaker mounting tables through a center hole in the magnet (bottom photo in Figure 1). This shaker system was described by Payne and Steffen [2]. The acceleration, in meters per second squared, is given by

$$A = \lambda \nu \pi^2 f^2 / 2 \tag{1}$$

where λ is the wavelength of He-Ne laser light in meters, ν is the integral number of fringe counts per vibration cycle, and f is frequency in hertz [4].

MINIMUM-POINT METHOD

Minimum Point calibration is documented in ISO 16063-11, Method 2, as a primary calibration method [4]. It uses the same interferometer as the fringe-counting interferometer, Figure 3. 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. In order to reject spectral components present in the output of the photo-detector other than those corresponding to the fundamental frequency of the vibration, the output of the photo-detector is filtered using a narrow band-pass filter centered at the fundamental frequency of the 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 minimum-point calibrations at each tested frequency, the number of the zero crossing was selected to obtain displacements corresponding to accelerations in the range of 50 m/s^2 to 200 m/s^2 based on the capacity of the shaker.

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:

$$\boldsymbol{A = (2 \pi f)^2 d.} \qquad (2)$$

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

As the above method is very time consuming and difficult to automate, NIST has used the Fringe Disappearance Method for many years. This method which is related to the Minimum Point Method above, and consists of finding the first zero-crossing of the Bessel function of first kind of order zero $J_0(4\pi d/\lambda)$. At this displacement the phenomenon of fringe disappearance occurs, and a constant intensity illumination is observed on the photodetector. The implementation of this method is described by Robinson and Payne [5].

SINE-APPROXIMATION METHOD

Sine-approximation calibration is documented in ISO 16063-11, Method 3, as a primary calibration method [4]. Using the setup shown in Fig. 4, calibration data can be obtained using the dual-coil shaker for frequencies up to 1 kHz using fringe-counting, and up to 5 kHz using the minimum-point method by monitoring the output from either Detector 1 or Detector 2. At frequencies higher than 5 kHz, the sine-approximation method is needed because of smaller displacement.

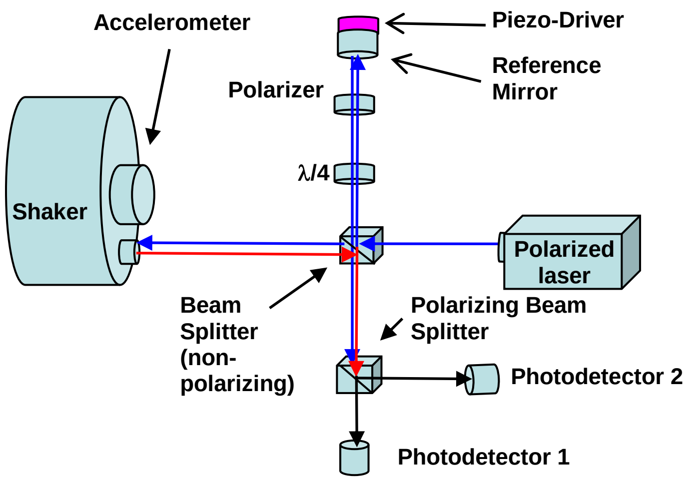


Figure 4. Interferometer for sine approximation

Sine approximation is most useful at higher frequencies where calibrations at smaller displacements must be made due to amplitude limitations in electro-dynamic shakers. In actual practice the sine-approximation method gives good results over a wide frequency range. Typically for the dual-coil shaker shown above (Fig. 1) the sine-approximation method has been used at NIST for calibration of accelerometers at accelerations of 50 m/s^2 to 100 m/s^2 from 100 Hz to 10 kHz, and fringe-counting has been used for frequencies of 100 Hz and below. This range of acceleration is used to minimize the heating effects on the shaker.

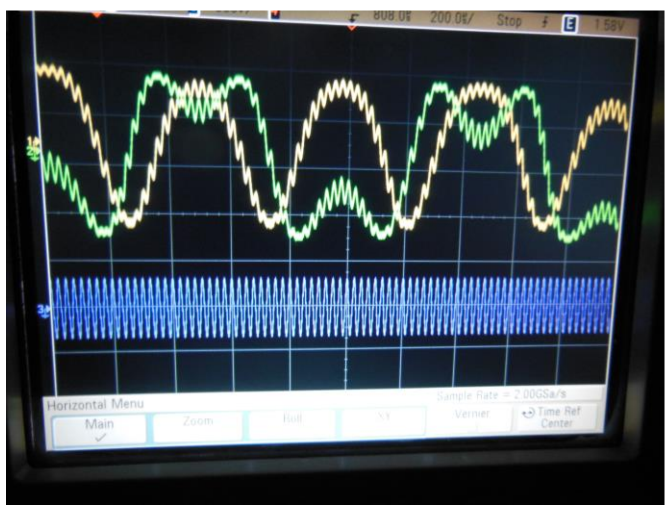


Figure 5. Photo-detector signals in quadrature with 1 kHz modulation on reference mirror. Blue (bottom) trace is accelerometer output.

The sine-approximation method is also used for calibrations that use piezo-electric shakers designed and used at NIST for frequencies of 5 kHz and higher. The small piezo-driver shown in Fig. 4 is used to modulate the reference mirror of the interferometer so that calibrations may be obtained at smaller displacements. Figure 5 shows an oscilloscope display of the two photodetector signals in quadrature with 1 kHz modulation on the reference mirror. The lower trace shows the accelerometer signal.

CALIBRATION USING DIGITAL VIBROMETRY

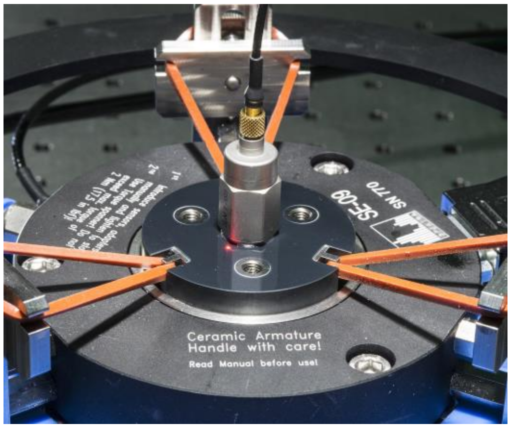
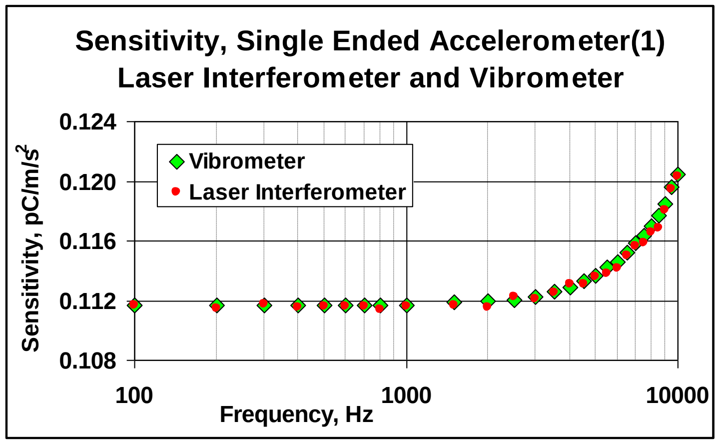


Figure 6. Ceramic shaker for calibration by laser vibrometry. Note the vibrometer laser spot next to accelerometer.

Improvements in shaker design and laser vibrometers have provided more precise calibration of accelerometers. Calibrations can be performed at frequencies from below 1 Hz to greater than 20 kHz with improved uncertainty and improved efficiency. Figure 6 shows a commercial ceramic shaker with low distortion and low cross-axis motion, with an accelerometer mounted for calibration.

The vibrometer is mounted directly above the accelerometer on a suspended mount on an isolation platform. The vibrometer mounting hardware includes a positioning goniometer to allow for alignment of the position of the laser at multiple, repeatable, and unique reference positions on the shaker's mounting table. Measurements are made at multiple – a minimum of three – locations around the accelerometer and this data is averaged to obtain final calibration results. Figures 7a and 7b show calibration measurements for two different single-ended accelerometers, comparing the results using the NIST laser sine-approximation method that uses the dual-coil shaker described above with results on the new laser vibrometer system. The vibrometer is programmed to also use Method 3, sine-approximation for calibration.



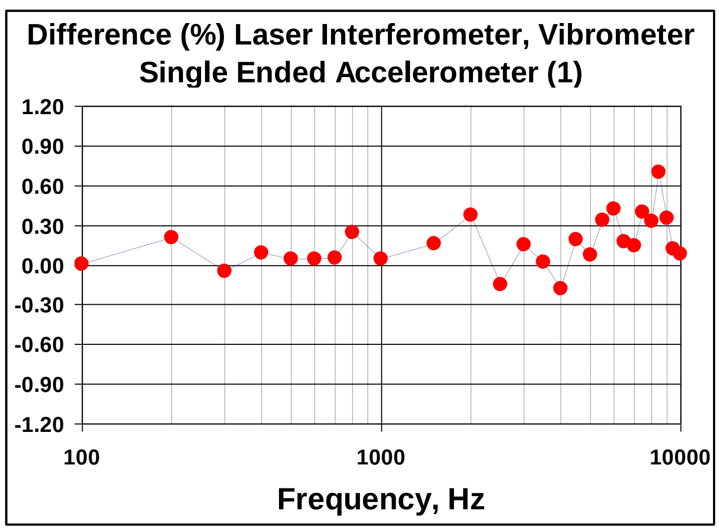


Figure 7a. Calibration results for single ended Accelerometer 1.

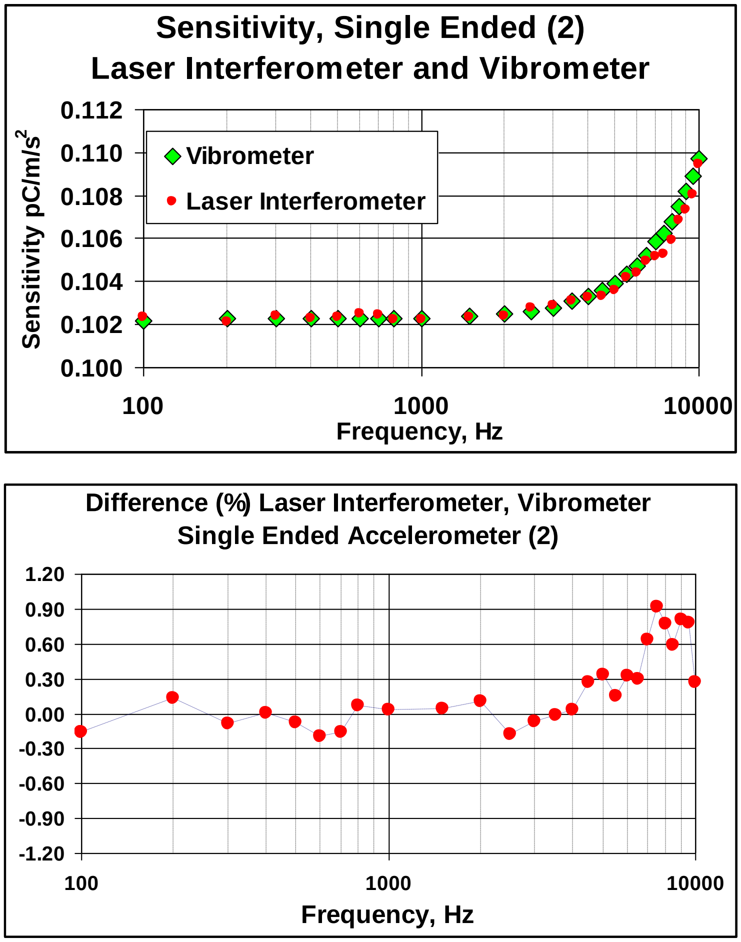


Figure 7b. Calibration results for single ended Accelerometer 2.

For the test results shown in Figure 7, the combined relative uncertainty was calculated in accordance with methodologies described in the Guide to the Expression of Uncertainty in Measurement [6] 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 [6]. Using a coverage factor of 2, the estimated expanded relative uncertainty, *U*, at 1 kHz is 0.3 %.

SUMMARY

The updated vibration calibration system, using ISO 16063-11, Method 3, sine approximation implemented by means of the heterodyne (laser vibrometer) provides many advantages for routine calibration of high precision accelerometers, including

1. Calibration over a wide amplitude and frequency range, 10 Hz to 20 kHz on the high frequency shaker, and < 0.5 Hz to 40 Hz for a low frequency shaker;
2. Automated digital system for ease of use;
3. Accommodates single-ended and ‘back-to-back’ sensors as well as end and side cable connections;
4. Calibration system provides for easy rotation of vibrometer to conveniently allow calibration at multiple points on the shaker table or on the top surface of the ‘back-to-back’ accelerometers; and
5. Significantly reduces calibration time and cost to customers.

This configuration also can measure the phase, and NIST is working to develop an uncertainty budget for this quantity. Once this is complete, phase will be reported alongside the sensitivity in accelerometer calibrations.

REFERENCES

1 Standard ISO 16063-12, “Primary vibration calibrations by Reciprocity,” *International Organization for Standardization*, Geneva Switzerland, 1999.

2 B. Payne and J. Steffen, “Primary Calibration of Accelerometers by Optical Methods, NIST and USAF,” Proceedings SAVIAC, 81st Annual Shock & Vibration Symposium, Oct 25-29, 2010, Orlando, FL

3 B. Payne, and D. Evans, “Comparison of Results of Calibrating the Magnitude of the Sensitivity of Accelerometers by Laser Interferometry and Reciprocity,” *Metrologia*, 1999, 36, 391-394

4 International Standard ISO 16063-11,“Primary vibration calibrations by laser interferometry,” *International Organization for Standardization*, Geneva Switzerland, 1999.

5 D.C. Robinson, M.R. Serbyn, B. F. Payne, A Description of NBS Calibration Services in Mechanical Vibration and Shock, NBS Technical Note 1232, 1987.

6. “Guide to the Expression of Uncertainty in Measurement”, 2nd Ed., *International Organization for Standardization*, Geneva, Switzerland, ISBN 92-10188-9 (1995).