Improvements in Accelerometer Calibration Using Fringe-Counting and Minimum-Point Methods

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Improvements in shaker and interferometer design at NIST have provided more reliable calibration of accelerometers by laser interferometry. A dual-coil shaker provides excitation with low distortion and low cross-axis motion. Calibrations are performed by fringe counting at frequencies from 50 Hz to 1 kHz and by the minimum-point method at frequencies from 1 kHz to 5 kHz. The interferometer design described in this paper provides for easier alignment because a small retroreflector is mounted on the moving element instead of a flat mirror. The small glass retroreflector is securely mounted in a stiff, titanium holder to ensure uniaxial motion at high frequencies. This system requires measurements to be made at only one reflection point on the moving element. Normally data is obtained at three points on the moving element for interferometers with a flat reflecting mirror. Calibrations using this system show excellent agreement at the upper frequencies with calibrations obtained using the fringe-disappearance method that was developed at NIST using piezoelectric shakers for the excitation. Comparison results are presented using the fringe-counting, minimum-point, and fringe- disappearance methods.

INTRODUCTION

This paper describes a calibration system for accelerometers built around a custom designed dual-coil shaker at NIST. This shaker design permits reduced uncertainties in accelerometer sensitivity measurements as a result of lower distortion and lower cross-axis motion of the shaker. This paper is a follow up of one given in October 2001 [1], which gave details of the shaker design. This paper focuses on a redesigned laser interferometer for fringe-counting and minimum-point method calibration of accelerometers. The interferometer uses a stabilized He-Ne laser with a retroreflector (corner cube) mounted on the moving element. It is shown in this paper that calibrations based on this single reflection design give comparable results to the traditional fringe-disappearance method at frequencies up to 5 kHz.

One advantage of this design is that the displacement is only measured at one position on the moving element instead of the three separate positions needed for fringe disappearance. Another advantage is the relative ease of alignment of the interferometer using the retroreflector to reflect the light from the vibrating moving element.

HARDWARE DESIGN

The shaker 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 [1]. Each end the moving element is equipped with nominally identical coils and axially oriented mounting tables, shown in figure 1. Minimal distortion and minimal cross-axis motion are essential for low uncertainty calibrations by interferometry. 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).

A 6.3 mm diameter retroreflector, rather than a flat mirror, is mounted on the moving element for quicker and easier alignment of the interferometer.

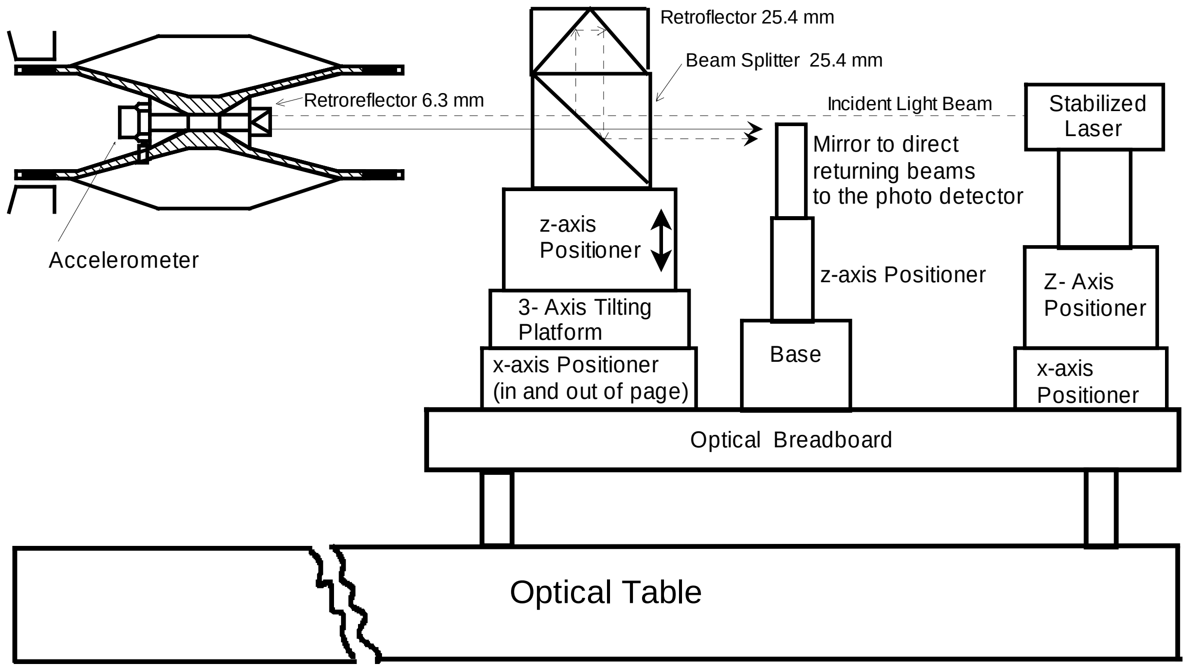

Figure 1. Laser interferometer setup for fringe-counting and minimum-point method calibration of accelerometers

The small retroreflector is mounted on a titanium holder, shown in figure 2, with high strength glue. The top surface of the holder is machined to match the bottom surfaces of the retroreflector. This gives good performance for high frequency calibrations, up to 5 kHz. Figure 3 shows a schematic of the calibration setup for fringe-counting and minimum-point methods.

Figure 2. Titanium holder before and after the small retroreflector was mounted

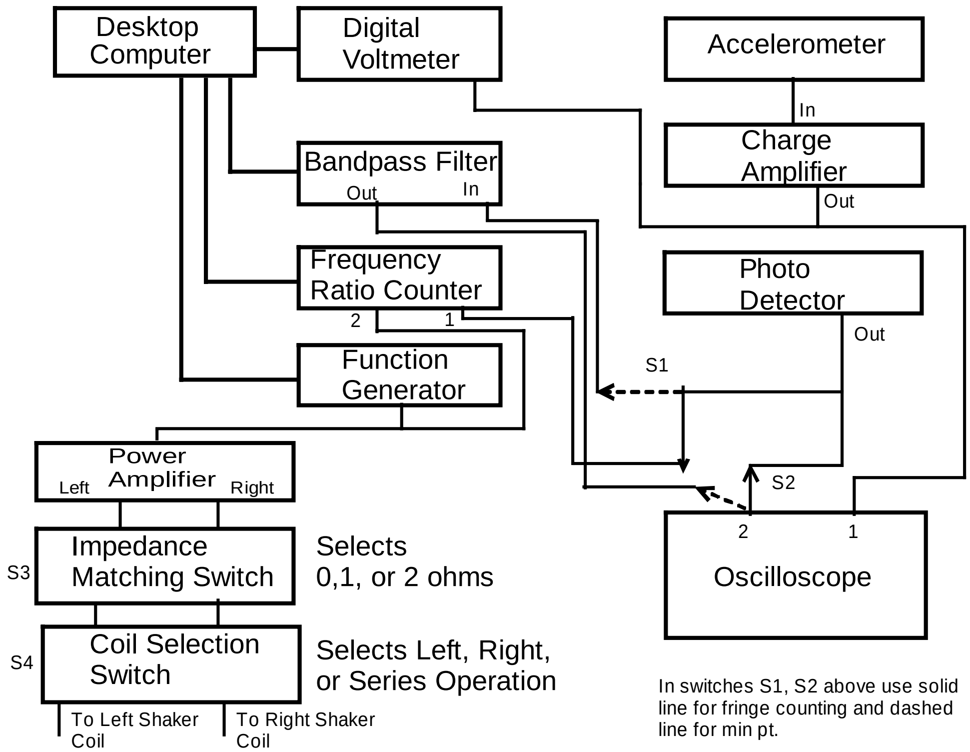

Figure 3. Schematic for dual-coil shaker calibration system

CALIBRATION BY FRINGE COUNTING

The fringe-counting method is based on the ISO International Standard 5347-1 [2]. Figure 1 shows a schematic representation of the NIST implementation of the fringe-counting laser interferometer which is located on the right side of the shaker. Figure 3 (switches S1 and S2 set as the solid line) shows a schematic of the calibration setup for fringe counting.

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, 632.8 x 10^{-9} m, 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 of the shaker can be driven in a push-pull configuration.

Having obtained the acceleration *A*, using fringe counting, the accelerometer sensitivity is calculated by dividing the peak voltage output of the accelerometer under test by the acceleration:

$$S = V_{peak} / A , \qquad (2)$$

where A is given by equation 1 above and S is the accelerometer sensitivity in Volts/m/ s^2. Table 1 shows the approximate number of fringes per vibration cycle, ν, in equation 1 above that correspond to an acceleration of 30 m/s^2 (about 3 g_n*).

* g_n = 9.80665 m/s^2

Frequency (Hz)	Fringes/Vibration Cycle (ν) for 30 m/s^2 acceleration
50	3783
100	933
500	36
1000	8.1

Table 1. Approximate fringes per vibration cycle for typical calibration frequencies

As can be seen from Table 1, the number of fringes per vibration cycle drops rapidly with increasing frequency at a constant acceleration. This yields a practical upper limit of about 1 kHz for fringe-counting calibrations for this system. In order to assure a low uncertainty in the measurement, the frequency counter is programmed to count over whatever interval is necessary to obtain four stable significant digits. Typically this results in sampling times of up to 2 s for calibrations at frequencies over 500 Hz.

Computer control for the fringe-counting calibration

The fringe-counting interferometer is automated using a standard PC computer with an IEEE-488 interface card, connected to the computer with a USB interface. The software program is written in Visual Basic and provides for selection of a preset calibration frequency at a preset acceleration or one may input, via the keyboard, any frequency and any acceleration within the range of the equipment. Another option is to request a series of calibration frequencies that cover the range of 50 Hz to 1 kHz. This option will perform all the calibrations in the preset list of frequencies and print a tabulation of the data at the end of the test. The results of the calibration are also recorded on the hard drive of the computer in a data file along with the date and time of the test.

CALIBRATION BY MINIMUM-POINT METHOD

Above 1 kHz, the minimum-point method is useful. The minimum-point method is also based on the ISO International Standard 5347-1 [2]. Figure 1 shows a schematic representation of the NIST implementation of the minimum-point laser interferometer which is located on the right side of the shaker. Figure 3 (switches S1 and S2 set as the dashed line) shows a schematic of the calibration setup for the minimum-point method.

For the minimum-point method calibration, the signal from the light detector is filtered through a bandpass filter, shown in figure 3, with the center frequency equal to the driving frequency of the shaker. This filtered signal has a number of minimum-points at displacements as shown in Table 2, column 2. After selecting the frequency, f, the shaker amplitude is adjusted to the value at which the filtered light detector signal, after reaching a maximum value, reaches a minimum value. This minimum value is minimum-point No. 1, at which the amplitude is 193.0 nm. Upon further increase of the shaker amplitude, the filtered light detector signal reaches another maximum. Continued increase in the amplitude will produce another minimum at 353.3 nm, minimum point 2 in Table 2. Similarly still other minimums may be obtained by increasing the shaker amplitude as shown in Table 2.

Having obtained a displacement d, the acceleration is calculated using the following:

$$A = (2\pi f)^2 d \qquad (3).$$

The accelerometer sensitivity is then calculated by dividing the peak voltage output of the accelerometer under test by the acceleration:

$$S = V_{peak} / A \qquad (4).$$

For accelerometer calibrations, various amplitudes may be selected up to the limits of the shaker providing the excitation. The NIST dual-coil shaker, using both driver coils, has a maximum acceleration of just over 20 $g_{n.}$ Table 2 shows possible values of amplitudes and all the corresponding accelerations for frequencies from 1 kHz to 5 kHz, which are in the useable range of the NIST dual-coil shaker system.

Min. Pt. No.	**d (nm)**	**f=1000 (Hz)**	**f=1500 (Hz)**	**f=2000 (Hz)**	**f=2500 (Hz)**	**f=3000 (Hz)**	**f=4000 (Hz)**	**f=5000 (Hz)**
1	193.0	g_n=.78	1.7	3.1	4.9	7.0	12.4	19.4
2	353.3	1.4	3.2	5.7	8.9	12.8		
3	512.3	2.1	4.6	8.9	12.9	18.5		
4	670.9	2.7	6.1	10.8	16.9			
5	829.4	3.3	7.5	13.4				
6	987.8	4.0	8.9	15.9				
7	1146.1	4.6	10.4	18.5				
8	1304.4	5.3	11.8	21.0				
9	1462.7	5.9	13.3					
10	1621.0	6.5	14.7					
11	1779.2	7.2	16.1					
12	1937.5	7.8	17.6					
13	2095.7	8.4	19.0					
14	2263.9	9.1	20.4					
15	2412.2	9.7						
16	2470.4	10.3						

Table 2. Displacement amplitudes and acceleration (in shaded areas) for possible minimum-point calibrations for current NIST dual-coil shaker system

Computer control for the minimum-point calibration

The minimum-point method is also partially automated using a standard PC computer with an IEEE-488 interface card, connected to the computer with a USB interface. The minimum-point method is selected from the main menu of the calibration program. One may then select from a list of preset calibration frequencies at a preset acceleration, based on the data in Table 2. Typically, calibrations are performed at accelerations between 3 g_n and 10 g_n, except at the higher frequencies where, even at significantly higher acceleration levels, only minimum-point number 1 may be possible.

After selecting a calibration frequency, the software automatically sets the bandpass filter to the proper settings for filtering the signal from the light detector and sets the function generator to obtain an acceleration slightly lower than that required to reach the minimum point. The user then manually trims the function generator output voltage to obtain a minimum using the trace on the oscilloscope. After the minimum point has been obtained with the use of the oscilloscope, one then clicks on a box in the menu and the calculations are displayed on the computer screen. Data is stored on the hard disk by clicking on the "save to file" box in the menu. The results of the calibration are then recorded on the hard drive of the computer in a data file along with the date and time of the test.

UNCERTAINTY DETERMINATION FOR FRINGE-COUNTING AND MINIMUM-POINT METHODS

The combined relative uncertainty for both the fringe-counting and minimum-point methods 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. For the fringe-counting method, using a coverage factor of 2, the estimated expanded relative uncertainty, *U*, at 100 Hz is 0.3 %. For the minimum-point method, again using a coverage factor of 2, the estimated expanded relative uncertainty, *U*, at 1 kHz is 0.5 %.

COMPARISON OF CALIBRATION DATA OBTAINED BY THREE METHODS

Calibration data for a single-ended accelerometer is shown in figure 4. The accelerometer was calibrated by fringe-counting from 10 Hz to 1000 Hz and by the minimum-point method from 1 kHz to 5 kHz.

Data from a fringe disappearance calibration [4] is also shown in figure 4. The NIST implementation of the fringe disappearance calibration method uses a piezoelectric shaker and has a calibration range of 3 kHz to 20 kHz. This method requires measurements be made at three separate locations on the mounting surface of the shaker and averaging of the resulting data.

The minimum-point calibration shown in figure 4 requires measurement at only one location, because a retroreflector is used instead of a flat mirror for reflecting light from the shaker.
The frequency range between 1 kHz and 3 kHz was previously not implemented at NIST for primary interferometric calibrations. Using the minimum-point method effectively fills in the range between the fringe-counting and the fringe disappearance methods.

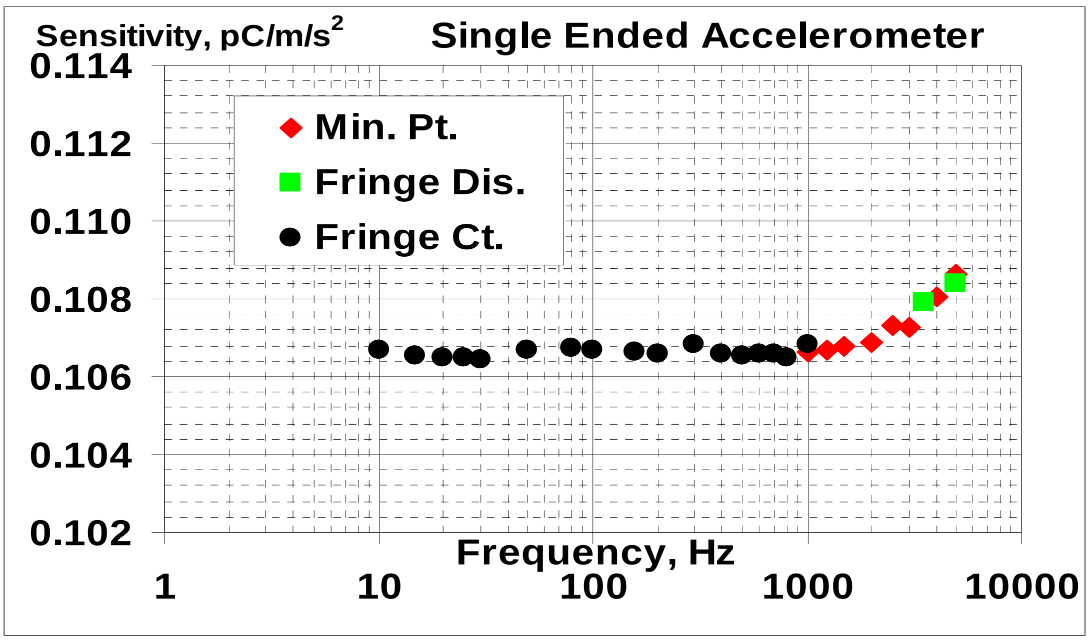

Figure 4. Calibration data for a single-ended accelerometer

SUMMARY

Primary interferometric calibrations of accelerometers can be performed on a dual-coil shaker over a frequency range of 10 Hz to 5 kHz. The measurement system uses a stabilized HeNe laser interferometer with a small retroreflector mounted on the right side of the moving element. The accelerometer under test is mounted on the moving element opposite the retroreflector. The small, 6.3 mm diameter, retroreflector is mounted securely on a titanium base so that calibrations can be performed up to 5 kHz with no degradations in waveform motion due to unwanted retroreflector movements. The measurement system is automated using a standard PC running under Windows XP and is menu driven and written for ease of use by laboratory technicians. Both fringe counting, from 10 Hz to 1 kHz, and minimum point, from 1 kHz to 5 kHz, are accommodated by a simple menu selection. Date and time stamps, together with detailed calibration data are automatically recorded on the computer's hard drive. Cardinal calibration frequencies are listed in the menu. Manual typing of the desired frequency into a menu box can accommodate frequencies within the calibration range that are not available on the menu.

This implementation of the minimum-point calibration required displacement measurements at only one location on the moving element, whereas conventional shaker design with only one mounting table required measurements at three locations. Test results show the single point technique equivalent to the three point technique for frequencies up to 5 kHz.

Company names and products are identified in order to specify experimental procedure adequately. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

ACKNOWLEDGEMENTS

This work was supported in part by the U.S. Air Force metrology center, AFMETCAL, Heath, OH. Alkan Donmez, David Evans, Manny Hahn, and Michael Kennedy, at NIST, gave valuable assistance for this project.

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