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Errors in accelerometer calibration using laser interferometry due to harmonic distortion and cross motion in the applied motion

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Abstract

The development of mechanical vibration generators (shakers) used in the precise calibration of accelerometers requires minimizing the amount of distortion and cross (transverse) motion present in the vibration of the moving element of the shaker. It is well known that both distortion and cross motion can introduce significant errors in the calibration of accelerometers. Potential effects on measured sensitivity due to the presence of harmonic distortion were determined experimentally. Varying amounts of harmonic distortion were systematically introduced into the drive signal of a shaker. Changes in the measured sensitivity of an accelerometer were noted for these varied amounts of distortion and compared with theoretical predictions. Measurements of the sensitivity of an accelerometer were also made using moving elements having varying amounts of cross motion in order to experimentally determine potential effects due to the presence of cross motion on measured sensitivity. The results of this study should be helpful in the development of error budgets for accelerometer calibration systems and in the design of shakers used as a part of such systems.

Keywords: accelerometers, calibration, exciters, laser interferometry, shakers, and uncertainty.

1. Introduction

Recent work at NIST in the area of mechanical vibration has focused on the development of a new calibration system and shaker for the absolute determination of the sensitivity of accelerometers with a relatively small uncertainty[1]. A principal goal in the design of this system was to minimize the sources of error in the uncertainty when determining accelerometer sensitivity. This paper focuses on experimentally investigating the potential effects of harmonic distortion and cross-axis motion on the measured sensitivity of accelerometers using this calibration system. Measurements of the sensitivity of a typical single-ended laboratory accelerometer were made by primary calibration methods using fringe-counting laser interferometry. Measurements of accelerometer sensitivity were repeated using differing amounts of harmonic distortion in the drive signal to the shaker of the calibration system. Effects due to the presence of cross-axis motion on the measured sensitivity of an accelerometer were examined by determining sensitivity over a frequency range where the amount of cross-axis motion present in the vibration of the moving element of the shaker varied as a function of frequency. The results of these tests are given below.

2. Effects of Harmonic Distortion on Measured Sensitivity

A theoretical relative standard uncertainty component, $u(d)$, due to total harmonic distortion may be computed using the following formula obtained from Annex A of ISO 5347-1[2]:

$$u(d) = \tfrac{1}{2}\,(d_{total}/100)^2 \qquad (1)$$

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where d is the total harmonic distortion, in units of percent, present in the mechanical vibration of the accelerometer under test.

Tests were conducted to simulate the effects on measured sensitivity due to harmonic distortion that may be present in accelerometer calibration systems. An accelerometer was calibrated at 100 Hz with varying amounts of second and third harmonic distortion added to a low-distortion sinusoidal signal.

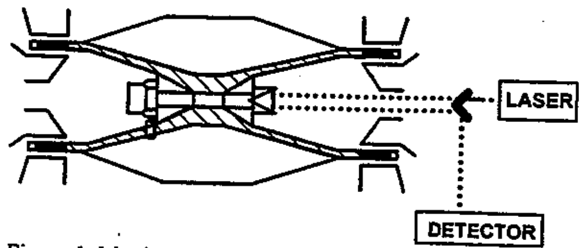

Figure 1 Moving element of the shaker configured for fringe-counting with a corner-cube reflector the shaker.

Figure 1 contains a schematic representation of the moving element of the shaker as it was configured for determinations of sensitivity in the presence of various amounts of harmonic distortion. A laser interferometer [3] was arranged to sense the motion of a corner-cube retro-reflector (shown in Figure 1 installed on the right-hand side of the moving element opposite the accelerometer under test).

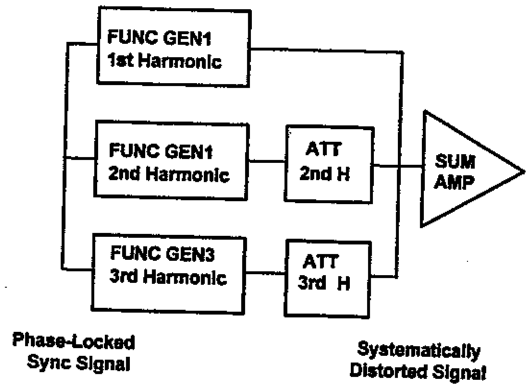

Figure 2 Harmonic distortion

Figure 2 is a block diagram of the instrumentation used to systematically vary the total harmonic distortion present in the drive signal to the shaker of the calibration system. This instrumentation was used in place of the function generator (FUNC GEN 1) normally used to provide a low-distortion sine wave to drive the shaker. In the case shown in Figure 2, FUNC GEN 1 produced both the 100 Hz fundamental sine wave (1st harmonic) of the waveform driving the shaker and a square wave that was synchronous with the fundamental. The square wave provided the reference frequency and a signal from which to obtain phase lock for the function generators providing the 2nd and 3rd harmonics of the fundamental (FUNC GEN 2 and FUNC GEN 3, respectively). The function generators providing the 2nd and 3rd harmonic components were followed by variable stepped attentuators (ATT 2nd H and ATT 3rd H) to enable repeatable adjustments of the amplitude of these signals relative to that of the fundamental. The 1st, 2nd and 3rd harmonic components were summed and amplified (SUM AMP). The amplified voltage supplied the input stage to a low-distortion power amplifier that in turn energized the shaker. The phase of each of the higher order harmonics could be adjusted independently relative to that of the fundamental. Two phase relationships were arbitrarily selected from the infinite number of possibilities. The first phase relationship was with the positive zero crossing of the fundamental in phase with a positive zero crossing of the higher order harmonics. The second phase relationship was with the phase of the higher order harmonics shifted relative to the first case such that the positive peak of the fundamental was in phase with a positive peak of each of the higher order harmonics; this was a phase shift of 45° of the fundamental, or 1.25 ms, in the case of the 2nd harmonic, and a phase shift of 60° of the fundamental, or 1.67 ms, in the case of the 3rd harmonic. In the legend of Figure 3, the first and second phase relationships are indicated by Ph(0) and Ph(90), respectively, with the 0 and 90 indicating the point at which, with respect to the phase of the fundamental, the harmonic components were in phase.

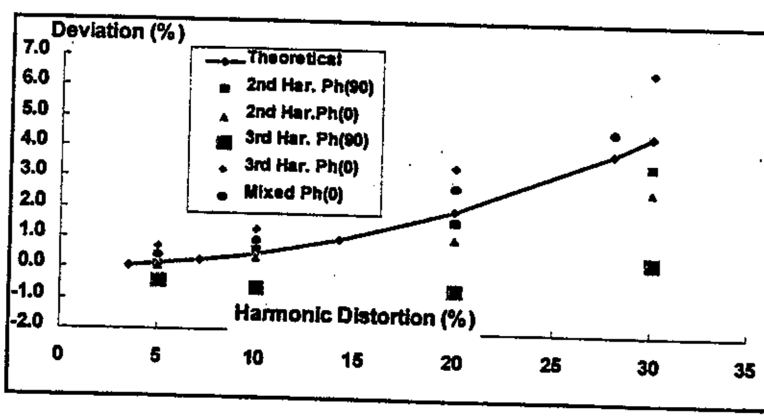

Figure 3 Theoretical and expermental deviation from estimated sensitivity vs. harmonic

Tests were conducted with the amplitudes of the 2 nd and 3 rd harmonic components adjusted relative to that of the fundamental to provide total harmonic distortion in the range of 5 % to 30 % as measured at the output of the amplifier of the accelerometer under test. In previous tests, the total harmonic distortion produced by the shaker when driven by a low-distortion 100 Hz sine wave was found to be on the order of 0.2 %[1]. The results of measurements made with the fundamental plus 2 nd harmonic, the fundamental plus 3 rd harmonic, and the fundamental plus 2 nd and 3 rd harmonics are shown in Figure 3 along with theoretical results based on Equation 1.

The harmonic-distortion tests indicated that measured sensitivities could deviate significantly from estimates of the sensitivity obtained using a low-distortion 100 Hz sine wave when 2 nd and 3 rd harmonic components were added to the 100 Hz fundamental. The amount of this deviation was a function of the amplitude and phase relationship of the harmonics to the fundamental. In some cases, these deviations were approximately a quadratic function of the amount of harmonic distortion present as would be predicated from Equation 1. However, in general, Equation 1 did not always model the results accurately, particularly in the case of 3rd harmonic distortion.

3. Effects of Cross-Axis Motion on Measured Sensitivity

Tests were conducted to examine the effects on measured sensitivity due to cross-axis motion that may be present in accelerometer calibration systems. The accelerometer used in these tests was the same one that was used in the tests described above for harmonic distortion. Prior to these tests, the accelerometer had been calibrated extensively with both interferometric and reciprocity based calibration methods using several different calibration systems and shakers. The results of these calibrations indicate that the accelerometer typically exhibits a flat frequency response (uniform sensitivity) over the frequency range of 100 Hz to 1 kHz, to within 0.2 % of the average value of measured sensitivity over this frequency range. Figure 4 contains a schematic representation of the moving element of the shaker as it was configured for determinations of sensitivity for these tests, with the laser beam of the interferometer incident from the right-hand side of the shaker. A flat mirror (reflector) is shown on the right-hand side of the schematic representation of the moving element opposite the accelerometer under test. A flat mirror was used in this case because the size and geometry of the corner-cube reflector described in the previous section was not suitable for high-frequency measurements.

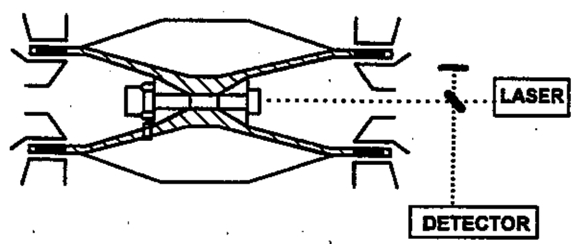

Figure 4 Moving element of the shaker configured for fringe-counting with a flat reflector on the shaker.

Measurements of displacement resulting from the vibration of the moving element were made at three points of reflection spaced approximately 120° apart on the flat mirror. In the discussion below, the term location refers to the point of reflection on the flat mirror shown in Figure 4. Prior to these measurements, the cross-axis motion of the shaker with the test accelerometer mounted on the moving element had been measured using a small light-weight wide-bandwidth triaxial accelerometer in

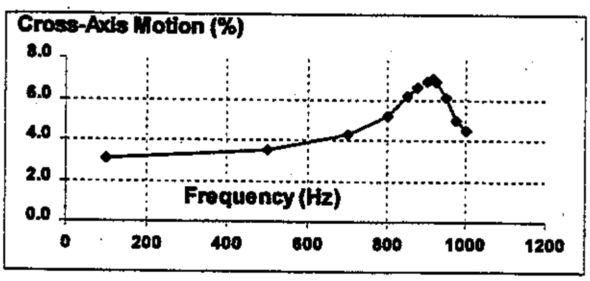

Figure 5 Cross-axis motion as a function of frequency

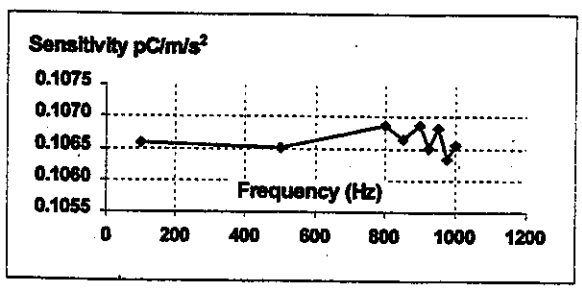

Figure 6 Measured sensitivity as a function of frequency.

place of the flat mirror. The results of the measurement of cross-axis motion from 100 Hz to 1 kHz are given in Figure 5. These results indicate that the cross motion was predominately in the vertical direction, and reached a maximum in amplitude at about 900 Hz. The maximum transverse sensitivity and the axial resonance frequency specified for the triaxial accelerometer by its manufacturer are 5 % and 80 kHz, respectively, so that the apparent cross-axial motion of 6 % to 7 % measured in the region of 900 Hz is attributed to motion in the vertical direction of the highly damped metal/rubber flexures supporting the moving element. No attempts were made to characterize changes in the transverse sensitivity of the accelerometer under test as a function of rotational angle about its axis of maximum sensitivity. The average sensitivity data of the test accelerometer obtained from an average of the spatial displacement measurements is given in Figure 6. Sensitivity determined from measurements of displacement at any given frequency and location repeated to within 0.5 % of the average value, and at frequencies of 100 Hz and 500 Hz repeated to within 0.1 % of the average value at any given location. The results indicated that sensitivity determined from measurements obtained at any one location could deviate by nearly 1 % of the average value of the sensitivities determined at 100 Hz and 500 Hz.

As can be observed by examining Figure 5 and Figure 6, estimates of the sensitivity vary as a function of frequency and this variance systematically increases with increasing cross motion. Further, the variations in estimated sensitivity are substantially more than the 0.1 % to 0.2 % typically observed when using other shakers to calibrate the test accelerometer over the same frequency region.

4. Conclusions

Tests were conducted to examine potential effects of harmonic distortion and cross-axis motion on the measured sensitivity of an accelerometer. The accelerometer used in these tests had a well established history of repeated calibrations using a number of different calibration systems and shakers.

The harmonic-distortion tests indicated that measured sensitivities could deviate significantly, from estimates of the sensitivity obtained using a low-distortion 100 Hz sine wave, when 2nd and 3rd harmonic components were added to the 100 Hz fundamental. The amount of this deviation was a function of the amplitude and phase relationship of the harmonics to the fundamental, but the results of the tests were not always accurately modeled by the theoretical values predicted using Equation 1.

Tests were also made to determine the potential effects of cross-axis motion on the measured sensitivity of an accelerometer. Unlike harmonic distortion, cross-axis motion could not readily be introduced into the calibration apparatus on a systematic basis. However, by measuring the accelerometer sensitivity in the presence of relatively large and small amounts of cross-axis motion, correlation between increased cross motion and scatter in measured sensitivity was observed. Cross-axis motion on the order of 7 % resulted in deviations as large as 0.3 % of estimates of the true value of sensitivity when the measurements were spatially averaged over the surface of the moving element of the shaker. Without spatial averaging, deviations of nearly 1 % of estimates of the true value of sensitivity were obtained. In practice, deviations larger or smaller than these could occur depending on the transverse sensitivity and the physical orientation (relative to that of the cross motion) of the transducer being calibrated.

5. References

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