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IMPROVED LOW FREQUENCY ACCELEROMETER CALIBRATION

Mark Schiefer [1], *Richard Bono* [2]

[1] The Modal Shop, Inc., Cincinnati, USA, mschiefer@modalshop.com
[2] The Modal Shop, Inc., Cincinnati, USA, rbono@modalshop.com

Abstract − This paper will discuss a newly developed implementation of low frequency accelerometer calibrations below 10 Hz. The goal is an improved low frequency accelerometer calibration methodology capable of performing superior quality measurements with significantly lower uncertainties while maintaining good throughput and the simplicity of traditional back-to-back calibration techniques. By using an optical encoder as the measurement reference instead of a traditional back-to-back reference accelerometer, limitations due to shaker stroke length are nearly eliminated, with the practical limitation for a quality calibration measurement at ultra low frequency being the resolution of the sensor under test itself.

Keywords: low-frequency accelerometer calibration

1. TRADITIONAL ACCELEROMETER VIBRATION SENSITIVITY CALIBRATION

Vibration calibration uses oscillatory (sinusoidal) excitation normally provided by an electrodynamic exciter or shaker with a back-to-back reference accelerometer (see Fig. 1). The procedure for measurement of accelerometer sensitivity is described by ISO 16063-21, "Methods for the calibration of vibration and shock transducers - Part 21: Vibration calibration by comparison to a reference transducer" [1]. The shaker is driven by a sinusoidal vibration signal and the sensitivity of the SUT is measured at that particular frequency. Sweeping through the desired range of frequencies then generates a frequency response curve of the SUT, as shown in Fig. 2. Typically the amplitude response showing voltage sensitivity is displayed in units of % deviation from the reference sensitivity (commonly either 100 Hz or 159 Hz).

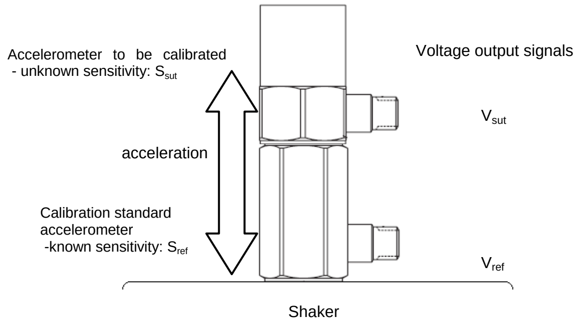

Fig. 1. Back-to-back technique

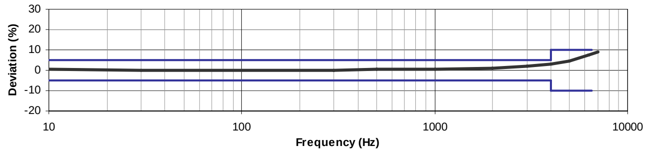

Fig. 2. Typical frequency response of an accelerometer. Deviation values refer to calibrated sensitivity at the reference frequency (100 Hz).

It should also be noted that the signal quality generated by the calibration shaker will significantly affect the calibration frequency response and resulting measurement uncertainty. Measurement systems should use only precision air-bearing shakers [2] specifically designed for accelerometer calibration, like the unit shown in Fig. 3. These air-bearing shakers meet the ISO 16063 recommended limits for transverse motion and distortion, which has previously been shown to be the root cause of large localized glitches in the frequency response function [3].

Fig. 3. Precision air-bearing calibration shaker

2. LOW FREQUENCY ACCELEROMETER CALIBRATION

Traditional back-to-back comparison calibration covers a frequency range from approximately 5 to 10 Hz to somewhere between 10k to 20k Hz, depending upon the specific design and quality of the calibration shaker and the specifications of the SUT. In addition to the air-bearing shaker, this methodology also employs a reference accelerometer for comparison purposes, typically a precision stable quartz transducer.

The limitations in frequency range below 5 Hz generally relate to the fact that shakers have a relatively small stroke length, and, as a result, have limitations on the acceleration range at low frequency based upon maximum displacement. For example, using the PCB 394A30 air-bearing shaker (10 mm pk-to-pk stroke), the maximum achievable acceleration at 5 Hz is 0.5 g pk. At 1 Hz, maximum achievable acceleration drops to just 20 mg pk, marginally higher than the reference accelerometer's broadband resolution specification. At this level, poor signal-to-noise ratio significantly affects the measurement quality, drastically raising uncertainties. As a result, low frequency calibration (below 5 Hz) is traditionally done using a second, specialized long stroke shaker (6 in pk-to-pk stroke) that is only used from about 0.5 Hz to maybe 10 Hz. At that point, the SUT is remounted on the mid- to high frequency calibration shaker to complete the frequency response measurement through the high frequency range and/or to its mounted resonant frequency.

Fig. 4 shows the theoretical acceleration levels at a constant displacement based upon the stroke of the air-bearing (10 mm) and long stroke (6 in) shakers. It clearly shows an increase of more than an order of magnitude in maximum achievable acceleration levels for each shaker at a given frequency. As a result better measurements are produced down to lower frequencies given the additional stroke (i.e. increased signal level) when using traditional back-to-back accelerometers as the reference transducer. The common frequency limits of each shaker and the 1 g crossover points are annotated for clarity.

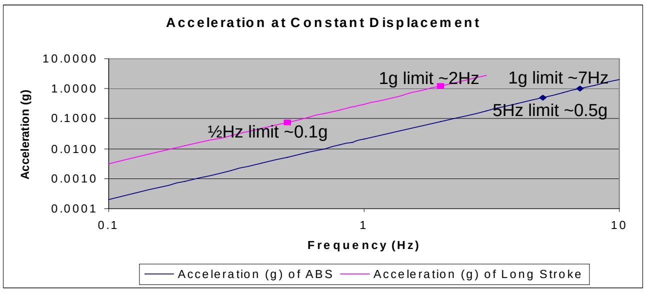

Fig. 4. Maximum theoretical acceleration limits for the 10 mm stroke air-bearing shaker (ABS) and the 6 in. long stroke shaker

3. NEW METHODOLOGY FOR LOW FREQUENCY ACCELEROMETER CALIBRATION

There is a different approach to improving low frequency accelerometer calibration. Instead of adding a second specialized shaker with significantly longer stroke in order to increase acceleration levels at low frequency, consider changing the reference transducer to one that is not restricted by any stroke limitations to start. By using an optical encoder as the measurement reference instead of a traditional reference accelerometer, limitations due to shaker stroke length are nearly eliminated, with the practical limitation for a quality calibration measurement at ultra low frequency being the resolution of only the SUT itself.

The resolution of the optical encoder reference is based directly upon displacement. Therefore, its signal to noise ratio does not lessen with the reduced acceleration levels at lower frequencies. The air-bearing shaker has a constant 10 mm stroke regardless of whether the excitation signal is 10 Hz, 1 Hz or 0.1 Hz. Therefore, the optical encoder maintains a superior quality measurement while any reference accelerometer will eventually hit its noise floor, shown graphically in Fig. 5. And due to the high quality air-bearing suspension the excitation signal exhibits very low distortion levels to these very low test frequencies.

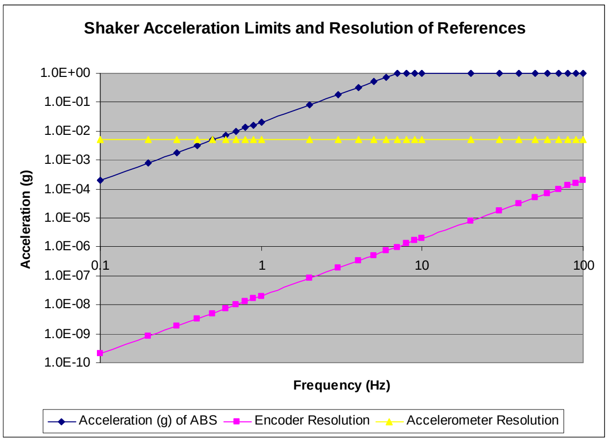

Fig. 5. Theoretical limits of accelerometer* and optical encoder reference sensors charted against air-bearing shaker acceleration limits due to maximum stroke. *Accelerometer resolution displayed is based upon the manufacturer's broadband RMS resolution of the air-bearing shaker's integral reference accelerometer.

Fig. 6 shows an optical encoder sensor mounted on an air-bearing shaker. The read-head sensor is firmly affixed to the top of the shaker body, while a read-strip optical scale is mounted onto the shaker armature. The optical encoder senses light emitted from an LED that varies based upon the relative position between an index grating in the read-head and the optical scale on the read-strip. One cycle of the photocurrent output represents 20 µm of motion. The cycles are reconstructed to determine the displacement (motion) of the scale at any point in time. By deriving acceleration from the function of displacement, a high resolution reference signal is measured. Fig. 7 illustrates this operation.

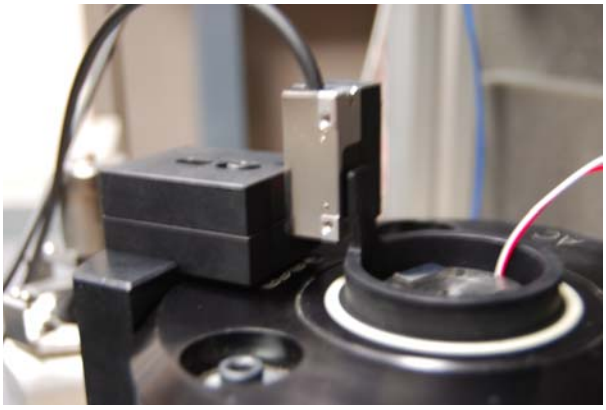

Fig. 6. Optical encoder read-head sensor and read-strip optical scale mounted on Model 394A30 calibration air-bearing shaker.

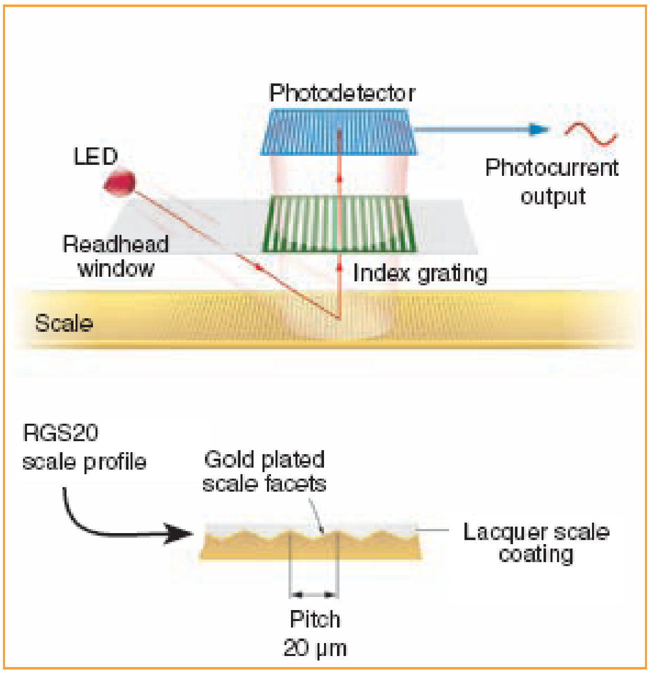

Fig. 7. Optical Encoder Operation

The resulting measurement is a superior quality reference signal that can be used to make calibration measurements at ultra low frequencies with uncertainties similar to those from a primary calibration by a laser interferometer. Data in Fig. 8 compares the signal output from the air-bearing shaker's internal 10 mV/g reference accelerometer with that from the optical encoder sensor. At 2 Hz, the reference accelerometer's signal quality is beginning to visually degrade, and by 0.5 Hz its noise floor has consumed the measurement. Below each of these traces is the signal simultaneously measured from the optical encoder reference sensor, which clearly shows a superior, low noise, high quality sinusoid even at 0.5 Hz.

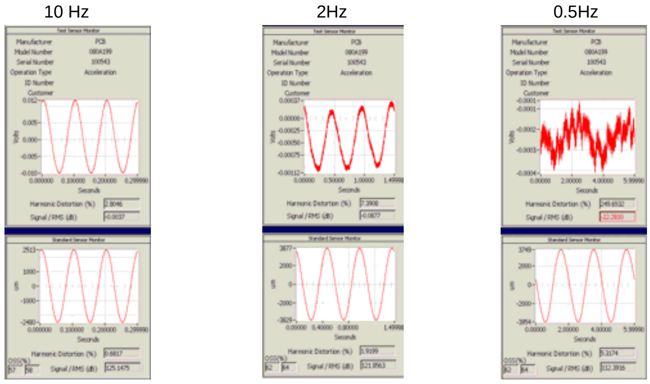

Fig. 8. Reference sensor measurement signals from accelerometer (upper plot) and optical encoder (lower plot), displayed at 10 Hz, 2 Hz and 0.5 Hz as indicated

4. EXPERIMENTAL DATA AND RESULTS

Calibration data was acquired using The Modal Shop 9155 accelerometer calibration workstation. The system uses a National Instruments 24 bit DSA data acquisition card with the 394A31 air-bearing shaker. This system also supports the use of a long stroke shaker as an option for low frequency calibration while using a traditional low frequency, high sensitivity back-to-back reference accelerometer.

A PCB Q353B51 500 mV/g quartz ICP® accelerometer was calibrated using the following 9155 system configurations down to 0.25 Hz:

1) Traditional back-to-back comparison calibration using 394A31 air-bearing shaker with internal 10 mV/g reference accelerometer
2) Traditional back-to-back comparison calibration using long stroke shaker with 500 mV/g low frequency reference accelerometer
3) New low frequency calibration using 394A31 air-bearing shaker with optical encoder reference sensor
4) New low frequency calibration using long stroke shaker with optical encoder reference sensor

The same transducer was also calibrated at the Laser primary calibration lab at PCB Piezotronics using a long stroke shaker. With a stated measurement uncertainty of 0.3% down to 0.5 Hz, this data was accepted as "true" results for comparative purposes. The calibration results from each of these tests are shown in Fig. 9.

The data shows excellent correlation between the three calibration sets performed on the long stroke shaker. The data from the air-bearing shaker referenced to the optical encoder is very reasonable, with a maximum % deviation from the laser primary standard of just 0.67% at 0.5 Hz. This is very impressive considering only 10 mm of stroke and that typical measurement uncertainties, for back-to-back secondary systems using long stroke shakers, are in the 1.8% to 3.0% range. (These stated measurement uncertainty numbers are taken from The Modal Shop and PCB Piezotronics published uncertainty budgets for A2LA certification of secondary calibration in the 0.5 to 5 Hz range.) Lastly, the data from the traditional back-to-back calibration using the air-bearing shaker with its accelerometer reference exhibit measurement differences pushing 1% below 5 Hz, reinforcing the recommendation that this configuration should not be utilized below 5 Hz.

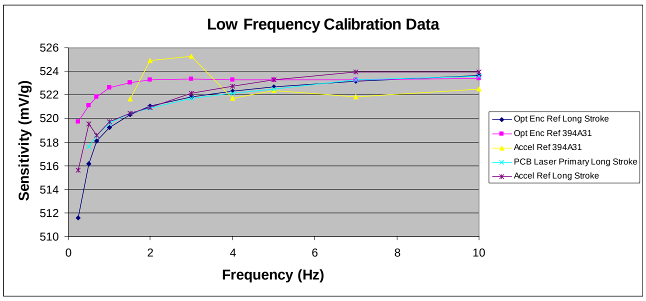

Fig. 9. Calibration results for different system configurations from 0.25 Hz to 10 Hz

Additionally, the contribution to the calibration measurement's random uncertainty from the signal-to-noise ratio of each of the reference sensors in each of these system configurations was assessed. Using the PCB Q353B51 accelerometer as a consistent "reference" across each of these system configurations, with other variables staying (essentially) constant, 30 repetitive calibration sweeps from 0.25 Hz to 10 Hz were completed. The random uncertainty % (statistical standard deviation of results over the 30 runs) at each data point for each system configuration is presented in Fig. 10. By comparing the traditional back-to-back technique (labeled "Accel Ref 394A31") to the new optical encoder technique (labeled "Opt Enc Ref 394A31"), the improvement in measurement quality is clearly evident, with substantially smaller uncertainty %'s below 5 Hz.

This data also shows that stroke can be a factor. Even while using the optical encoder reference, the random uncertainty still rises substantially approaching 0.25 Hz. The resulting uncertainty, however, is typically acceptable (random uncertainty % still under 0.2% at 0.5 Hz, and just 0.03% at 1 Hz) given traditional back-to-back secondary level calibration. Certainly the best case is the optical encoder reference on the long stroke shaker, which ensures both the quality of the reference signal as well as the SUT given the achievable acceleration levels. As such, this system solution (optical encoder reference installed on a specialized long stroke shaker) is the recommended hardware configuration of choice for primary and national metrology labs.

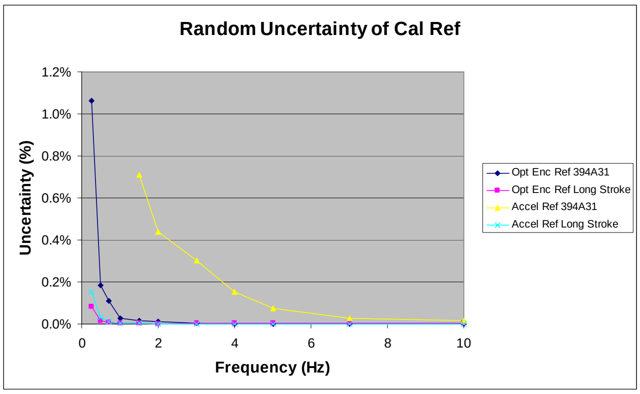

Fig. 10. Random Uncertainties using PCB Q353B51 accelerometer on both 394A31 air-bearing and long stroke shakers

5. LIMITATIONS OF OPTICAL ENCODER METHODOLOGY

There are two limitations with the optical encoder methodology. Since the reference sensor measurement resolution is based upon displacement, the signal quality degrades as the displacement reduces with increasing frequency – essentially the inverse affect of what happens to reference accelerometers at lower frequencies. As the calibration sweeps up in frequency, electrodynamic shakers are not able to drive large acceleration levels that would be necessary to maintain large displacements. Therefore, at some frequency it is necessary to switch the reference signal from the optical encoder sensor to a traditional reference accelerometer. Typically this is about 10 to 20 Hz. Within this range, both reference transducers (accelerometer and optical encoder) exhibit excellent signal quality with no degradation of calibration data from switching.

The second limitation is the dependence upon the SUT measurement resolution. Similar to the limitation of reference accelerometers having poor signal quality at low excitation levels due to shaker stroke length, SUTs may also have signal-to-noise ratio issues. Fortunately, accelerometers that are intended to be used at very low frequency ranges (below 5 Hz) possess a relatively high sensitivity with adequate resolution. For example, a typical 10 mV/g piezoelectric accelerometer may have a broadband resolution around 5 mg. However, a typical 100 mV/g piezoelectric accelerometer may have a broadband resolution around 0.5 mg, while a typical 1000 mV/g piezoelectric accelerometer may have a broadband resolution around 0.005 mg. These higher sensitivity, higher resolution accelerometers, generally used for lower frequency, lower level measurements, do have sufficient resolution and output to be adequately calibrated on a single shaker, even at these low levels.

6. CONCLUSION

By integrating an optical encoder sensor as the reference transducer for low frequency accelerometer calibration, superior measurement quality and near-laser primary uncertainties are achievable. Additionally, this is accomplished on a single shaker platform capable of covering ultra-low to high frequencies, eliminating the need for a second specialized long stroke shaker and allowing seamless calibration over the entire frequency range.

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