Primary calibration system for vibration transducers from 0.4 Hz to 160 Hz

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Abstract. This paper presents a system developed at the Vibration Laboratory of Inmetro, which is used for primary calibration of vibration transducers by the fringe counting method. This system includes a vibration exciter, a Michelson interferometer, a data acquisition board, a band-pass filter, a universal counter and a software for measurement automation. It allows the laboratory to perform calibrations in accordance with the international standard ISO 16063-11 in the frequency range from 0.4 Hz to 160 Hz. Some experimental results are presented herein.

1. Introduction
Vibration measurements at low frequencies are used in several applications, as for example: environmental monitoring, seismic measurement, human-body vibration assessment, mechanical tests, transportation of goods, large structures vibration monitoring, inertial navigation and so on. Since the demand for low-frequency vibration calibration services has grown up during the last years, the Vibration Laboratory (Lavib) of Inmetro has started the development of specific systems to attend this field.

A comparison calibration system requires a calibrated reference standard to quantify the measurand with high accuracy. In comparison accelerometer calibrations the sensitivity of the device under test (DUT) is determined by direct comparison of the voltage outputs given by the reference and DUT measuring chains when both transducers are submitted to a given motion input [1].

Reference vibration standards shall preferably be calibrated by a primary method capable of providing metrological traceability to SI units with low measurement uncertainties. For the purpose of mutual recognition and participation in interlaboratory comparison activities, it is important that the uncertainties are comparable with the ones claimed by the leading National Metrology Institutes (NMI) in the field.

In order to achieve this goal, a new primary interferometric system based on a Michelson interferometer was developed at Lavib for performing automated calibrations of reference vibration transducers at low frequencies.
2. Calibration Method

The primary calibration method used in this new system is in compliance with the requirements of the Method 1, which is described in the international standard ISO 16063-11 [2] and known as the fringe counting method. This method is based on primary measurement by laser interferometry of the displacement amplitude of a sinusoidal harmonic motion, generated by a vibration exciter and applied to the transducer under calibration.

The sensitivity of the transducer is determined as a function of excitation frequency by calculating the ratio between the electrical output quantity provided by the transducer under calibration and the corresponding motion input quantity.

A two-arm Michelson interferometer is used to measure the displacement amplitude of the vibration by the well known fringe counting method. The ratio $R_f$ is determined by measuring the number of optical interference fringes per period of sinusoidal vibration motion. In practical terms this is done by measuring the ratio of two frequencies: the frequency of the optical interference signal captured by a Silicon photodetector and the frequency of motion given by a signal generator, which drives the vibration exciter.

The magnitude of the displacement is directly proportional to the ratio $R_f$. Assuming a sinusoidal motion of the moving table with a frequency $f$, then the magnitude of corresponding velocity and acceleration can be calculated using the angular frequency $\omega = 2\pi f$.

Measuring the voltage output $V_{obj}$ furnished by the device under test (DUT), it is possible to calculate its sensitivity $S_{obj}$ at each frequency by

$$S_{obj}(f) = \frac{8\sqrt{2}}{(2\pi f)^2 \lambda} \left( \frac{V_{obj}(f)}{R_f} \right)$$

where $\lambda$ is the wavelength of the light emitted by a He-Ne laser.

3. Calibration System

The basic block diagram of the primary low-frequency accelerometer calibration system is presented in figure 1.

![Figure 1. Block diagram of the calibration system.](image-url)
In order to obtain a transducer output with a good signal-to-noise ratio at low frequencies it is important to use a vibration exciter capable of generating a motion with large displacement amplitudes. This occurs because the acceleration level \( a_{pk} \) is proportional to the displacement amplitude \( d_{pk} \) multiplied by the angular frequency squared \( (a_{pk} = d_{pk} \omega^2) \). Considering that most commonly used transducers respond to acceleration, then larger displacements are needed for calibrations at lower frequencies for a given acceleration level.

In the system depicted in figure 1, the mechanical vibration is generated by an electrodynamic exciter APS Dynamics model 129, which has a 25 x 25 cm moving table guided by a linear air bearing. This exciter can generate up to 75 mm displacement amplitude motion and offers a payload capacity up to 23 kg. The exciter base is rigidly mounted on the top of a 1200 kg concrete inertial mass, which lies on rubber sheets. The air bearing linear guide model was selected because it produces low-friction and low noise levels, also helping to generate a linear sinusoidal motion with reduced effect of transverse and rocking motions.

A function generator 33120A and a power amplifier APS model 124 provide the sinusoidal signals necessary for driving the exciter with at the desired amplitudes and frequencies. The default calibration frequencies are the nominal 1/3-octave frequencies in the range from 0.4 Hz to 160 Hz.

An acceleration measuring set, which includes a B&K 4370 piezoelectric accelerometer and a B&K 2626 charge amplifier, is used to control the acceleration levels of the moving table. The measurement of the displacement of the table is made by a Michelson interferometer with a non-stabilized 15 mW laser. Retroreflectors are used in both arms of the interferometer in order to facilitate the optical alignment along the large displacements of the moving table. The interferometer is mounted on an optical breadboard, which lies on helical steel springs and an independent seismic block. The use of passive isolation and two independent massive blocks are important to avoid any mechanical short-circuit and isolate the interferometer setup from any undesired vibrations.

A programmable filter Krohn-Hite is used for pre-conditioning of the frequency modulated signal obtained by the photodetector. The filtered signal is then directed to a universal counter configured in frequency ratio mode for measuring of the ratio \( R_f \).

An analog to digital conversion board is applied for measurement of the electrical output signals provided by the DUT and the control accelerometer. A 12 bit 4-channel, simultaneous sampling data acquisition board (DAQ) National Instruments model PCI-6115 is used. This DAQ can be configured with a maximum sampling rate of 10 MS/s per channel.

A computational program was developed in LabVIEW environment for automation of the calibration process. This software configures and controls all the equipments via an IEEE 488 interface, also controlling the acceleration level provided by the vibration exciter. Beyond this, it also configures the DAQ for the measurement of the electrical output voltage signals of the DUT and control accelerometer chains. The program front panel includes graphical indicators of the measured signal, both in time and frequency domain, and presents the calibrated sensitivity results graphically in real time. The measured data is saved in an ASCII file for further post-processing and analysis.

The voltage values of the DUT are measured at the fundamental frequency of the vibration excitation by a Fast Fourier Transform (FFT) routine. The Total Harmonic Distortion is also measured for assessment of the quality of the movement during the calibration.

Figure 2 shows the moving table of the exciter (A) with a mounting adaptor (C) used to hold both the DUT (D) and the moving retroreflector (B) of the interferometer. In addition, it shows the control accelerometer (E) mounted on a bracket.

In figure 3, the whole interferometric setup is presented, including the adaptor mounted on the exciter moving table (B) and the interferometer mounted on the optical breadboard. The photodetector and the fixed retroreflector are identified in this figure as B and A, respectively. The same mechanical adaptor presented here is also used for comparison calibrations of accelerometers. In this case, the retroreflector is just replaced by a standard reference accelerometer.

In order to minimize the effects of any transverse vibrations acting on the transducer under test, two measurements are usually carried out in sequence. Initially, the transducer is first calibrated in a
certain position. In sequence, it is rotated 180° degrees relatively to its own axis and is calibrated again. The arithmetic mean of the sensitivities measured at these two positions is reported as the final calibration result. This procedure minimizes the effect of any coupling between the transverse sensitivity of the DUT and the transverse accelerations generated by the exciter or even to the earth gravity field.

![Image](image1.png)

**Figure 2.** Moving table of the exciter (A), retroreflector (B), mounting adaptor (C), accelerometer under test (D) and control accelerometer (E).

![Image](image2.png)

**Figure 3.** Michelson interferometer view: Retroreflectors (A and B) and photodetector (C).

4. Experimental Results

This section presents some results obtained by the primary calibration system. Figure 4 presents the results of sixteen sensitivity calibrations of a servo-accelerometer Allied Signal QA3000, used as a reference standard in the comparison calibration system. This kind of transducer is applied for inertial navigation and has a high temporal stability. Therefore, this test basically evaluates the repeatability level achievable with the calibration system developed.
Figure 4. Results of sensitivity obtained for a servo-accelerometer QA-3000.

Figure 5 presents the deviation (%) of the same measurements shown in figure 4 relative to the mean sensitivity calculated for the servo-accelerometer. It can be observed that most of the individual results lie within 0.1 % of the mean sensitivity value.

Figure 5. Deviation of the sensitivity values from the arithmetic mean (in %) for sixteen calibrations of the servo-accelerometer QA-3000.

5. Measurement Uncertainty
The expanded measurement uncertainty \( (U) \) estimated for the results of magnitude of the sensitivity obtained by the primary calibration system for vibration transducers at low frequencies was 0.35%, under normal calibration conditions and for the whole range of frequencies. This uncertainty was calculated in accordance with the Guide to the Expression of Uncertainty in Measurement – GUM [3] and the Annex A of the international standard ISO 16063-11[2]. This value is given by the multiplication of the combined standard uncertainty with the coverage factor \( k = 2 \), which defines an interval having a level of confidence of approximately 95%.

6. Interlaboratory Comparison
Figure 6 shows the results of the interlaboratory bilateral comparison AFRIMETS.AUV.V-S2, which was developed between Inmetro and the National Metrology Institute of South Africa (NMISA) [4].
The transducer used for this comparison was an IEPE type accelerometer, PCB 301M26, in the frequency range from 0.4 Hz to 50 Hz. The expanded uncertainty reported by both institutes was 0.3%. This reduced value is possible due the especial conditions dedicated to the comparison, including more measurements than the usual for a normal calibration.

The good agreement obtained between the results demonstrates the capability of Inmetro’s system and provides the technical support to the typical uncertainty of 0.35% reported to general customers.

![Sensitivity Results](image)

**Figure 6.** Results of the bilateral interlaboratory comparison carried out between Inmetro and NMISA.

7. Conclusion
The system presented in this article allowed the Vibration Laboratory of Inmetro to extend and improve its capability to realize primary laser calibrations of vibration transducers at low frequencies.

This system is currently able to execute calibrations of accelerometers and vibration measuring systems in the range from 0.4 Hz to 160 Hz with a 0.35% expanded uncertainty of measurement, considering a level of confidence of approximately 95%.

The calibration process is fully automated, minimizing the influence of the operator. Some results were presented, including the results obtained in an international bilateral interlaboratory comparison, which validates and supports the claimed uncertainties.

Therefore, the system implemented at Lavib will enable Inmetro to provide the needed traceability to the International System of Units to several economic sectors in Brazil.

Lavib will continue to develop researches at low frequencies, and intends to implement in the near future a quadrature interferometric system. This further improvement will provide the additional capability to measure the phase shift of complex sensitivity of vibration transducers.

References
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