

IMEKO 2010 TC3, TC5 and TC22 Conferences  
 Metrology in Modern Context  
 November 22–25, 2010, Pattaya, Chonburi, Thailand

## A NEW SYSTEM FOR PRIMARY INTERFEROMETRIC CALIBRATION OF VIBRATION TRANSDUCERS AT LOW FREQUENCIES

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**Abstract** – This paper presents a primary interferometric calibration system that was developed in the Vibration Laboratory at INMETRO for the calibration of vibration transducers and measuring instruments at low frequencies. This system is based on a long-stroke air bearing shaker, and on a data acquisition board. It has been used for calibration of accelerometers and servo-accelerometers within the frequency range from 0,4 Hz to 160 Hz. Optionally, the system can be adapted to calibrate laser vibrometers for their further use as comparison reference transducers. Fully automated calibrations are carried out in compliance with the international standard ISO 16063-11 employing the fringe counting method. Some experimental results obtained with this system will be presented herein.

**Keywords:** Vibration, Acceleration, Metrology.

### 1. INTRODUCTION

The comparison low-frequency calibration system developed in the Vibration Laboratory (LAVIB) at INMETRO has already been presented during the XIX IMEKO World Congress [1]. In order to assure the traceability of comparison calibrations in low frequencies, it was necessary to build a new system to perform primary interferometric calibrations of reference vibration transducers in accordance with the international standard ISO 16063-11 [2].

The design of this new primary calibration system took into consideration the technical requirements described in the measurement protocol of the future Low-Frequency Interlaboratory Supplementary Comparison [3], which is to be carried out within the Interamerican Metrology System (SIM). This protocol requires each participant laboratory to perform primary calibrations of accelerometers from 2 Hz to 160 Hz.

Even though INMETRO already had the capability of performing primary acceleration calibrations above the frequency of 10 Hz with other systems, it was desired by the Vibration Laboratory to extend the limits of the new low-frequency system in order to cover from the lower frequency limit of 0,4 Hz stated in standard ISO 16063-11 up to the reference frequency of 160 Hz.

The calibration system has been designed in such a way to allow easy transition between the experimental

configurations to perform primary and comparison calibrations. The use of a common platform allows comparison of measurement results obtained by the different calibration methods after making some minor configuration changes.

Another calibration system already available in the Vibration Laboratory employs a vibration exciter APS model 500, and has been mostly applied for primary interferometric calibrations of reference transducers. Unfortunately, this first low-frequency primary calibration system has not ever been computer automated, requiring a lot of human interaction. Another drawback of this system is that the vibration exciter used has a small 79,5 x 79,5 mm moving table, with a maximum load capacity of 2,7 kg. This was a limiting factor for the capability to provide calibration services of massive low-frequency transducers and integrated measuring instruments. For instance, some vibration meters and data loggers used for transportation and elevators monitoring and for geological applications could not be calibrated without disassembling their vibration sensors. Therefore, it was necessary to develop a new system capable to attend the demand for calibration of heavier measuring instruments, which is increasing considerably during the last years.

Another important reason for the development of a new system was that the vibration exciter APS model 500 was temporarily unavailable. It was being used in a doctoral research project developed by one of our researchers. Since the experimental setup assembled for this project was quite complicated and the time needed to conduct the experiments would be considerably long, it was decided to build a new fully automated facility. Later on the automation developed for the new system can also be used in the first system.

In the next sections, this paper will demonstrate that the new system represents a major improvement on INMETRO's capability to perform calibration of vibration transducers and vibration measuring instruments in low frequencies down to 0,4 Hz.

### 2. CALIBRATION SETUP

The new calibration setup is based on an electrodynamic vibration exciter APS model 129. This exciter offers a stroke rating of 158 mm, and allows the mounting of up to 23 kg on its load table measuring 254 x 254 mm. This load

table is fixed to a large area precision linear air-bearing stage of rectangular cross section. The electrodynamic driver unit employs permanent magnets and the moving coil is also guided by air bearings.

The driver unit and the rigid guide bar assembly are mounted on a common rigid aluminium base. This base is fixed to the top surface of a 1200 kg seismic block mounted on rubber pads. An independent and smaller seismic mass of about 700 kg is used to support an optical breadboard, which is mounted on steel springs. A picture of the low-frequency calibration system is presented in Fig.1.



Fig. 1. Low-frequency acceleration calibration system

A laser interferometer is mounted on the top of the optical breadboard. A Michelson interferometer with two flat mirrors can be used for specific purposes, but usually a configuration using two-retroreflectors is preferred due to the benefit of easier alignment. The calibration setup is schematically presented in Fig. 2.

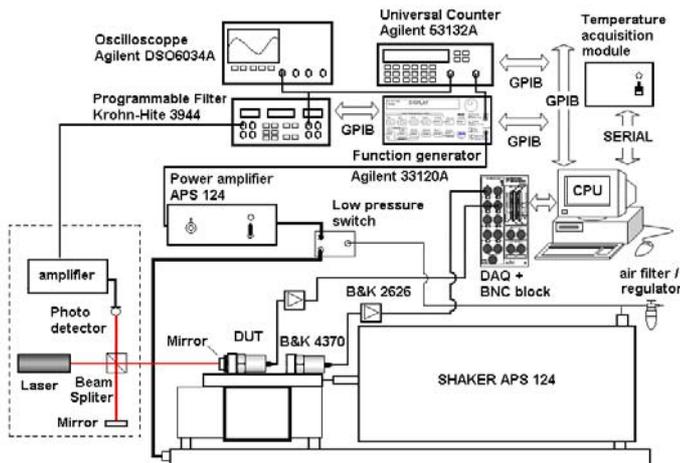


Fig. 2. Low-frequency primary acceleration calibration system

A piezoelectric accelerometer is used as feedback sensor for the control loop of the selected acceleration amplitude for the calibration. A fixed feedback sensor was chosen for safety reasons, considering that its output is independent of the interferometric alignment and of the device under test (DUT). A piezoelectric accelerometer B&K4370 was

selected for this purpose because it presents high robustness and high sensitivity. A charge amplifier B&K2626 is used for signal conditioning of its high impedance output signal.

A function generator Agilent 33120A is used to generate the sinusoidal driving signals at the desired measuring frequencies. A power amplifier APS model 124 provides the power required to feed the armature coil of the shaker APS 129.

A 16-bit, 333 kS/s multi-channel digital acquisition board (DAQ) National Instruments model NI-6052E is used for acquisition of the signals output by the feedback sensor and DUT.

An oscilloscope Agilent DSO6634A is used for visual monitoring of the interference fringes during the optical alignment of the interferometer and during calibration. The number of fringes per period of vibration is measured with a universal counter Agilent 53132A configured in frequency ratio mode. A programmable filter Khron-Hite 3944 is used for conditioning of the photodetector output signal before frequency ratio measurements.

All input signals are connected to the acquisition board through a connector block NI BNC-2110. An interface IEEE-488 is employed to control the function generator, the programmable filter and the frequency counter. A temperature acquisition module is controlled via interface RS-232.

A program developed in LabVIEW environment is used to automate the entire calibration process, including the control of the instrumentation and the management of the measurement data transfer.

A modular mounting system, based on an aluminum cube allows direct mounting of Q-Flex type servo-accelerometers. Flat mirrors, solid glass retroreflectors and accelerometers can be mounted in-line with appropriate adapters. The cube includes a threaded hole pattern to allow different angular positioning of the adapters and two mountings of the servo-accelerometers, 180° apart from each other. This modular mounting system is shown schematically in Fig. 3.

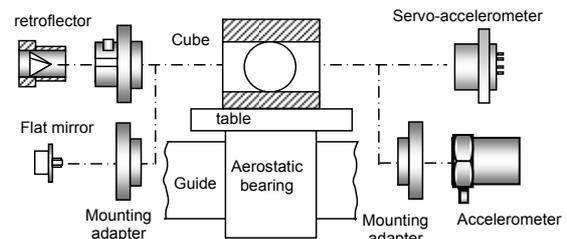


Fig. 3. Modular mounting system

### 3. CALIBRATION METHOD

The calibration is conducted in compliance with the international documentary standard ISO 16063-11, using stepped-sine excitation at the nominal 1/3-octave center frequencies from 0,4 Hz to 160 Hz. The acceleration level chosen for calibration is adjusted by the calibration program automatically. After a specified settling time for motion stabilization, the analog voltage output of the DUT is

sampled and the acquired data is presented in time and frequency domain graphs.

The Discrete Fast Fourier Transform (DFT) is used to convert the acquired data to the frequency domain. The rms voltage value of the DUT is measured then at the excitation frequency. The total harmonic distortion of the DUT output is also measured for evaluation of the motion quality during calibration. The excitation frequencies, sensitivities, standard deviations, acceleration levels, measured voltages and distortion results are presented on the screen and saved in ASCII output files. The post-processing is carried out in an Excel standardized spreadsheet.

The magnitude of the voltage sensitivity of an accelerometer calibrated by the fringe counting method is determined by applying the following equation:

$$S_{ua}(f) = \frac{8\sqrt{2}}{(2\pi f)^2 \lambda} \left( \frac{V_{rms}}{R_f} \right), \quad (1)$$

where  $f$  is the frequency,  $\lambda$  is the laser wavelength,  $V$  is the voltage output and  $R_f$  is the frequency ratio.

#### 4. CALIBRATION RESULTS

This section presents some results obtained with the new primary low-frequency calibration system.

Fig. 4 presents the sensitivity of a servo-accelerometer Allied Signal model QA-3000 calibrated from 0,4 Hz to 160 Hz. This type of transducer provides a current output proportional to the acceleration input. This specific device presented here already has a precision 1 kΩ resistor soldered to its output pins. The output voltage was measured across this resistor; therefore the sensitivity reported here refers to the set including accelerometer and resistor. The measurements were carried out for two mounting positions m1 and m2. At m2, the servo-accelerometer is mounted rotated by a 180° angle relative to m1. The final calibration result  $Su_{mean}$  is determined by averaging the sensitivities  $Su_{m1}$  and  $Su_{m2}$  measured respectively at positions m1 and m2. This averaging procedure is usually carried out to minimize the effect of coupling between the transverse acceleration generated by the vibration exciter and the transverse sensitivity of the DUT.

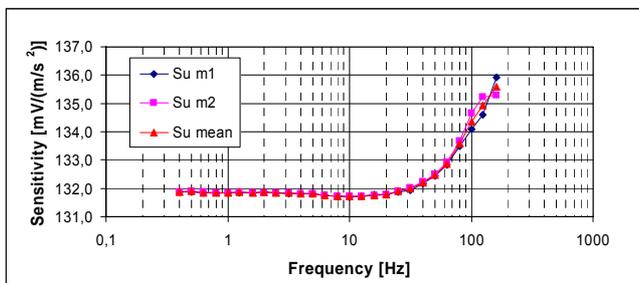


Fig. 4. Voltage sensitivity of a servo-accelerometer Allied Signal QA3000 determined by the fringe counting method with the new system.

Fig. 5 shows that the dispersion between the results obtained at mounting positions m1 and m2 is significant

above 100 Hz, being higher than 0,2 %. This dispersion is caused by the transverse acceleration generated by the vibration exciter APS 129, which is lower than 5% at frequencies smaller than 100 Hz, but reaches values higher than 20% at 125 Hz and 160 Hz [1].

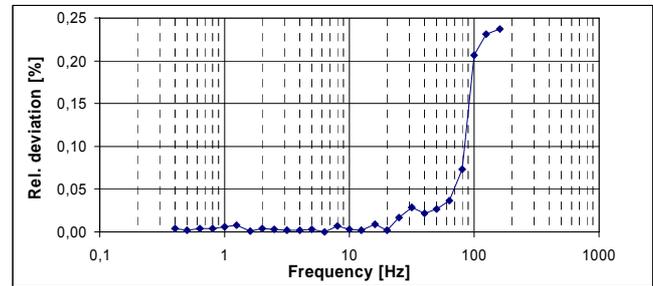


Fig. 5. Relative deviation of the results measured at 2 mounting positions m1 and m2.

In order to demonstrate the reproducibility achievable with the calibration system, a series of full calibration cycles of a servo-accelerometer Allied Signal model QA3000 were carried out. This transducer is considered to be a highly stable low-frequency acceleration standard. Fig. 6 presents the voltage sensitivity of 10 repeated runs and the respective mean value obtained.

The relative standard deviations computed with these sensitivity results present values lower than 0,06 % in the entire frequency range of analysis. The relative deviation between each repeated run and the mean is presented in Fig. 7. This figure shows that all results are within ± 0,1 % of the calculated mean value.

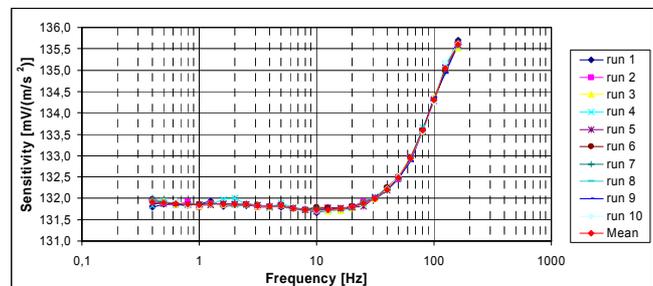


Fig. 6. Results of the voltage sensitivity of a servo-accelerometer Allied Signal QA3000 measured in 10 calibration runs.

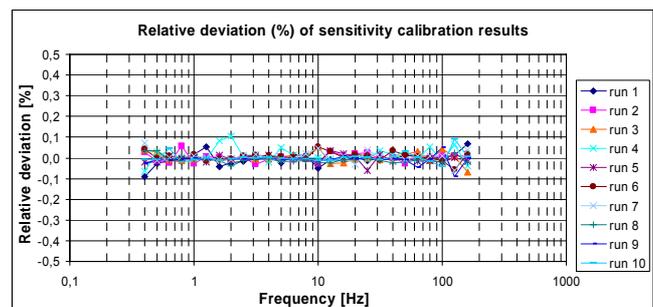


Fig. 7. Relative deviation of the voltage sensitivities shown in Fig. 6 to the mean value.

Fig. 8 compares the sensitivity results furnished by the new low-frequency system described in this paper (FC LFS) with the ones obtained in other systems available at INMETRO for an acceleration measuring set (accelerometer Endevco 2262A25 + amplifier 106). This figure includes results obtained by the mid-frequency range system running the fringe counting method (FC MFS), by a homodyne quadrature system running the sine-approximation method (SAM), and a comparison against a CLV laser vibrometer. Y bars were included to show that all these results lie within  $\pm 0,5 \%$  of the sensitivity determined by comparison to the CLV vibrometer.

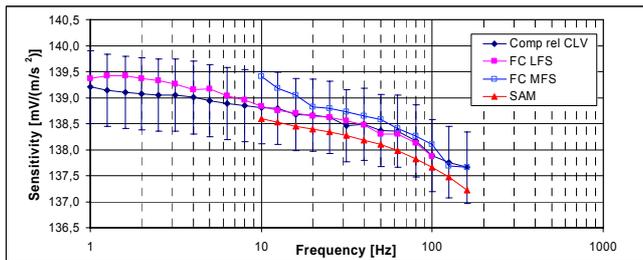


Fig. 8. Comparison of results obtained in different systems for an acceleration measuring set (Endevco accelerometer 2262A25 + amplifier 106)

During the Peer Review of the Vibration Laboratory of INMETRO, which happened in July, 2009, the technical assessor asked for the calibration of an accelerometer Kistler model 8330A3 in the new low-frequency system. Some measurements were carried out in the frequency range from 1 Hz to 100 Hz and compared with the ones obtained at CENAM/Mexico. The results obtained agreed within 0,2 %.

The calibration system has already been used to calibrate different types of accelerometers, including servo, piezoresistive, variable capacitance, piezoelectric and also some MEMS. Fig. 9 presents the calibration results of sensitivity obtained for a MEMS accelerometer Analog Devices model ADXL 103.

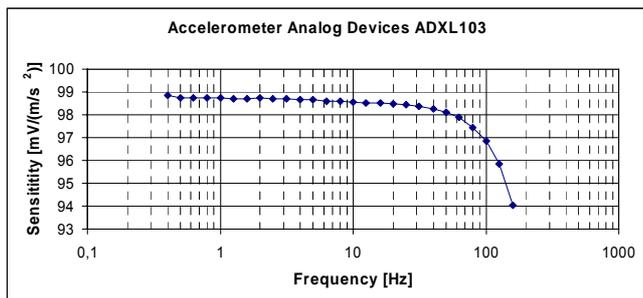


Fig. 9. Sensitivity of a MEMS type accelerometer Analog Devices model ADXL103.

It was verified that the system composed by the vibration exciter APS 129 and power amplifier APS 124 limits the maximum acceleration level achievable to about 5 m/s<sup>2</sup> rms between 10 Hz and 80 Hz and to 3,5 m/s<sup>2</sup> rms from 100 Hz to 160 Hz. These acceleration limits are imposed by the output voltage limit of the amplifier APS 124 and by the

electrodynamic driver coil impedance, which increases remarkably with frequency.

The amplifier APS 124 has a BNC connector for monitoring the current flow through the coil of the electrodynamic driver unit, but this signal does not show the occurrence of clipping as clearly as when monitoring directly the voltage output. When voltage clipping occurs, the vibration motion presents considerable distortion.

In order to reach higher levels of acceleration amplitude, a power amplifier with increased voltage output can be used in substitution to the APS 124. Some tests carried out using a power amplifier Camco model Vortex 2.6 have shown that it is possible to successfully maintain acceleration levels of 5 m/s<sup>2</sup> rms up to 160 Hz.

#### 4. UNCERTAINTY

The vibration laboratory of INMETRO estimates expanded uncertainties of 0,35 % for the magnitude of sensitivity results from 0,4 Hz to 160 Hz with the present primary calibration system, assuming a level of confidence of approximately 95 % and a coverage factor  $k = 2$  [4]. This level of uncertainty requires the accelerometer to present high sensitivity and low internal noise.

#### 5. CONCLUSIONS

The new system presented in this paper allowed INMETRO to extend and improve its measurement capability to perform primary calibration of vibration transducers and measuring instruments at low frequencies frequency range of calibration with reduced uncertainties.

It was shown that fully automated primary calibrations of accelerometers and acceleration measuring sets can be carried out from 0,4 Hz to 160 Hz with estimated expanded uncertainties of 0,35 %. The system is in compliance with the requirements of ISO 16063-11 and employs the fringe counting method. Calibration of several types of transducers has already been carried out and some results were presented in this paper.

The frequency range covered by this calibration system complies with the requirements stated in the technical protocol of the next Low-Frequency Primary Acceleration Comparison that will be carried out within the Interamerican Metrology System (SIM).

The possibility of making automated measurements in a single system offers a significant advantage and a considerable time reduction. Even if it is chosen to use another system to calibrate the transducers at increased acceleration levels, the frequency overlap available provides sufficient information to compare the results obtained in the different systems used.

This low frequency primary calibration system presented here provides the necessary traceability to the SI units to the low-frequency comparison calibration system, which runs using the same experimental platform and allows INMETRO to perform high accuracy calibrations.

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