IMEKO 23rd TC3, 13th TC5 and 4th TC22 International Conference
30 May to 1 June, 2017, Helsinki, Finland

IMPROVEMENT OF THE PRIMARY LOW-FREQUENCY ACCELEROMETER CALIBRATION SYSTEM AT INMETRO

G.P. Ripper [1], *C.D. Ferreira* [1], *R.S. Dias* [1], *G.B. Micheli* [1]

[1] INMETRO / DIMCI / DIAVI / Vibration Laboratory, Duque de Caxias, Rio de Janeiro, Brazil, lavib@inmetro.gov.br

Abstract – This paper presents the results of recent improvements of the primary low-frequency accelerometer calibration system at INMETRO. The interferometric system was upgraded, a new software developed and the sine-approximation method was implemented. This new system allows the calibration of the complex sensitivity of accelerometers from 0,2 Hz to 100 Hz with reduced uncertainty.

Keywords: vibration, accelerometer, calibration, interferometry, metrology

1. INTRODUCTION

The Vibration Laboratory (Lavib) of INMETRO is continuously looking forward the improvement of its calibration systems and methods in order to fulfill the rising metrological demands in Brazil.

Low-frequency vibration measurements are of interest of many different fields, as for instance, energy production, environmental assessment, and transportation. Eolic generators and wind farms are currently an important contributor to the energy grid in Brazil. Renewable energy sources are growing in importance and there are currently 108 wind farms operating, which totalize a 2,5 GW installed capacity. The perspective is to reach 8,7 GW at the end of 2017.

The increase in size of wind power generators and their spread in northeast and south of Brazil require extended measuring capabilities in low-frequencies. The strong and constant winds found in the northeast region of Brazil generate higher structural demands than the usually found in Europe. Therefore, vibration needs to be properly considered during the development and design of wind generators and their components to comply with the specific local conditions. In addition, vibration measurements are required for different applications as for instance: experimental modal analysis, rotor balancing, vibration monitoring for operational and predictive maintenance purposes and vibration tests. Considering the regulations and financing policies for the Eolic sector, the level of national content of wind turbines shall increase. This requirement will induce the development of local industry and the need for static and dynamic tests, generating then an increasing demand for vibration measurements at low frequencies and consequently for calibration and traceability.

In addition, there is a study under development to build a national integrated research and technology center for development of human resources and to perform tests of aero-generators considering the specific meteorological and environmental demands of the country.

The first low-frequency primary interferometric calibration system initially developed at Lavib [1] was based on the fringe counting method [2], which is capable of determining the magnitude of the complex sensitivity of an accelerometer. Using this system, INMETRO has already participated in a supplementary bilateral comparison with the National Metrology Institute of South Africa (NMISA) in 2010 [3]. The results of this comparison have demonstrated metrological equivalence for the magnitude of voltage sensitivity of an acceleration measuring chain in the frequency range 0,4 Hz to 50 Hz. A relative expanded uncertainty of 0,3 % was reported by INMETRO for this exercise.

For several applications, just magnitude is not enough and the capability to measure direction is also needed. In these cases, it is necessary to know the phase response of the transducer used to measure the motion quantity. Therefore, the implementation of a method, which is capable to provide both magnitude and phase information of the complex sensitivity was desired.

This has motivated the Lavib to improve the former calibration system, implementing the necessary modifications to run the sine approximation method (SAM) [2]. This is a narrow-band measurement method, which additionally offers the possibility of improving the accuracy of sensitivity magnitude measurements. Therefore, this might allow a future reduction on the uncertainty claimed by INMETRO for low-frequency calibrations.

2. SINE APPROXIMATION METHOD (SAM)

The sine approximation method is described in details by the written standard ISO 16063-11 [2], which refers to it as method 3.

The SAM is based on the A/D simultaneous conversion of the reference in-quadrature output signals (I&Q) given by a quadrature homodyne, or alternatively by a heterodyne interferometer, and the output voltage signal of an acceleration measuring chain under calibration. It is assumed that both the accelerometer and the reference point used to determine the motion quantity by laser interferometry are under the same sinusoidal vibration.

The 90º out-of-phase I&Q signals can be digitally processed with an arc-tangent demodulation scheme, followed by a phase unwrap routine to eliminate discontinuities at integer multiplex of π, in order to obtain a resulting time-varying signal which is proportional to the vibration displacement.

Sine and cosine functions are fitted by the least squares method to this reference displacement vector as well as to the digitized accelerometer output voltage vector. The parameters obtained by these curve fitting processes allow the calculation of the magnitude and phase shift of the accelerometer under test.

3. EXPERIMENTS

A preliminary system was setup using an optical head Polytec OFV-505 taken from a commercial laser vibrometer Polytec VDD-660. This system includes an analog circuitry for down conversion of the 40 MHz centered signal given by its Mach-Zender heterodyne interferometer. In addition, a junction box VDD-Z-011 was specially customized by the manufacturer for Lavib, in order to include two BNC connectors for direct access to the I&Q baseband analog outputs. These signals can be measured using an independent data acquisition and signal processing system as the one developed in-house at Lavib without interfering with the remaining Polytec VDD-660 measuring system.

For reflection of the laser beam emitted by the optical head OFV-505, it was used a flat mirror attached to the vibration exciter moving table.

In a second stage, a quadrature homodyne interferometer was set up. In this interferometer, two retroflectors were used to facilitate the process of optical alignment, which can be tricky for low frequencies, when large displacements are present.

All the measurements presented in this paper were carried out using a servo-accelerometer Allied Signal model QA3000 as device under test.

This transducer offers high long-term stability and gives an output current signal proportional to the input acceleration, with a 1,33 mA/(g_n) nominal sensitivity magnitude. A fixed 5 kΩ shunt resistor was used to obtain a voltage output signal. Therefore, the nominal sensitivity of this set under analysis is approximately 678 mV/(m/s^2).

The main experimental setups tested were the following:

A. Calibration with the fringe counting method using a Michelson interferometer modified with 2 retroflectors and a photodetector Thorlabs PDA36A (FC).

B. Calibration with a commercial laser vibrometer Polytec VDD-660 and its own software Vibsoft 4.1. This system uses a DAQ NI PCI-6110 and processes the signals using a FFT algorithm (VDD 660 + Vibsoft).

C. Calibration with SAM implemented by Lavib in LabVIEW and using the Polytec optical head (SAM / OFV 505).

D. Calibration with SAM implemented by Lavib in LabVIEW and using a homodyne interferometer with 2 reflectors (SAM / homodyne interferometer).

3. CALIBRATION SYSTEM

An overview of the new calibration system is presented in Fig. 1. This system allows the calibration at low frequencies by both Method 1 (fringe counting) and Method 3 (sine approximation) described in the international standard ISO 16063-11 [2].

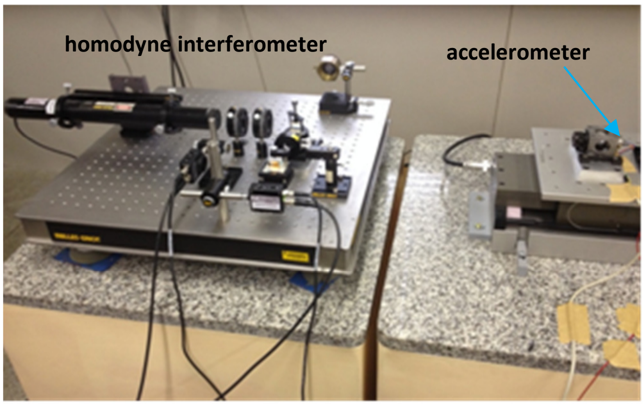

Fig. 1. Low-frequency accelerometer calibration system (homodyne interferometer with 2 retroflectors).

In Fig. 2, the homodyne quadrature interferometer is presented in details. It includes a He-Ne laser; a λ/4 retarder plate (WP-λ/4) placed in series with a polarizer (P); a non-polarizing beam splitter (BS); two retroflectors, one fixed reference (R1) and one moving (R2) which is mounted on the moving table of a vibration exciter APS 129; a λ/2 retarder plate (WP-λ/2); a polarizing beam splitter (PBS) and two photodetectors Thorlabs PDA36A (Ph1 and Ph2), for opto-electrical conversion of the I&Q signals.

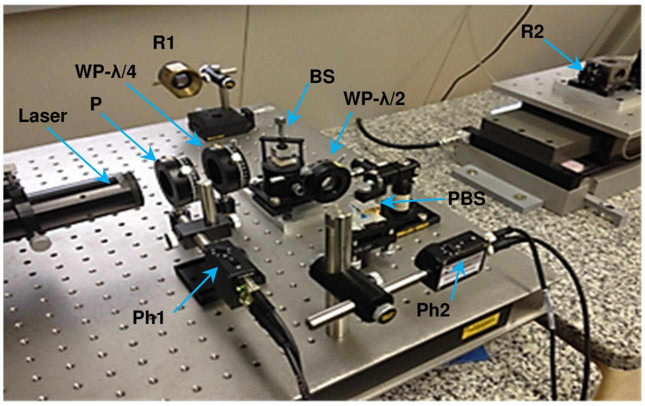

Fig. 2. Homodyne interferometer

In the homodyne quadrature interferometer the I&Q signals are obtained by optical means with the polarizing beam splitter cube (PBS). Due to the optical splitting process allied to gain differences in the two opto-electrical converters, the resulting I&Q signals can present deviations in orthogonality and amplitude, which cause the elliptical deformation of the expected circular Lissajous figure. Therefore, a correction algorithm proposed by Heydemann

[4] is applied to minimize this effect before applying the arc-tangent demodulation.

This correction algorithm was applied also with the heterodyne interferometer signals obtained when using the Polytec optical head OFV-505 to maintain the same signal processing conditions used with the two different interferometers.

The analog I&Q output signals given by the Polytec system or by the photodetectors used in the homodyne interferometer built at Lavib were digitized by 4-channel simultaneous acquisition boards (DAQ).

The Polytec system VDD-660 uses a DAQ NI PCI-6110, which offers a maximum sampling rate of 5 x 10^6 Sa/s. For the system developed at Lavib a 10 x 10^6 Sa/s DAQ NI PCI-6115 was used. A typical sampling rate of 2 x 10^6 Sa/s was used for all measurements with the program developed in LabVIEW environment in the frequency range 0,2 Hz to 160 Hz.

The PC used in this calibration system was configured with an Intel i7 processador, 32 GB RAM, 240 GB SSD, 2 TB HDD, and video board with 2 GB embedded memory. The operational system used was Windows 7 Pro 64-bits and the program environment chosen was the LabVIEW 32-bits version.

The extended memory management capability provided by the 64-bits OS is of great importance for this low-frequency calibration system because it allows the acquisition and processing of large data vectors. This feature is a basic requirement because on one hand, a high sampling frequency is necessary for the acquisition of I&Q signals, while on the other hand there is an interest on capturing the accelerometer output signal for enough time to include at least 10 periods of vibration.

The computational program developed at Lavib tries to optimize the memory use. The signals are acquired in smaller data packages during specific time lengths in a cyclic way, streaming them to the solid state drive (SSD). These smaller packages can then be retrieved and sequentially appended to each other in order to obtain data vectors with time resolution and length compatible with each vibration frequency. This procedure allows minimization of spectral leakage and the need of using time windows.

The front panel of the calibration program developed for controlling the calibration using the sine approximation method is presented in Fig. 3.

This screen allows the analysis of the quadrature signals plotted in a Lissajous figure; the ellipse correction parameters obtained from the Heydemann algorithm; both the interferometrically obtained displacement and the accelerometer output signals in the time domain. These output signals are also presented in the frequency domain, what is helpful to evaluate several parameters as for instance, harmonic distortions, noise distribution and spectral leakage.

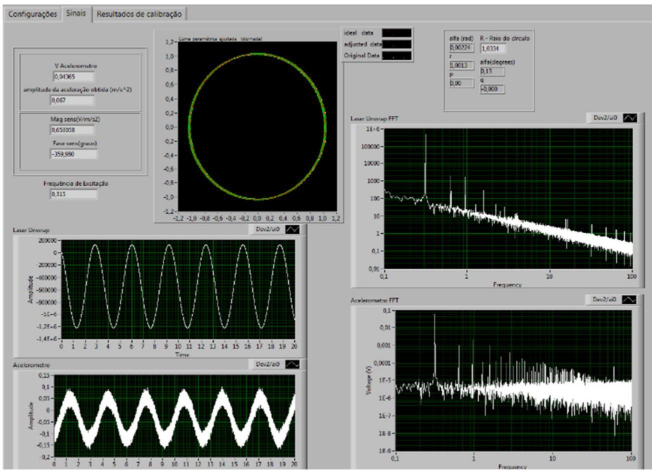

Fig. 3. Front panel of the low-frequency SAM calibration program.

4. RESULTS AND ANALYSIS

In this section, some results of sensitivity calibrations that were obtained for the servo-accelerometer Allied Signal QA3000 with the 5 kΩ shunt resistor will be presented.

In Fig. 4, the results of voltage sensitivity magnitude obtained using the fringe counting method (Mag FC) and the sine approximation method (Mag SAM) with the homodyne quadrature interferometric system are compared. These two methods require different instrumentation and independent computational programs for the calibration control and data processing.

A deviation can be observed between the frequency response curves in Fig. 4 above 5 Hz, when the acceleration level rises from 2 m/s^2 up to 3,5 m/s^2. This increase in acceleration level is usually applied to improve the signal-to-noise ratio on the transducer output signal, once it responds to the acceleration of the input vibration. At lower frequencies the acceleration amplitude is limited by the maximum stroke of vibration exciter. In the current system, where an exciter APS 129 is used, it was decided to use a 30 mm maximum peak displacement for safety reasons.

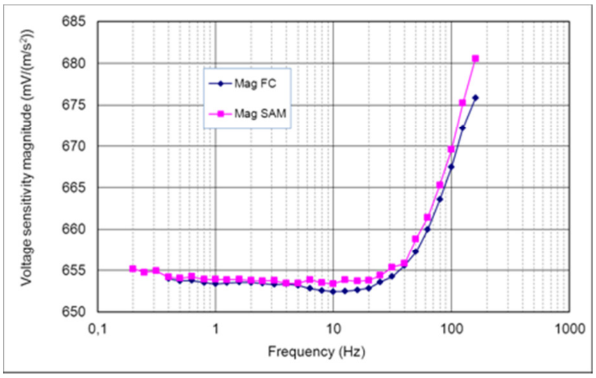

Fig.4. Voltage sensitivity magnitude results of a servo-accelerometer Allied Signal QA3000 with a 5 kΩ shunt using the fringe counting method (Mag FC) and the sine approximation method (Mag SAM).

This difference can be explained by the higher susceptibility of the fringe counting method to distortions on the vibrational motion since it is a broadband measuring technique. Noises and higher harmonic components than the fundamental sinusoidal frequency can generate additional interference fringes that are computed during the fringe counting process. Consequently, there is an increase in the reference motion amplitude, which results in a smaller transducer sensitivity obtained by the FC method.

As for both methods, FC and SAM, the measurement of the accelerometer output signal was carried out at Lavib using narrowband measuring techniques, the effect of distortions and noise on the DUT output measurements was minimized.

In order to check this assumption, it was decided to perform a amplitude linearity test varying the acceleration level from 1 m/s^2 to 8 m/s^2 at 10 Hz. The results of this experiment are given in Fig. 5, which shows the relative difference in % from the arbitrarily chosen reference acceleration condition at 1 m/s^2. As expected, there was a larger dependence between acceleration and change in sensitivity using the fringe counting method. While for the SAM, only +0,08 % rel. difference was observed, for the FC a larger -0,25 % change in sensitivity magnitude occurred due to the acceleration increase from 1 to 8 m/s^2. For phase shift measurements, which are only possible with the SAM, there was no significant change, with differences lower than 0,01°.

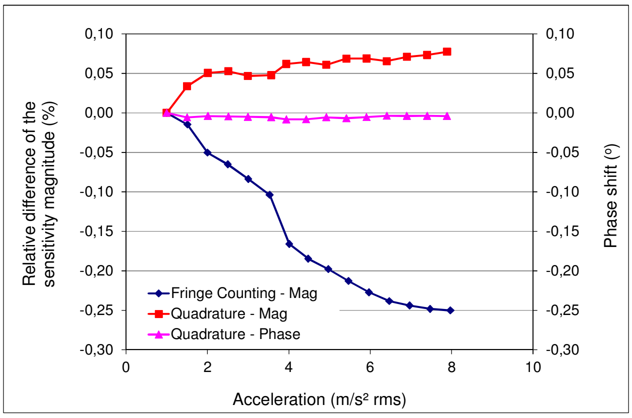

Fig. 5. Results of the amplitude linearity test carried out with the servo accelerometer QA3000 with a 5 kΩ shunt at 10 Hz. Sensitivity differences relative to 1 m/s^2 acceleration.

Some results obtained for the phase response of the servo-accelerometer QA3000 using the SAM between 0,2 Hz and 160 Hz are shown in Fig. 6. This includes results obtained using: the homodyne quadrature system developed at Lavib; the commercial system Polytec VDD-660 with its software Vibsoft; and the optical head Polytec OFV-505 with the Lavib developed SAM software in LabVIEW. The phase shift determined using these three different measuring setups did not present any significant difference.

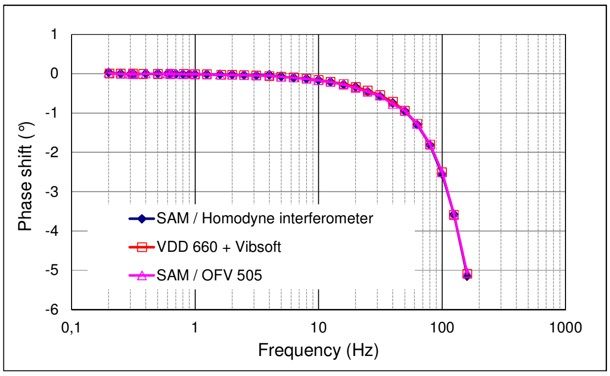

Fig. 6. Phase shift response of the servo accelerometer QA3000 with a 5 kΩ determined by SAM using three different setups.

5. RESULTS OBTAINED IN INTERLABORATORY KEY COMPARISON

This new calibration system based on SAM was used by to calibrate the complex sensitivity of the reference artifact circulated for the low-frequency vibration key comparison CCAUV.V-K3 [5, 6].

Calibrations of both sensitivity magnitude and phase shift were carried out by INMETRO from 0,2 Hz to 40 Hz. Fig. 7 presents the unilateral degrees of equivalence (DoE) between the results reported by INMETRO and the Key Comparison Reference Value (KCRV) calculated for CCAUV.V-K3.

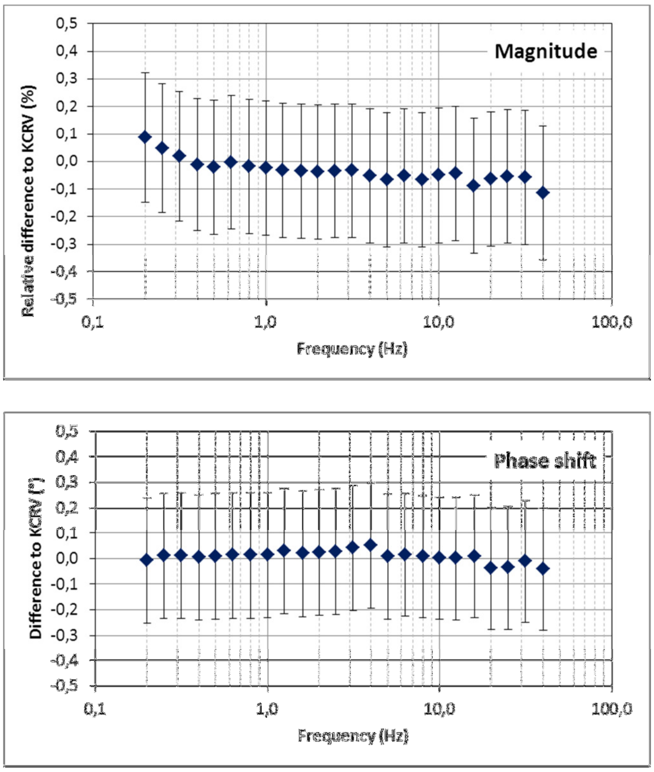

Fig. 7. Unilateral degrees of equivalence of INMETRO from the KCRV determined for key comparison CCAUV.V-K3.

It should be noted that the stability of the results at the lowest frequencies dependent highly on the internal noise produced by the device under test. In this specific case, the artifact circulated was a high quality servo-accelerometer developed by the National Metrology Institute of China (NIM). This device was selected in order to allow proper comparability of the best measurement capabilities available in the field.

INMETRO reported results with an estimated expanded uncertainty of 0,25% for magnitude and 0,25° for phase in the entire frequency range of analysis. The relative differences from these results to the KCRV (zero-line in Fig. 7) were all smaller than their respective expanded uncertainties. This demonstrates full compliance between INMETRO´s results and the reference value calculated for the comparison. Therefore, these results can be used for supporting a future update of INMETRO´s CMC, which is maintained in the appendix C of the Mutual Recognition Arrangement (MRA).

4. CONCLUSIONS

This paper describes the improvement of INMETRO´s low-frequency primary accelerometer calibration system, which was carried out at its Vibration Laboratory. This new system allows the calibration of magnitude and phase shift of the complex sensitivity of accelerometers and acceleration measuring chains between 0,2 Hz and 100 Hz.

With the use of the sine approximation method, which is a narrow band signal processing method, the measurements now present a higher immunity to noise and harmonic distortions that may be present on the vibration motion. This has helped us to reduce the influence of important uncertainty components that affect the fringe counting method.

It was demonstrated that with this new system, a reduction of the expanded uncertainty for sensitivity magnitude could be obtained and the capability to measure phase response was achieved. The current CMC of INMETRO states 0,35 % for sensitivity magnitude from 0,4 Hz to <10 Hz. Calibrations down to 0,2 Hz are now possible, depending on the internal noise produced by the device under test.

The results of the comparison CCAUV.V-K3 can be used as a supporting evidence to justify the future improvement of INMETRO´s CMC, which is maintained in the appendix C of the Mutual Recognition Arrangement (MRA).

ACKNOWLEDGMENTS

This research project received financial support from the Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), through the program ADT1 2012/02, process number E-26/190.046/2013.

REFERENCES

[1] Ferreira C.D. *et al.*, "*Sistema de calibração primária para transdutores de vibração de* 0,4 Hz *a* 160 Hz", Anais do 7º Congresso Brasileiro de Metrologia, Ouro Preto, 2013.

[2] ISO, International Standard 16063-11, "*Methods for the calibration of vibration and shock transducers – Part 11: Primary vibration calibration by laser interferometry*", International Organization for Standardization, Geneva, 1999.

[3] Veldman I., Ripper G., "*Final Report on supplementary comparison AFRIMETS.AUV.V-S2*", Metrologia vol. 49, 09001, Issue 1A, Technical supplement 2012.

[4] Heydemann, P.L.M., "*Determination and correction of quadrature fringe measurement errors in interferometers*", Applied Optics, Vol. 20, No. 19, pp. 3382-3384, October 1981.

[5] Sun Q., Yang L., "*Technical Protocol of the CIPM Key Comparison CCAUV.V-K3*", BIPM KCDB, available at http://kcdb.bipm.org/appendixB/KCDB_ApB_info.asp?cmp_idy=1356&cmp_cod=CCAUV.V-K3&prov=exalead

[6] Sun Q. *et al.*, "*Final report of CCAUV.V-K3: key comparison in the field of acceleration on the complex charge sensitivity*", Metrologia, Vol. 54, Technical supplement 09001, 2017.