Primary calibration of vibration standards in Brazil

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Abstract: This paper presents the current capability of measurement and calibration of the Brazilian National Institute of Metrology, Standardization and Industrial Quality (INMETRO) in the field of vibration. The vibration national standards developed by the Vibration Laboratory at INMETRO will be presented in details. These national standards comprehend primary interferometric calibration systems, which allow the calibration of the sensitivity of reference accelerometers under sinusoidal excitation with very low uncertainty in the frequency range between 10 Hz and 10 kHz. These systems apply different signal processing techniques, as the fringe counting method, the minimum-point method and the sine-approximation method. Currently, the complex sensitivity can be determined with uncertainties of 0,25% for magnitude and 0,25 degrees for phase shift at the reference frequency of 160 Hz. The compliance with the stated uncertainties by INMETRO and the degree of equivalence with other leading National Metrology Institutes have been positively verified through interlaboratory comparisons, as will be shown. Since these calibration systems hold the highest position in the Brazilian metrological hierarchy, they are important for all vibration measurements developed in the country, which need traceability, high accuracy and international recognition. Among the many applications that can benefit from these systems, we can cite for example: experimental modal analysis, FEM model update, comparison calibration of dynamic transducers, etc. Comparison methods against accelerometers calibrated by INMETRO can then be employed by accredited and non-accredited secondary calibration laboratories or researchers in many fields to calibrate the main sensitivity of their dynamic transducers. In addition, a broad range of other dynamic quantities can be experimentally determined through measurements referred to acceleration, including: dynamic force, dynamic torque and dynamic pressure. Therefore, the improved calibration capability that is presented here can help a large number of experimentalists to solve their dynamic problems in mechanics. The theory of each method, the schematics of each calibration setup and typical experimental results will be presented.

Keywords: Vibration; Calibration; Metrology; Accelerometer; Interferometry

INTRODUCTION

The Vibration Laboratory (LAVIB) of INMETRO is responsible for the establishment, maintenance, and dissemination of the units of translational vibration (i.e. acceleration, velocity and displacement) in Brazil.

Interferometric methods are being used worldwide by National Metrology Institutes (NMI) for primary calibration of standard accelerometers and vibration measuring chains because they provide the lowest uncertainties of measurement and allow the coverage of a broad frequency range. At primary calibration level, the realization of the acceleration unit is traced back to length and time base units of the International System of Units (SI, 2006) by means of interferometric measurement of the motion quantity. The measurement of the output signal from the device under test is traced back to units of electrical quantities (e.g. charge or voltage) and the transducer sensitivity is determined by the ratio of the electrical output to the mechanical input. The calibrated sensitivity of a standard accelerometer, which is usually given in terms of mV/(m/s²) or pC/(m/s²), might then be used to link motion measurements back to the respective units of electrical, length and time physical quantities.

This paper describes three primary calibration systems, which have been developed at LAVIB to calibrate the sensitivity of standard accelerometers within the frequency range from 10 Hz to 10 kHz (Ripper, 2005). These systems are basically composed of a laser interferometer, a vibration exciter, measuring instrumentation and a software. All of these calibration systems and the measurement methods employed are in compliance with the requirements of the international standard ISO 16063-11 (1999).

LASER INTERFEROMETRIC CALIBRATION METHODS

The series of international documentary standards ISO 16063 covers the methods for the calibration of vibration and shock transducers. The part 11 focuses specifically on primary vibration calibration by laser interferometry and describes the basic requirements for the instruments and devices required, the theory of three calibration methods and addresses the minimum components to be included in the estimation of the uncertainty of measurement. A review of the laser interferometric methods described in ISO 16063-11 is presented in this section.

The methods 1 and 2 require the use of a Michelson laser interferometer, as the one shown in Fig 1. It can be seen that this type of interferometer is composed of two optical arms, where one is called the reference arm and the other is
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known as the measurement arm. Assuming the use of a He-Ne laser as light source, a non-polarized beam splitter BS is used to split the incident beam into two orthogonal beams. The reference beam is directed onto a fixed mirror M1 and the measurement beam is directed onto the vibrating surface M2. The reflections of these two beams return into the beam splitter and are then realigned to interfere on the sensing element of photo-detector P, which converts the optical signal into an electrical output. The relative motion between the reference and measurement arms generates interference fringes, which are used to measure the mechanical motion at the measurement point. In the case of accelerometers calibration, the measurement is usually made on the top reference surface of double-ended accelerometers or close to the mounting reference surface of single-ended accelerometers.

![Michelson interferometer](image)

**Figure 1 – Michelson interferometer**

**Method 1 – Fringe counting**

Assuming a harmonic oscillation with angular frequency $\omega_1$ and amplitude $\dot{s}$ of the moving mirror M2, the time varying displacement is given by

$$s(t) = \dot{s} \cos(\omega_1 t).$$

(1)

The irradiance on the photo-detector takes then the format

$$I_{12}(t) = A + B \cos\left(\frac{4\pi}{\lambda} (L + s(t))\right),$$

(2)

where $A$ and $B$ are constants, $L$ is the difference between the two optical paths of the interferometer, $\lambda$ is the wavelength of the laser and the argument of the cosine function is the total phase $\phi_{\text{mod}}(t)$ of the interferometric signal, which represents the phase shift between the two arms of the interferometer. This term takes the form a time-variant function, which can be decomposed in two terms:

$$\phi_{\text{mod}}(t) = \left(\frac{4\pi}{\lambda}\right)L + \left(\frac{4\pi}{\lambda}\right)s(t) = \phi_0 + \phi_M(t),$$

(3)

where $\phi_0$ is the initial phase shift, which depends on the optical path difference of the system under steady conditions, $\phi_M(t)$ is the modulated phase shift associated with the moving mirror displacement.

Figure 2 shows an example of the resulting time-variant irradiance due to a sinusoidal motion of the moving mirror. This irradiance varies as a frequency modulated sine wave, where the maxima and minima are seen as interference fringes.

![Interference fringes](image)

**Figure 2 - Interference fringes (F) generated by a sinusoidal displacement (s) of the moving mirror on a Michelson interferometer**

As the amplitude of the modulated phase is given by

$$\phi_M = \left(\frac{4\pi}{\lambda}\right)\dot{s},$$

(4)

the distance between two interference fringes equals half of a laser wavelength because it corresponds to a full phase cycle variation of the interferometric signal (i.e. $\Delta\phi_M = 2\pi$). In order to the moving mirror complete a full oscillation
period \((T = 2\pi/\omega)\), it is necessary that it covers 4 times the distance \(\hat{s}\). Therefore, the number of fringes per vibration period \(R_f\) is given by

\[
R_f = \frac{4\hat{s}}{2} = \frac{8\hat{s}}{2}. \tag{5}
\]

This equation shows that the displacement amplitude \(\hat{s}\) of the oscillation can be determined by counting the number of interference fringes per oscillation cycle. Once the displacement \(\hat{s}\) is determined, the velocity amplitude \(\hat{v}\) and acceleration amplitude \(\hat{a}\) can be obtained by applying the relations:

\[
\hat{v} = \omega_1 \hat{s}, \quad \hat{a} = \omega_1^2 \hat{s}. \tag{6}
\]

As Method 1 is based on counting the number of interference fringes, which is proportional to the displacement amplitude of the measurement arm of the interferometer, it is applicable from low to mid-frequencies, typically under 1 kHz.

**Method 2 – Minimum-point of Bessel function J1**

This method requires the filtering of the photo-detector output signal with a narrow band-pass filter centered at the vibration frequency \(f_1\) and then taking the alternating part of the resulting signal. The following voltage signal is obtained

\[
U_1(t) = K J_1 \left(\frac{4\pi \hat{s}}{\lambda}\right), \tag{7}
\]

where \(K\) is a constant and \(J_1\) represents a Bessel function of 1\textsuperscript{st} kind and 1\textsuperscript{st} order. This filtered signal alternate maximum and minimum voltage points, which are associated with zero irradiance and correspond to the zeros of the Bessel function \(J_1(\phi_M)\), as shown in the Fig. 3. The measurement of the output signal of a transducer oscillating with a displacement amplitude corresponding to a zero of Bessel function \(J_1\) allows the determination of its sensitivity at this specific condition.

\[
J_1(\phi_M) = 0 \quad \Rightarrow \quad \hat{s} = \frac{\lambda}{4\pi} \phi_M. \tag{8}
\]

Since the zeros of the Bessel function are only obtained at specific amplitudes, this is basically a discrete method. Normally, it is applicable for frequencies higher than 1 kHz. Considering a He-Ne laser, with a wavelength of 632.8 nm, the first minimum point of Bessel function \(J_1\) corresponds to a displacement amplitude of 193 nm. This condition may require excessively high acceleration amplitudes, as for instance, 762 m/s\(^2\) at 10 kHz. Such a high level of acceleration is a strong limiting factor for the use of this method with air-bearing calibration shakers. Most models commercially available are limited to acceleration peak levels around 100 m/s\(^2\) for continuous sinusoidal excitation.

**Method 3 – Sine approximation method (SAM)**

A quadrature homodyne interferometer employs two photo-detectors, which furnish output voltages proportional to the in-phase (I) and quadrature (Q) components of the total interferometric phase \(\phi_{Mod}\):

\[
\begin{align*}
\hat{u}_1(t) &= \hat{u}_1 \cos \phi_{Mod}(t), \\
\hat{u}_2(t) &= \hat{u}_2 \sin \phi_{Mod}(t).
\end{align*} \tag{9}
\]
Figure 3 - Output signals of a homodyne quadrature interferometer plotted against time and in Lisajous format

Figure 3 shows two interferometric output signals in quadrature. Assuming that both signals have the same amplitude ($u_1 = u_2$), and there is no phase shift between the displacement $s(t)$ and the sinusoidal phase modulation term $\phi_M(t)$ of the total interferometric phase, then phase demodulation can be used to measure displacement. By applying an arc tangent demodulation scheme, the total interferometric phase can be obtained.

$$\phi_{\text{Mod}}(t) = \tan^{-1}\left(\frac{u_2(t)}{u_1(t)}\right).$$

(10)

Since a complete rotation of the total phase vector ($2\pi$) corresponds to a $\lambda/2$ displacement amplitude of the moving mirror, it follows that displacements much smaller than this value can be determined with high resolution through the measurement of $\phi_{\text{Mod}}(t)$, as graphically presented in Fig. 3.

A highly accurate digital phase demodulation procedure may be applied to measure the displacement parameters as follows. Both quadrature signals are equidistantly sampled giving a series of measurement values $u_1(t_i)$ and $u_2(t_i)$ over a sampling period $T$. A discrete-time series of modulation phase values $\phi_{\text{Mod}}(t_i)$ is then obtained by applying an arc tangent demodulation

$$\phi_{\text{Mod}}(t_i) = \tan^{-1}\left(\frac{u_2(t_i)}{u_1(t_i)}\right) + n\pi,$$

(11)

where an integer number $n$ is chosen to avoid discontinuities due to the ambiguity of the arctangent function at $n\pi$. After a phase unwrapping routine is applied, a displacement time series can then be obtained:

$$s(t_{i+1}) - s(t_i) = \frac{\lambda}{4\pi} [\phi_{\text{Mod}}(t_{i+1}) - \phi_{\text{Mod}}(t_i)].$$

(12)

Expanding the equation that represents $\phi_{\text{Mod}}(t_i)$ yields

$$\phi_{\text{Mod}}(t_i) = \phi_0 + \phi_M \cos \phi_s \cos \omega t_i - \phi_M \sin \phi_s \sin \omega t_i.$$

(13)

This equation shows that the discrete-time phase signal $\phi_{\text{Mod}}(t_i)$ may be approximated by a sine function. This process is usually named the sine-approximation method (SAM), which allows both amplitude and phase information to be obtained. Equation (13) can be written in the matrix format

$$Y = X\beta + \varepsilon,$$

(14)

where $Y$ is a $n \times 1$ vector containing $n$ observations of the dependent variable $\phi_{\text{Mod}}(t_i)$, $X$ is a matrix of dimension $n \times 3$ with known shape, $\beta$ is a $3 \times 1$ vector of independent variables $b$ and $\varepsilon$ is a $n \times 1$ vector of errors. The solution by the least squares method (Draper and Smith, 1966) furnishes the vector $b$ as the best estimate of $\beta$. The vector $b$ is calculated by

$$b = (X^T X)^{-1} X^T Y.$$

(15)

The modulation phase amplitude $\phi_M$ and the displacement initial phase $\phi_s$ can then be obtained by using the following formulae:

$$\phi_M = \sqrt{b_0^2 + b_1^2},$$

(16)

$$\phi_s = \tan^{-1}\left(\frac{b_2}{b_1}\right).$$

(17)

where $b_0 = \phi_0$, $b_1 = \phi_M \cos \phi_s$, $b_2 = -\phi_M \sin \phi_s$. 
Amplitude and initial phase of the acceleration are calculated through the relations
\[ \hat{a} = \pi \lambda f^2 \phi_M, \]  
\[ \phi_a = \phi_i + \pi. \]  

Similarly, the sine-approximation method is applied to the sampled output values \( u(t) \) of the acceleration measuring chain in order to obtain the amplitude \( \hat{u} \) and initial phase \( \phi_u \). The magnitude \( \hat{S}_{ua} \) and the phase shift \( \Delta \phi_{ua} \) of the accelerometer voltage sensitivity are then calculated as
\[ \hat{S}_{ua} = \frac{\hat{u}}{a}, \]  
\[ \Delta \phi_{ua} = (\phi_u - \phi_a). \]  

**NATIONAL MEASUREMENT STANDARDS**

The Brazilian vibration national measurement standards comprehend primary calibration systems used to realize the SI units related to vibration quantities, i.e. acceleration, velocity and displacement. Additionally, at secondary level, comparison calibration systems are used for the dissemination of these units. In absolute calibrations, the sensitivity of a transducer is determined by measurements based on fundamental and derived units of the SI, for the related physical quantities. The units realized by the vibration national measurement standards are disseminated to accredited and non-accredited calibration laboratories by standardized calibrations of reference and transfer standards. These reference standards are mainly standard accelerometers, or standard reference sets (accelerometer and associated signal conditioner). For high impedance piezoelectric accelerometers, the charge sensitivity of the transducer is reported. For low impedance piezoelectric accelerometers and for standard reference sets, the voltage sensitivity of the transducer or of the set can be reported depending on the request of the customer.

The absolute national measurement standards mainly consist of a vibration exciter to generate the motion quantities, an interferometric measurement system to accurately quantify this motion and appropriate equipment for the measurement of the signal put out by the transducer under calibration. Basically due to limitations of commercial vibration exciters, a single system can not be used to cover all calibration frequencies in a broad frequency range (Ripper, Dias and Garcia, 2006a). In order to minimize disturbing influences on the generated motion, different exciters are used. In addition, as already mentioned, each method is better applicable to a specific frequency range. Therefore, the LAVIB needs to employ different calibration systems. Hereunder are presented the characteristics of three calibration set-ups currently used to carry out primary vibration calibrations within the frequency range from 10 Hz to 10 kHz.

**Primary level calibration set-ups:**

1) Mid-frequency absolute calibration system – frequency range: 10 Hz to 5 kHz
   - Calibration method: fringe counting
   - Uncertainty: 1 % (10 Hz to 40 Hz); 0.5 % (50 Hz to 1 kHz); 1 % (1.25 kHz to 5 kHz).

2) High-frequency calibration system – frequency range: 4 kHz to 10 kHz
   - Calibration method: minimum-point
   - Uncertainty: 1 % (4 kHz to 5 kHz); 1.5 % (6.3 kHz to 10 kHz).

3) Quadrature homodyne calibration system – frequency range: 10 Hz to 10 kHz
   - Calibration method: sine-approximation
   - Uncertainty: under validation through interlaboratory comparison CCAUV.V-K1.1.

The calibration of accelerometers and vibration standard sets are carried out at LAVIB by laser interferometric methods in accordance with the standard ISO 16063-11:1999. Currently, the Method 1 – “Fringe-counting method” is being used in the frequency range from 1 Hz to 1 kHz and the Method 2 – “Minimum-point method” can be applied from 1.25 kHz to 10 kHz. Since method 2 is limited to discrete amplitudes, is very time-consuming and difficult to automate, it tends to be substituted by Method 3.

Traditionally, the fringe counting method has been used for primary calibrations at frequencies lower than 1 kHz. Figure 4 shows the set-up used at the LAVIB. A signal generator and a power amplifier drive the vibration exciter with sinusoidal motion. A frequency counter configured for frequency ratio measurements is used to determine the number of fringes per oscillation period. The voltage output from the device under test is measured by a true rms voltmeter. Thermocouples connected to a data logger are used to monitor the environmental and accelerometer temperatures during calibration process. The harmonic distortion of the accelerometer output is evaluated with a FFT analyzer and an oscilloscope is used for alignment of the interferometer and visual monitoring of the fringe interference pattern. The
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entire calibration process is controlled via IEEE-488 interface by a control program developed in LabVIEW environment.

Figure 5 shows one set-up used to apply the $J_1$ minimum-point method. The main difference from the system in Fig. 4 is the filter used to band-pass filter the output signal from the photodetector. An analog voltage divider is included between the signal generator and the power amplifier to increase the resolution of the amplitude setting. This helps to achieve the minimum point condition when a digital waveform generator is used. Unfortunately, the application of the minimum-point method is not very easy to automate and is mostly carried out based on visual detection. More recently, many NMI have been developing calibration systems, which combine interferometry and digital signal processing techniques as the sine-approximation method. This combination provides superior flexibility and controllability of the calibration process because frequency-selective analysis techniques can be applied and many sources of error can be identified and then corrected or even avoided.

A fully automated calibration system capable of applying the Method 3 – “Sine-approximation method” from 10 Hz to 10 kHz has already been implemented in the vibration laboratory. This system is based on a homodyne quadrature interferometer, which is capable of calibrating both magnitude and phase-shift of the complex sensitivity. Figure 6 presents the set-up implemented in the LAVIB. Since this is the most recent system, it will be explained in more details in the next section.

It is important to note that the calibration systems here described integrate commercially available instruments and components with software developed specifically to control the calibration process, capture and process the measurement data. These systems do not suffer major limitations as the ones imposed by closed commercial systems running proprietary softwares. Since the laboratory holds full controllability of all stages of the measurement process, it has a high degree of adaptability to diverse applications. This furnishes the capability to substitute equipments, configure special measurement conditions, evaluate different signal processing techniques, export measurement results, etc.

The results obtained by LAVIB are periodically checked using reference transducers calibrated at other NMIs and by the results obtained in interlaboratory comparisons. The deviations obtained so far have shown very good agreement with the uncertainties of measurement estimated, giving high confidence on the results reported in the calibration certificates issued by LAVIB. In addition, partial overlapping of the frequency ranges of the different calibration systems available at the LAVIB allows the development of intra-laboratory cross-checks among them.
Figure 6 - Primary accelerometer calibration system by the sine-approximation method (ISO 16063-11:1999, Method 3)

HOMODYNE QUADRATURE INTERFEROMETRIC SET-UP

An interferometer with quadrature signal output was implemented, as shown in Fig. 7. A 1 mW stabilized He-Ne laser is used as a light source. The laser tube is rotated so that the polarization of the emitted laser beam is at 45° relative to the surface of the optical table. A Faraday rotator FR introduces an additional 45° rotation, so that the light becomes vertically polarized. This element protects the laser cavity from spurious reflections returning into it with a 30 dB extinction factor. After passing through a beam expander BE, the light beam crosses a ¼-wavelength retarder plate (R-λ/4) and becomes circularly polarized. A non-polarizing beam splitter BS splits the incident beam into two orthogonal beams with a 50/50 ratio. The reference beam is then polarized by P1 and directed onto the flat mirror M1. A beam steering set of mirrors M3 allow the alignment of the measurement beam onto the surface of the moving mirror M2, which is fixed to the accelerometer reference surface. The beam reflects on M2 and returns following the same optical path in the inverse direction. After the BS, both reference and measurement beams pass through a ½-wavelength retarder plate (R-λ/2), which is adjusted to produce optical interference at the polarizing beam splitter PBS. Two beams with similar intensity and in phase quadrature are obtained. The photoelectric conversion of the optical quadrature signals is made by the two Si photo-detectors PD1 and PD2. These elements furnish the quadrature output voltages \( u_1(t) \) and \( u_2(t) \).

Figure 7 - Scheme of the homodyne quadrature interferometric set-up.
MEASURING SYSTEM

An electrodynamic shaker rigidly mounted on a 200 kg inertial block is used to generate mechanical motion. The interferometer is mounted on an optical breadboard with air-spring vibration isolation, as shown in Fig.8. The measuring system is based on an analog-to-digital conversion card fitted into a PC. This card allows 4-channel simultaneous sampling with a maximum rate of 5 MSa/s and with 12-bit resolution.

A phase-locking scheme fully synchronizes the measurements with the vibration. A digital high-pass recursive moving average filtering algorithm and a flexible setting of the sampling rate are implemented to minimize the influence of low frequency noise caused by relative movement between the shaker and the interferometer. These implementations minimize leakage problems and permit the use of spectral analysis without any windowing (Ripper, Garcia and Dias, 2006b).

The computer program fully automates the calibration process at each measuring point. Stepped sine calibrations are performed at 44 selected frequencies within 10 Hz and 10 kHz. The calibration parameters are easily controllable, allowing the selection of limited frequency ranges and any number of measurements. Acceleration amplitudes are self-adjusted by an iterative algorithm to match the desired calibration levels and interferometric quadrature non-linearities are corrected at each cycle using a least squares ellipse-fit method (Heydemann, 1981). Time and frequency domain graphic windows allow visual analysis of the calibration results. In addition, displacement, voltage and sensitivity results are displayed on the computer screen and saved in ASCII files for post-processing in Excel spreadsheets.

A unique characteristic of the software is the parallel analysis of the displacement and voltage time series, \(s(t_i)\) and \(u(t_i)\), with three techniques:

- Sine-approximation method;
- Single sine correlation method;
- Discrete Fourier Transform (DFT).

The homodyne quadrature system is currently being used to calibrate the complex sensitivity of standard accelerometers in the frequency range from 10 Hz to 10 kHz. Measurements have already been carried up to 50 kHz, but this requires the change of the vibration exciter. This system is very versatile and can also be easily adapted to calibrate laser Doppler vibrometers with analog output (Ripper, Garcia and Dias, 2005). Further research will be carried out to extend the calibration capability for vibrometer with digital output.

CALIBRATION RESULTS

An example of a typical result obtained for a single-ended standard accelerometer is shown in Fig. 9. This figure includes calibration results obtained with the system shown in Fig. 4 using the fringe counting method (FC) and results obtained with the quadrature system (Fig. 8) using the sine-approximation method (SAM). The modulus of the charge sensitivity is presented in Fig. 9 (a) and the phase shift in 9 (b). The estimated expanded uncertainties with a coverage factor \(k = 2\) are presented as vertical bars for the SAM.
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**Charge sensitivity - Modulus**

0,106
0,108
0,110
0,112
0,114
0,116
0,118

10 100 1000 10000

Frequency [Hz]

**Modulus [pC/(m/s 2)]**

SAM
FC

**Charge sensitivity - Phase shift**

-2,00
-1,50
-1,00
-0,50
0,00
0,50
1,00
1,50
2,00

10 100 1000 10000

Frequency [Hz]

**Phase shift [°]**

SAM

(a) Sensitivity modulus  
(b) Phase shift

Figure 9 - Calibration results obtained for a single-ended standard accelerometer.

It should be noted that fig. 9 (a) compares the results obtained by two totally independent calibration systems and methods as well. An agreement within ± 0,20 % is observed between the results from 10 Hz to 20 Hz and within ± 0,10 % from 20 Hz to 1000 Hz.

**UNCERTAINTY ESTIMATE**

The combined relative uncertainty for the sine-approximation method was calculated in accordance with methodologies described in the Guide to the Expression of Uncertainty in Measurement (ISO/IEC Guide 98-3, 2008) using Type A and Type B evaluations of uncertainty components, including those contained in the international standard ISO 16063-11 (1999). The values in Table 1 and 2 may be confirmed soon by the results of interlaboratory comparisons.

**Table 1: Estimated expanded uncertainty, \(U\), using a coverage factor \(k = 2\) for the modulus of the complex sensitivity measured by the sine-approximation method**

<table>
<thead>
<tr>
<th>Frequency interval [Hz]</th>
<th>(U) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 to 20</td>
<td>0,35</td>
</tr>
<tr>
<td>25 to 2500</td>
<td>0,25</td>
</tr>
<tr>
<td>3000 to 4500</td>
<td>0,35</td>
</tr>
<tr>
<td>5000 to 6500</td>
<td>0,60</td>
</tr>
<tr>
<td>7000 to 10000</td>
<td>0,80</td>
</tr>
</tbody>
</table>

**Table 2: Estimated expanded uncertainty, \(U\), using a coverage factor \(k = 2\) for the phase shift of the complex sensitivity measured by the sine-approximation method**

<table>
<thead>
<tr>
<th>Frequency interval [Hz]</th>
<th>(U) [degree]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 to 3000</td>
<td>0,25</td>
</tr>
<tr>
<td>3150 to 5000</td>
<td>0,50</td>
</tr>
<tr>
<td>5500 to 10000</td>
<td>1,0</td>
</tr>
</tbody>
</table>

**INTERLABORATORY COMPARISON**

The degree of equivalence between the Brazilian national standards and the ones of other countries is determined through the results obtained in interlaboratory comparisons. Usually, standard accelerometers or acceleration sets are circulated through the participating laboratories, which perform calibrations following a pre-agreed technical protocol. The calibration results reported by each NMI are used to compute the degrees of equivalence between pairs of laboratories and between each participating laboratory and the reference value of the comparison. In case of being a key-comparison of the Consultative Committee in Acoustics, Ultrasound and Vibration (CCAUV), the reference value is called a key-comparison reference value (KCRV).

Key comparisons carried out within a regional metrology organization, as the Inter-American Metrology System (SIM) in the Americas must be linked to CCAUV key-comparisons. Supplementary comparisons can be taken at
regional level to account for specific local necessities. The results in comparisons are used to demonstrate conformity of the measurement results with the estimated uncertainties declared by a NMI.

The quadrature homodyne system presented here has already participated in three interlaboratory comparisons. The first one was a bilateral comparison with INETI / Portugal. The second one was a bilateral comparison named SIM.AUV.V-K1.1, which was carried out between CENAM / Mexico and INMETRO / Brazil. The third one was the key comparison CCAUV.V-K1.1, which was carried out among PTB / Germany, NIM / China, NPLI / India and INMETRO / Brazil. The results of these comparisons will serve as objective evidences of the improvement of our measurement capability and allow INMETRO to claim for lower uncertainties than the currently established in its Calibration and Measurement Capability (CMC), which is available at the BIPM web page and is part of the BIPM key comparison database concerning Appendix C of the Mutual Recognition Arrangement between National Metrology Institutes (MRA, 1999).

SUMMARY

Primary laser interferometric methods used for calibration of vibration standards have been reviewed. Three calibration systems developed in the Vibration Laboratory at INMETRO have been presented, with emphasis on a primary calibration system based on a homodyne quadrature interferometer. This system allows the calibration of both modulus and phase shift responses of standard accelerometers and acceleration measuring chains (accelerometer plus conditioning amplifier) in the frequency range from 10 Hz to 10 kHz. This system performs automated calibrations of voltage and charge sensitivities in accordance with the Method 3 of the international standard ISO 16063-11. An overview of the measuring set-up was presented, including a description of some distinguished features of the developed computer program. A typical calibration result using this system is presented and in addition, it is compared to the modulus of the sensitivity obtained by a totally independent calibration system using the fringe-counting method. The estimated expanded uncertainties for this new system represent a considerable improvement of the measurement capability of the laboratory. It is currently being evaluated through interlaboratory comparisons and will be the basis for a subsequent claim for improvement of our CMC.

REFERENCES


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