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The development of a new primary calibration system for laser vibrometers at inmetro

Gustavo P. Ripper, Guilherme A. Garcia, Ronaldo S. Dias

INMETRO-National Instituto of Metrology, Standardization and Industrial Quality,
DIAVI - Division of Acoustics and Vibration Metrology, LAVIB – Vibration Laboratory.
Av. Nossa Senhora das Graças 50, Xerém, D. Caxias, 25250-020 Rio de Janeiro, Brazil,
lavib@inmetro.gov.br

Abstract

The laser vibrometer (LV) is a powerful non-contact transducer capable of accurately measuring point motion quantities by means of interferometric techniques. According to the requirements in standard ISO/IEC 17025, measurement traceability to the International System of Units (SI) is to be established through an unbroken chain of calibrations, linking measuring and testing equipment to the national or international measurement standards. At present, standard procedures specifying how to calibrate a laser vibrometer are still an open issue. As laser vibrometers are becoming more and more a standard measurement tool for the mechanical engineer, the establishment of standards and calibration procedures becomes more urgent. Otherwise, LVs can not be used in many applications such as a reference for the calibration of accelerometers by secondary laboratories. The vibration laboratory of INMETRO has two digital laser vibrometers and is developing a new calibration system to trace them back to the Brazilian national measurement standards. Basically, two alternative methods are applicable: primary calibration by laser interferometry, and secondary calibration by comparison to a reference transducer traceable to a national standard. This paper focuses on the primary calibration of laser vibrometers against a homodyne quadrature interferometric system. The system under development may be able to calibrate LVs with both analog and digital outputs. The theory of the method is briefly described. The scheme of the new experimental setup is presented and some experimental results obtained in a preliminary implementation are given.

Keywords: calibration, vibrometer, vibration, metrology

1. Introduction

The number of publications covering the calibration of laser vibrometers (LV) has increased considerably during the last few years [1-6] demonstrating an increasing interest of calibration laboratories and national metrology institutes (NMIs) in the subject.

An international standard directed specifically to this subject is currently under development (ISO 16063-41) [7], therefore its circulation is limited to the respective ISO technical committee (i.e. ISO TC 108/SC 3). The German Calibration Service (DKD) dealt with this problem and issued the DKD-Richtlinie DKD-R 3-1/Blatt 4 [8], which is a guide to primary calibration, including the calibration of vibrometers. Since this document is mostly dedicated to accredited laboratories, it is superficial regarding the calibration of vibrometers and leaves many points open, especially for the level of interest of national metrology institutes. Meanwhile, the use of LVs is being substantially increased and their users are demanding for traceability to national standards [9-10]. This rising demand directed the vibration laboratory of the Brazilian national metrology institute (INMETRO) towards the necessity of developing a calibration system capable of measuring the complex sensitivity of laser vibrometers.

A preliminary calibration system was already implemented as an adaptation of the homodyne interferometric system used to calibrate accelerometers [3], in which the sine-approximation method [11] is applied. This system is currently active and capable of measuring magnitude and phase shift of the complex sensitivity in a frequency range from 10 Hz to 10 kHz. Some results obtained with this system will be presented here.

A new calibration system is under development and its design and main characteristics will be discussed here. It will be composed of a vibration excitation subsystem, a homodyne quadrature interferometer, data acquisition hardware and control software. The calibrations carried out with this new system shall be in conformity with the requirements of the international standards ISO 16063-11 [11] and the future release of ISO 16063-41 [7].

2. Laser doppler vibrometers

Laser vibrometers offer the capability of making accurate non-contact measurements, which are useful to determine motion quantities in many industrial and metrological applications. This powerful tool can be divided in a number of classes, which will be briefly described in this section.

A vibrometer can be classified either as a vibration measuring instrument, if it includes a readout display or as a vibration transducer, if it furnishes an output signal proportional to motion, as shown in figure 1. In the first case, calibration refers to comparing the instrument output reading against a reference standard capable of measuring accurately input motion quantities (e.g. acceleration, velocity or displacement). In the second case, calibration refers to the measurement of the sensitivity of the transducer, which is determined as the ratio of the output quantity generated by an input motion quantity.
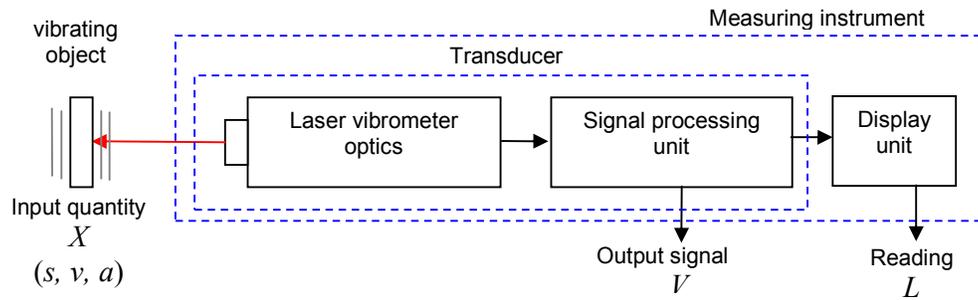
Figure 1: Laser vibrometer – transducer x measuring instrument

They can also be classified according to the type of interferometer used, i.e. homodyne or heterodyne and also by the different signal processing techniques used to demodulate the interferometric output signals.

The instantaneous value of displacement can be obtained by applying phase demodulation techniques and the instantaneous value of velocity by frequency demodulation. These quantities can be traced back to the wavelength of the laser light according to equations

$$\varphi_M(t) = (4\pi/\lambda)s(t),$$ (1)

and

$$f_D(t) = (2/\lambda)v(t),$$ (2)

where

$\varphi_M(t)$ is the instantaneous value of the modulation term of the total interferometric phase,

$f_D(t)$ is the instantaneous value of the Doppler frequency of the interferometric signal,

$s(t)$ is the instantaneous value of displacement,

$v(t)$ is the instantaneous value of velocity,

λ is the wavelength of the laser light.

Vibrometers, as shown in figure 1, comprehend at least an optics front-end and a signal processing unit, where the signal demodulation occurs. Usually, a phase demodulator is called a velocity decoder and a frequency demodulator is called a displacement decoder.

Common models of LVs use analog demodulation circuits, which are affected by linearity and drift errors. Some newer models use digital demodulators, which are more accurate and less sensitive to these problems. There are commercial models that digitally process the in-phase and quadrature (I&Q) signals in a PC applying the arctangent demodulation as in ISO 16063-11 [11]. Polytec systems VDD-650 and VDD-660 do this, but instead of applying the single frequency sine-approximation method recommended in the ISO standard, the Fast Fourier Transform (FFT) is used [12].

Digital demodulation offers many advantages over analog demodulation:
- improved velocity resolution and lower noise floor,
- higher measurement linearity and accuracy,
- linear phase response,

- higher independence to aging effects and environmental influences,
- high long-term accuracy stability,
- digital low pass output filters with excellent properties,
- digital signal interface to data storage or processing,
- minimized EMC influence on accuracy.

According to Bauer et al. [12], currently available digital-vibrometer systems provide outstanding measurement precision. Although suitable for many industrial and metrological applications, these systems cannot yet cope with very high velocities or frequencies. The current limits of the PC-based Polytec VDD-650 system are v_{max}= 0,8 m/s and f_{max}= 2 MHz, which are mainly determined by the properties of the A/D converter. Actual designs of digital velocity decoders achieve a velocity limit of 0,5 m/s in the vibration frequency range 0,5 Hz- 350 kHz.

Some digital vibrometers provide in addition to the conventional analog output, a S/P-DIF (Sony/ Philips Digital Audio Inter Face) standard digital output, which connects easily to PC sound cards and digital audio recorders (mini-disk, DAT), bypassing data acquisition electronics. Figure 2 shows a digital signal processing scheme of an all-digital velocity decoder with both analog and S/P-DIF digital outputs. Current solutions support 24-bit amplitude resolution at a sample rate of 48 kS/s in the frequency range from 0 to 22 kHz. Bauer [12] reports that the inherent amplitude accuracy of a digital decoder (0,2%) is available at the digital output, while the D/A converter introduces another 0,2% error to the analog output.
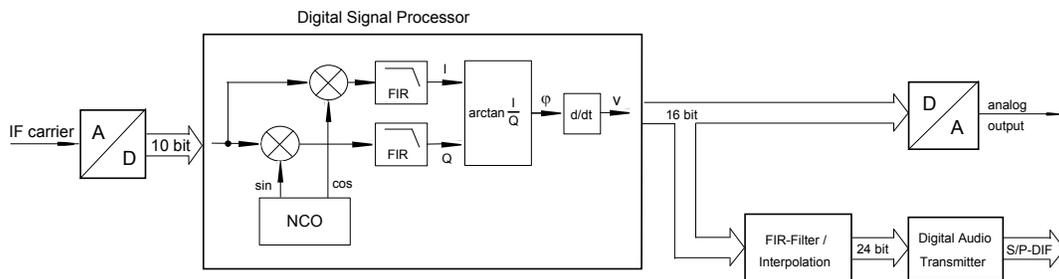

Figure 2: Signal processing scheme of an all-digital velocity decoder

A characteristic of sequential digital data processing is a certain propagation delay. Current designs of DSP velocity decoders as shown in figure 2 run at clock frequencies above 50 MHz, resulting in a total delay in the order of 10 µs referred to the 16-bit analog output. Compared to a conventional velocity decoder with same bandwidth, the digital solution is currently slower by a factor of 3 to 4. This has to be considered in conjunction with phase related measurements. Due to the additional decimation and interpolation process, propagation delay referred to the 24-bit digital output is about 1 ms. Since these delay times are absolutely constant, digital decoders are characterized by a strictly linear phase response over the full operating frequency range, which can readily be compensated during the subsequent data processing.

The draft of ISO 16063-41 [7] defines a Laser Vibrometer Standard (LVS) as a reference standard containing a laser interferometer, designed and intended to serve as a reference to calibrate laser vibrometers and/or vibration transducers. It may implement all or portions of the data processing chain needed for Method 3 (i.e. sine-approximation method) [11]. So a quadrature pair of outputs can be provided in analog or digital format for further processing. Alternatively, one or more data streams, representing the time histories $s(t)$, $v(t)$ or $a(t)$ or averaged magnitudes may be available at a standard serial interface. A Laser Vibrometer (LV) is defined as a measuring instrument containing a laser interferometer, designed and intended to perform vibration measurements.

Vibrometers operating as digital transducers transform a sinusoidal input motion quantity into one or more sequences of time-discrete samples of displacement, and/or velocity and optionally acceleration. Therefore, LVSs typically include digital signal processing and standardized digital output.

It should be noted that despite of the inherent higher accuracy of digital decoders, the digital output via S/P-DIF is currently limited to 22 kHz and the phase shift is considerably higher than in analog demodulators. Due to this reason, many users use mixed systems, including both digital (more accurate) and analog (wider bandwidth) decoders.

Considering all the points described before, INMETRO designed and is currently implementing a new calibration system capable of carrying out calibrations of both "reference" laser vibrometer standards (LVS) and "working" laser vibrometers (LV). This system will be used for calibration of the complex sensitivity (magnitude and phase shift) of laser vibrometers with digital and analog outputs, and of LVs with $s(t)$, $v(t)$ or $a(t)$ display readings or averaged magnitudes output. In addition, the system may be able to process quadrature pair of outputs provided from laser vibrometer standards under calibration to evaluate different signal processing implementations against the ones in the national standard [3].

3. Theory of the method

In this section, the device to be calibrated will be assumed to be a laser vibrometer with an analog output.

Given a sinusoidal displacement

$$s(t) = \hat{s}\cos(\omega_1 t + \varphi_s), \tag{3}$$

a laser vibrometer outputs a voltage signal, which follows the relationship

$$u(t) = \hat{u}\cos(\omega_1 t + \varphi_u), \tag{4}$$

where $\hat{s}$ and $\hat{u}$ are respectively amplitudes of the displacement and vibrometer output, ω_1 is the angular frequency of the harmonic vibration and φ_s and φ_u are respectively the initial phases of the displacement and vibrometer output.

The output of the two photodetectors of the quadrature homodyne interferometer comprise an in-phase (I) and a quadrature (Q) component of the total interferometric phase:

$$u_1(t) = \hat{u}_1 \cos \varphi_{Mod}(t) \tag{5}$$

$$u_2(t) = \hat{u}_2 \sin \varphi_{Mod}(t) \tag{6}$$

where

$$\varphi_{Mod}(t) = \varphi_0 + \varphi_M(t) = \varphi_0 + \hat{\varphi}_M \cos(\omega_1 t + \varphi_s) \tag{7}$$

is composed of the initial phase angle, φ_0, which depends on the optical path difference between the arms of the interferometer and a modulation term, $\varphi_M(t)$. The amplitude $\hat{\varphi}_M$ is proportional to the displacement:

$$\hat{\varphi}_M = (4\pi / \lambda)\hat{s}. \tag{8}$$

4. The sine-approximation method

Assuming that the interferometer I&Q output signals have equal amplitudes ($\hat{u}_1 = \hat{u}_2$) and that there is no phase shift between the displacement $s(t)$ and the sinusoidal phase term, $\varphi_M(t)$, a phase demodulation can be used to measure displacement.

A digital phase demodulation procedure can be applied if both signals $u_1(t)$ and $u_2(t)$ are equidistantly sampled with a sampling interval $\Box t = t_i\text{-}t_{i+1}$, where i = 0, 1, 2, ..., N, 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 $\varphi_{Mod}(t_i)$ can then be obtained by applying an arctangent demodulation

$$\varphi_{Mod}(t_i) = \tan^{-1}\left(\frac{u_2(t_i)}{u_1(t_i)}\right) + n\pi, \tag{9}$$

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

$$s(t_i) = \frac{\lambda}{4\pi}\varphi_{Mod}(t_i). \tag{10}$$

Expanding Eq. 7 yields

$$\varphi_{Mod}(t_i) = \varphi_0 + \hat{\varphi}_M \cos\varphi_s \cos\omega_1 t_i - \hat{\varphi}_M \sin\varphi_s \sin\omega_1 t_i. \tag{11}$$

This function can be transformed into the linear form of a multiple regression [13]

$$Y = b_0 + b_1 x_1 + b_2 x_2, \tag{12}$$

where $Y = \varphi_{Mod}(t_i)$, $x_1 = \cos\omega_1 t_i$, $x_2 = \sin\omega_1 t_i$, $b_0 = \varphi_0$, $b_1 = \hat{\varphi}_M \cos\varphi_s$, and $b_2 = -\hat{\varphi}_M \sin\varphi_s$.

Approximating the discrete-time phase signal $\varphi_{Mod}(t_i)$ by a sine function, what is usually named the sine-approximation method (SAM), allows the amplitude and phase information to be obtained. This is achieved by solving a system of $N+1$ equations for the three unknown parameters b_0, b_1 and b_2,

using a least-squares sum method. The modulation phase amplitude $\hat{\varphi}_M$ and the displacement initial phase φ_s can then be obtained by using the following formulae:

$$\hat{\varphi}_M = \sqrt{b_1^2 + b_2^2} \, , \tag{13}$$

$$\varphi_s = \tan^{-1}(b_2 / b_1). \tag{14}$$

The amplitude and the initial phase of the velocity are calculated through the relations

$$\hat{v} = f \frac{\lambda}{2} \hat{\varphi}_M \, , \tag{15}$$

$$\varphi_v = \varphi_s + \pi / 2 \, . \tag{16}$$

Similarly, the sine-approximation method is applied to the time series of sampled vibrometer output values $u(t_i)$ in order to obtain the amplitude $\hat{u}$ and initial phase φ_u. The magnitude $\hat{S}_{uv}$ and the phase shift $\Delta\varphi_{uv}$ of the vibrometer complex sensitivity are then calculated:

$$\hat{S}_{uv} = \frac{\hat{u}}{\hat{v}} \, , \tag{17}$$

$$\Delta\varphi_{uv} = (\varphi_u - \varphi_v). \tag{18}$$

5. The interferometric set-up

A modified Michelson-type interferometer with quadrature signal output was implemented, as shown in figure 3.
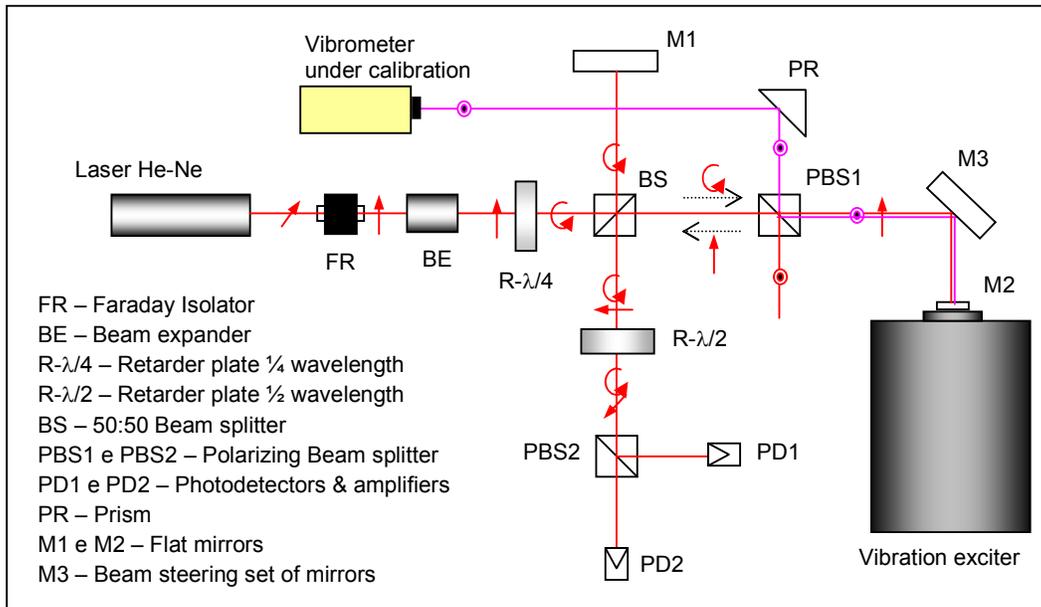

Figure 3: Homodyne quadrature interferometric set-up used for calibration of vibrometers

A linearly polarized red helium-neon laser is used as light source. The laser tube is rotated so that the polarization of the emitted laser beam is at a 45° angle relative to the surface of the optical table. A Faraday rotator FR introduces an additional 45° rotation and the light becomes vertically polarized. This element protects the laser cavity from spurious back-reflections returning into it with a 30 dB extinction factor. In sequence, after passing through a beam expander BE, the light beam crosses a quarter wavelength retarder plate (R-λ/4) and becomes circularly polarized. A non-polarizing beam splitter BS splits the incident beam into two orthogonal beams. The reference beam is directed onto the flat mirror M1 and the measurement beam is linearly polarized by a polarizing beam-splitter PBS1, which works as a directional coupler, allowing the horizontally polarized beam emitted by the vibrometer under calibration and the measurement beam of the homodyne interferometer to be directed onto the vibrating surface without optical interference. The set of mirrors M3 act as a beam steering device and allow proper alignment of the two beams (vibrometer and homodyne interferometer) onto the surface of the moving mirror M2, which is fixed to the vibration exciter table. After reflecting on M2, the two beams return following the same optical path in the inverse direction up to PBS1. At this point, the vibrometer beam is directed to PR and then back into the vibrometer. The vertically polarized measurement beam of the homodyne interferometer passes through PBS1 and after being reflected by the beam splitter BS it is realigned with the circularly polarized reference beam reflected by M1. 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 PBS2. Two beams with similar intensity and in phase quadrature are obtained and transformed by photodetector PD1 and PD2 into output quadrature voltages $u_1(t)$ and $u_2(t)$.

6. The instrumentation set-up

6.1 Preliminary set-up

The first experimental set-up for calibration of laser vibrometers was implemented at the vibration laboratory of INMETRO in 2004 [3]. It was an adaptation of the existing homodyne quadrature calibration system of accelerometers to allow calibration of the complex sensitivity of vibrometers with analog output.

This system employs an electrodynamic vibration exciter to generate motion quantities. The reference homodyne interferometer and the vibrometer under calibration are mounted on the top of a vibration isolated optical table. Analog-to-digital conversion of the interferometer I&Q output signals and vibrometer output are carried out with a multifunction data acquisition (DAQ) board, which allows 4-channel simultaneous data sampling with a maximum rate of 5 MSa/s and 12 bits resolution.

A computer program developed in LabVIEW controls the calibration process and generates appropriate output data files for post-processing. The program performs stepped-sine calibrations with servo-control of the vibration

amplitude and proper adjustment of the A/D converter input ranges at each calibration frequency. After simultaneously sampling of the reference interferometer and LV output signals, the lack of quadrature of the reference interferometric signals is corrected by the least squares ellipse fit technique proposed by Heydemann [14]. The corrected I&Q series are then submitted to digital arctangent demodulation followed by a phase unwrapping routine. The result is the total modulation phase, from which the displacement time series is obtained as shown in figure 4.
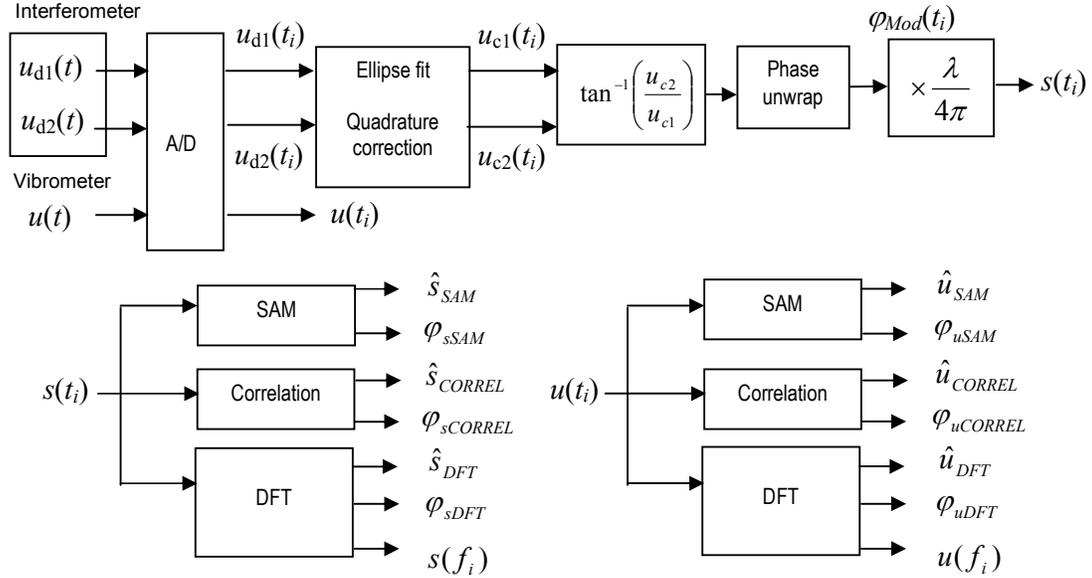

Figure 4: Sequence of signal processing

Optionally, a zero-delay high-pass filter can be selected for calibration at frequencies higher than 1 kHz, in order to minimize the influence of low frequency noise when small displacements are to be measured. A unique characteristic of the developed software is that it applies three signal analysis techniques in parallel to the displacement and voltage time series, as shown in figure 4 [3]:

- Sine-approximation method [11];
- Windowed single sine correlation method [15];
- Discrete Fourier Transform (DFT).

Numerical outputs of the results obtained by applying these different analysis methods are presented on the computer screen, allowing direct comparison among them and against the output display of measuring instruments under calibration.

6.1.1 Results obtained with the preliminary system

This system was used successfully in many measurements. It was applied to the calibration of the complex sensitivity of LVs in the frequency range from 10 Hz to 10 kHz and amplitude linearity tests were performed at

fixed frequencies. Measurements were carried out up to 20 kHz and different vibration exciters were tested, including electrodynamic and piezoelectric models.
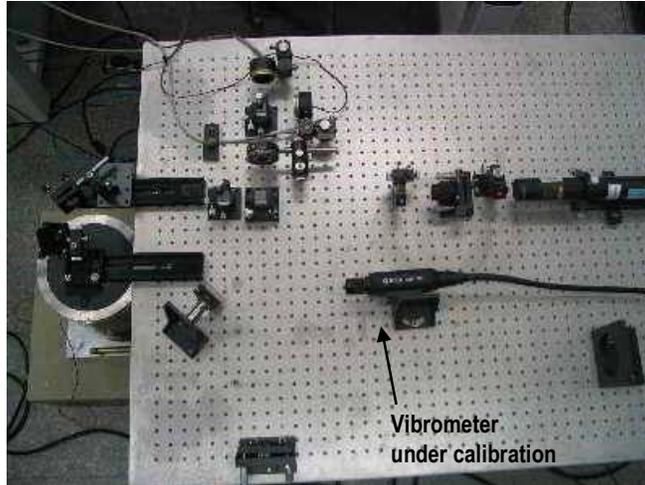

Figure 5: Preliminary set-up used for calibration of vibrometers

Figure 5 shows the calibration of a modular vibrometer Polytec CLV-1000 configured with a digital velocity decoder M050. This decoder has one analog and one digital (S/P-DIF format) output and three scale factor selections. All results presented here refer to the analog output.

Figure 6 shows the results of sensitivity magnitude and phase shift obtained for the scale factor 50 mm/s/V. The linear phase response provided by the digital velocity decoder is shown by the straight line fitted to the experimental data. The slope of the adjusted line corresponds to a constant time delay of 17,68 μs, which is close to the nominal value of 18 μs specified by the manufacturer for the selected scale factor.

An example of an amplitude linearity test carried out from 50 m/s^2 to 500 m/s^2 at 5 kHz is presented in figure 7. A least squares line fit confirms the good linearity of the digital decoder at the tested conditions and demonstrates the measurement capability of the preliminary calibration system.
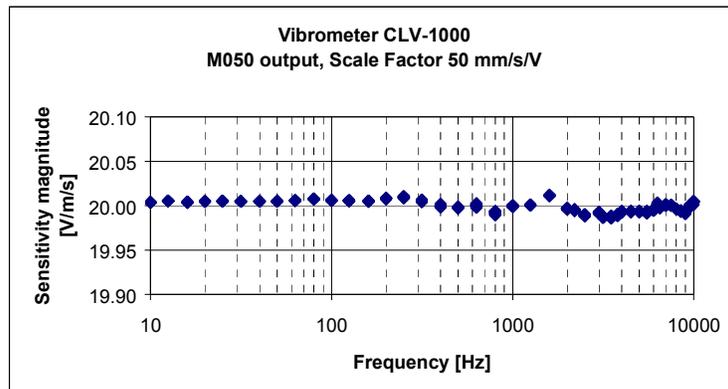
(a) Sensitivity magnitude
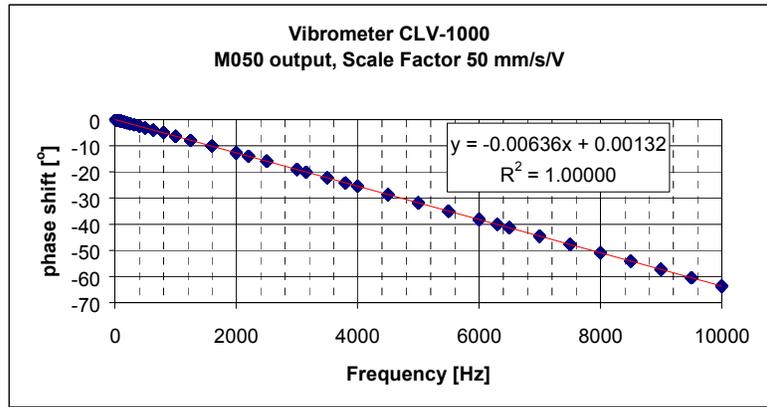
(b) Phase shift

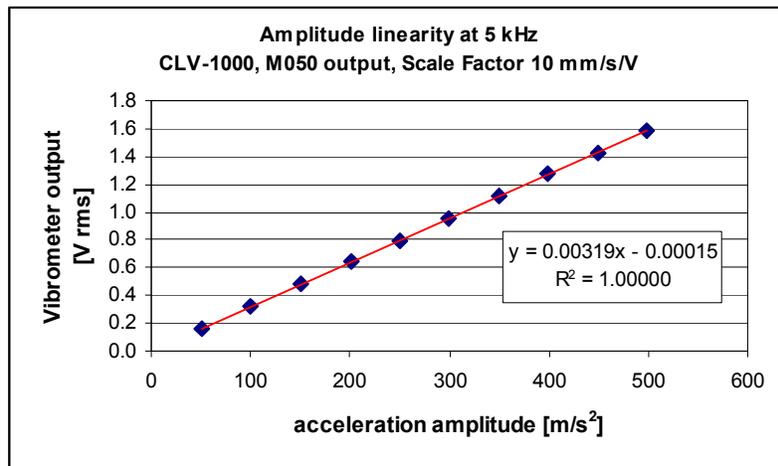Figure 6: Results obtained for the complex sensitivity of a vibrometer

Figure 7: Amplitude linearity test performed at 5 kHz

6.2 New experimental set-up

The new system is being developed to allow the calibration of the whole range of laser vibrometers. It was designed to allow calibration of vibrometers as vibration measuring instruments and as transducers with both analog and digital output, as shown in figure 8. In a first stage, a homodyne quadrature interferometer similar to the one implemented in the preliminary set-up is being used. In the future, it is intended to implement a heterodyne interferometer.

Reference interferometer
output signals:

$$u_1(t) = \hat{u}_1 \cos \varphi_{MOD}$$
$$u_2(t) = \hat{u}_2 \sin \varphi_{MOD}$$

PXI-chassis   10 MHz clock

Signal conditioner

Accel. Ref. signal

16 bit, 500 kS/s, 4 AI, simultaneous sampling NI PXI-6122

$u_1(t)$

$u_2(t)$

12 bit 10 MS/s, 4 AI, simultaneous sampling, NI PXI 6115

LDV Analog output

14 bit, 100 MS/s, 2 AI simultaneous sampling digitizer / Oscilloscope NI PXI-5122

Reconfigurable I/O, FPGA NI PXI 7831R

S/P-DIF
LDV Digital output

PCI Bus

PXI-PC interface

PCIe

Reference homodyne quadrature interferometer

True r.m.s. voltmeter

IEEE 488

Vibrometer under test

Sine-wave generator

Power amplifier

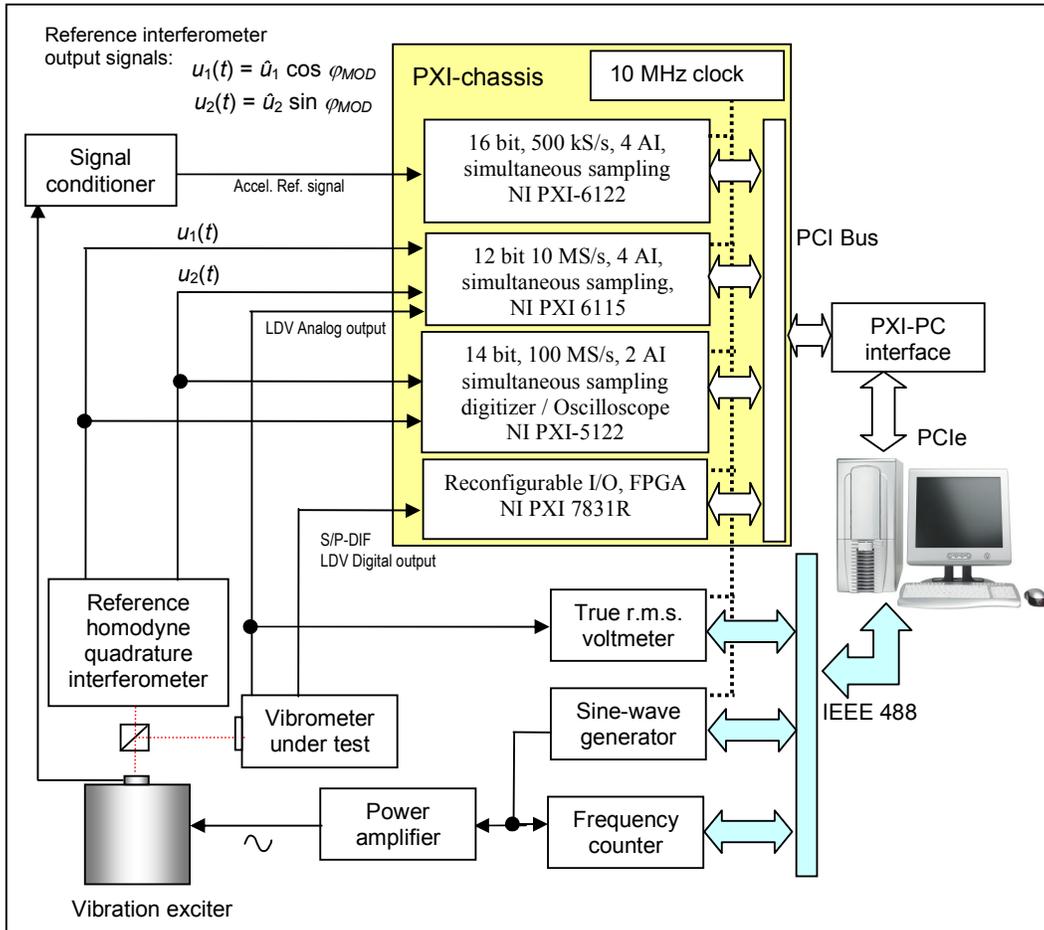Frequency counter

Vibration exciter

Figure 8: Scheme of the new set-up for calibration of vibrometers with digital or analog output

For generation of the motion quantities, this system will use an air-bearing vibration exciter, capable of generating sinusoidal vibrations up to 50 kHz with low levels of cross-axis motion and distortion. Its moving table incorporates an internal reference accelerometer which can be used as reference for the control loop of the vibration amplitude. A flat plane polished adapter fixed to the center of the moving table is used to reflect the measuring arms of the reference interferometer and of the vibrometer to be calibrated.

The optical system will allow the measuring beams from the reference standard and the laser vibrometer under calibration to be appropriately focused on the same spot of the light reflecting element. With proper adjustments, the light spot can be located in the middle of the reflecting element at a distance smaller than 1 mm from the center axis of the moving table, as recommended by the draft of ISO 16063-41. The measuring beams from both laser optic transducers will travel concentrically or in close distance in parallel, and hit the reflector orthogonally. This alignment capability is an important pre-requisite for achieving low uncertainties of measurement.

Many stand alone equipments were substituted by a modular PXI system. The PXI chassis includes a PXI-PCI express interface for connection to a controller PC and the following modules:

- a 16 bit, 500 kS/s, 4-channel analog input, simultaneous sampling module (NI PXI-6122) to measure the output of the control accelerometer;
- a 12 bit, 10 MS/s, 1-channel analog output and 4-channel analog input, simultaneous sampling module (NI PXI-6115) for acquisition of the reference interferometer and LV I&Q output signals or the reference I&Q output signals and LV under calibration analog output signal;
- a 14 bit, 100 MS/s, 2-channel analog input simultaneous sampling digitizer (NI PXI-5122) to be used as oscilloscope and for future direct digitizing of heterodyne signals;
- a reconfigurable input/output FPGA module (NI PXI-7831R) for direct acquisition of digital output signals as the S/P-DIF standard.

In addition, the system incorporates:

- a true rms voltmeter to measure the analog output of a LV under calibration;
- a sine-wave generator and a power amplifier to drive the vibration exciter;
- a frequency counter to measure the excitation frequency.

The voltmeter and the frequency counter in ratio mode will also be used for implementing the fringe counting method (Method 1) up to 1 kHz. The possibility of running a different method will be an important feature at the qualification stage of the calibration system.

At the present stage, the calibration software is being adapted to run on the PXI platform and a subroutine is being written to acquire S/P-DIF signals through the reconfigurable I/O FPGA module.

6.2.1 Results obtained with the new system

Since the system is still under development, it is not possible to present experimental results in this written paper. It is expected that some preliminary data will be available for visual presentation at the IMEKO TC22 meeting.

7. Summary and/ or conclusions

A new homodyne quadrature interferometric system is being developed at INMETRO for the calibration of laser doppler vibrometers. This system was designed and is being implemented to perform automated primary calibrations of reference standard vibrometers and working vibrometers by comparison against a homodyne quadrature interferometric system.

Successful results obtained in a preliminary experimental set-up have shown the capability of the system to calibrate the complex sensitivity of vibrometers in the frequency range from 10 Hz to 10 kHz at user-selectable amplitude levels. The new system under development may allow the increase of

the upper frequency limit to 20 kHz. The authors expect this new calibration system to be fully operational by mid-year 2008.

8. Acknowledgements

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