VIBRATION CONTROL APPLIED TO AN ELECTRODYNAMIC EXCITER TO IMPROVE ACCELEROMETER CALIBRATIONS

Ronaldo da Silva Dias, rsdias@inmetro.gov.br
National Institute of Metrology, Standardization and Industrial Quality - **Inmetro**
Acoustics and Vibration Metrology Division, Vibration Laboratory
Av. N. Senhora das Graças, 50, 25250-020, Xerém, RJ, Brazil

Max Suell Dutra, max@mecanica.coppe.ufrj.br
COPPE - Federal University of Rio de Janeiro - **UFRJ**
Mechanical Engineering Program
CP 68503, 21945-970, Rio de Janeiro, RJ, Brazil

Abstract. *Most of the primary accelerometer calibrations that are currently performed by National Metrology Institutes use interferometric measuring techniques. Optical methods offer optimal measurement of the displacement amplitude. On the other hand, best accuracy requires a uniaxial, stable and distortion-free vibratory motion of the accelerometer at the desired calibration frequencies and amplitudes. Therefore, the vibration exciter is one of the most important elements of the calibration system. Unfortunately commercial exciters usually present high levels of transverse and rocking motion and can suffer from relatively low stiffness and harmonic distortion. To overcome these problems some primary laboratories have developed their own exciters and sometimes use two or more different models to cover a broad frequency range. The objective of this paper is to present a proposal for an active-controlled system to minimize the undesirable movements of the moving element of an electrodynamic exciter using piezoelectric actuators. These actuators are mounted between the moving element and the accelerometer under calibration, acting as active filters to correct the vibration movement. A system to measure the vibration level at some defined points of the moving element, the control system of the actuators and some preliminary results are presented.*

Keywords*: Vibration control, Piezoelectric actuators, Accelerometers, Primary Calibration, Automation*

1. INTRODUCTION

Most of the primary accelerometer calibrations, also called absolute calibrations, are currently performed by interferometric measuring techniques (ISO 16063-11, 1999). The reciprocity technique, which is another absolute calibration technique recommended by international standards, has been substituted along the last years because of being very time consuming and having a limited frequency range of application. Nowadays, most National Metrology Institutes (NMI) offer calibration services from a few hertz to some kilohertz. Different optical-processing techniques can cover this broad frequency range and some of these allow automation of the complete calibration process.

Most of the necessary instruments to implement an accelerometer calibration system are available nowadays with metrological requirements compatible with the international standards. The exception is the vibration exciter (shaker), which should furnish uniaxial, stable and distortion-free vibratory movement to the transducer under calibration at any desired frequency and amplitude (Ripper *et al*, 2006). Unfortunately this ideal condition is not achieved in real life. Most commercial vibration exciters have limitations to their use in primary calibrations over a broad frequency range. At low frequencies, they suffer the influence of the maximum displacement limit. At mid-frequencies, some projects present resonances at or close to calibration frequencies. At high frequencies, problems due to rocking motion and heating usually show-up and can strongly affect the calibration result.

Some NMIs have developed their own calibration shakers to overcome many of these problems (Dimoff and Payne, 1963), (Usuda *et al*, 2004), (von Martens *et al*, 2004). NIST/USA and PTB/Germany have designed many different exciters during the recent years. Some of these designs use the electrodynamic moving-coil principle, while others use piezoelectricity to generate motion. Air bearing guides were also implemented in many projects to keep low levels of transverse motion and to avoid the resonances that typically appear in flat-spring suspensions.

The international standard ISO 16063-11:1999 imposed tighter transverse motion limits for shakers to be used in primary interferometric calibrations of vibration transducers. These limits contributed to the development of some new projects by different shaker manufacturers. Some models using air-bearing guides are already commercially available today. APS, Bouche Labs, Endevco, TMS and TIRA are some of the companies that currently produce exciters with this kind of bearings.

The objective of this work is to present an active system developed at the Vibrations Laboratory of INMETRO to reduce the rocking movements of the vibration exciter moving element, also called exciter table, which influences negatively a primary accelerometer calibration. The actuating system was developed to permit two orthogonal rotations, both orthogonal to the exciter table moving axis. This system permits the overlap of these two orthogonal rotations to the exciter table movement, and if they are selected conveniently will allow the reduction of the rocking motion applied to the accelerometer under calibration.

2. INTERFEROMETRIC CALIBRATION

The interferometric calibration of an acceleration measuring set (accelerometer + conditioning amplifier) comprehends the measurement of the amplitude of a motion quantity on the reference surface of the accelerometer by interferometry and the measurement of the corresponding voltage output of the conditioning amplifier. Figure 1 shows a typical calibration system in which the amplitude of the motion is measured using the fringe counting method. This system is suitable for calibrations from a few hertz to 1 kHz.

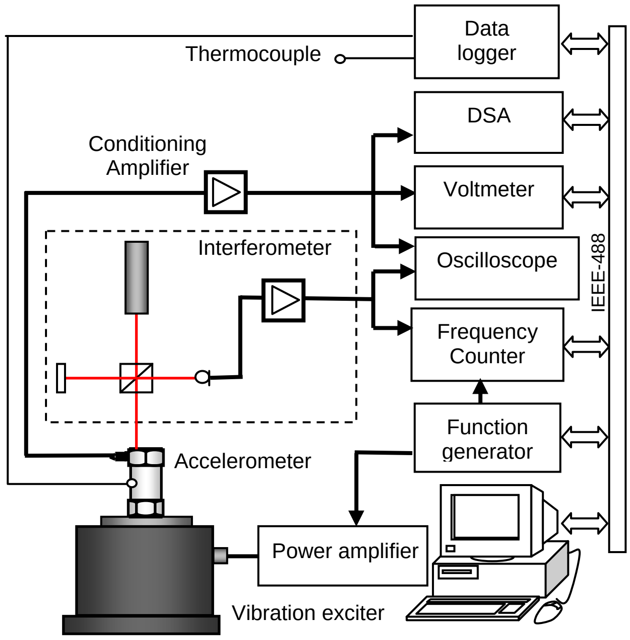

Figure 1: Interferometric calibration system - Fringe counting method

Considering a sinusoidal excitation, the voltage sensitivity S_{ua} of the acceleration measuring chain is obtained by Eq. (1), where $\hat{u}$ is the output voltage amplitude, $\hat{s}$ is the amplitude of the displacement at the accelerometer reference surface and f is the vibration frequency. This sensitivity is the product of the charge sensitivity of the accelerometer and the sensitivity, or gain, of the conditioning amplifier. Therefore the conditioning amplifier must be electrically calibrated to one obtain the charge sensitivity of the accelerometer.

$$S_{ua} = \frac{\hat{u}}{(2\pi f)^2 \hat{s}} \tag{1}$$

Let's assume that the measurement of the displacement $\hat{s}$ is carried out at a single point at the reference surface, which is the top surface of a back-to-back standard accelerometer or the mounting surface of a single-ended transfer standard accelerometer. If we are working with an ideal exciter, where the movement of the table is free of transversal movements like the rocking motion and presents a pure axial motion, this procedure is correct. Unfortunately the shaker exhibits different transversal displacements depending on the position of measurement and frequency of excitation, and the simple procedure described above are subject to large systematic errors.

Measuring techniques can be applied to minimize the effects of some errors and improve the quality of the final calibration result, like averaging the results obtained in sequential measurements at different points of the reference surface. Some multiple beam interferometers can be used to automatically minimize the influence of one of the worst problems, which is rocking motion, but a very limited number of laboratories have already implemented them.

The ISO 16063-11, at the apparatus specification section, requires a transverse motion of less than 1% of the motion in the intended direction for calibrations from 1 to 10 Hz, and a maximum of 10% is permitted above 10 to 1 kHz. In spite of the high values permitted, when the final uncertainty of the calibration were calculated, we can observe that the traverse vibration contribution corresponds up to 30% of the uncertainty total value, therefore its reduction has a great impact on the calibration results.

3. PROBLEMS OF VIBRATION EXCITERS

3.1. Low stiffness of the exciter table

The moving element of a vibration exciter should be as stiff as possible to work as a rigid body and keep the same motion on its entire mounting area. Many shakers are built with aluminum alloy moving elements because this material allows easy machining of relatively lightweight tables. In the case of back-to-back (BTB) accelerometers, they do not cause many problems because the reference surface is on the top of the transducer and the piezoelectric elements are mounted in an inverted compression configuration. In the case of single-ended (SE) transfer accelerometers, larger problems can occur because usually the laser beam has to be focused on the exciter table beside the accelerometer. In addition, accelerometers of this type are usually built in a compression configuration, which is more sensitive to base bending.

This problem can be verified very easily measuring the sensitivity of the accelerometer with a single beam laser interferometer focused onto different points of the table, one that at a time. Sometimes this problem can be minimized by the use of some stiff adapter between the shaker table and the accelerometer. Care must be taken when designing these adapters to get high stiffness and low mass, otherwise the maximum acceleration level obtainable with the shaker may be unacceptably lowered and heating problems may appear.

3.2. Heating of the moving element

Electrodynamic shakers can suffer from heating by the driving coil. The temperature increase on the mounting table depends on the acceleration amplitude and thus on the driving current. Therefore, this problem usually shows up at higher frequencies due to the use of higher acceleration levels. This differential heating from the mounting base induces systematic errors on the measurement due to the temperature sensitivity of the accelerometer. Temperature variations of more than 20 ^{o}C can be found in some exciters and no manufacturer states sensitivity changes due to differential heating on accelerometers specifications.

Lower acceleration levels or increasing the air flow around the driving coil of electrodynamic exciters can minimize this problem. Another way to deal with this problem is to intercalate low frequency and high frequency calibrations to keep the temperature rise within acceptable limits (Lauer, 1995).

3.3. Rocking ad tranverse motion

Instead of a piston-like linear motion, the moving table can also present a rocking behavior. Since the laser is usually focused onto a point away from the center axis of the accelerometer (or exciter table), an error may occur when a displacement measurement is made. Transverse motion can also be coupled to the longitudinal motion of the table. Since most accelerometers suffer of some misalignment of the maximum sensitivity axis, a transverse sensitivity is always present. Some standard accelerometers may be bought with the value of its transversal sensitivity and its maximum direction stated in the calibration certificate, but it's not a usual procedure. The coupling of the shaker rocking or transverse motion and the accelerometer transverse sensitivity axis creates an error on the sensitivity determination.

Many ways to deal with this problem have been reported. Some authors have suggested taking the mean of measurements on 3 points; others on 6 points (Dickinson and Clark, 1999), but measuring on 2 diametrically opposed points already works very well. These calibrations can be performed in sequence or simultaneously. Simultaneous measurements are better because they avoid the effect of drifts in the amplifiers, increase the optical resolution if a two beam interferometer is used and require a shorter time for the calibration (Lauer, 1995). On the other hand, the interferometer is a little more complex and the laboratory needs to have optical lapping capabilities. This is because a flat polished reference surface is required on the top of the accelerometer, to allow parallel optical reflections from multiple points. Interferometers with 4 reflections or more (Basile *et al*, 2004) have already been reported for vibration measurements.

These methods intend to minimize the errors in the displacement measurements only, and the effects of the rocking and transverse movement over the output signal of the accelerometer itself still remain. A simple way to minimize this effect on the final results is to take the mean of two calibrations, which differ by mounting the accelerometer on two positions, rotated 180^{o} around its main axis (Lauer, 1995). This simple procedure theoretically cancels out the influence of the transversal sensitivity component. In the case of shakers that have a single central threaded hole, mounting adapters can be used to allow the implementation of this procedure. Residual effects can show up due to cable influences that are not perfectly canceled, or due to the accelerometer itself.

3.5. Resonances

Every shaker has resonances and some of them can unfortunately lie very close to some frequency of interest. Irregularities in the frequency response function can appear due to resonance of the mass-spring system or of the suspension system. Most electrodynamic exciters that use flat-spring suspensions suffer of many internal resonances, which manufacturers try to dampen out by gluing layers of rubber to the springs. Air bearing shakers that use O-ring suspensions are also subjected to resonances that can impose difficulties to the calibration. For example, one of our commercial air-bearing shakers resonates very close to the reference frequency of 160 Hz.

Piezoelectric shakers can be used at high frequencies, usually above 3 kHz. They have the advantages of being very stiff and to easily maintain the optical alignment. However some care is needed because high voltages are usually employed. Piezoelectric shakers normally present very low damping and, below resonance, their ascending frequency response can maximize the effect of the upper harmonics of the driving frequency, contributing to signal distortion. Strong signal distortions can also occur if a good impedance match is not achieved between the power amplifier and the exciter (Jingfeng and Tianxiang, 2004). Stacked piezoelectric shakers that incorporate layers of damping material present a better behavior since a flatter frequency response is obtained (Jones *et al*, 1969).

Resonances are a design problem, which is very difficult to overcome during the calibration stage. Therefore, it is better to avoid resonance frequencies at all. Depending on the system, sometimes it is possible to change suspensions or add some loading mass to avoid a specific resonance frequency. Since this is not always feasible, there is a tendency in accelerometer calibration the use of different types of exciters to cover specific sub-ranges of the frequency range of interest.

4. PROPOSED ACTUATING SYSTEM

The objective of this actuating system is to compensate the rocking movement, generated by the moving table of a vibration exciter, applied to the accelerometer under calibration. It was assumed that a rocking motion is a rotation of the moving table around an axis orthogonal to the main movement axis. The system proposed is mounted between the moving table and the accelerometer. It can generate two rotations around orthogonal axis and then these rotations, superimposed to the moving table movement, and could compensate the rocking movement over the movement supplied to the accelerometer. There are other requirements for the project, like a system that must be rigid enough in the direction of the movement to avoid distortions, and must be light enough to avoid mass loading.

Piezoelectric actuators were the choice to generate the control movement, because of their relative light weigh and small size compared with other actuators. They are rigid enough to be mounted between the exciter and the accelerometer and transmit the vibration movement. The chosen configuration to generate a rotation was the assembly of two actuators at diametrically opposite positions, fed by out of phase signals. The opposite actuation allows that one actuator expansion reduces the traction forces over the other one. The four piezoelectric actuators were mounted over an adapter 90° apart each other and 6,5 mm apart from the center. The tilting table, a disk with 39 mm of diameter and 8,5 mm of thickness is mounted over them attached to the adapter by a flexible coupling. The adapter width is 40 mm and 20 mm of thickness, and it is mounted over the exciter moving table, and the accelerometer under calibration is attached to the tilting table. Both are manufactured with aluminum alloy to guarantee low weight to the system.

A partial exploded view of this system is shown in Fig. 2, where the tilting table is moved from its position to show the actuators. The mounting screw that fixes the tilting table to the flexible coupling is not shown.

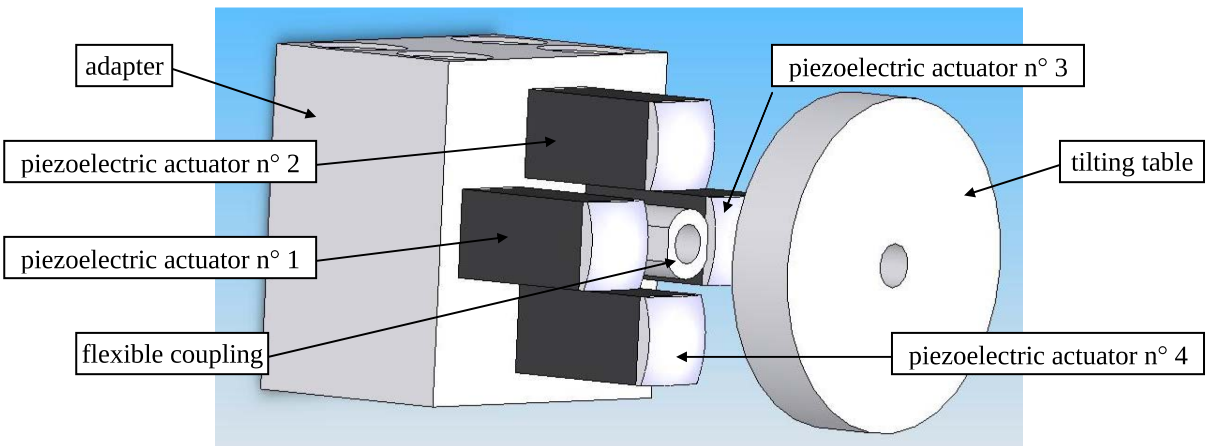

Fig. 2: Actuation system. The tilting table is moved to show the actuators.

The diametrically opposite actuators works in opposite directions, so the signal supplied to actuator 3 has a phase shift of 180° from the signal applied to actuator 1, generating a rotation around the vertical axis. The same situation occurs with actuators 2 and 4, generating a rotation around the horizontal axis relative to the tilting table surface plane.

The piezoactuators were selected from Physik Instrumente (PI) catalog, model P-888.50 PICMA® piezo actuators with a rounded top piece for decoupling lateral forces, and its dimensions are 10 x 10 mm and 18 mm long. These actuators are low voltage devices with operating voltage from -20 to +120 V, and maximum displacement of 15 μm. The voltage amplifiers were selected considering the capacitance of these actuators and the frequency range of interest. The amplifier model E-505 that can supply 40 V to the actuators at 1 kHz with a fixed gain of 10 and a DC offset control was chosen. The flexible coupling is the model P-176.50 from PI too, what has a relative flexibility to bending at two orthogonal directions and high axial rigidity. Figure 3 shows the prototype mounted on an APS exciter moving table with an accelerometer Endevco model 7751-500 mounted on top.

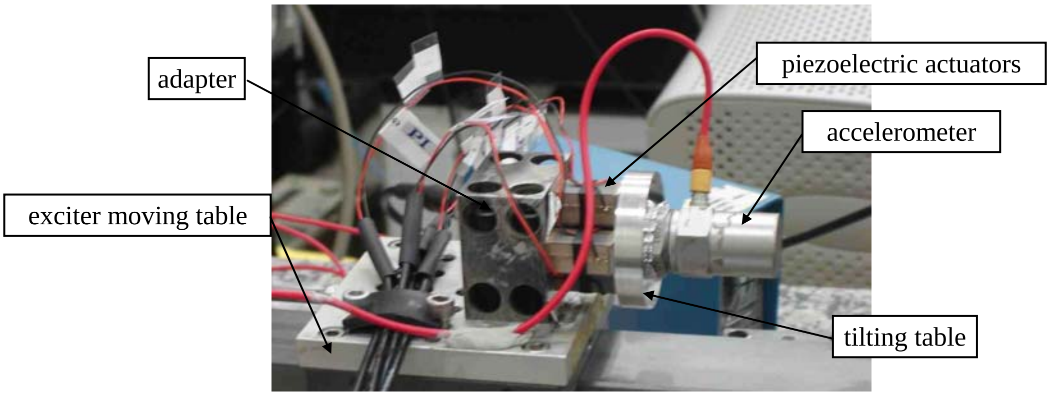

Fig. 3: View of the system mounted over the APS exciter.

5. LOW FREQUENCY CALIBRATION SYSTEM

The prototype of the actuation system was tested on the low frequency calibration facility of the Vibrations Laboratory of the National Metrology Institute of Brazil (INMETRO). This system performs absolute or comparative calibrations in the range of 1 to 100 Hz with an APS-500 long stroke (15 cm) exciter mounted on a concrete block weighting 2000 kg as a reaction mass. This shaker consists of an ELECTRO-SEIS long stroke air bearing driver attached to a load mounting table and air bearing guide. At absolute calibrations the displacement of the exciter table is measured with a Michelson interferometer using the fringe counting method, mounted on a breadboard isolated of the concrete block by springs. To test the prototype the interferometer was substituted by a laser vibrometer from Polytec, composed by an OFV-5000 Modular Vibrometer Controller with a DD-600 Digital Decoder board installed in and an OFV-505 Standard Optic Sensor Head. The original interferometer is mounted on the breadboard, and the measurement at different points demands a difficult procedure deflecting the laser bean with steering mirrors. On the other hand, the OFV-505 head is moved easily among the different measurement points, and the phase information between the movement and the accelerometer signal is available from the vibrometer measurements, while it is not available from the Michelson interferometer of the original system. The low frequency calibration system is shown in Fig. 4(a) and a detailed view of the vibrometer and the prototype is shown in Fig. 4(b).

(a) (b)

Fig. 4: View of the low frequency calibration system (a) and the APS-500 exciter (b).

The experience with this calibration system and specifically with this exciter shows that the rocking movement of its moving table is more pronounced around the horizontal axis. The force generated by the driving coil and the inertial force due to mass loading over the table generates a momentum. Considering that the air bearing has a necessary clearance to the air flow, and this air film has a low rigidity, this exciter is suitable to a rotation in the vertical plane coincident with the motion axis, as shown at Fig. 5. The symmetry over the horizontal plane of the force directions and the guidance motion axis is the reason of a low level of rocking motion at this plane.

The measurements showed that the rocking movement along the horizontal plane is not critical; therefore it was decided to control only the rocking on the vertical plane. This behavior allowed a reduction to a pair of actuators configured to actuate at opposite directions to generate the desired rotation. To reduce the rocking motion at the accelerometer is necessary that the two opposite measurement points over the tilting table present the same displacement amplitudes. The necessary actuation at each opposite actuator will be half of the difference in the displacement measurements, at opposite directions. The prototype was then configured for this working condition, and referring to Fig.2 only the actuators 2 and 4 will be controlled.

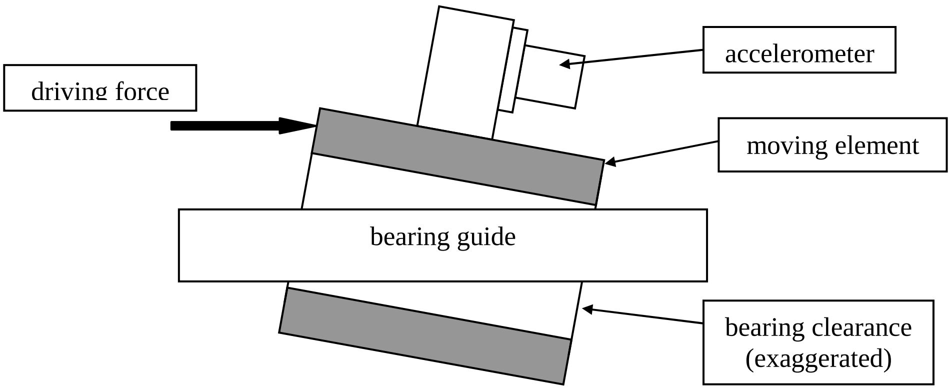

Fig. 5: Effect of the bearing clearance over the accelerometer.

The electrical connections of the system are shown in Fig. 6. A two channel function generator HP3245A is used to generate the signals to drive the exciter and the actuators due to its capability of syncronization and control the phase between the two channels. The same signal is feed to the two E-505 amplifiers of the actuators 2 and 4, but one actuator has its wire connections inverted. This configuration was applied because it’s not possible to invert the signal at the input connectors of the amplifiers. They are mounted in the same case and have a common ground, and this connection would cause a short circuit at the generator output. The direction of movement (expansion or contraction), are related to the polarity of the piezoelectric actuators electrical connections, and its top and bottom faces are electrically isolated.

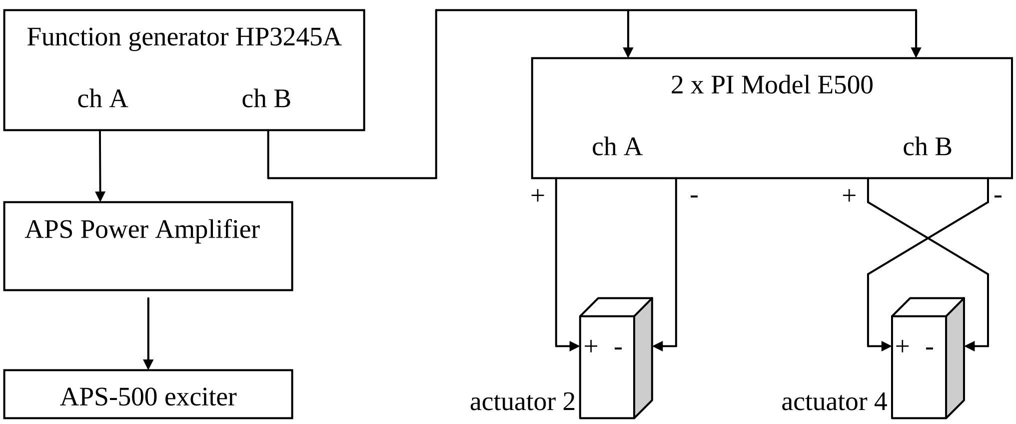

Fig 6: Electrical connections of the piezoelectric actuators.

6. CALIBRATION PROCEDURE

A typical absolute calibration requires that the interferometric measurement of the displacement is carried out at least at two diametrically opposite points of the reference surface. In this work the reference surface is the tilting table where an Endevco 7751-500 accelerometer is mounted and the displacement was measured at four points, which location and denomination is presented at Fig. 7. They are located 15 mm apart from the center of the tilting table, where the accelerometer is mounted on. The adopted procedure was divided in two steps: the first was to measure the displacements at the four indicated points at each single vibration frequency in the range from 1 to 100 Hz with the actuators turned off. The results obtained indicate a path difference among the points and the necessary displacement that should be generated by each actuator. The second step was to turn on the actuators applying the corrections, verifying if the path differences lied within acceptable limits of errors. If the control was effective the accelerometer calibration should were carried out, and if not the residual and not acceptable differences may generate another set of correction values applied to the actuators. So this second step was repeated until acceptable values for the path differences are achieved.

To control the actuators motion is necessary to know the relationship between the applied voltage and the rotation angle of the tilting table. This calibration was carried out measuring the displacement on point 4 for voltages varying from 0,1 to 1 Volt peak-to-peak at the frequencies of 10, 50 and 100 Hz. In this calibration it was considered the voltage output of the HP3245A generator, so the calibration was performed at a system composed by the actuators and the correspondent voltage amplifiers. The actuators present a linear behavior as shown in Fig. 8, and these results are used to calculate the necessary voltage V_{pkpk} at the signal generator as a function of the necessary displacement D_{nm} in nanometers using the Eq. (2). This calibration was performed with the accelerometer mounted over the tilting table, as shown in Fig. 3.

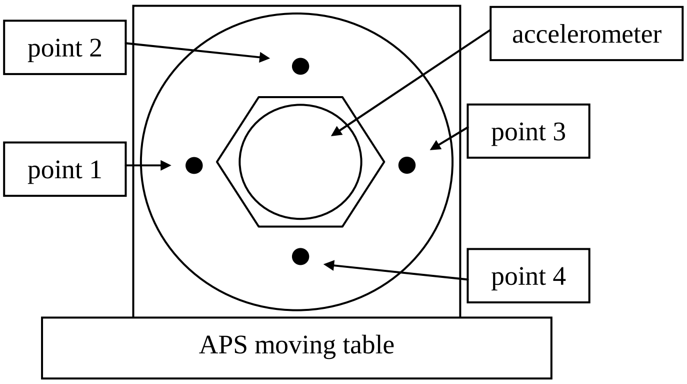

Fig. 7: Location of the measurement points.

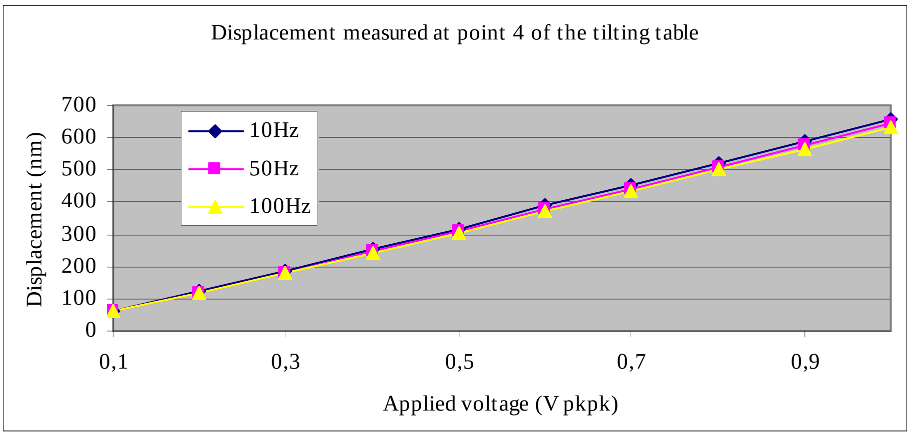

Fig. 8: Calibration of tilting table rotation versus applied voltage.

$$V_{pkpk} = 0{,}0015 \cdot D_{nm} + 0{,}0166 \tag{2}$$

Some measurements were made to evaluate the rocking motion of the moving table and to decide the necessary steps to test the prototype. Figure 9 shows the sensitivities of the set composed by the Endevco accelerometer and the PCB 482A10 ICP Power Supply, calculated considering the individual displacements at the four measurement points indicated in Fig. 7. Figure 10 shows the phase shit of these signals. These results indicates that the points 1 and 3 presented the same displacement level and furnish the same sensitivity results, indicating that no considerable rocking motion is present in the horizontal plane, as explained at section 5.

The critical rocking motion appears at the measurements at points 2 and 4 specifically at frequencies above 20 Hz, and we can see that the acceleration level measured at point 4 is larger than the measured at point 2, resulting in a lower value of the calculated accelerometer sensitivity. The accelerometer is subjected to the same acceleration level when the acceleration levels were measured, furnishing the same voltage output, so the variations at the displacement measurements reflects directly on the calculated sensitivities. Figure 9 indicates that the difference in the sensitivity values at points 2 and 4 is practically the same. The phase shift between the accelerometer and the vibrometer signals decrease with the frequency and is less than 1° above 20 Hz, indicating that no phase correction is necessary. The higher values at the lower frequencies are probably due to the electronics in the Endevco 7751-500 accelerometer, which is a piezoelectric device with a charge amplifier incorporated. This type of transducer has no response to near 0 Hz excitation, also called DC excitation, and thus presents a relative phase shift at this region.

The voltage to be applied to the actuators was calculated using Eq (2) with the values of relative motion between the points 2 and 4 obtained a priori. The synchronization of the signal applied to the exciter and to the actuators was assured by the implementation of the electrical system connections indicated in Fig. 6 and the proper configuration of the HP3245A generator. According to the calibrating procedure described in section 6, the second step was applied and the measurements of the displacement at points 2 and 4 were carried out with the actuating system turned on.

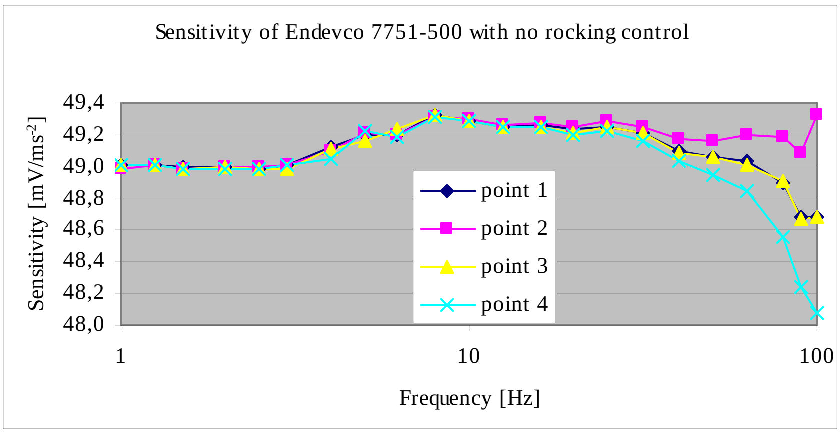

Fig. 9: Sensitivity of the Endevco 7751-500 calculated at each measurement point.

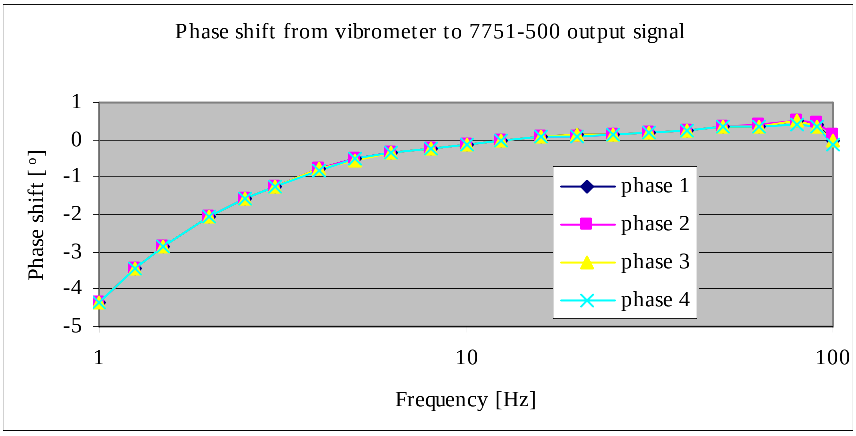

Fig. 10: Phase shift of the Endevco 7751-500 and vibrometer signals at each measurement point.

The measurement results of each control cycle are shown in Fig. 11. This figure presents the relative difference between the displacement measured at points 2 and 4 normalized by the mean value of these displacements. A first control cycle was applied, then to reduce the rocking effect the HP3245A output voltage was calculated again using Eq. (2), and the new voltage values obtained were added to the old ones and applied to the actuators. This procedure was repeated three times to achieve the lowest rocking levels around 0,01%.

Figure 12 shows the displacement difference measured between points 4 and 2 with no correction applied. During the accelerometer calibration the acceleration level was maintained close of 5 m/s^2 rms in the frequency range from 10 to 100 Hz, but the displacement is inversely proportional to the frequency to the square. Despite of the increase of the rocking motion showed in Fig. 11, the displacement difference showed in Fig. 13 is relatively flat. As explained in section 5 before, in Fig. 5, the clearance of the air bearing guide is the first responsible for the rocking motion, and it is close to all frequencies.

Figure 13 shows the final sensitivity results, where the results from 1 to 10 Hz are obtained from the calibration with no rocking control, and the results from 10 to 100 Hz are from the calibration with the rocking control applied. The value at 10 Hz is plotted twice to show the continuity of the curve. We can see that the dispersion between the curves is larger before the correction, and at frequencies from 4 to 6,25 Hz the dispersion increases and no fixed direction to the rocking motion in visible. Probably a two axis motion control actuating at will be necessary at those frequencies. Figure 14 shows the results of the two calibrations, and we can see differences up to 0,2% between the measured sensibility with and without control. Considering that the limit of the uncertainty of measurement specified by ISO16063-11 for the magnitude of sensitivity is 0,5%, the differences found are critical.

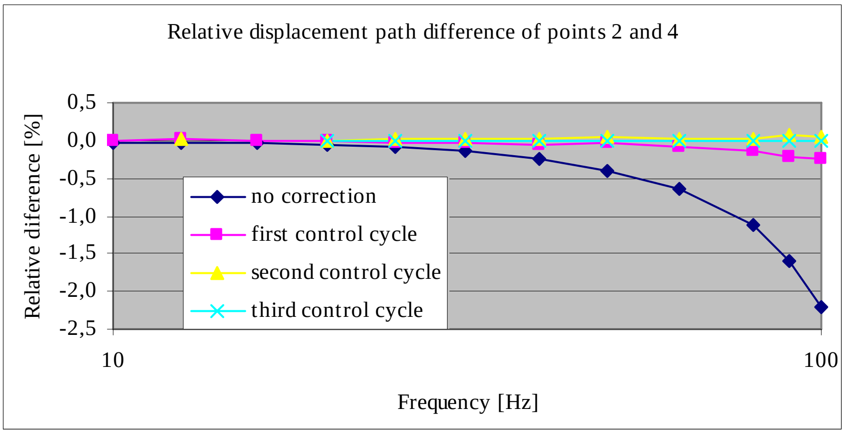

Fig. 11: Relative displacement between points 2 and 4.

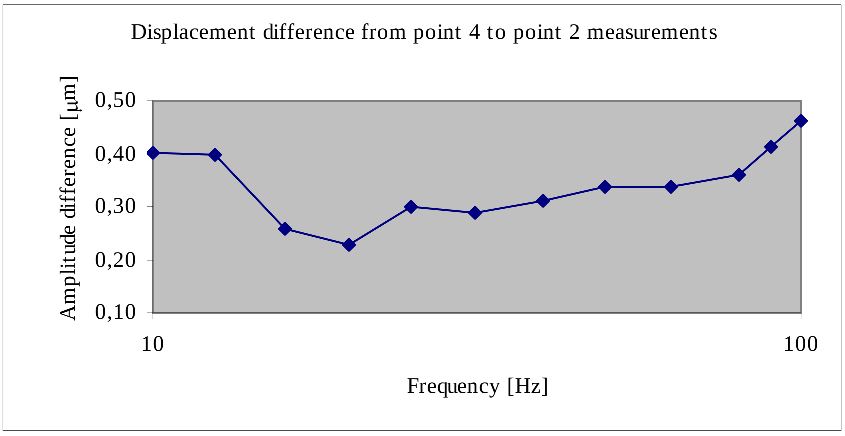

Fig. 12: Amplitude difference from point 4 to 2.

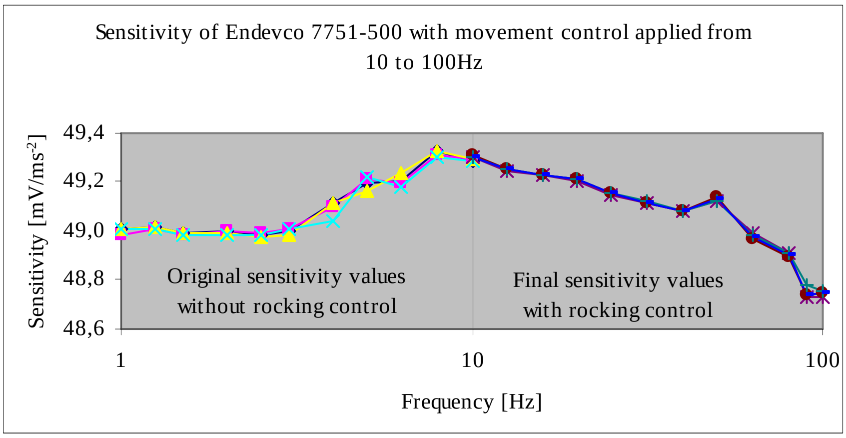

Fig 13: Final values of the sensitivity of accelerometer Endevco 7751-500.

7. CONCLUSIONS

The active system proposed to control the rocking motion of the moving table of vibration exciters used in absolute calibrations reached the foreseen objectives, reducing from 2% to 0,01% of the displacement measurements at different points over the reference surface. All the measurements presented in this paper were made manually, which is very time consuming, including the movement of the vibrometer from one point to the other. One critical step was the repetitivity on the measuring positions, because one single measuring cycle represents four repositioning movements of the vibrometer, and a set of mechanical stops were set-up to guarantee the same measuring positions.

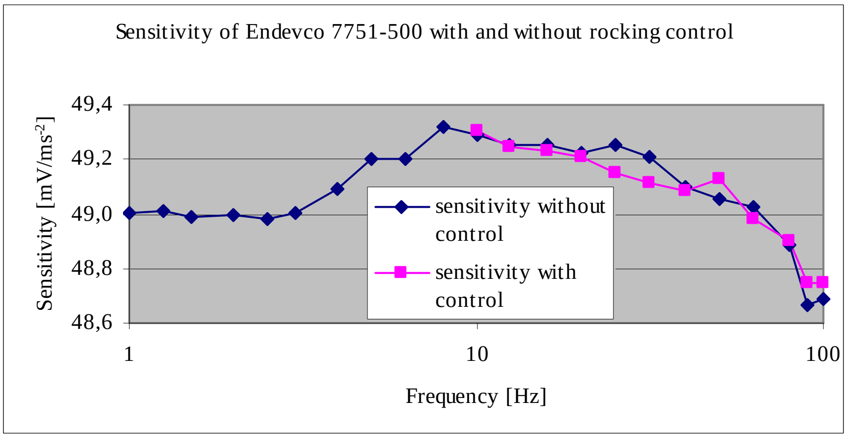

Fig. 14: Comparison among the sensitivities with and without correction.

The future work includes the automation of the vibrometer measurements, the control system itself and the implementation of an automated moving system to the OFV-505 sensor head. Some work will be done at the lower frequency range from 1 to 10 Hz at this exciter to implement a two axis motion control. A next step will be the design of dedicated systems based on this technique to other vibration exciters used for absolute calibration at the Vibration Laboratory of INMETRO, allowing the reduction of the uncertainty level currently offered to our costumers.

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