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VIBRATION CONTROL APPLIED TO AN ELECTRODYNAMIC EXCITER TO IMPROVE ACCELEROMETER CALIBRATIONS

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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 using piezoelectric actuators to minimize the undesirable movements of an electrodynamic exciter during an accelerometer calibration. 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, 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 exciters 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 exciters to be used in primary interferometric calibrations of vibration transducers. These limits contributed to the development of some new projects by different exciter 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 primary accelerometer calibrations. 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.

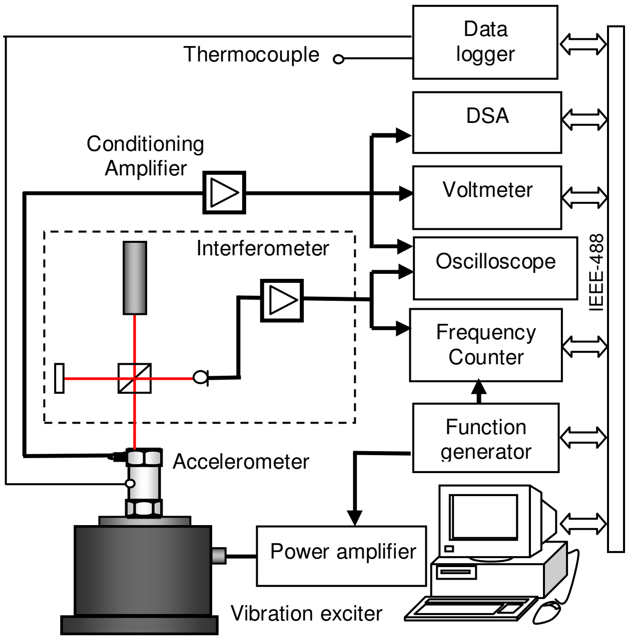


Figure 1: Interferometric calibration system - Fringe counting method

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. If we are working with an ideal exciter, where the movement of the table is free of transverse movements like the rocking motion and presents a pure axial motion, this procedure is correct. Unfortunately the exciter exhibits different transverse 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.

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 exciters 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 directly 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 in a radial direction, one that at a time. Sometimes this problem can be minimized by the use of some stiff adapter between the exciter 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 exciter may be unacceptably lowered and heating problems may appear.

3.2. Heating of the moving element

Electrodynamic exciters 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 transverse sensitivity and its maximum direction stated in the calibration certificate, but it’s not a usual procedure. The coupling of the exciter 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 minimize the errors only in the displacement measurements, and the effects of the rocking and transverse movement over the output signal of the accelerometer itself still remain. A suggested solution 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 transverse sensitivity component. Residual effects can show up due to cable influences that are not perfectly canceled, or due to the accelerometer itself.

3.5. Resonances

Every exciter 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 exciters that use O-ring suspensions are also subjected to resonances that can impose difficulties to the calibration.

Piezoelectric exciters 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. These exciters 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 exciters 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 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.

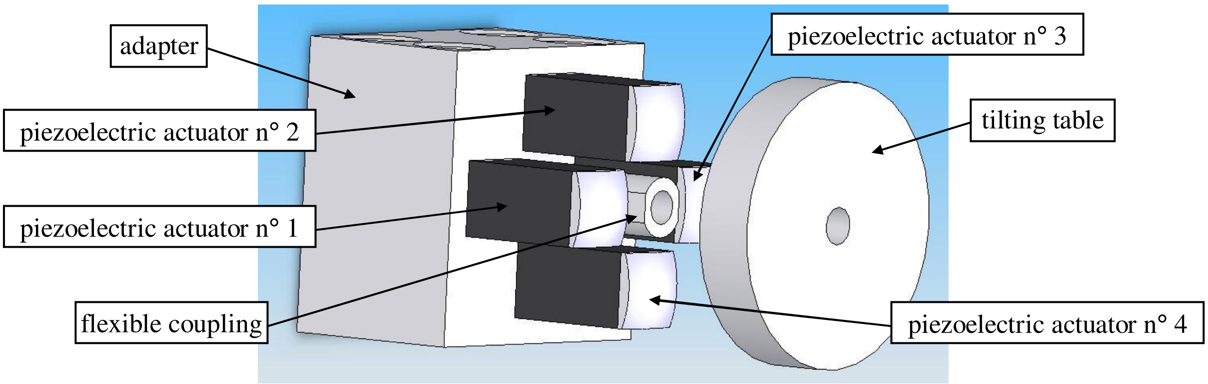
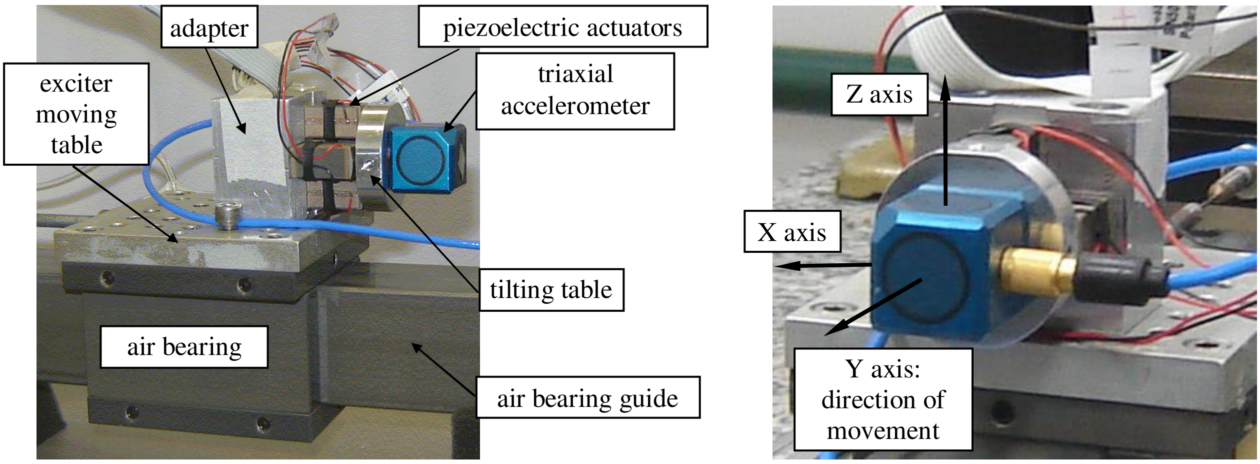


Figure 2: Actuation system. The tilting table is moved to show the actuators.



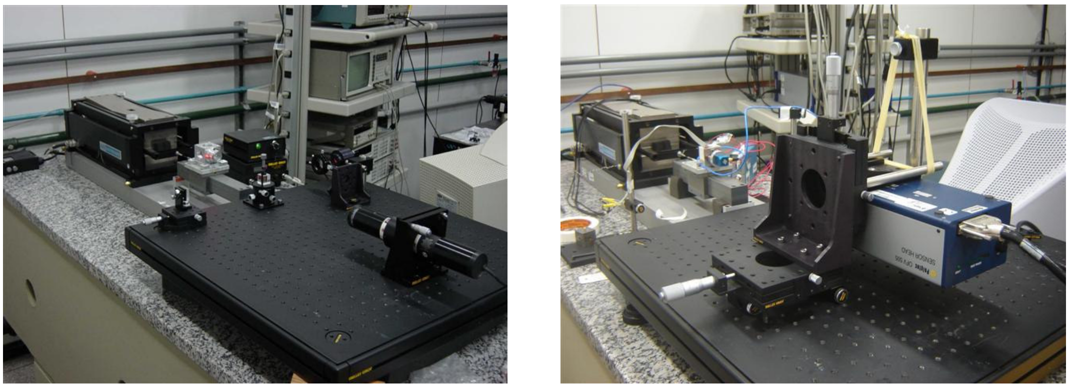
(a) (b)

Figure 3: View of the system mounted over the APS exciter moving table (a) and orientation of the triaxial accelerometer axis (b).

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® piezoactuators 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 a triaxial accelerometer PCB model 482A03 mounted on top.

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 exciter 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 original low frequency calibration system is shown in Fig. 4(a) and a detailed view of new system with the vibrometer and the prototype is shown in Fig. 4(b).



(a) (b)

Figure 4: View of the original low frequency calibration system (a) and the new system with the vibrometer (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 at a horizontal axis. Considering that the air bearing has a necessary clearance to keep the air flowing, and this air film has a low rigidity, this exciter is suitable to a rotation as shown at Fig. 5. The symmetry over a vertical plane defined by the force directions and the guidance motion axis is the reason of a low level of rocking around a vertical axis.

The measurement of the transverse vibration is typically performed with triaxial accelerometers, which consists of three accelerometers mounted with its sensitivity axis orthogonally positioned relative to each other. So if one axis of the triaxial is aligned with the main movement of the exciter table the other two axes will measure the two orthogonal components of the transverse vibration, and its magnitude and direction can be calculated. The transverse vibration levels are usually reported as a percentage relative to the longitudinal vibration level. The triaxial accelerometer showed in Fig. 3 was used to measure the transverse vibration levels that occur at the moving table of the low frequency exciter before and after the implementation of the proposed system. Figure 6(a) shows the results of the relative output signals correspondent to transverse vibration measurements at the directions indicated at Fig. 3(b). The results of Fig. 6(b) shows that the transverse vibration level is lower than 0,5% below 31,5 Hz, so the vibration control was applied only from this frequency to 100 Hz.

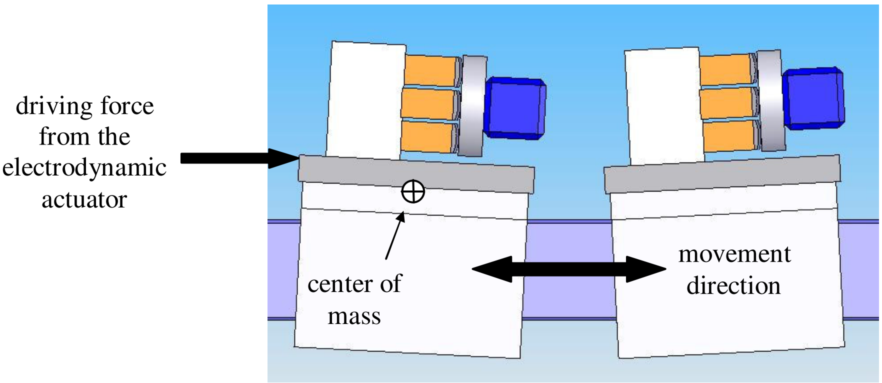
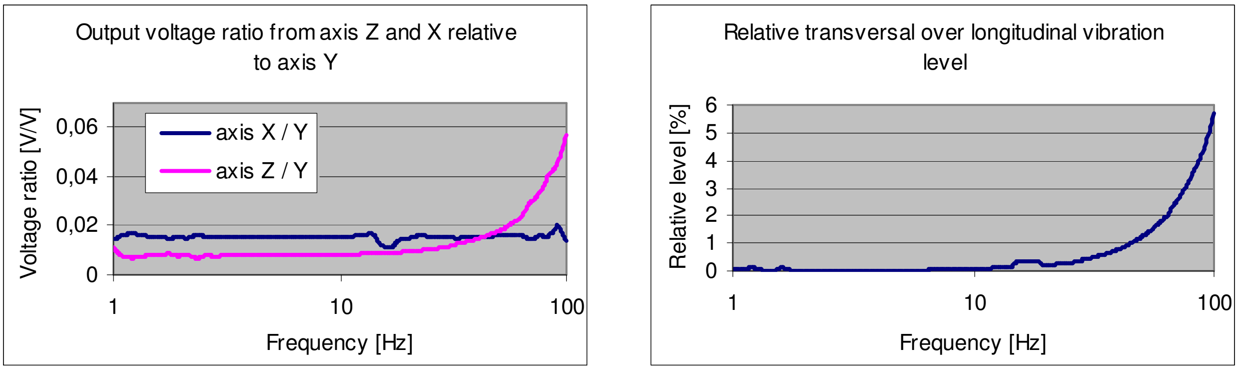


Figure 5: Effect of the bearing clearance over the transverse movement.



(a) (b)

Figure 6: Relative transverse vibration in Z and X axis (a) and triaxial accelerometer and its correspondent axis (b).

5.1. Characterization of the exciter transverse movement

Considering the transverse movement of the moving table as a result of a rotation around an axis orthogonal to the longitudinal axis, the accelerometer is exposed to a tangential a_T and a centrifugal a_C acceleration obtained from the Eq. (2), where R is the distance from the center of rotation, θ_M is the maximum angular displacement and ω is the angular frequency of the harmonic movement. This rotation movement has the same frequency of the excitation applied to the moving table during an accelerometer calibration. The measurements shown that the value of θ_M is of the order of 10^{-5} radians, so the centrifugal acceleration a_C is much smaller than the tangential component and can be neglected.

$$a_T(t) = \theta_M \cdot \omega^2 \cdot sin(\omega \cdot t) \cdot R \qquad\qquad a_C(t) = \theta_M{}^2 \cdot \omega^2 \cdot \cos^2(\omega \cdot t) \cdot R \qquad (2)$$

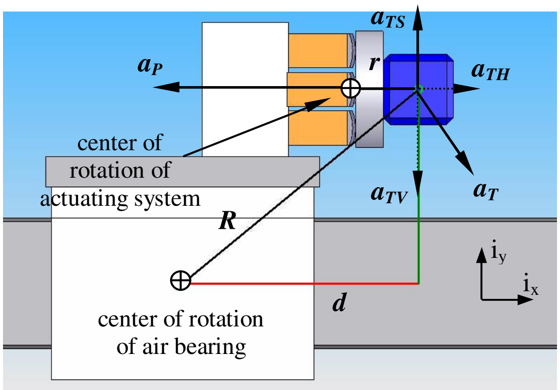


Figure 7: Geometry, center of rotation and accelerations acting over the accelerometer.

A typical model of vibration exciters is built with its moving table supported by a flexible suspension composed of flat springs diametrically disposed, which acts as a linear guide to the table movement also. Resonances at the system springs and table generate non symmetrical movements of these springs which results in a rotation of the table around an axis that intercepts the symmetry axis of the table. The accelerometer is mounted at the center of the table, so its sensitivity axis is aligned with the symmetry axis of the table. This geometry results that the directions of the accelerations a_T and a_C are perfectly perpendicular and parallel with the sensitivity axis of the accelerometer. The moving table of the low frequency exciter in which the prototype was tested is guided by an air bearing that is not aligned with the accelerometer sensitivity axis. The air bearing clearances are the responsible for the rotation, as explained in section before, and the center of this rotation is located at the center of the air bearing, as showed in Fig. 7. This geometry results that only the vertical component a_{TV} of the tangential acceleration a_T is responsible to excite the transverse sensitivity of the accelerometer, and as the horizontal component a_{TH} is in or out of phase with the movement it only increase or decrease the longitudinal acceleration a_P. The proposed system should generate an acceleration a_{TS} with the same magnitude of a_{TH} but in the opposite direction.

6. IMPLEMENTATION OF THE ACTUATING SYSTEM

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 the triaxial accelerometer is mounted and the displacement was measured only at points 2 and 4, located at the same distance apart from the center of the tilting table, referring to Fig. 9.

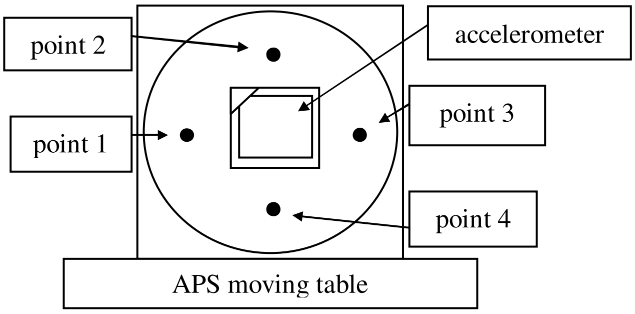


Fig. 8: Location of the measurement points.

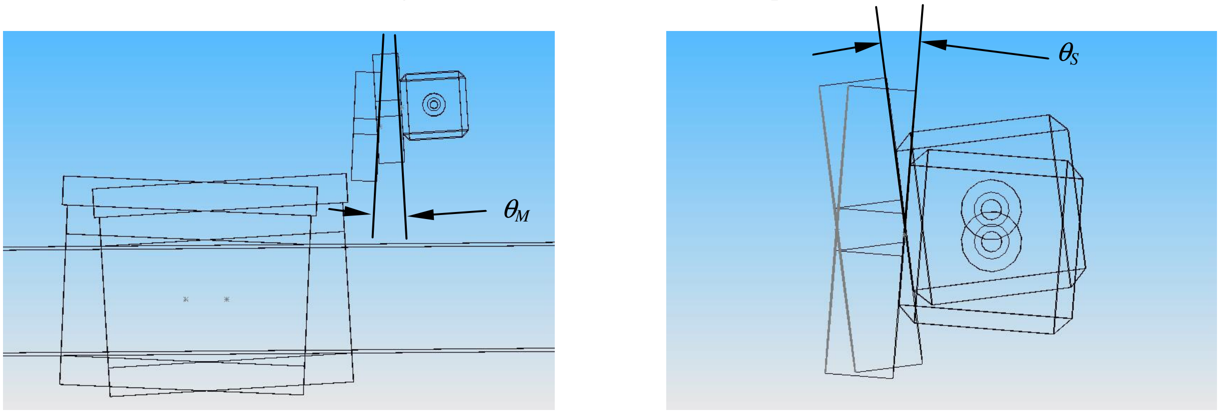


Figure 9: Rotation angles θ_M and θ_S.

To calculate the component a_{TV} of the tangential acceleration acting over the accelerometer under calibration, according to Eq. (2), is necessary to measure the rotation angle θ_M when the exciter is generating the desired vibration level at a chosen frequency ω. This angle is obtained from Eq. (3), where δ_2 and δ_4 are the displacements measured by the vibrometer at points 2 and 4, and Δ_p is the distance between the two points.

$$\theta_M = \arctan\left[\frac{\delta_4 - \delta_2}{\Delta_p}\right] \text{ radians} \qquad (3)$$

This angle is a rotation around the center of rotation of the air bearing, and the actuating system should generate a tangential acceleration a_{TS} proportional to a rotation θ_S around an axis located at the contact point between the top of the piezoactuators and the left face of the tilting table.

The angle θ_S is calculated from the value of θ_M and the geometry of the system in Fig. 7, considering that the accelerations a_{TV} and a_{TS} have the same magnitude value. The minus signal indicates that the two rotations have opposite directions, according to the reference indicated in Fig. 7.

$$a_{TV} = -\theta_m \cdot \omega^2 \cdot d \quad \therefore \quad a_{TS} = \theta_S \cdot \omega^2 \cdot r \quad \Rightarrow \quad \theta_S = -\theta_m \cdot \frac{d}{r} \tag{4}$$

6.1. Calibration of the actuating system

The behavior of the transverse movement of this exciter allowed a reduction to a pair of actuators configured to actuate at opposite directions to generate the desired rotation around the horizontal axis. The prototype was then configured for this working condition, and referring to Fig.2 only the actuators 2 and 4 will be controlled.

The electrical connections of the system are shown in Fig. 10. A two channel function generator HP3245A is used to generate the signals to drive the exciter and the actuators due to its capability of synchronization 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 and the direction of movement of the piezoelectric actuators are related to the polarity of its electrical connections.

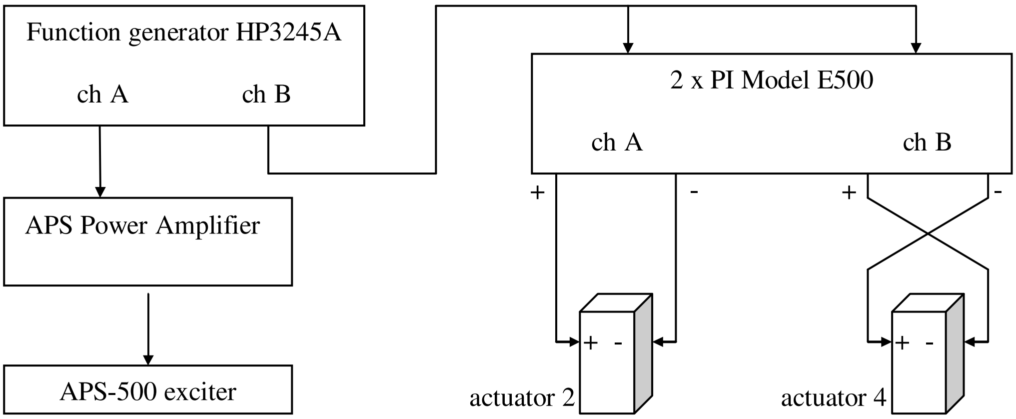


Figure 10: Electrical connections of the piezoelectric actuators.

To control the actuators motion is necessary to know the relationship between the applied voltage and the rotation angle θ_S of the tilting table. This calibration was carried out measuring the displacement δ_2 on point 2 and the correspondent voltages configured at channel B of the function generator HP3245A at the frequencies of 50 and 100 Hz. In this calibration it was considered that the system is composed by the actuators and the correspondent voltage amplifiers. The system presents a linear behavior, and the results were used to obtain the Eq. (5). This calibration was performed with the accelerometer mounted over the tilting table, as shown in Fig. 3.

$$V_{pkpk} = 21535 \cdot \theta_S + 0{,}075 \tag{5}$$

During this calibration procedure the correspondent acceleration level indicated by the axis Z of the triaxial accelerometer was measured. These measurements were made with a 4 channel spectrum analyzer HP35670A, configured in linear spectrum mode with a flat top window. According to Eq. (4) and considering that this acceleration level is equal to a_{TS}, a correct value of r was obtained and was used to calculate the values of R and d. Figure 11 shows the distance r and the location of the Z axis. The phase shift λ_S between the electrical signal from channel B of the generator and the movement of the tilting table was measured also by the vibrometer software at each single frequency.

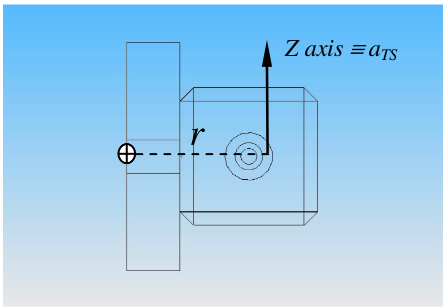
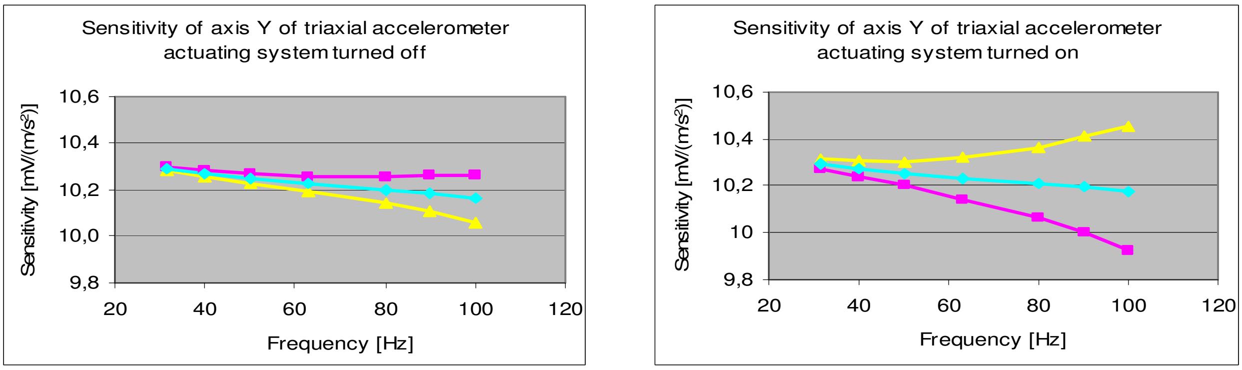


Figure 11: Location of the Z axis and distance r.

6.2. Accelerometer calibration procedure and results

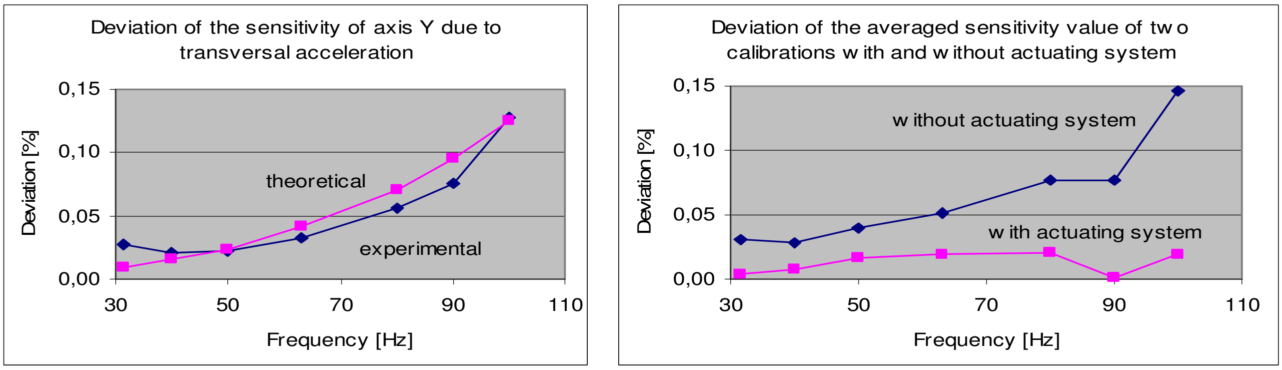
The calibration of the sensitivity of axis Y of the triaxial accelerometer is performed at the standardized one-third-octave vibration frequencies in the range from 31,5 to 100 Hz, with an extra point at 90 Hz, with an acceleration level of 10 m/s^2. The first step was to measure the displacements δ_2 and δ_4 at point 2 and 4 and the output voltage of axis Y, with the actuating system turned off. The sensitivity values obtained at these two points and the average are plotted at Fig. 12(a).

It was measured also the phase shift λ_M between the displacement of point 2 and 4 relative to the electrical signal of channel A of the generator. To control the acceleration a_{TV} is necessary to know its magnitude and phase related to a fixed reference. The phase between the electrical signal from channel A and the longitudinal movement of the exciter table remains below 0,5° over the entire frequency range, so λ_M can be considered the phase from the transverse and the longitudinal movement. The next step is to calculate the angle θ_M with Eq. (3), θ_S with Eq. (4), V_{pkpk} with Eq. (5) and the phase shift equals to 180 + $\lambda_M - \lambda_S$, and configure the values of voltage and phase shift at channel B of the generator. New measurements were made with the actuating system turned on and the final results, the average of the sensitivity obtained at point 2 and 4, are showed at the blue curve of Fig. 12(b). Note that the difference between the sensitivity results increase from Fig. 12(a) to (b), because the actuating system has a rotation radius r smaller than the air bearing rotation radius R. So the angle θ_S should be larger than θ_M , and typical values of the two angles are 2,92x10^{-5} and 1,03x10^{-4} radians, respectively. These values were approximately the same to all the frequencies because the moving table rotation is mainly due to the air bearing clearance. The values of δ_2 vary among 380 to 37 µm from 31,5 to 100 Hz, but the values of δ_2 - δ_4 vary only from 0,6 to 0,78 µm in the same range.



(a) (b)

Figure 12: Sensitivity results (a) before and (b) after the actuating system turned on [pink curves: results at point 2, yellow curves: results at point 4 and blue curves: average of two results]



(a) (b)

Figure 13: Influence of the transverse acceleration at the results (a), deviation from the results with and without the actuating system relative to the correct value.

The output signal of Z axis was measured during the calibrations, and the relative difference between this acceleration level and the value of a_{TV} obtained by the vibrometer measurements was less than 1%. This acceleration level must be corrected, because the correspondent accelerometer presents a transverse sensitivity of 0,6% of the principal sensitivity. At 100 Hz, for instance, the measured output voltage of Z axis was 6,77 mV and the calculated voltage considering the value of a_{TV} was 6,12 mV. The difference of 0,65 mV corresponds to the longitudinal acceleration of 10 m/s^2 acting over the transverse sensitivity, and the phase shift between these two magnitudes was

4,2°. When the actuating system compensates the transverse acceleration a_{TV}, this difference of approximately 0,65 mV is the output signal measured at Z axis at the entire frequency range.

Figure 13(a) shows the deviation from the initial sensitivity values and the final ones obtained with the actuating system on, and the theoretical deviation considering the acceleration a_{TV} acting over the transverse sensitivity of the Z axis. The transverse sensitivity of this axis is 2%, and the good agreement among the curves indicates that the transverse acceleration is the most important influence in the deviation of the sensitivity results.

Another calibration was performed with the triaxial accelerometer mounted in a position rotated 180° from the previous one, and referring to Fig. 3(b) the Z axis is down and the X axis is to the right. This procedure was explained in section 3.3, and it was considered that the correct sensitivity values are the average of the sensitivity obtained without the actuating system at the two calibrations. Figure 13(b) shows that the deviation from the sensitivity values obtained with the actuating system controlling the transverse acceleration relative to the correct value remains below 0,02%, so in practice it would not be necessary to accomplish a second calibration to obtain the correct sensitivity value.

7. CONCLUSIONS

The active system proposed to control the transverse acceleration that occurs at the moving table of vibration exciters used in absolute calibrations reached the foreseen objectives, reducing from 5% to less than 0,1% the relative transverse vibration level. It was showed that with this reduction the results obtained in just one calibration can be considered satisfactory.

All the measurements presented in this paper were made manually, which is a very time consuming procedure. So the future work must include the automation of the vibrometer measurements, the control system itself and the implementation of an automated moving system to the OFV-505 sensor head.

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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9. RESPONSIBILITY NOTICE

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