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PRIMARY ACCELEROMETER CALIBRATION PROBLEMS DUE TO VIBRATION EXCITERS

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Abstract: The main purpose of this paper is to discuss the problems that are imposed to primary accelerometer calibration due to the use of imperfect vibration exciters. A review of the main problems is presented. Solutions are discussed and some calibration results are presented.

Keywords: vibration, accelerometer, calibration, metrology shaker.

1. INTRODUCTION

Most of the primary accelerometer calibrations that are currently performed use interferometric measuring techniques [1]. The reciprocity technique has been substituted along the last years because it is very time consuming and has 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.

The vibration exciter (shaker) is one of the most important items of the calibration system. Assuming a stepped sine calibration, the ideal exciter should furnish uniaxial, stable and distortion-free vibratory movement at any desired frequency and amplitude. No additional source of uncertainty should be generated by the exciter.

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 cross-motion and heating usually show-up and can strongly affect the calibration result.

Some NMIs developed their own calibration shakers to overcome many of these problems [2-10]. 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 cross motion and to avoid the resonances that typically appear in flat-spring suspensions.

The international standard ISO 16063-11:1999 [1] 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. 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 [11-16].

2. INTERFEROMETRIC CALIBRATION

The interferometric calibration of an acceleration measuring set (accelerometer + conditioning amplifier) comprehends the measurement of the displacement amplitude on the reference surface of the accelerometer by interferometry and the measurement of the corresponding voltage output of the conditioning amplifier. Fig.1 shows a typical calibration system based on the fringe counting method.

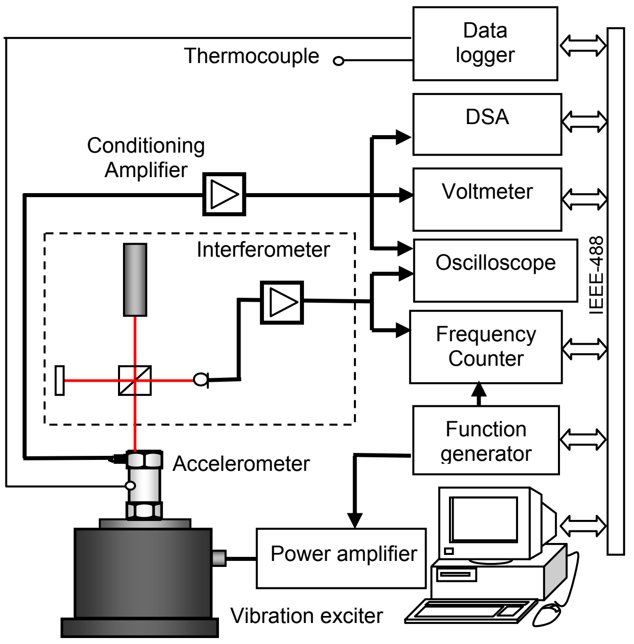


Fig. 1. Interferometric calibration system - Fringe counting method

The voltage sensitivity of the acceleration measuring chain is obtained by

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

where $\hat{u}$ is the amplitude of the output voltage, $\hat{s}$ is the amplitude of the displacement at the accelerometer reference surface and f is the vibration frequency.

In an ideal situation, the measurement of the displacement could be carried out at a single point in any place of 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. Unfortunately most of the calibrations using only this simple procedure 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. Some of the most common problems will be reviewed here.

3. PROBLEMS OF VIBRATION EXCITERS

3.1. Low stiffness of the moving element

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 moving elements because this material is cheap and allow 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 with laser scanning vibrometers, or even measuring the sensitivity of the accelerometer with a single beam laser interferometer focused onto different points of the table, one 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 increase as well.

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 driving current and thus on the acceleration amplitude. Therefore, this problem usually shows up at higher frequencies due to the use of higher acceleration levels. This situation is then very likely to happen, especially if the J1-null method is used. This differential heating from the mounting base induces systematic errors on the measurement due to the temperature sensitivity of the accelerometer [17].

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.

This problem can be minimized by using lower acceleration levels or increasing the air flow around the driving coil of electrodynamic exciters. Adding some adapter with low temperature transmission coefficient only delays the heating, but does not diminish its magnitude. In addition, these materials usually present low stiffness coefficient. Another way to deal with this problem is to intercalate low frequency and high frequency calibrations to keep the temperature rise within acceptable limits [18].

3.3. Rocking 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 table), an error may occur when a displacement measurement is made.

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 [19], 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 and require a shorter time for the calibration [9][18]. 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 [20] or more [21] have already been reported for vibration measurements.

3.4. Transverse motion

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. The coupling of the shaker transverse motion and the accelerometer transverse sensitivity creates an error on the sensitivity determination.

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 [18]. This simple procedure theoretically cancels out the influence of the transversal sensitivity component. In the case of shakers that have a single centre 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.

3.4. 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 [10]. Stacked piezoelectric shakers that incorporate layers of damping material present a better behavior since a flatter frequency response is obtained [6].

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 to use different types of exciters to cover specific sub-ranges inside broader frequency ranges.

3.5. Air-bearing guides

Air bearings have been used for many years in shakers designed by some NMIs [2]. Nowadays they are available in commercial calibration shakers. Since most models were designed for comparison calibrations, they still present some limitations for interferometric calibrations. The airflow can introduce broadband noise in the measurements. This problem is worse with models that have large bearing clearances, especially when single-ended accelerometers with side-connectors are being calibrated. This happens because the signal cable cuts the airflow that exits the bearing. Almost all shakers that currently use air bearings have low maximum acceleration limits. Therefore, their use is not possible with the J1-null method at high frequencies.

There is not much to do with the airflow problem. Since it depends on the design of the bearing, the best thing to do is to buy shakers with smaller clearances and lower airflows.

3.6. Harmonic distortion

Shakers are displacement-limited at low-frequencies. Measurements of large displacements tend to suffer from harmonic distortions. This problem also appears when the shaker is driven too hard at high frequencies. The effect of motion distortion is present both in the interferometric signal and in the voltage output. As it is difficult to treat, it is better to be avoided, especially if the fringe counting and J1-null methods are being used [22]. Since the sine approximation and Discrete Fourier Transform (DFT) methods are frequency-selective methods, they are less influenced by distortion.

4. CALIBRATION RESULTS

Some of these problems described in the last section are exemplified here.

The problem of low stiffness of the moving table is shown in fig. 2. The charge sensitivities obtained for a standard single-ended accelerometer with aluminum-table shakers (A and B) were much higher than expected at 3 kHz and 5 kHz. Just mounting a stiff adapter on the table of shaker B allowed us to get equivalent results as the ones obtained with an air-bearing shaker (C) which has a very stiff beryllium table.

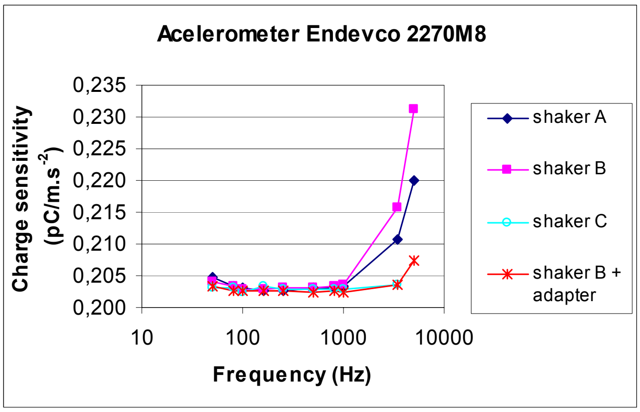


Fig. 2. Influence of table stiffness on sensitivity

Bad designed adapters can worsen even more the problem, fig. 3. It is necessary to evaluate each design to verify if the sensitivities measured at different points do not differ significantly. If this happens, it is a symptom that a rigid body motion was not achieved. In this case, the adapter behaves like a membrane and the interferometric system will measure displacement amplitudes different than the one found at the centre axis position where the accelerometer is mounted.

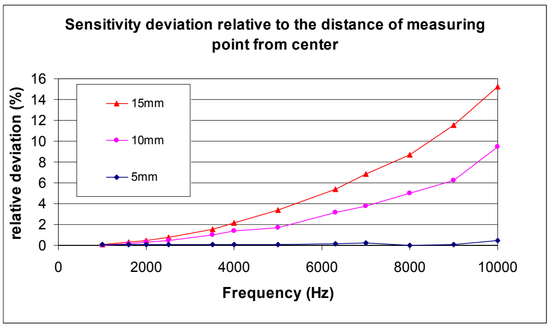


Fig. 3. Influence of table stiffness on sensitivity

A good adapter design is shown in fig. 4. It consists of an aluminum plate with 4 mounting holes for attachment to the shaker table and of a titanium plate with 6 mounting holes, which is used to mount the accelerometer and to glue small mirrors. The combination of these two plates allows rotation of the accelerometer in discrete angles of 30^o or 90^o with no influence on the mounting torque. This feature improves the capability of comparing results at different positioning angles.

Fig. 4. Mechanical adapter

The influence of heating of the moving element over the built-in reference accelerometer of an air-bearing shaker can be seen in fig.5. The sensitivity of this transducer decreases significantly with the rise of the table temperature. A 4 ^{o}C temperature rise was measured during a period of 25 minutes for a loading condition of just 10 grams and acceleration amplitude of 50 m/s^2 at 300 Hz. This represents a corresponding drift of 0,17 % in sensitivity.

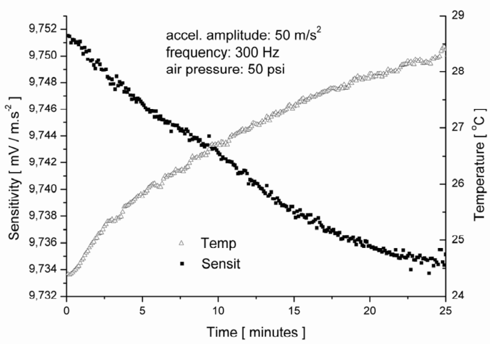
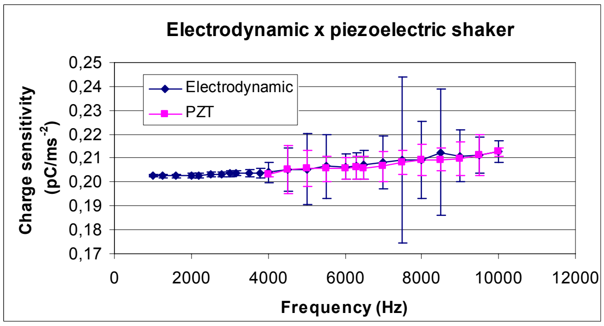
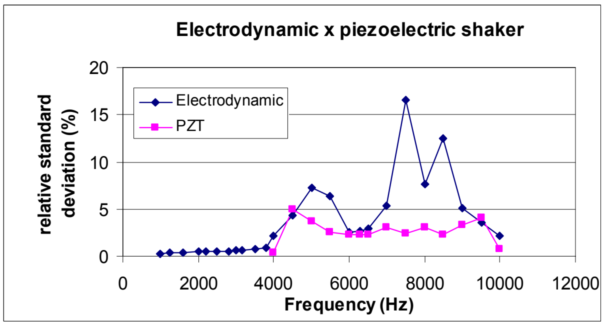


Fig. 5. Variation of the sensitivity of a built-in accelerometer due to the increase of temperature

A comparison of the calibration results of an accelerometer type Endevco 2270m8, which were obtained with a commercial electrodynamic shaker and with a home-built piezoelectric shaker is shown in fig. 6. The relative standard deviations of 4 measurements (i.e. 2 points at 2 mounting positions) are presented as error bars around the mean values calculated for each shaker. This graph shows that the applied methodology furnishes consistent final results with two very different exciters. It is easily seen that the dispersion of the measurements is much lower with the piezoelectric shaker, with a maximum relative standard deviation of 5 % versus 17 % for the electrodynamic exciter, within the frequency range from 4 to 10 kHz.



(a) magnitude of charge sensitivity

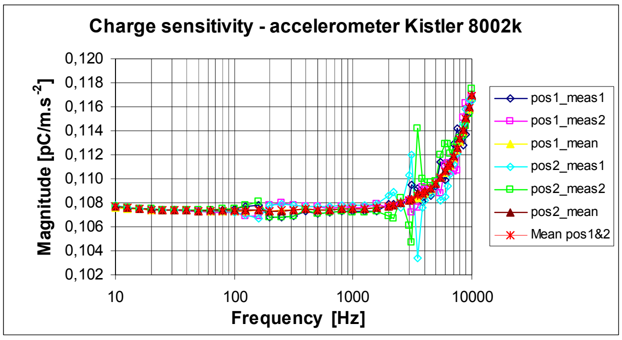


(b) relative standard deviation

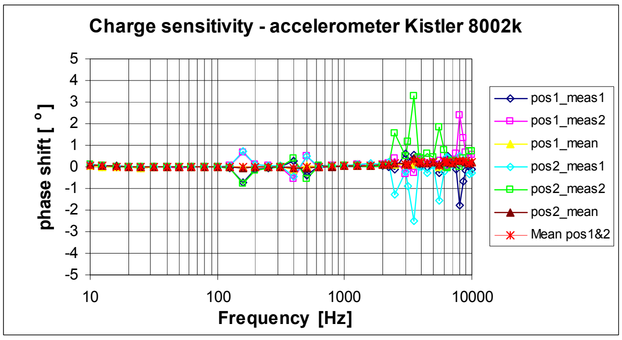
Fig. 6. Dispersion of the sensitivity of a single-ended accelerometer measured on 2 points and 2 positions with two different shakers.

A typical calibration result obtained by our homodyne quadrature interferometric system is shown in fig. 7 as "Mean pos 1&2". This figure also includes the individual magnitude and phase-shift measurements at the two mounting positions. For this specific accelerometer, the influences of rocking and transverse motions were very well compensated by the averaging technique.

Unfortunately, sometimes the cancellation is not so perfect at some calibration frequencies. This situation is detected with some back-to-back standard accelerometers in some very specific frequencies, very probably due to case resonances. Fig. 8 shows that there is a very strong relationship between the relative transverse acceleration measured at the reference surface of an accelerometer and the relative standard deviation calculated from the 4 individual measurements.



(a) magnitude of charge sensitivity



(b) phase shift

Fig. 7. Sensitivity of a single-ended accelerometer on a flat-spring suspension electrodynamic shaker

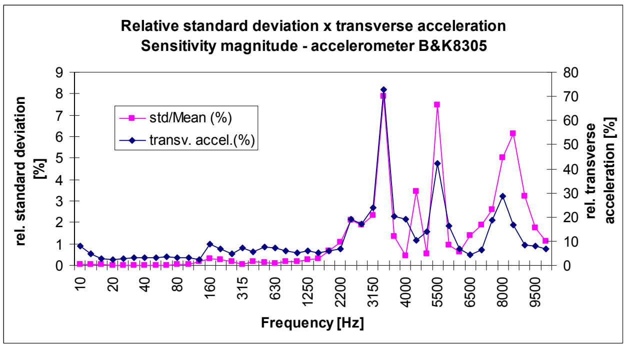


Fig. 8. Relationship between rel. standard deviation and transverse acceleration measured at the reference surface of a BTB accelerometer.

Fig. 9 shows the quite strong influence of the suspension resonance of an air-bearing shaker around 160 Hz. The averaging of the measurements made at two points diametrically opposed on the shaker table is sufficient to obtain a reliable result. The systematic error present in a single point measurement, which is caused by rocking of the table very close to the standardized reference frequency, is cancelled out when the mean is computed. This figure also shows that the dispersion of the individual measurements of this SE standard transfer accelerometer is much smaller than in fig. 7(a), which corresponds to a calibration carried out with an electrodynamic shaker with a flat-spring suspension. Due to the smaller maximum excursion obtainable with the air-bearing shaker, the calibration curve in fig. 9 is limited to frequencies above 20 Hz. Lower frequencies can only be driven with very small amplitudes and higher distortion levels.

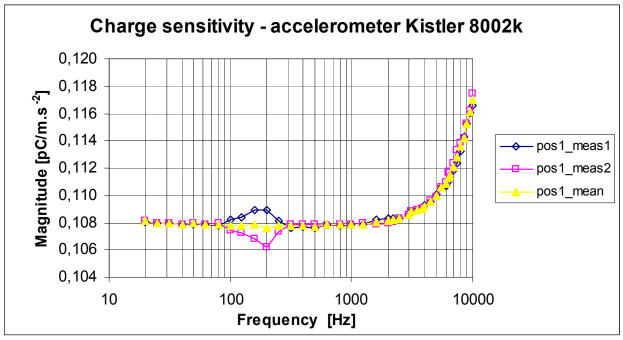


Fig. 9. Sensitivity of a single-ended accelerometer on a air-bearing electrodynamic shaker

5. CONCLUSIONS

Vibration exciters are widely used for the generation of motion quantities. They are available commercially from different manufacturers in a wide selection range. Some models are classified as calibration shakers, being designed for comparison calibration of accelerometers. Both general-purpose and calibration exciters are used by a great number of laboratories in their interferometric primary accelerometer calibration systems.

The quality of the vibration motion is very important for a primary accelerometer calibration system, presenting a significant influence on the accuracy of the final results. The uncertainty of measurement depends directly of many components of influence which are caused by the shaker. Rocking and transverse motion, harmonic distortion, base bending, temperature gradients, noise, hum, internal resonances, etc. are some of the problems that can be generated by the excitation system.

A few NMIs developed their own shakers, including models using air-bearing guides to improve their capability of generating rectilinear motion with rigid body behavior of the moving element within the frequency range of interest. Since the development of state-of-the-art shakers requires large investments, most of the laboratories keep using commercially available systems, sometimes including minor home-made improvements.

Some international inter-laboratory comparisons apparently suffered strong influences due to shaker problems [23-25]. The regional comparison SIM.AUV.V-K1 [24] and the CIPM key comparison CCAUV.V-K1 [25] presented greater dispersions at high frequencies for single-ended accelerometers than for back-to-back models. A key comparison reference value was even not determined for frequencies above 2 kHz for the single-ended accelerometer that was calibrated for the CIPM key comparison.

Some multiple beam interferometers can be used to automatically cancel out the influence of one of the worst problems, which is rocking motion, but a very limited number of laboratories has already implemented them. Averaging the results obtained in sequential measurements at different points of the reference surface is a good alternative for laboratories that use single beam interferometers.

This paper reviews some of the typical problems that can influence primary calibration of accelerometers and are shaker-dependent. Some of the described problems can create large systematic deviations that show great repeatability, giving to the technician a wrong confidence on the results. The knowledge of the potential sources of error and the implementation of some of the suggested measuring techniques can lead to improvements of the measurement capability of the laboratory.

It can be concluded that despite many possible problems, a calibration laboratory can minimize the effect of most of them and obtain reliable results. There is no perfect shaker available commercially and any design will suffer from some of the effects described here. Even the current state-of-the-art shakers may need to be used together with averaging techniques if lower uncertainties are desired.

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