IMEKO 20th TC3, 3rd TC16 and 1st TC22 International Conference
*Cultivating metrological knowledge*
27th to 30th November, 2007. Merida, Mexico.

# Comparison of the Calibration of a Heavy Multi-Component Vibration Transducer on Different Exciter Systems (Calibration of Heavy Triax-Transducer)

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**Abstract**

The performance specifications of a shaker may be strongly affected by the load which it is driving. When using a shaker for calibration purposes, the mass and mass distribution of the device under test as well as its mounting configuration may deteriorate seriously the purity of the motion of the shaker armature along the desired axis. In this paper the authors present an attempt to reduce the magnitude of parasitic movements by an improved mounting configuration. Although the resulting motion is significantly improved, transverse, bending and rocking acceleration could not be diminished to less than 10 % as recommended by the ISO standard [1]. In spite of this unsatisfactory large resulting parasitic motion, a reasonable calibration of a device under test is nevertheless possible when selecting carefully the axis of the reference laser vibrometer. We were able to validate this approach by a comparison with a calibration carried out on an alternative vibration exciter of inherently better quality (but considerable higher cost).

*Keywords*: Secondary calibration, vibration transducer, shaker, rocking motion

## 1. Introduction

For secondary calibration of a vibration transducer the device under test (DUT) is rigidly coupled with a reference transducer and set in motion by means of a shaker. Based on the assumption that the mechanical coupling of the transducers ensures identical movement, the DUT sensitivity can be evaluated from the simultaneously measured electrical signal outputs and the known reference sensitivity [1].

The ISO standard [1] defines certain requirements to be met by the equipment used while performing the calibration in order to reach a given uncertainty. While the shaker performance can sometimes be specified separately, this may be insufficient in other situations. In our case, we attempted to calibrate a sensor weighting about the same as the moving armature of the employed shaker. When considering the originally intended mounting configuration (see Fig. 1) one observes an offset between the applied force and the center of mass of the moving parts. As a result, we generated considerable torques with devastating effects on the purity of the motion along the desired axis. While the bearing of the shaker armature could limit the effect of these torques at low frequencies and correspondingly extended displacement amplitudes, the quality degraded dramatically with increasing frequency as the displacement amplitude got small.

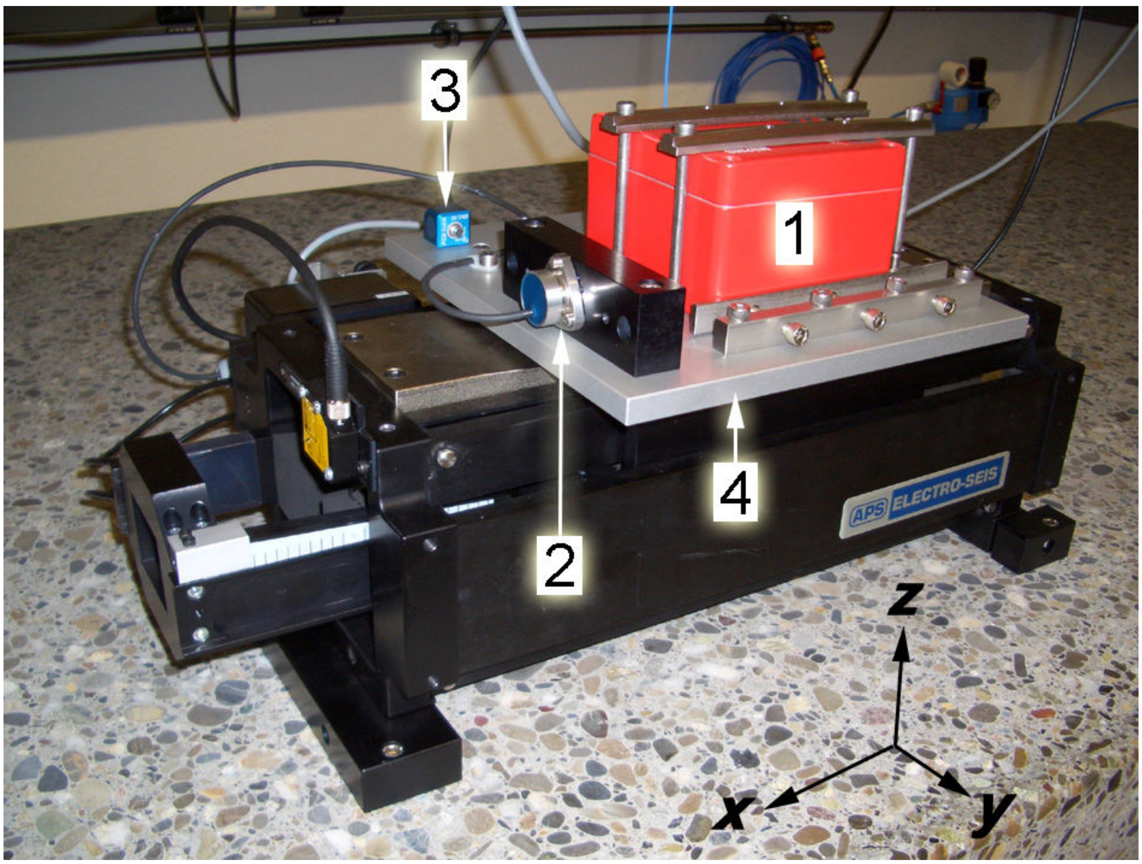


Figure 1. Original mounting configuration of the DUT (1), reference sensor (2) and monitoring triax (3) on the auxiliary table (4) of the APS-113 shaker in horizontal operating mode

## 2. Device under test

METAS was approached to investigate its possibilities to calibrate a device manufactured by SYSCOM Instruments SA, Switzerland according to a German DIN standard [2]. The challenge of this task resides in the fact that this velocity sensor (Type MS2003+), which is quite popular with civil engineers, is relatively heavy. The triaxial version weighs 1.55 kg and covers according to its specifications, nevertheless, a relatively wide frequency range (1 Hz to 350 Hz). Its users are, indeed, interested in these frequencies to measure structure vibrations on one hand (1 Hz to 80 Hz) and to assess structure borne sound on the other (up to 315 Hz) [3]. Furthermore, this velocity sensor is characterized by a large dynamic range (> 130 dB) [4].

## 3. Original mounting configuration

The vibration laboratory at METAS employs a commercial calibration system developed by SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, Germany. This calibration system presents a modular structure and can be combined with different vibration exciters. For our purposes the APS-113 shaker turned out to be the most promising option. It is equipped with four ball bearings and can accommodate heavy loads in horizontal as well as vertical operation. This shaker comes with an auxiliary table onto which the equipment to be tested can be mounted. While this auxiliary table can be centered on the shaker axis in the vertical mode of operation, this is obviously not the case in the horizontal mode (see Fig. 1). This fixture is certainly adequate for low frequency long-stroke movements. One understands, however, that the efficiency of the guidance provided by the ball bearing diminishes as the movement amplitude gets smaller, which is generally the case for increasing frequency.

In a first trial we tried to use this configuration to calibrate the sensitivity of the triaxial velocity sensor (SYSCOM MS2003+) in the horizontal mode along the x-axis up to 200 Hz excitation frequency. The device to be calibrated presents no reference plane to which a reference sensor ought to be attached. The housing can however be regarded as perfectly stiff for the relevant frequency range. Therefore, we attached the reference sensor (QA2000 by Honeywell) for the x-acceleration to an adapter screwed onto the auxiliary table. The table movement was additionally monitored by a triaxial accelerometer (356B08 by PCB).

Figure 2 shows the resulting frequency-dependent acceleration amplitudes (components $a_x$, $a_y$, $a_z$) as measured by the monitoring triax and the nominal displacement $d_x$ measured by the reference sensor at their corresponding positions. It is obvious that only for small excitation frequencies (< 40 Hz) the movement can be regarded as predominantly one-dimensional along the x-axis. At 44 Hz for example, the parasitic acceleration component along the vertical z-axis is of similar magnitude as the nominal horizontal x-component. At higher frequencies the situation even gets worse and such an excitation would be clearly unsuitable for calibration purposes.

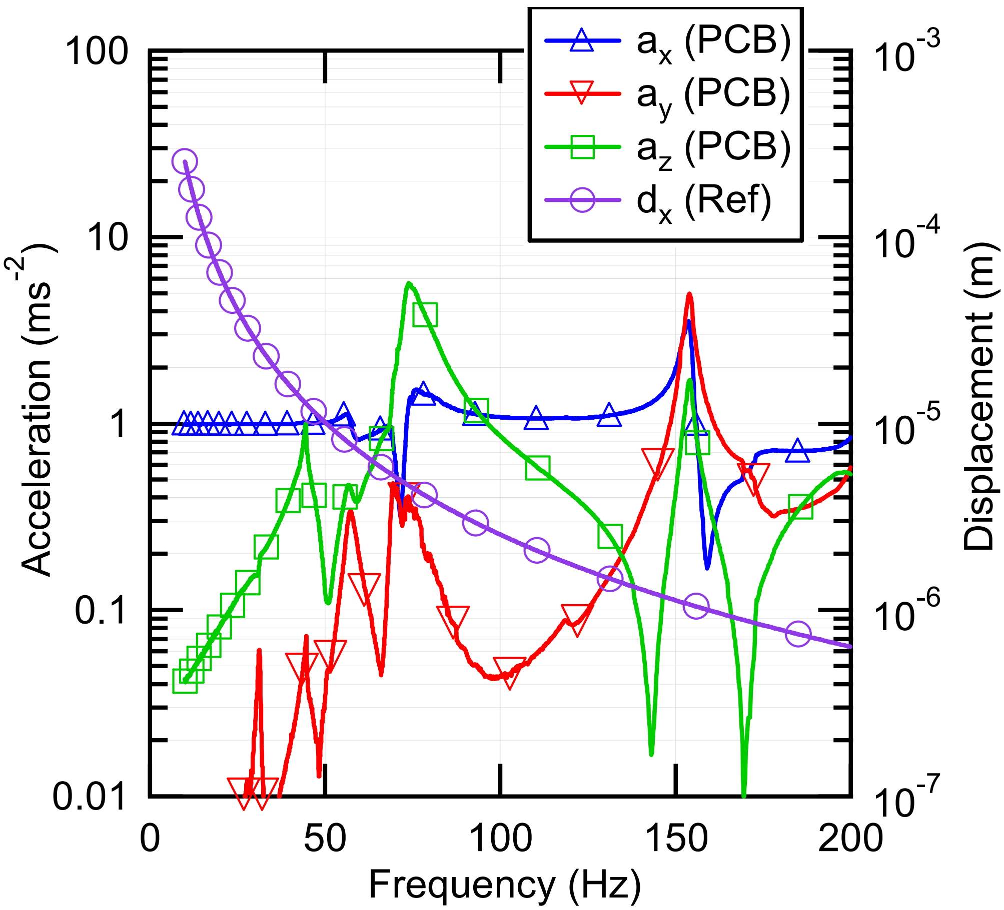


Figure 2. Table movement of the original mounting configuration: the three acceleration components were measured by a small triaxial accelerometer (PCB), the nominal displacement was obtained from a reference accelerometer (Ref).

One can further note that the acceleration along the x-axis is position dependent. The monitoring triax measures large amplitude variations as a function of frequency in spite of an efficient closed-loop control of the shaker drive which uses the reference acceleration as control input. The reason for this behavior is related to the fact that the resulting rocking motion of the auxiliary table also involves rotational components which can be translated into position-dependent linear accelerations (see Fig. 3). Because of the differing mounting locations, each of the three sensors experiences slightly different linear accelerations. This means that the reference accelerometer and the monitoring triax-sensor measure different x-accelerations as soon as rotation is involved.

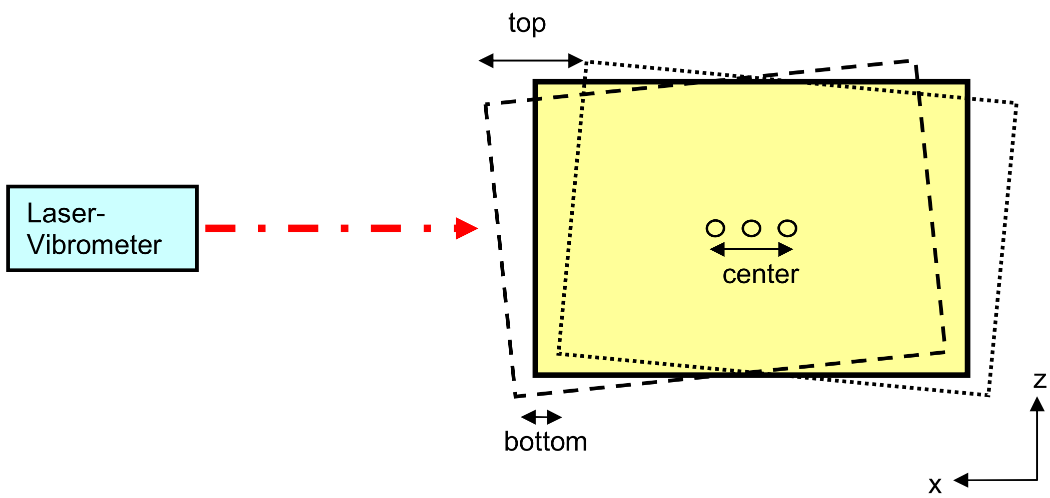


Figure 3. Illustration indicating how a rocking motion of big objects affects the measurement of linear movement.

## 4. Optimized mounting configuration

One of the problems identified when using the original mounting configuration for horizontal excitation was the large vertical offset between the line of action of the driving force and the center of gravity of the moving part (including the device under test). As a remedy we modified the fixture of the horizontal table as illustrated in Fig. 4. With this improved setup we observed a remarkably improved purity of the motion (see Fig. 5) when performing a horizontal excitation along the x-axis under the same conditions as before. Now, the parasitic acceleration along both orthogonal axes (y- and z-axis) remains below the nominal acceleration along the x-axis over the full frequency range. But while the y-acceleration is generally smaller than 10 % of the nominal acceleration, there is still considerable orthogonal acceleration along the z-axis. Thus, this parasitic movement is still not satisfactory. Part of the observed z-axis movement could be explained by a true linear acceleration along the z-axis. More probably, however, the measured signal arises from rotational movement around the center of mass of the movable part of the system. This is illustrated in Fig. 3 which shows how rocking motion translates into position-dependent linear displacements.

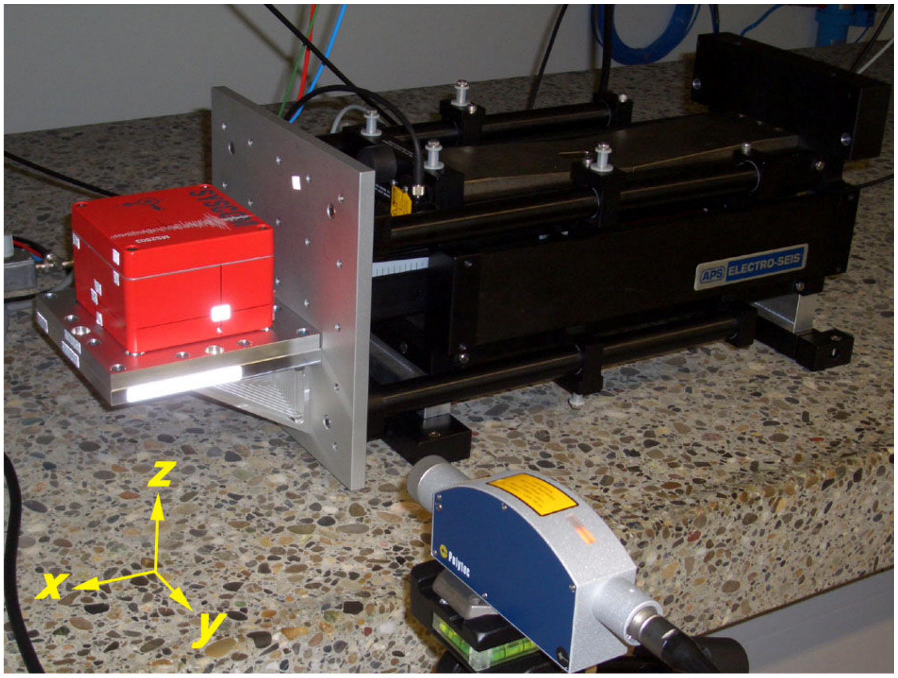


Figure 4. Optimized mounting configuration for which the resulting driving force vector acts onto the center of mass of the total moving structure.

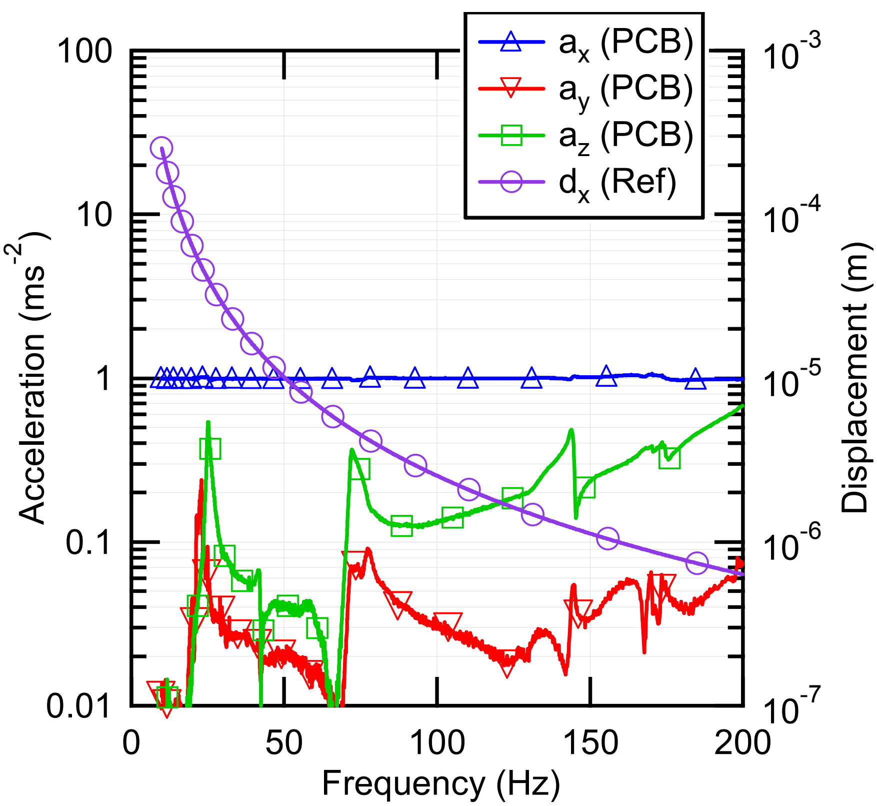


Figure 5 Table movement of the optimized mounting configuration: the three acceleration components were measured by a small triaxial

accelerometer (PCB), the nominal displacement was obtained from a reference accelerometer (Ref).

## 5. Correcting for non-perfect motion

In order to discriminate between translational and rotational movement, we decided to use a laser vibrometer (LV) as a second reference. It pointed sequentially at different locations while an identical excitation of the device under test was maintained by means of the independent reference sensor QA2000 which fed the closed-loop control of the shaker drive. The vibrometer measurements of Fig. 6 shows that the x-axis velocity amplitudes at different DUT housing positions differ as much as 70 % with respect to the independently mounted reference sensor. The phase relationship (not shown) was, however, the same for every probing location indicating that the movement can, indeed, be considered as a movement of a rigid object in the considered frequency range.

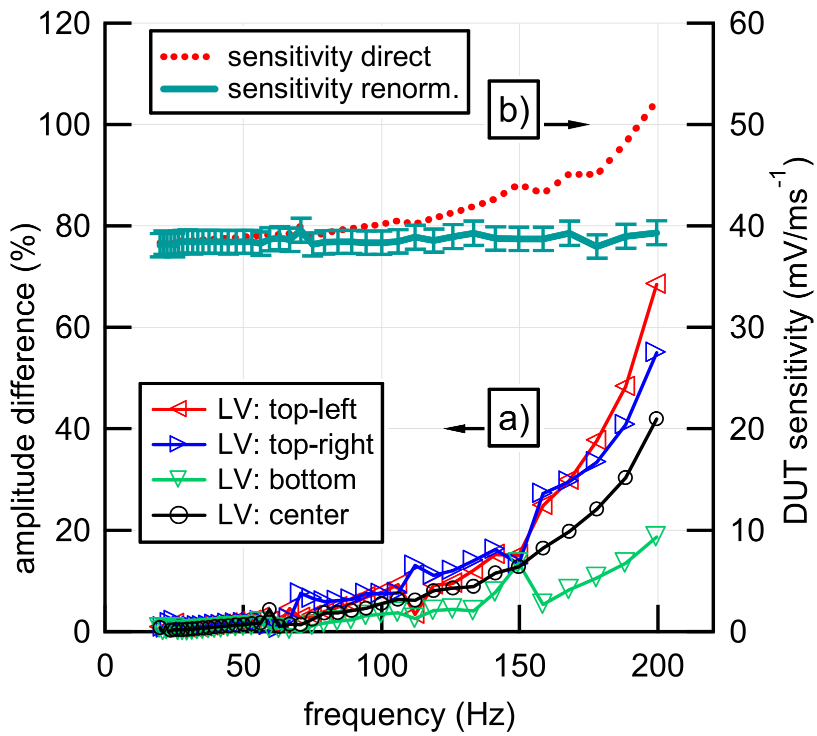


Figure 6. Calibration of the DUT using an additional laser vibrometer, performed with the shaker at METAS:
a) Frequency-dependent difference of velocity amplitudes as measured by a laser vibrometer at different locations (top left, top right, bottom, center of the DUT housing) with respect to the reference amplitude.
b) Frequency-dependent sensitivity of the DUT when using the arbitrarily positioned reference sensor QA2000 (red) or the laser vibrometer aligned to the DUT's sensitivity axis (green), respectively.

For a rigid plane, the x-axis velocity $\dot{x}_{\mathrm{P}}$ of an arbitrary point P can be interpolated from the measurement of the x-axis velocities $\dot{x}_{\mathrm{A}}$, $\dot{x}_{\mathrm{B}}$ and $\dot{x}_{\mathrm{C}}$ at three different locations A, B and C by the following expression:

$$\dot{x}_{\mathrm{P}} = \dot{x}_{\mathrm{A}} + \alpha \cdot (\dot{x}_{\mathrm{B}} - \dot{x}_{\mathrm{A}}) + \beta \cdot (\dot{x}_{\mathrm{C}} - \dot{x}_{\mathrm{A}}). \quad (1)$$

Thereby, $\alpha$ and $\beta$ correspond to the coordinates of P expressed in terms of the vectors $\overrightarrow{\mathrm{AB}}$ and $\overrightarrow{\mathrm{AC}}$:

$$\overrightarrow{\mathrm{AP}} = \alpha \cdot \overrightarrow{\mathrm{AB}} + \beta \cdot \overrightarrow{\mathrm{AC}} \quad (2)$$

These coefficients $\alpha$ and $\beta$ can be calculated by evaluation of the transformation matrix $\mathrm{M_B}$ corresponding to the base change defined by:

$$\mathrm{M_B} \cdot \overrightarrow{\mathrm{AB}} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ and } \mathrm{M_B} \cdot \overrightarrow{\mathrm{AC}} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (3)$$

One obtains then:

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \mathrm{M_B} \cdot \overrightarrow{\mathrm{AP}} \quad (4)$$

In our case we observed that the interpolation of the x-axis velocity of a given point of our DUT surface determined from sequential vibrometer measurements at three different locations (differing by as much as 40 %) agreed with an actual measurement in this same location to within < 1%. This indicates a very good reproducibility of the frequency dependent vibration modes in sequential runs.

The DUT assembly is based on three individual one-dimensional vibration sensors. It doesn't have a marked reference point. But based on the construction of the device, the positions of its three sensitivity axes (oriented in space like none-intersecting edges of a cube) can be estimated. For the calibration of the three sensor axes on our non-ideal APS-113 exciter we pointed the beam of the reference laser vibrometer at positions on the DUT housing in such a way as to make it coincide with the respective sensor axis under test. One can show that in this way both linear vibration signals (the one of the laser vibrometer reference as well as the one of the DUT) are affected to the first order in the same way by rotational movement in spite of the horizontal offset of the measuring location along the beam. By this "normalization" approach we obtain a sensitivity curve of the DUT which is essentially flat (Fig. 6).

## 6. Calibration using an alternative shaker

In order to validate the above described approach of a calibration performed on a non-ideal shaker, we carried out a comparison using the high quality exciter available at the PTB [5]. This multi-component acceleration exciter (see Fig. 7) consists of three orthogonally arranged shakers acting on a measuring table via a cross-coupling unit with hydrostatic bearings [5, 6]. Unwanted translational movements (along the axis orthogonal to the primary excitation axis) can be eliminated by means of a cross-compensation matrix. In combination with the machine’s large bearings of narrowly designed play (< 15 µm), rotational movement is suppressed to a large extent. Compared with the APS shaker available at METAS, the excitation system at PTB offers higher quality of motion as well as a widely extended operation range in terms of load, force and frequency range.


Figure 7. View of the multi-component exciter available at PTB. This shaker provides mechanical excitations of outstanding quality. Rocking motion is suppressed to large degree.

On this exciter system, we carried out a calibration of the DUT using a reference accelerometer (Endevco 151-100) fixed at the vibration table to control its amplitude. The excitation frequency range was slightly extended up to 300 Hz. Again, we used a laser vibrometer to determine sequentially the movement of the DUT housing at different locations. Once again, the measured frequency responses showed an x-axis velocity which also depends on the chosen measuring location in the y-z-plane while maintaining a constant reference amplitude (Fig. 8). The figure demonstrates, however, that this effect (related to rocking motion) occurs on a scale an order of magnitude smaller when using this high quality shaker. Obviously, the calibration result is still affected somewhat by rotational motion when using the accelerometer attached to the table as a reference. When using the laser vibrometer pointing aligned with the sensitivity axis of the DUT, one obtains a perfectly flat sensitivity curve confirming the result found previously at METAS.

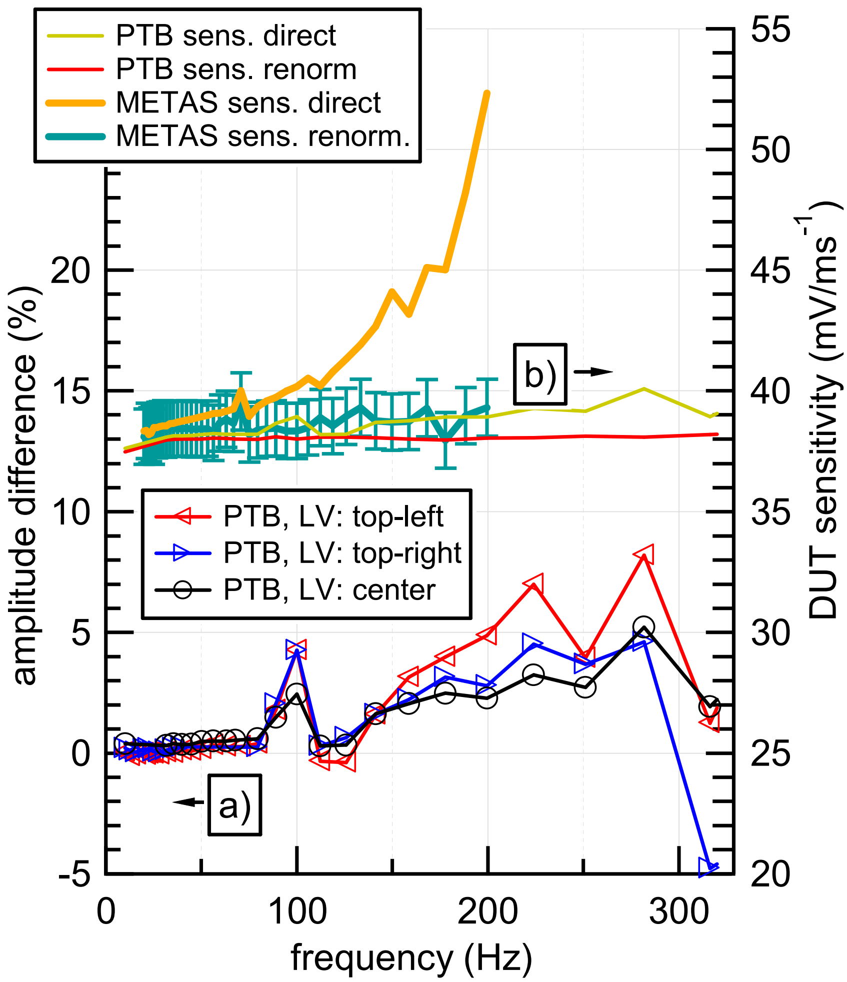


Figure 8. Calibration of the DUT using an additional laser vibrometer, performed with the multi-component shaker at PTB:
a) Frequency-dependent deviations of local velocities along the x-axis (measured by laser vibrometer) from the shaker table velocity (measured by reference sensor). Note the different scales with respect to Fig. 6.
b) Frequency-dependent DUT sensitivity as determined by METAS ("direct": using the separately mounted reference sensor; "renorm.": using the laser vibrometer signal measured on the sensitivity axis.) and PTB (with corresponding nomenclature).

## 7. Conclusions

We calibrated a heavy triaxial vibration sensor on two different excitation systems. We found that applying a well-defined mechanical excitation confined to a single degree of freedom represents a difficult challenge for the shaker especially in the horizontal mode of operation. The resulting motion may be strongly influenced by the mass and mass distribution of the mounted device under test. On the shaker available at METAS a modification of the mounting configuration improved the situation dramatically. A better suppression of unwanted parasitic excitations - especially of the rotational degrees of freedom - as implemented at the PTB is realized at high expenses and can not be achieved perfectly. When using an imperfect exciter system the location of the reference sensor has to be carefully selected to minimize the degree to which the rocking motion affects the calibration result.

## 8. Acknowledges

The authors would like to thank Thomas Bruns for valuable discussions and his precious help with the measurements performed on the multi-component exciter.

## References

[1] ISO 16063-21:2003, “Methods for the calibration of vibration and shock transducers — Part 21: Vibration calibration by comparison to a reference transducer”, International Organization for Standardization, Geneva, 2003.

[2] DIN 45669-3:2006, “Measurement of vibration immission – Part 3: Test (calibration and assessment) of the vibration measuring instrumentation; Primary test, verification, intermediate test, functional check in situ”, DIN Deutsches Institut für Normung e.V.

[3] DIN 45669-1:1995, “Measurement of vibration immission – Part 1: Vibration meters – requirements, verification”, DIN Deutsches Institut für Normung e.V.

[4] SYSCOM brochure: “MS2003-e/74700074/09.2006”, pdf available at http://www.syscom.ch/_pdf/brochures/ms2003%2B_data_en.pdf

[5] Weissenborn, C.: "Kalibrierung von Beschleunigungsaufnehmern bei mehrachsiger Anregung", PhD thesis, PTB-MA-68, Braunschweig, November 2001

[6] Aoki, H. et. al. "Vibration testing apparatus with increased rigidity in static pressure bearing", US patent N° 5'549'005, United States Patent and Trademark Office, 1996