PRIMARY CALIBRATION OF
GEOPHYSICAL AND SEISMIC VELOCITY SENSORS

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Abstract − This paper describes first measurement results determined with a new primary calibration system according to ISO 16063-11 that can handle very heavy devices under test (DUT) with a weight up to 50 kg allowing a precise vertical excitation of the DUT. This required the development of a new vibration exciter that can compensate the high payload and covers the broad frequency range from 0.05 Hz to 400 Hz without exceeding the cross motion and THD limits defined in the ISO standard.

Keywords: ISO 16063-11, seismic sensors, geophysical sensors, seismometer, geophone, shaker with payload compensation

1. INTRODUCTION

Whether it be for geophysical applications as well as for the monitoring of buildings or building sites a lot of different sensors are available on the market. They have in common a high weight (from some kilogram to some ten kilogram) and huge dimensions (up to some ten centimeters in diameter). Many of them implement a magnet-coil velocity transducer with a very high sensitivity (up to 10 000 V/m/s). Beyond these common characteristics the frequency range of the sensors can be very different. The pass band of some geophysical sensors covers the very low frequency range from 0.05 Hz to some 10 Hz. Other sensors like sensors for the monitoring of building sites for example work from 0.5 Hz to 315 Hz.

Especially the calibration of seismic sensors with huge dimensions is a big challenge that was not well solved in the past. For that reason these sensors are much more undergoing functional tests than being really calibrated. Many of such sensors have a build-in excitation coil additional to the measurement coil that can be used for such functional tests in laboratory and at remote operation sides (e.g. CP ZM). With such a configuration when a current is injected in the excitation coil, its interaction with the magnet induces an electromechanical force which excites the sensitive moving element of the sensor. The resulting motion is simultaneously measured with the measurement coil. The main limitation of this 'electrical calibration' method is the self-capacitance and the coupling capacitance phenomenon that appears inside and between the two coils during the measurement. The result is a significant decrease of the sensitivity in the higher frequency range and an increase of the damping [1].

Another 'calibration method' uses the very high sensitivity of these sensors that are designed to deliver a significant output signal caused by even the slightest movements. So it is quite common to mount and co-localize two sensors on a rigid seismic block and to measure the 'background noise' which is the natural vibration of the block. Under the hypothesis that the seismic block can be regarded as rigid in the interesting frequency range, that the coupling is the same between sensors and block and that the two measurement axis are in parallel, then both sensors see the same input signal. Thus the comparison of the output signal can at least give information if the output signal of both sensors is consistent.

However, both methods are far away from an absolute calibration of such sensors and thus a calibration system that allows the absolute calibration according to ISO 16063-11 is regarded as necessary. The challenge is to find a vibration exciter that

- Can handle and compensate high payloads
- Has a low noise guidance system
- Operates in a wide frequency range (DC to 400 Hz)
- Has a big payload table to mount the DUT
- Operates inside the limits given by the ISO 16063-11 standard.

2. DEVICES UNDER TEST

Measurement results of two types of devices are shown in this paper, sensors for building sites and seismic sensors.

2.1. Sensor for building sites - SINUS 902219.7

Vibration immissions can have effects on buildings or humans in buildings. So vibration control regulations require measurements to be made in order to assess such effects and to test the effectiveness of protective measures. As an example the German standard DIN 45669-1 [2] defines properties of vibration meters that can be used for such measurements. The sensor SINUS 902219.7 (see Fig. 1) is a typical sensor according to this standard. It has a weight of 2 kg and a diameter of 150 mm and covers a frequency range from 0.5 Hz to 315 Hz.
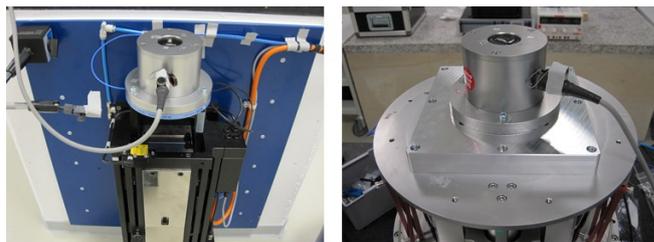

Fig. 1. Sensor SINUS 902219.7 mounted on
an APS 113-AB shaker (left) and on a SE-13 shaker (right)

The nominal transfer function of such a sensor according to DIN 45669-1 is shown in Fig. 2.The function describes a combination of a high-pass and a low-pass filter each a two-pole filter with Butterworth characteristics.
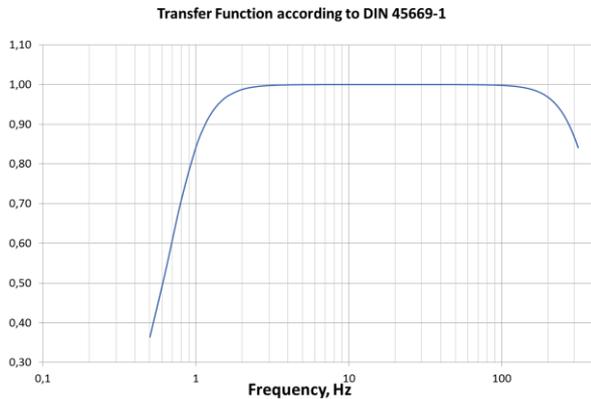

Fig. 2 Nominal Transfer Function of a Sensor according to DIN 45669-1

2.2. CP ZM 500

The CP ZM 500 sensor is a vertical axis geophysical transducer designed by the CEA. Its measurement frequency range is from 0.5 Hz or 1 Hz up to 100 Hz. The velocity transducer comprises a permanent magnet and a 30000 turns measuring coil. The weight is 11 kg and the diameter is 300 mm.

An integrated adjustable electronic low noise amplifier is used to obtain four different voltage gains (1, 4, 8 and 32). At the smaller gain value gain = 1, the nominal velocity sensitivity value is set to 2250 V/m.s^{-1}. The natural frequency of the oscillator is 1 Hz and the damping factor is adjusted to a value of $\frac{\sqrt{2}}{2}$.

The velocity transfer function model H is given by

$$H = S \frac{p^2}{p^2 + 2\varepsilon\omega_0 p + {\omega_0}^2} \qquad (1)$$

where,

$\varepsilon = \frac{\sqrt{2}}{2}; \ \omega_0 = 2\pi F_0; \ F_0 = 1 \ Hz; S = 2250 \ V/(m/s).$

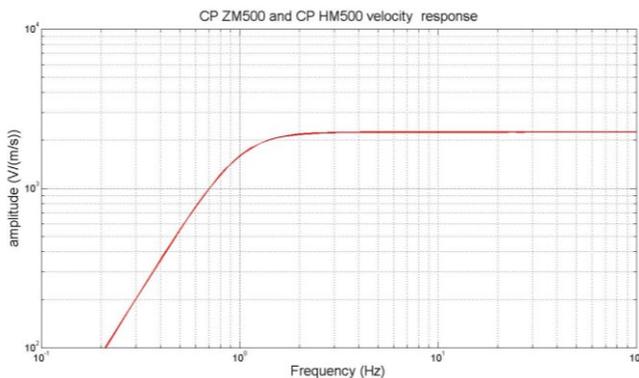Fig. 3 shows the nominal amplitude velocity response of a CP ZM 500 1 Hz sensor.

Fig. 3 CP ZM 500 nominal amplitude velocity response.

Fig. 4 CP ZM 500 vertical seismometer; cover removed

3. THE CALIBRATION SYSTEM

The calibration system is based on the renowned SPEKTRA CS18P VLF calibration system that uses the SPEKTRA SRS35 vibration controller with integrated signal conditioners and a Polytec CLV 2534 laser vibrometer with a VD-06 digital velocity decoder. The decoder output signal is grabbed via a digital S/PDIF interface by the CS18 software that uses sine approximation for the further data processing of the laser vibrometer signal as well as of the A/D-converted DUT signal.

For horizontal excitation shakers like the APS 129 shaker and the APS 600 shaker with an air bearing table that can carry up to 25 kg and more are already available on the market. For the vertical excitation these shakers are not sufficient since the payload table is mainly designed for horizontal excitation and cannot handle high overhang loads in the vertical excitation mode. Smaller long stroke air bearing shakers like the APS 113-AB are neither capable to support big sensor nor to suspend the high payloads in vertical excitation mode nor do they have enough force to excite the DUT in the higher frequency range above 100 Hz sufficiently. Thus a new shaker, the SPEKTRA SE-13 (Fig. 5), was designed for this purpose. It has a special pneumatic load suspension system that additionally acts as an air bearing.

Fig. 5 SE-13 shaker with CP ZM 500 DUT mounted on the table

The special design allows smooth motion of the DUT with low mechanical noise while it suspends payloads up to 50 kg. The stroke of the shaker is limited to 25 mm (peak-peak) although it is used at frequencies far below 1 Hz. DUT's described in section 2 are velocity sensors with a very high sensitivity. So they typically do not require much

stroke to achieve a sufficient output signal even at very low frequencies. As an example a geophysical sensor with a sensitivity of 10 000 V/m/s would only require a velocity of 1 mm/s to provide a 10 V signal output. But even at 0.1 Hz a velocity amplitude of 1 mm/s requires only 3 mm stroke (peak-peak). So as a compromise the stroke of the SE-13 shaker was limited to 25 mm (peak-peak) to simplify a stiff design of the shaker table for better performance in the frequency range above 100 Hz.

For the calibration of the sensors described in section 2.1 a rigid design of the shaker table is required in order to avoid resonances in the frequency range up to 400 Hz. Furthermore a sufficient force is required in this frequency range. For example the moving mass of the shaker table and a typical sensor according to DIN 45669-1 adds up easily to 15 kg. Thus for a velocity amplitude of 10 mm/s at 315 Hz a force of 300 N is needed to move this mass. So a design goal of the shaker was a rated force in the range of 500 N.

4. MEASUREMENT RESULTS

First measurements were performed with a SINUS 902219.7 sensor according to DIN 45669-1. The goal was to compare the performance of an APS 113-AB with the new SE-13. The APS 113-AB that is commonly used for vertical operation in a CS18P VLF calibration system has some known issues in the frequency range above 80 Hz. The small armature does not allow to mount big and heavy sensors easily. Furthermore heavy payloads can shift the natural frequencies of the shaker far below 315 Hz. Fig. 6 shows results of frequency sweeps using a PCB 3701G2FA3G as reference accelerometer. A green dotted line in the graph shows the ideal theoretical frequency response and the red dotted lines show the tolerance limits according to the DIN standard. The weak points of the APS shaker regarding this special task can be seen in the unsteady frequency response above 80 Hz that is mainly caused by mounting issues and resonances. Sweeps with the same DUT and reference accelerometer on the SE-13 show in contrast a smooth frequency response up to 350 Hz.
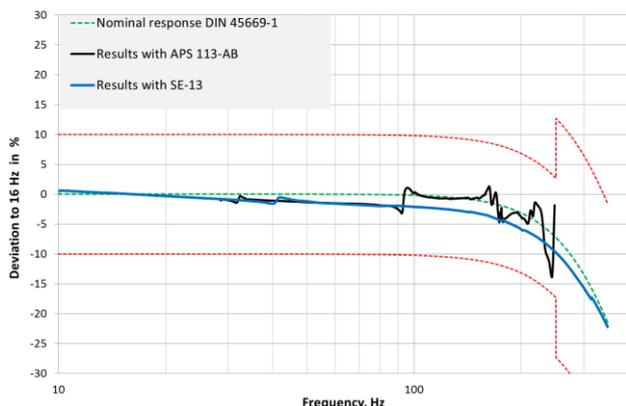

Fig. 6 Frequency Sweep with a DUT SINUS 902219.7 mounted on an APS 113-AB shaker and on a SE-13 shaker

Fig. 7 shows the results of a primary calibration of the same DUT according to ISO 16063-11. The results comply very well with former calibrations on other shakers in the SPEKTRA primary calibration laboratory. Although the

limited number of measurements do not allow final conclusions regarding the measurement uncertainty of a CS18P VLF calibration system with SE-13 shaker yet, the repeatable and stable results above 80 Hz indicate that the limits of the current system using an APS 113-AB shaker can be significantly expanded with the new shaker. It should be possible to expand the limits from 80 Hz (payload up to 3 kg) to 400 Hz (payload up to 5 kg).
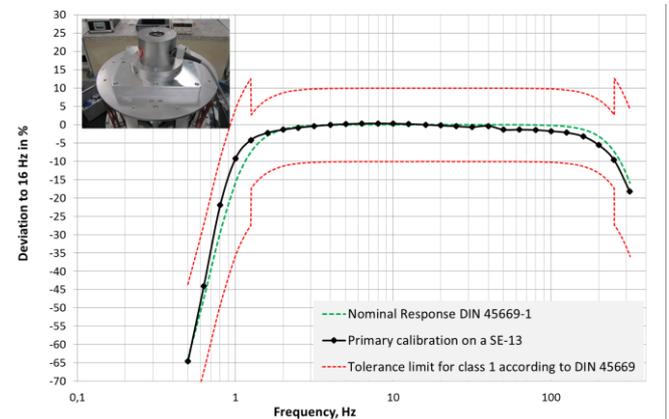

Fig. 7 Results of a calibration according to ISO 16063-11

An additional challenge the new shaker is designed for, is the calibration of even heavier and bigger DUT like the CP ZM 500 described in section 2.2. This class of DUT raises some more questions e.g. how such a DUT should be mounted on the shaker table for best calibration results up to 100 Hz.

Fig. 9 shows results of primary calibration runs where the DUT was mounted in four different ways on the SE-13 shaker. For each mounting option shown in Fig. 8 the reference laser vibrometer spot was positioned on the shaker table at four positions around to the DUT. The determined sensitivity is the average value from the four measurement spots.

Mounting variant A follows the idea that a calibration is a measurement under well-defined conditions. Thus the DUT was fixed with screws directly on the shaker table to allow no relative motion between shaker and DUT. Variant D reflects the typical operation situation in the field where the sensor is simply standing on his three adjustable feet on the ground. Variants B and C are mixtures between A and D where the DUT is standing on his feet (adjusted to different lengths) and is additionally clamped in order to minimize relative motion.
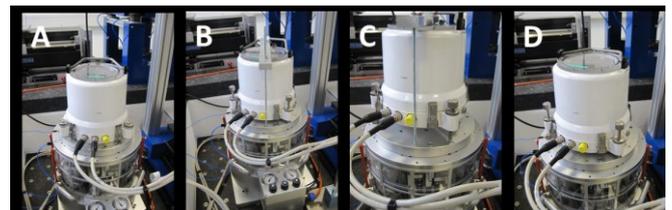

Fig. 8 Four mounting variants (details see text)

As could be expected the determined sensitivity is nearly independent from the DUT mounting in the low frequency range (see Fig. 9). The dotted black line shows the theoretical sensitivity determined from the design data of the

sensor (see also section 2.2). The measured sensitivity is slightly higher than the calculated but follows perfectly the expected frequency response down to 1 Hz. The sensitivity offset of this particular DUT (see also Fig. 10) can be easily explained by a gain setting of the internal amplifier that is slightly too high but still in the specified limits.
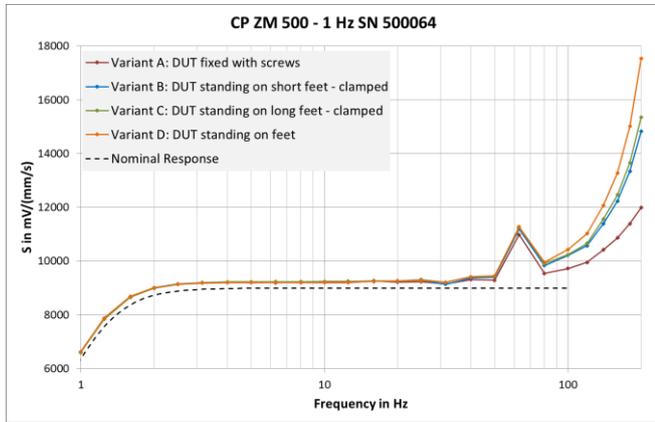

Fig. 9 Results of calibrations according to ISO 16063-11 of a CP ZM 500 sensor

The next obvious sensitive deviation in the higher frequency range is the peak around 60 Hz. This peak is not related to the mounting conditions and will be discussed later. However, the measurements show that at frequencies above 40 Hz sensor mounting becomes an issue. The best compliance with the theoretically expected sensitivity could be determined with the DUT bolted directly on the shaker table (variant A). On the other hand the highest deviations were observed with the DUT standing on his feet. Clamping the DUT (variant B and C) reduced these deviations only slightly.
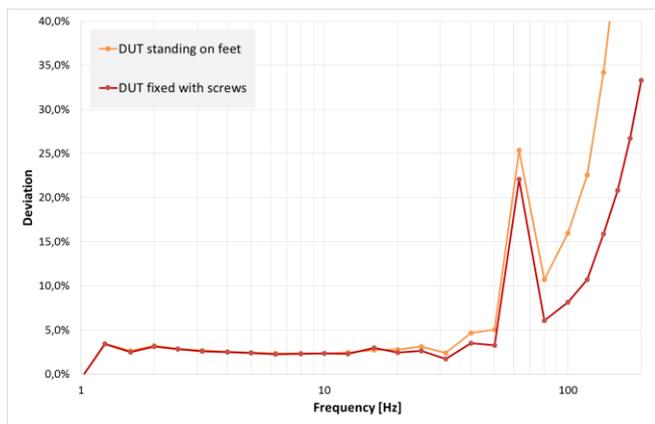

Fig. 10 Deviation of measured DUT sensitivity compared to calculated nominal sensitivity

The deviation at higher frequencies is obviously influenced by the different mounting variants of the DUT on the shaker table. This leads to the question how such sensors shall be calibrated, standing on their feet like in the standard operation use case or bolted on the shaker table? Both variants show a significant deviation compared to the nominal sensitivity at high frequencies. This indicates that the deviation is caused by the mechanical design of the DUT and its coupling to the ground (or the shaker table). Thus a

calibration setup comparable to the operation setup in the field may make more sense than the artificial sensor mounting with screws if the results from a primary calibration of the DUT shall be used by a measurement system.

As already mentioned above a peak in the sensitivity around 60 Hz was observed that could not be related to the mounting on the shaker. So further measurements were necessary to investigate the dynamics of the mounted DUT in depth. For this purpose the DUT was again bolted on the shaker table in order to allow no relative movement between DUT and shaker. But now the laser beam was positioned at different positions on or around the DUT (see Fig. 11) in order to get information about the dynamic behavior of the DUT or parts of it.
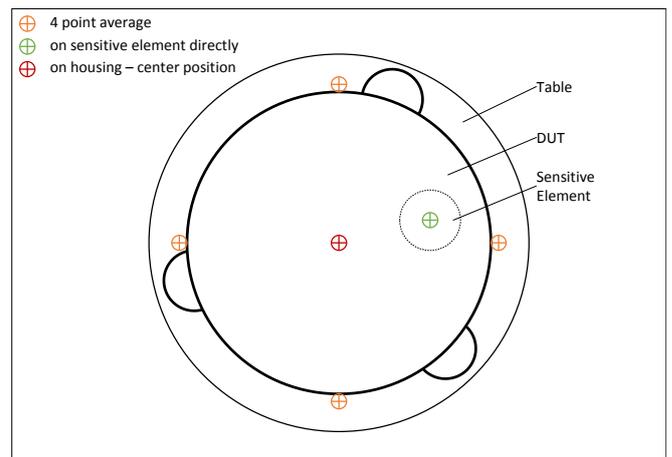

Fig. 11 Position of laser beam

The 'four-point average' measurement where the laser beam is positioned at four points around the DUT close to the housing was used as a reference measurement. So the laser measured directly the movement of the shaker table. For the next measurement the laser spot was positioned on the sensitive element inside the sensor housing. The CP ZM 500 allows to remove the housing of the sensor (see Fig. 4) giving access to the interior. For a third measurement the laser beam was positioned at the same position but now on top of the housing (reflection tape on top of the housing). For the fourth measurement the laser spot was positioned on top of the housing (again on a reflection tape) but now exactly in the center of the DUT. The results of these measurements are shown in Fig. 12.

It can be seen that the sensitivity peak around 60 Hz shows up independently from the measurement position of the laser. This indicates that the sensitive element of this particular device has an internal resonance that leads to the observed sensitivity peak. So the vibration calibration of the DUT reveals a mechanical issue of the DUT that could not be seen in earlier calibration runs by means of the electrical method described in section 2. Only the mechanical excitation can help to find such unwanted deviations.
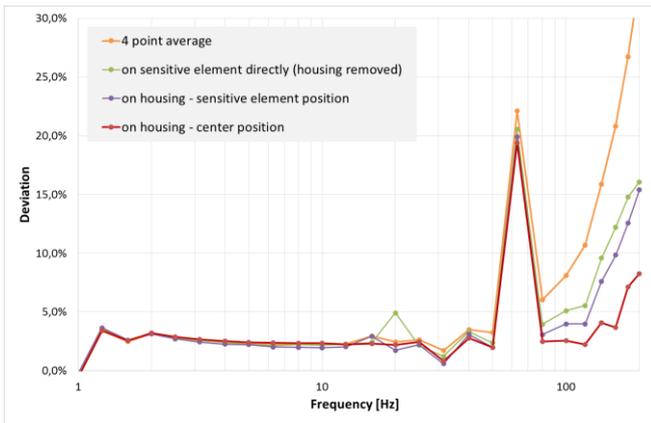
Fig. 12 Deviation of measured DUT sensitivity
compared to calculated nominal sensitivity
– position of the laser beam was varied

But the results also reveal another challenge regarding the calibration of such heavy devices that could not be seen in the first measurement series. Around 20 Hz both measurement setups that had the reference laser spot positioned at an off-centre position at the sensitive element of the DUT, show a sensitivity peak that cannot be seen in the 'four-point avarage' measurement. Since the peak of these measurements was shifted to a higher frequency when the housing of the DUT was removed and thus the weight was lower, it was assumed that these peaks are related to a cross resonance of the setup 'shaker with mounted CP ZM 500'. In fact additional measurements with a triaxial accelerometer confirmed that this assumption was correct. Because the CP ZM 500 cannot be mounted on the shaker in such a way that the centre of gravity matches with the centre of the shaker table (high off-centre load on the shaker table) and the sensor cables are very stiff, a cross-resonance of this setup cannot be avoided. The shaker handles this combination of a high payload and a high-off centre load very well except of this small cross resonance around 20 Hz. But this example shows that cross motion due to off-centre loads and cables cannot always be avoided for such heavy DUT. Thus the authors suggest to examine the cross motion of such calibration setups with very heavy sensors carefully before a calibration run will be started. With the 'four point average' measurement the impact of this cross motion is averaged out and thus this should be the preferred measurement method. But under very unfavourable conditions it may even be necessary to skip such cross-resonance frequencies in order to avoid an impact on the calibration results.

A third result of these additional measurements is that it is mandatory to position the laser beam on the shaker table and not on the housing of such a big DUT. At frequencies above 60 Hz the sensitivies measured in the different laser positions are very different. In this example the measurement with the laser in the centre on top of the housing shows the lowest deviation to the nominal sensitivity in this frequency range. But a comparison of the results from the different measurement positions shows that this is an accidental match. In fact a change in the laser position on the DUT housing can lead to completely different results at higher frequencies. Thus only the direct measurement of the movement of the shaker table can be a good reference and the 'four-point average' measurement reduces the impact of any cross-motion efficiently. Due to the big shaker table this measurement method is possible even for big DUT.

5. CONCLUSIONS

Large and heavy vibration transducers require a special shaker to allow accurate primary calibrations according to ISO 16063-11. The first measurements shown above indicate that the newly developed SE-13 shaker is capable to excite both broadband seismic transducers according to DIN 45669-1 up to 315 Hz as well as very heavy seismic transducers like the CP ZM 500 with a weight of 10 kg or more in a frequency range from 0.05 Hz to 100 Hz within the performance limits given by ISO 16063-11. Thus the design is an improvement compared to long stroke shakers that were commonly used for this task. These shakers were not capable to excite very heavy seismic transducers in vertical direction at all due to the high weight or could not provide a good performance at higher frequencies as required by some sensors for building sites for example. More measurements have to be performed in order to quantify the possible measurement uncertainty improvement of a primary vibration calibration system due to the new shaker.

However, the absolute calibration of seismic sensors with a weight of some 10 kg with vertical excitation that is now possible, raises some new questions. Regarding the mounting of the DUT on the shaker the calibration results with the DUT bolted on the shaker table may be closer to the theoretically expected sensitivity. But this does not reflect the 'real transfer function' between mechanical vibration input and sensor signal output. For the operation in the field such sensors are standing on their integrated feet and are not bolted on the ground. So this setup that reflects the application setup should also be preferred for the calibration. But on the other hand is a calibration of the transducer standing on spikes on the aluminum surface of a shaker table really closer to the real use case where the transducer may stand on a concrete base or on a rock at the measurement site? Further investigations are necessary in order to quantify also the impact of the material of the shaker table on the calibration results.

Finally an absolute calibration system according to ISO 16063-11 that can handle such transducers, also offers the possibility to improve the sensor design as well as to develop appropriate technical rules for the calibration of this class of transducers. It can reveal issues of such sensors that cannot be seen with the usual electrical calibration method.

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