# Calibration of Very Low Frequency Accelerometers – A Challenging Task

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**The calibration of accelerometers in the very low frequency range below 1 Hz is a special challenge. Since the maximum acceleration that can be provided by a vibration calibration exciter is limited by its maximum stroke, the acceleration and the electrical output of the accelerometer decreases rapidly with frequency (12 dB/ octave). Therefore, the lower the frequency, the larger the problems with noise generated by shaker bearings, electrical noise or ambient vibration coming from the laboratory floor. As a result, use of an excellent air-bearing, long-stroke vibration exciter mounted on a heavy rigid table that is well isolated from environmental vibration is mandatory. This article gives an overview of the requirements that a very low frequency calibration system has to meet to reach best measurement uncertainties.**

Many applications like the measurement of building vibrations, seismic activities, blasting and earthquakes, etc., require sensors able to measure acceleration or velocity in the extreme low-frequency range below 1 Hz. Such sensors are available in different sizes and using different sensor technologies. Small, lightweight accelerometers may have a weight of 10 grams and a size of 25 × 25 × 10 mm or less. The other extreme is seismic sensors that may have a weight in kilograms and a size of 120 × 120 × 80 mm or more. The various technologies used to build such sensors require different signal conditioners like constant-current or constant-voltage power supplies or charge amplifiers.

A calibration system for the very low requency range should be capable of handling these extreme requirements regarding weight and size of the device under test (DUT) as well as the different types of sensor signals. The vibration exciter should not only be able to bear a heavy payload such as the seismometer shown in Figure 1, but also should be able to move with low transverse motion (according to the limits defined in ISO 16063-21) if a heavy DUT is mounted. Furthermore, it must be possible to mount a sensor with a base diameter of 100 mm or more to the shaker armature.

## Very Low Frequency Means Very Low Acceleration

A special challenge in the very low frequency range is the low acceleration that is available even from long stroke exciters. This is due to the fact that every vibration exciter has a maximum stroke limit.

$$x(t) = x_0 \sin(\omega t) \quad (1)$$

$$v(t) = x_0 \omega \cos(\omega t) \quad (2)$$

$$a(t) = x_0 \omega^2 \sin(\omega t) \quad (3)$$

As shown in Equation 2, the relation between the velocity amplitude $v_0$ of a vibration exciter having a maximum stroke $x_0$ and the frequency $\omega$ is $v_0 \sim x_0\omega$. This means the maximum velocity amplitude decreases at 6 dB/octave if the vibration exciter is operated within its maximum stroke. For the acceleration amplitude $a_0$, the relationship is even worse, since it decreases proportionally to the square of the frequency or 12 dB/octave (see Figure 2). In other words, the maximum acceleration at 0.1 Hz is only 0.01% of the acceleration that can be provided at 10 Hz by a certain exciter.

To illustrate how dramatic this decrease is, let's take a look at a typical calibration exciter for the low-frequency range down to 1 Hz. Such exciters typically have a maximum stroke of about 10 mm peak to peak. So at 1 Hz, the maximum acceleration that can be provided by this shaker would be only 20 mg, which may hardly be sufficient to calibrate very sensitive sensors. But at 0.1 Hz, only 0.2 mg could be provided, which is almost nothing.

To overcome this "lack of acceleration" at very low frequencies, more stroke is needed. A long-stroke calibration shaker like the APS 113AB, which is usually used up to a stroke of 100 mm peak to peak for calibration purposes, can already provide a peak acceleration of 0.2 g at 1 Hz. But at 0.1 Hz, the peak acceleration is still only 0.002 g (2 mg). The acceleration amplitude scales linearly with stroke, but it scales quadratically with frequency. So to provide accelerations that are usually used in the medium frequency range, the maximum stroke of the vibration exciter would have to be in the range of meters. It is obvious that such vibration exciters would need very special mechanical solutions like an expensive linear motor drive that may also cause other mechanical problems. Such an exciter could not be practically used in a normal laboratory. So in practice, compromise solutions like long-stroke calibration exciters with 100-mm stroke are used to cope with low acceleration output.

*Figure1. Example of seismometer; weight 3 kg, diameter 120 mm.*

## Fighting Noise and Transverse Motion

As shown previously, even a special calibration exciter for use in the very low frequency range will provide only low acceleration at lowest frequencies. So any kind of mechanical noise coming from the guidance of the coil and armature or other parts of the exciter must be avoided to achieve the best signal-to-noise ratio of the mechanical signal (movement). Since the long stroke does not allow using spring guidance of the armature, one may consider using ball bearing guidance of the armature and coil instead. But ball bearings cause a lot of noise that can not only be heard but also measured with an acceleration sensor. In the direction reversal points of the movements, stick-slip effects cause a lot of distortion (see Figure 3).

Air bearings reduce this distortion significantly. The total harmonic distortion of an air bearing vibration exciter like the APS129 is in the range of less than 2% (THD at 1 Hz and 110 mm p-p). Another source of distortion can be the rubber bands commonly used to hold the armature of the vibration exciter in a definite position. Due to the long stroke in the low frequency range, such bands are extremely stretched and behave like nonlinear springs. The nonlinear behavior can cause a lot of harmonic distortion that may influence the measurement. This shortcoming can be avoided by using an electronic position controller that measures the current displacement of the armature by means of a position sensor and adds a DC voltage to the AC voltage from the vibration controller (see Figure 4). So the center position of the armature is controlled by the zero-position controller, and the characteristics of the controller can be programmed in such a way that it acts like a very soft rubber flexure to avoid additional harmonic distortion.

Another item that has to be carefully taken into account in the design of a vibration calibration exciter is transverse motion. In fact, transverse vibration is an unwanted but inevitable feature of all vibration exciters. It emerges from the fact that up to now, no one has succeeded yet in finding a design by which the movable armature of the vibration exciter is guided so that it can move only with one degree of freedom. As already noted, the long-stroke vibration calibration exciters used in the very low requency range must also be able to carry high payloads, since some seismic sensors can have a weight of a few kilograms.

Air bearings with tight gaps may be capable of carrying such loads if the vibration exciter is operated horizontally. With a heavy

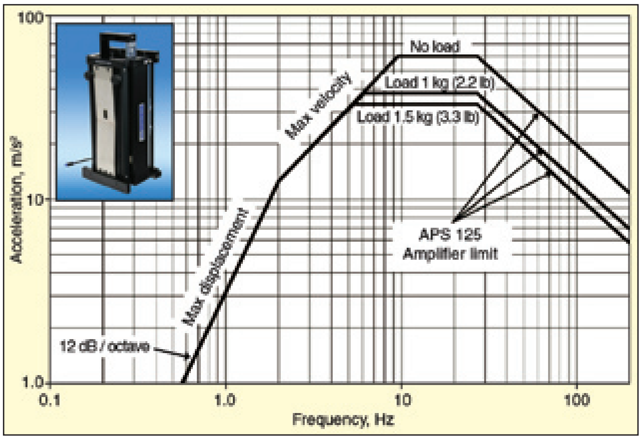


*Figure 2. Performance chart of a APS113 AB long-stroke calibration exciter showing 12-dB/octave decrease of maximum acceleration at low frequencies.*

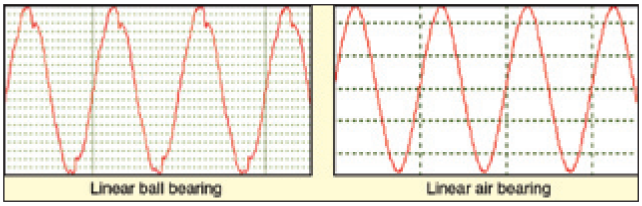


*Figure 3. Stick-slip effects from ball bearings at direction reversal points increases distortion and noise in the mechanical output of exciter.*

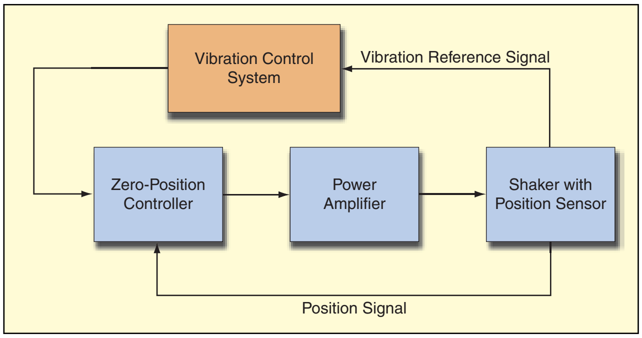


*Figure 4. Working principle of electronic zero-position controller.*

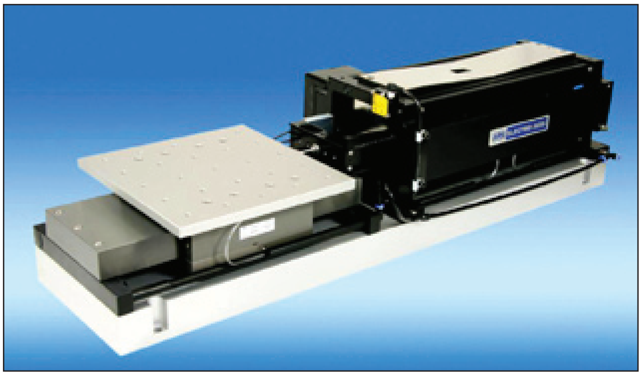

*Figure 5. APS129 – example of a calibration exciter capable of supporting heavy DUTs in a horizontal direction with low transverse motion.*

DUT mounted directly on the armature, the huge overhung load tends to make the exciter movement unstable and causes transverse motion. This transverse motion is not much of a problem at the lowest frequencies, but it is in a range above about 10 Hz, depending on the DUT mass.

To avoid too high a transverse motion, the maximum payload for calibration operation should be limited to a certain value. If operated vertically, the payload can be well centered on the armature, and the DUT applies a force in the direction of the armature movement rather than perpendicular to its movement. Therefore, the payload limit can be several times higher in vertical operation

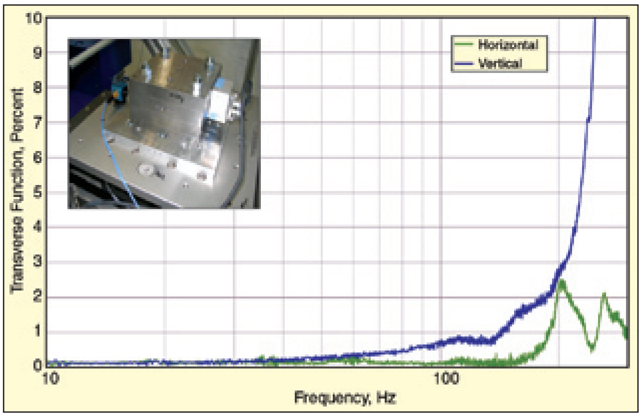


*Figure 6. Measured transverse motion of APS 129 vibration exciter with mounted dummy load.*

than it can be horizontally without the risk of a worse measurement uncertainty. For example the APS113AB integrated in a SPEKTRA CS18 VLF calibration system allows a three-times-higher payload in the vertical direction than operated horizontally if the required measurement uncertainty must be the same in both operation modes (900 grams in horizontal direction, 3 kg in vertical direction). A limitation of the upper calibration frequency (depending on the DUT mass) should also be taken into account.

Since some heavy triaxial seismic sensors require two-axis calibration in the horizontal direction perpendicular to the gravity field, vibration exciters for the calibration of such DUTs need additional characteristics. A possible solution is an additional payload table separated from the electrodynamic drive and guided by its own air bearing (see Figure 5). The payload table and drive are mounted on a heavy metal plate and can be adjusted very precisely in their relative position to reduce unwanted transverse motion. Since drive and payload table are mechanically coupled by a flexible stinger, transverse motion coming directly from the armature of the drive is efficiently suppressed (see example in Figure 6).

These results show that measured transverse motion stays below the limits allowed by standard ISO 16063-21 (< 6% up to 20 Hz and < 10 % up to 200 Hz). It can also be seen that vertical transverse motion is increasing more than horizontal transverse motion at higher frequencies due to the mass on top of the payload table (above the point where the drive force is applied to the table). Transverse motion is dependent on the mounted mass.

In the low-frequency range, the measurement ends at 10 Hz. This is due to the fact that the triaxial sensors commonly used for such measurements allow only a limited measurement uncertainty in the very-low-frequency range. So the maximum transverse motion at lower frequencies was estimated from the mechanical parameters of the air bearings. Knowing the maximum gap of the air bearings and assuming that the exciter will be operated properly without damaging the bearings, the maximum tilting movement of the payload table can be calculated from the geometry of the bearings. The maximum relative transverse motion can be calculated by setting this movement in relation to the linear motion of the table. Furthermore, it is assumed that the maximum transverse motion will appear if the exciter is operated at maximum stroke. Taking all that into account, the calculated maximum transverse motion possible in the very low frequency range can be achieved. As shown in Figure 7, it is far below the limits allowed by the ISO standard.

## Vibration Isolation

Another source of unwanted vibration and noise is the table on which the vibration exciter is mounted. Since the natural frequencies of common ceilings in buildings are usually in the range of 5-50 Hz, they overlap with part of the frequency range of a low-frequency vibration calibration system. So a setup of the calibration system on a concrete floor is recommended. Since the vibration exciter will be used to drive some kilograms of mass, from a theoretical point of view, it should be attached to a seismic mass. The weight of the block should be at least 2000 times the mass that is moved

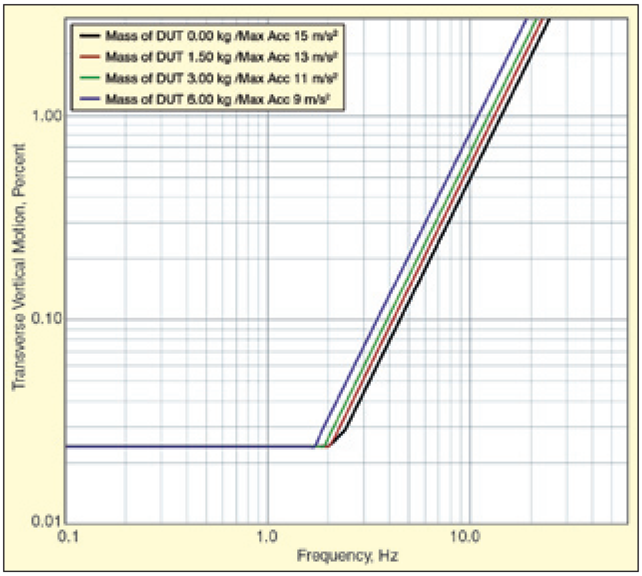


*Figure 7. Calculated maximum transverse motion in very low frequency range.*

in the calibration operation. If we assume that the armature and calibration object have a maximum total weight (mass) of 1 kg, the result would be a block weighting 2 tons. Experience shows that the mass should be set in the ground and completely decoupled from the building (see Figure 8). If this is not possible and the calibration system has to be set up on an upper floor, the vibration exciter should be mounted on a vibration-isolated seismic mass. This spring-mass system should be designed so that its natural frequency lies far enough below the lowest calibration frequency.

## Signal Processing

As shown previously, even a long-stroke vibration calibration exciter can only provide mg output in the very low frequency range at 0.2 Hz or less. So even a high sensitive reference accelerometer with a nominal sensitivity of 1000 mV/g will deliver an output signal in the µV region. An accurate measurement of such low and noisy signals is a challenge.

Normally, the complete amplifier chain is made up of a high-pass filter with selectable cut-off frequency, a low-noise amplifier, and a low-pass (anti-aliasing) filter with selectable cut-off frequency. Its overall characteristics depend on measurement frequency, selected gain, and selected cut-off frequencies. Since these characteristics can be determined by system setup, the influence of the amplifier chain can be easily corrected.

Using a high-pass filter at the beginning of the measurement chain has some pros and cons at very low frequencies. The advantage of such a filter is that trouble with a possible drift in DC offset (due to thermal effects) of a sensor can be avoided. On the other hand, the low input signal may be attenuated if the cut-off frequency is in the range of the lowest calibration frequencies.

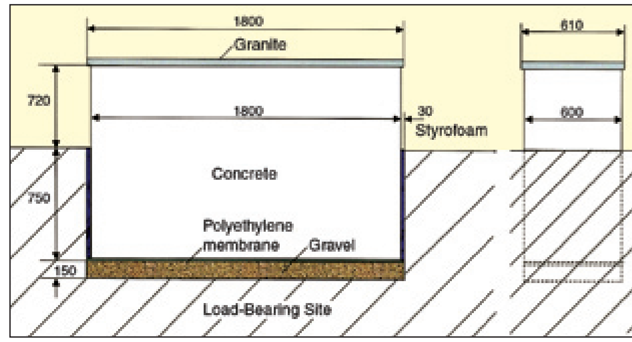


*Figure 8. Example of a seismic mass with flat granite slab on top; set up in a concrete floor and decoupled from building vibration (measurements in mm).*

After an analog to digital conversion of the input signal behind the amplifier filter chain, further digital signal processing is applied. If phase information can be disregarded, measurement data can be fed to a digital root-mean-square calculator (squaring, summation, and extraction of root). it may be supplemented by a digital narrow-band filter and a band-stop filter. If the phase difference is needed, the sample sequence must be processed using sine approximation according to ISO 16063-11. This allows very low signal voltages to be processed accurately with minimal measurement uncertainty.

## Operator Influence

Even the best-designed calibration system is operated by a human being who can make mistakes. In practice, it turns out that many bad calibration results are not caused by a failure of the calibration system but by operator error.

Cable routing is a source of many mistakes. Due to the long stroke of the vibration exciter in the very low frequency range, accurate routing is mandatory. Cables that are too short or thick or inflexible influence the movement of the shaker and measurement results significantly. Also, cables that are too long, hit the table surface, or routed so that they are sharply bent due to armature movement cause a lot of trouble.

## Conclusions

Accurate sensor calibration in the very low frequency range below 1 Hz is a challenge due to low available acceleration and necessary long stroke of the vibration exciters. Modern calibration systems are capable of providing excellent mechanical performance combined with precise electrical measurement of the sensor signals and subsequent digital signal processing. A secondary calibration system like the SPEKTRA CS18 VLF, specialized for operating in this frequency range, can perform calibrations at frequencies below 0.4 Hz with a measurement uncertainty of only 2.5%. Using this primary calibration system with a laser vibrometer as primary reference standard, the uncertainty decreases to 1%. SV

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