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LOW FREQUENCY PRIMARY VIBRATION CALIBRATION USING A MULTI-COMPONENT SHAKER

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Abstract:
The multi-component vibration calibration device at PTB consists of a triaxial shaker which is suitable and convenient for calibrating multi-axial seismometers. Three laser vibrometers are furthermore utilised as references. The frequency range was further extended for a European research project. Instead of a closed-loop control system limiting the vibration frequency down to 0.4 Hz, a signal generator is now used to provide the excitation voltage to the amplifier of the shaker in open-loop mode. This excites the shaker yielding vibrations with significantly lower frequencies. The first test measurements with a seismometer were carried out. The results demonstrate that a calibration down to 10 mHz is easily achievable.

Keywords: primary vibration calibration; seismometer; multi-component shaker; low frequency

1. INTRODUCTION

Low frequency sound and vibration phenomena have long been used as indicators of major natural activities, such as monitoring for earthquakes, tsunamis, and volcanic activity, as well as weather prediction, and climate change. But the frequency range most relevant in these applications is not yet covered by current measurement standards. The European research project Infra-AUV [1] aims to develop new primary calibration methods and establish the first primary measurement standards for sound in both air and under water. This project also addresses vibration in a lower frequency range (10 mHz – 20 Hz) than is currently possible. Such developments are needed for environmental measurements, but are not yet covered by global calibration capabilities within the framework of the CIPM-MRA. Secondary calibration methods for devices that can be transferred to the field will also be developed for the dissemination of traceability through specific methods for on-site calibrations.

The current international standard ISO 16063-11 describes the primary vibration calibration methods for accelerometers. The frequency range recommended in the standard ranges from 1 Hz to 10 kHz. In the research project, the methods of this standard will be applied to seismic sensors with an expanded frequency range towards much lower frequencies. The seismic sensor under calibration is located on a vibration exciter. The movement of the surface of the exciter is observed by an interferometer as the reference. Simultaneously, the seismometer also measures the movement. By comparing the measuring signal of the interferometer and the analogue voltage output of the sensor, the transfer function of the seismic sensor is then determined.

During the last several years, a multi-component shaker [2], [3] was used at PTB to excite the vibrations for the calibration of seismometers and accelerometers. Vibration frequencies down to 0.4 Hz were achievable with that device. Several improvements have been carried out on the existing calibration facility at PTB to expand the calibration range further below that limit to improve the calibration capabilities.

2. MEASUREMENT FACILITY

Multi-component calibration facility

Figure 1 depicts the primary calibration facility at PTB. The vibration exciter enables multi-component excitations with magnitudes of up to 50 mm. It consists of three shakers. One shaker vibrates in the X-direction, one in Y-direction, and the third one in the vertical Z-direction. The shakers are coupled with a hydraulic coupling element [4]. By setting the magnitude and phase of each shaker, the multi-component exciter is able to excite vibrations in an arbitrary spatial orientation. Using the multi-component shaker is convenient for the calibrations of multi-axial seismic sensors, as it enables the calibration in all three measuring directions without re-mounting or moving the sensor.

For each measuring axis, a laser vibrometer is utilised as a reference. Moreover, to reduce the disturbance on the measurement, the vibrometers are located on vibration isolation, and the multi-component shaker is on a foundation separated from other measuring devices.

For data acquisition (DAQ) and signal generation, we utilise a computer equipped with a compact National Instruments (NI) PXIe (PCIe eXtensions for Instrumentation) chassis [1] with analogue input and output modules, a counter module, as well as a synchronisation module. This provides all we need for measurement and data evaluation.

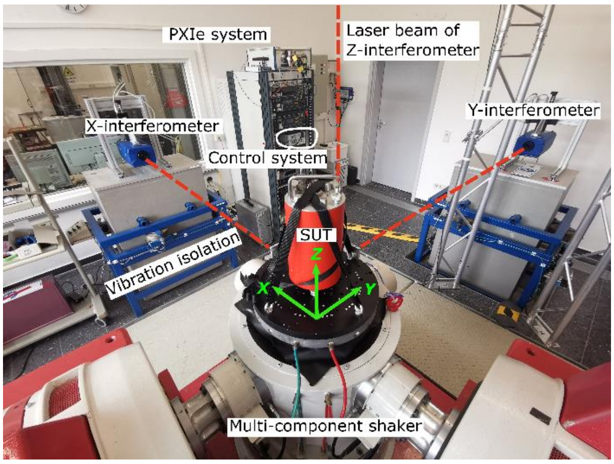

Figure 1: The multi-component vibration calibration facility at PTB with the measuring coordinate system in green, the reference vibrometer's laser beams illustrated in red, and the sensor under test (SUT).

Infrared laser vibrometer

Modernising the reference vibrometers now includes utilising infrared (IR) laser vibrometers with a laser wavelength of about 1550 nm as the reference for each measuring axis. These devices are used instead of helium-neon laser interferometers with a laser wavelength of about 633 nm. The control unit of the IR vibrometer is integrated into the measuring head, which makes it portable and very compact. Unlike a vibrometer with a helium-neon laser, the IR vibrometer is capable of measuring even on poorly reflective surfaces or on objects that are far away. This is due to a significantly higher output power and the higher photon efficiency of the laser diodes in the IR laser's wavelength. The vibrometers are customised to provide two modes of output signal: (1) a velocity-proportional voltage providing the means for a quick observation of the measuring signal, and (2) a frequency-modulated raw signal which is recorded by a counter for offline analysis. Using the heterodyne fringe counting method for data evaluation described in [5], velocity values traceable to the wavelength can be derived.

A calibration of the vibrometer (e.g. according to ISO 16063-41) is not necessary, as we use the phodiode output and process the data on our own.

However, unlike the helium-neon laser whose wavelength is already well known with documented stability [6], the wavelength of the laser modules typically used in IR vibrometers is tuneable. Such a wavelength therefore needs to be calibrated, and its stability must be monitored. The wavelength of the IR vibrometer is given as about 1550 nm according to the specification of the manufacturer. As the frequency can no longer be assumed to be within a certain range as with a helium-neon laser, the wavelength needs to be calibrated regularly instead. All three IR vibrometers are equipped with a fibre-optic output port to connect a wavelength meter for the calibrations. With these measures, traceability to the national standards for time and frequency can be achieved, and the calibrations carried out with the IR laser interferometers remain primary calibrations.

Generation of excitation voltage

Previously, a commercial closed-loop vibration controller was used in our calibration facility to generate and control the excitation voltage to the amplifier of the shaker. The simplified block diagram of the control process is described in Figure 2.

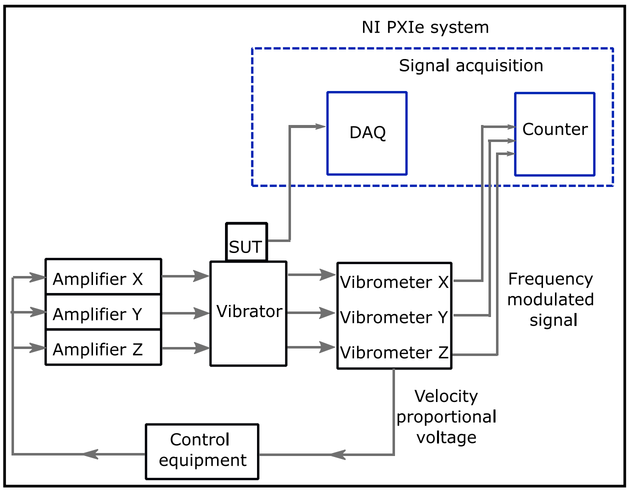

Figure 2: Block diagram of excitation voltage generation in closed-loop mode.

The output channels of the commercial vibration control equipment generate the excitation voltage and bring the vibrator into vibration. The three vibrometers observe the magnitude and phase of the vibration of each axis and then transfer the velocity-proportional voltage data back to the input channels of the vibration control equipment. The vibration control equipment is based on a PID closed-loop

[1] Commercial devices are identified in this paper only to adequately specify the experimental set-up. Such identification does not imply recommendation by PTB, nor does it imply that the equipment identified is necessarily the best available for the purpose.

controller. It continuously calculates the error value between the desired value and the measured value and then adjusts the control value over time. In this way, the output voltage values are adjusted according to the input voltage from the vibrometers, and this keeps the vibration at the desired level. After achieving the desired sinusoidal vibration, the output signal of the sensor under test (SUT) and the raw signal of the vibrometers are recorded by the PXIe data acquisition system. By comparing the measured signal of the SUT and the vibrometer, the transfer function of the seismic sensor can then be determined.

With the closed-loop control system, the sinusoidal vibration is controlled to be stable at the desired magnitude with a high accuracy. However, as the performance of a PID controller depends strongly on the time coefficients for integral and derivative terms, the vibration control in very low frequency ranges seems to be difficult. We ran several tests with the commercial vibration controller and due to the response of the control system, the lower frequency of the sinusoidal vibration has been limited to about 0.4 Hz.

Aiming to extend the frequency further to an even lower degree, the excitation voltage is now generated in an open-loop mode instead of the closed-loop for lower frequencies. As indicated in Figure 3, an analogue output module with 24-bit resolution is now utilised providing the excitation voltage for the power amplifier. Without being limited by the response of the control system, small sinusoidal excitations with 1 mm/s velocity amplitude were successfully generated and applied down to frequencies as low as 10 mHz.

The operation of the open-loop control is possible at these low frequencies, because there is no mechanical and electrical resonance present in the desired frequency range. This is different at higher frequencies which still require closed-loop control.

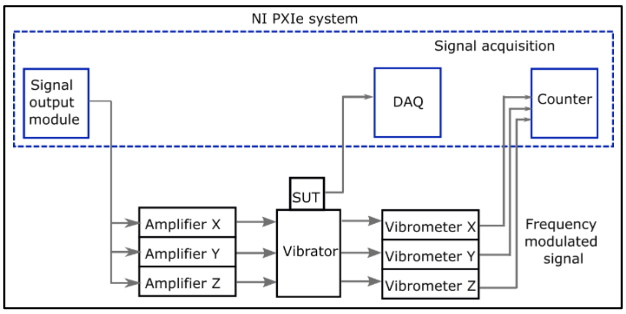

Figure 3: Block diagram for excitation voltage generation in the open-loop mode without the use of a control system.

The sensitivity of the excitation system, including the power amplifiers, significantly decreases at these very low frequencies. This needs to be considered when generating the excitation voltages.

Excitation with multiple frequencies

Another challenge of low frequency calibration is that carrying out measurements at lower vibration frequencies requires longer measuring times. During the calibration of a seismic sensor, a set of different frequencies are necessary, and for each frequency, the data recorded should span over several full periods. For low frequencies such as 10 mHz, one vibration period alone has a duration of 100 s. Therefore, a full calibration process can take several hours.

To become more efficient, vibrations with multiple frequencies are used instead of exciting one single frequency after another. This is realised by a superposition of several sinusoidal signals at discrete frequencies. To avoid exciting even or odd multiples of certain frequencies, which could also be caused by harmonic distortions, the vibration frequencies were selected based on primes which are deviant from the standard [7] for the first measurements. At a later date, calibrations with the usual frequencies according to ISO 266 will also be carried out. If harmonic distortions are generated by the exciter, these will cause no problems as they will be measured by both the sensor and the reference. However, if the SUT alone shows non-linearities, these will be impossible to detect. This means that such properties of the SUT need to be determined independently.

A test measurement with five discrete vibration frequencies of 10 mHz, 16.1 mHz, 25.7 mHz, 38.7 mHz, and 64.8 mHz was carried out on the multi-component shaker.

Figure 4 indicates that in 800 seconds, we can run eight periods of 10 mHz alone, but when we used vibrations with multiple frequencies, measurements with five different frequencies were completed in the same time duration.

3. MEASUREMENT RESULTS

After all these modifications, a primary calibration was tested on the vibration calibration facility. The SUT was a triaxial seismometer of the type of Trillium Compact. The first test was carried out in the frequency range from 10 mHz to 6.48 Hz. The magnitude response and phase response of the sensor as the measurement result are presented in Figure 5.

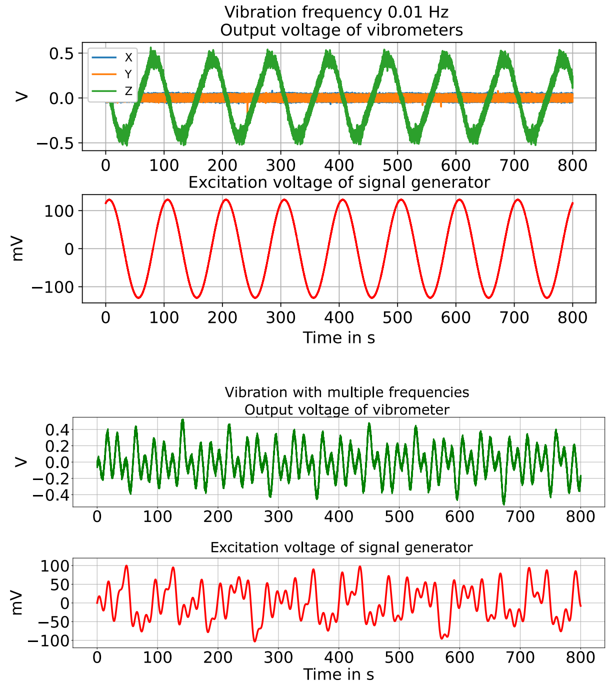

Figure 4: Sinusoidal vibration with 0.01 Hz (above); Vibration with multiple frequencies (below).

According to the characteristics of the seismometer given by the manufacturer, the bandpass bandwidth has its -3 dB points at 50 mHz and 108 Hz. The sensitivity of each axis should perform similarly [8]. However, in the first experiments, a deviation from the expected flat response in both horizontal axes (X and Y) was observed below 0.5 Hz. The deviation increased with decreased vibration frequencies. Similar deviations in low frequency accelerometer calibrations were also detected during previous measurements on a horizontal APS 129 shaker. It was proven that this deviation resulted from the curvature of the air-bearing guideway. This curvature led to a position-dependent inclination angle of the accelerometer. Under the combined effect of the inclination angle and the gravity, an acceleration component in the measuring direction was introduced. The acceleration component resulting from the inclination was detected by the seismic sensor but cannot be measured by the laser interferometer. The curvature influenced the measuring result of the horizonal measurements and led to incorrect results [9].

With a constant velocity value, vibrations with lower frequencies need a longer vibration displacement, where the inclination angle is also larger. This also explains why the deviation increases with decreased vibration frequencies.

The relation of the corrected sensitivity S_0 and the measured (uncorrected) sensitivity S' is dependent on the vibration frequency ω_{vib}, the local gravity g_{loc} and the inclination coefficient k_α as

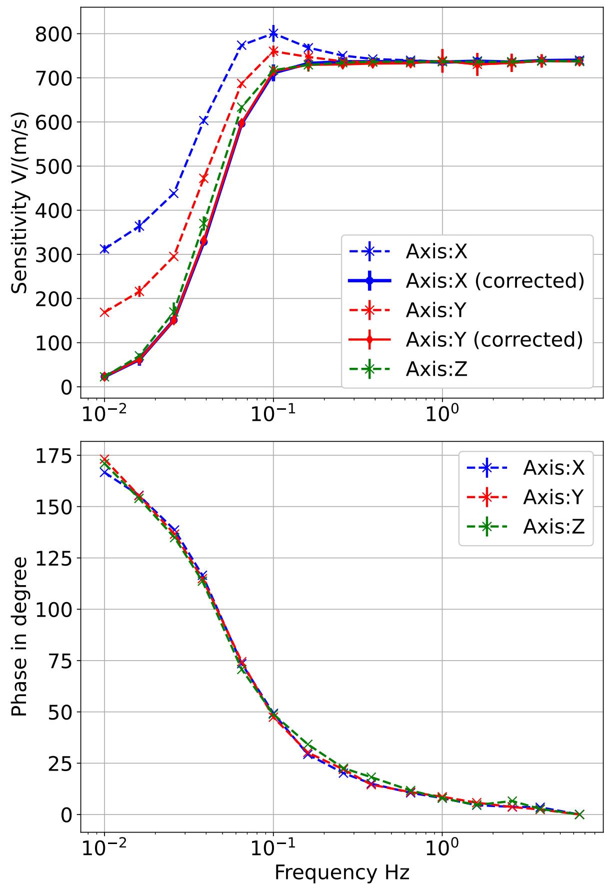

Figure 5: Calculated sensitivity of the seismic sensor using vibrations with multiple frequencies, magnitude response (above); phase response (below).

can be found from equation (8) in [9] as follows

$$S_0 = S' \cdot \frac{\omega_{\text{vib}}^2}{\omega_{\text{vib}}^2 + g_{\text{loc}} \cdot k_\alpha}. \quad (1)$$

Using the equation above, we ran a correction on the measured sensitivities of the X- and the Y- axis. In our calibration, the vertical Z-axis was free from the inclination effect and can be assumed to be the "expected response". The local gravity and vibration frequencies are, additionally, known values. By comparing the measured data of each horizontal axis with the vertical Z-axis, the curvature of each horizontal axis can then be determined. In our measurement, the inclination of the X-axis was found to be 0.005 rad/m, while being 0.0025 rad/m for the Y-axis. In Figure 5, the sensitivity of the X- and Y-axis after correction (blue and red solid lines) are also presented.

We can see that after applying the correction to the measured data, the deviations from the expected response below 0.5 Hz in both horizontal axes were reduced significantly. An autocollimator will be used for measuring the inclination angle in further investigations of the deviation resulting from the curvature of the air-bearing guiding system.

4. SUMMARY

This paper presents several improvements of the existing calibration device at PTB to extend the frequency range towards lower frequencies. The IR vibrometer shows good capability and stability during its application. Additionally, more investigations will be carried out on the IR vibrometers to determine their long-term stability. Instead of using a commercial vibration controller in a closed-loop operation mode, a 24-bit resolution analogue signal generator is now utilised for generating excitation voltage in an open-loop mode for lower frequencies. The excitation with frequencies down to 10 mHz is achievable in the open-loop mode. For a more efficient calibration process, the simultaneous excitation of multiple frequencies is introduced. Finally, test measurements were carried out with the calibration facility by exciting the vibrations with multiple frequencies. Deviations caused by curvature were observed in the measuring result, and after carrying out corrections, plausible calibration results have been presented. To further investigate the deviation resulting from the curvature, we also plan to measure the inclination angle using an autocollimator.

5. ACKNOWLEDGEMENT

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