Seismometer Calibration Using a Multi-Component Acceleration Exciter

Leonard Klaus, Michael Kobusch
Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
E-mail: leonard.klaus@ptb.de

Abstract. Seismometers are widely used all over the world, but rarely calibrated traceably. PTB analysed its capabilities for seismometer calibration and identified its multi-component acceleration exciter as suitable for carrying the comparably heavy seismometers. Additionally, multi-axial seismometers can be calibrated in all axes without moving the device. The calibration device needed to be analysed and tested for the required small excitation magnitudes and low excitation frequencies. The results show that it is capable of generating small sinusoidal excitation of less than 1 mm/s in a frequency range down to 0.4 Hz. For this purpose, the feedback control needed to be adapted. Additionally, a temperature control of the shaker armature prevents the problem of temperature increase due to hot hydraulic fluids near the armature.

The vibrations in all three translational degrees of freedom are measured by laser vibrometers and then processed according to ISO 16063-11 by sine fit procedures.

1. Introduction

Seismometers are used all over the world for the detection of seismic events or for the monitoring of nuclear explosions. Devices summed up under the term seismometer cover a wide range of excitation levels and spectral bandwidth. Typically, seismometers are very sensitive devices, that require only small excitation levels for their calibration. Up to now, no standardised calibration procedures exist and traceable calibration is rare. Often, internal checks or procedures are used to assure that the instrument is working as expected. These internal procedures do not replace traceable calibrations [1].

After requests, PTB analysed its capabilities for seismometer calibration. The best-suited solution among the available calibration set-ups was the multi-component acceleration exciter. This calibration device has the advantage over uni-axial solutions that three-axial seismometers could be calibrated without moving the device under test during calibration of the different axes. However, the multi-component calibration device was not intended for this purpose; therefore, its suitability needed to be analysed. The multi-component acceleration exciter [2], depicted in figure 1 consists of three orthogonally arranged electro-dynamic shakers coupled to a hydraulic bearing unit. The oscillations are controlled by a vibration control system, which uses accelerometers for the feedback control. The maximum force in each axis is about 10 kN, the maximum payload is 100 kg.
2. Limitations and improvements of the calibration set-up

For seismometer calibrations, several limitations of the original set-up needed to be overcome:

- The excitation levels were much higher than the required levels below 1 mm/s. It was unclear if the system is capable of generating the required small excitation levels with sufficient quality.
- The specified frequency range of 10 Hz to 1 kHz is too high for the calibration of seismometers, which require frequencies below 1 Hz.
- A vibration control would not be possible with the comparably insensitive installed accelerometers. Alternative options for the feedback control were needed.
- The moving armature is close to the hydraulic bearing unit. This leads to temperature increases of the armature (up to 50°C), which could also heat up the device under test undesirably.

The extension of the frequency and excitation range towards lower frequencies and smaller excitation magnitudes required a careful assessment of the exciter’s capabilities. The lower excitation frequency is limited by high-pass filters installed in the power amplifiers. It needed to be tested if the frequency range could be extended down to 1 Hz or even lower. This was not only a limitation of the filters, but of the control system as well. All tests – as well as calibration measurements – were carried out using monofrequent sinusoidal excitations.

In a first step, the existing laser vibrometers, which are usually only used for measurements, were utilised as the feedback for the control system. This approach was not tested before, because a reliable and robust control seemed to be questionable: The output of the vibrometers can be disturbed by speckle noise and if a laser beam is blocked, the output would be disrupted. However, tests showed that a robust vibration control was possible with additional safety measures to avoid the blocking of the laser beam.

For small magnitudes, the generated sinusoidal vibrations kept their quality, as shown in figure 2 for magnitudes of 0.7 m/s. The higher frequency components in the 10 Hz signal remain for higher excitation magnitudes and are caused by the bearing unit. They only appear at certain frequencies. The extension of the frequency range towards lower frequencies showed that an application down to 1 Hz is possible without problems (cf. figure 3). It was even feasible to generate frequencies down to 0.4 Hz with an increasingly unstable vibration control.

The temperature increase of the armature during operation was a well-known effect, which was already expected during the commissioning of the device. Therefore, an external cooling of the armature table was already designed and partly integrated into the exciter system. With
Figure 2. Sinusoidal vibrations generated by the multi-component acceleration exciter in vertical direction (z-axis) with a magnitude of 0.7 m/s at excitation frequencies of 100 Hz (left), 50 Hz (centre), and 10 Hz (right), measured by the laser vibrometer.

Figure 3. Low frequency excitation of the z-axis at 0.5 Hz (left), 1 Hz (centre), and 1.6 Hz (right).

these already existing parts, a control of the surface temperature was possible by means of water cooling and a recirculating cooler.

3. Traceability and data analysis
The generated vibrations in all of the three axes are measured by means of three laser Doppler vibrometers. To decouple the vibrometers from parasitic excitations, the exciter and the vibrometers are placed on different foundations (for the horizontal axes), and additionally, the vibrometers are placed on vibration isolation systems. The velocity proportional voltage outputs of the vibrometers are used for both – the calibration measurements and the feedback control. The vibrometers’ decoders are calibrated electrically by simulating the output signal of the photo diode and measuring the complex transfer function.

The electric output signals of the reference vibrometer and of the device under test are acquired by a modular data acquisition system made by National Instruments. This PXI system is equipped with a flexible resolution (18 bit to 24 bit, depending on the sampling rate) data acquisition card, which was analysed in terms of its suitability for metrological applications [3, 4]. The data acquisition card as well as the internal oscillators, which are responsible for timing and time resolution, are calibrated by means of a dynamic voltage standard and PTB’s distributed optical frequency. In addition, four input channels are provided by a 16 bit resolution data acquisition card.

The acquired time domain data of the input data channels is processed in a computer system.
The transformation into the frequency domain is carried out for each excitation frequency according to ISO 16063-11 [5] by means of a sine fit. Based on the magnitude and phase values of each channel, the complex transfer function of the device under test is derived.

4. Calibration experience
Our experience with different seismic sensors showed that the multi-component acceleration exciter is well suited for the purpose of seismometer calibration. All measurements were carried out with only a single axis excitation. For multi-component seismometers, the different axes were excited subsequently without moving or removing the device under test. We found that it might be difficult to adjust the coordinate system of multi-axial seismometers under test in order to coincide with the reference coordinate system. The seismometers are often lacking reference surfaces in their housings. These heavy seismometers usually do not need to be fixed to the surface of the armature, because the excitation levels are so low. However, for horizontal excitation it seems advantageous to place the seismometer on duct tape in order to prevent it from moving horizontally.

The right place for the reference measurement remains an open question. The vibrometer’s laser beams could be directed near to the devices under test on reference surfaces rigidly connected to the armature. Alternatively, probing the housing near to the sensing elements of the device under test is imaginable. In the authors’ opinion, a measurement on a reference surface best represents the actual measuring application – the sensing of environmental motion.

5. Summary and outlook
The analysis of the multi-component acceleration exciter proves that it is suitable for the calibration of seismometers. Compared to other systems developed specifically for the calibration of seismometers [6], some limitations remain. The lower frequency is limited to about 0.4 Hz and the excitation signals of uni-axial exciters might be less disturbed by parasitic disturbances. A significant advantage is the possibility of calibrating multi-axial sensors in all translational degrees of freedom without moving the device under test.

At present, a comparison between the Commissariat à l’énergie atomique et aux énergies alternatives (CEA), Spektra Schwingungstechnik GmbH, and PTB is carried out organised by the Laboratoire national de métrologie et d’essais (LNE) in which the calibration results derived with different shaker systems will be compared.

References
[1] Larssonier F et al. 2014 Seismometer Calibration: Comparison between a Relative Electrical Method and a Vibration Exciter Proc. of IMEKO TC3, TC5 and TC22 International Conferences (Cape Town, South Africa) URL http://www.imeko.org/publications/tc22-2014/IMEKO-TC22-2014-013.pdf
[2] Christof Weißenborn 1999 A New Calibration System for Simultaneous Multicomponent Calibration of Motion Transducers Sensor 99: Proceedings vol II (Nuremberg, Germany: AMA Service GmbH) pp 309–314
[3] Overney F et al. 2011 Characterization of Metrological Grade Analog-to-Digital Converters Using a Programmable Josephson Voltage Standard IEEE Trans. Instrum. Meas. 60 2172–2177 ISSN 0018-9456, 1557-9662 doi:10.1109/TIM.2011.2113950
[4] Rietveld G et al. 2011 Characterization of a Wideband Digitizer for Power Measurements up to 1 MHz IEEE Trans. Instrum. Meas. 60 2195–2201 ISSN 0018-9456, 1557-9662 doi:10.1109/TIM.2011.2117330
[5] ISO TC 108/SC 3/WG 6 1999 ISO 16063-11:1999, Methods for the Calibration of Vibration and Shock Transducers – Part 11: Primary Vibration Calibration by Laser Interferometry (Geneve, Switzerland: International Organization for Standardization (ISO))
[6] Martin Iwanczik et al. 2015 Primary Calibration of Geophysical and Seismic Velocity Sensors Proc. of XXI IMEKO World Congress (Prague, Czech Republic) URL http://www.imeko.org/publications/wc-2015/IMEKO-WC-2015-TC22-434.pdf