Dynamic calibration system for seismometers: Traceability from 0.03 Hz up to 30 Hz

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ABSTRACT

Mechanical calibration and traceability of seismometers in operating conditions are still a technical challenge, since very low-frequency ranges (below 0.1 Hz) are involved, and sensors under investigation are generally heavy and bulky. Recently, within the vibration metrology field, some pioneering works proposed to evaluate the seismometers' sensitivity by applying laboratory mechanical calibration procedures, against primary or secondary standards, according to the ISO 16063 methods. By following this path, at INRIM, it has been developed a suitable system for short period horizontal and vertical ground velocity calibration of 3-axis seismometers. The calibration system allows to directly evaluate the sensitivities of the 2 axes perpendicular to the gravity field, with respect to the horizontal ground velocity (S-waves), and to derive the sensitivity of the vertical axis, parallel to the gravity field, with respect to the vertical ground velocity (P-waves), in the frequency range between 0.03 Hz and 30 Hz.

1. Introduction

In the long tradition of modern instrumented seismology, starting from Robert Mallet's work "On the Dynamics of Earthquakes" in 1847 [1], the accurate quantification of the actual earthquake "magnitude", in terms of energy released, has always been (and it is) a challenging and debated topic. Earthquakes magnitude classifications are based on qualitative and quantitative observations: from Mercalli intensity scale in 1902 [2], Shindo seismic scale (1884), and Liedu scale (1980), based on observation of earthquake effects on people and environment, up to the measurements of earthquake's inherent forces, based on seismic magnitude scales, such as Richter magnitude scale M_L in 1935 [3], moment magnitude scale M_w currently used since 1979 [4], and the recent energy magnitude scale M_e in 1995 [5]. In very general terms, earthquakes occur when the seismic activity involves oscillatory phenomena ranging in frequency between 10^{-3} Hz and 10 Hz (by including surface traveling waves, P-waves, and S-waves, for $M_w > 2$), with amplitudes of ground displacement ranging between 10^{-9} m and 1 m [6]. Thus, the reliability and the accuracy of seismometers play a crucial role in the improvement of earthquake magnitude determination, and related geophysical and seismology models.

As recently proposed, dynamic calibration procedures [7–9] based on methods described in the ISO 16063-11 [10], allow to accurately quantify the actual sensitivity of the seismometers, with respect to traceable mechanical quantities, such as displacement or velocity, within well-defined confidence level, and associated uncertainties. Currently, seismometers are calibrated (or better "adjusted") by electrical methods in situ [11], but this is not sufficient to validate the seismometer responsiveness concerning mechanical excitations. Moreover, as recognized in the BIPM – CCAUV strategy document 2019 to 2029 [12], traceability and mutual recognition of measurement are fundamental requirements for ultra-low-frequency seismometers, used for ground motion velocity detection, in the frequency range from 20 Hz down to 0.02 Hz (even down to 0.008 Hz, for vibration transducers used for earthquake monitoring systems, such as the Global Seismographic Network).

Nevertheless, dynamic calibration of seismometers is mainly limited by several technical issues, such as large mass and volume of devices, thermal conditions, positioning effects, high sensitivity, and the broadband frequency response, particularly at very low-frequency ranges; moreover, usual test benches (conceived for traditional accelerometers calibration in the laboratory) are not suitable to operate in above-mentioned conditions [8], thus reliability of seismometers indications cannot be directly related to the mechanical quantities occurring in the seismic activities.

To fill these lacks, a preliminary inter-laboratory comparison of seismometers dynamic calibration, piloted by LNE with the participation of CEA, PTB, and SPEKTRA, according to ISO 16063-11 procedures, was promoted [9]. As a first result, once proper technical methods and suitable test benches (based on newly developed vertical and horizontal vibrating tables), have been identified and investigated, traceable and reproducible data have been achieved.

Starting from these evidences, at INRIM, a newly developed highly performant horizontal shaking table has been used as an excitation system, for frequency below 1 Hz down to 0.03 Hz; and a sliding table fixed to a vibrating horizontal table has been used for the frequency range from 0.5 Hz up to 30 Hz; as a standard reference for displacement and velocity a Laser-Doppler vibrometer traceable to the SI, is used. The calibration procedure allows to directly evaluate the sensitivities of the 2 axes perpendicular to the gravity field and to derive the sensitivity of the vertical axis, parallel to the gravity field.

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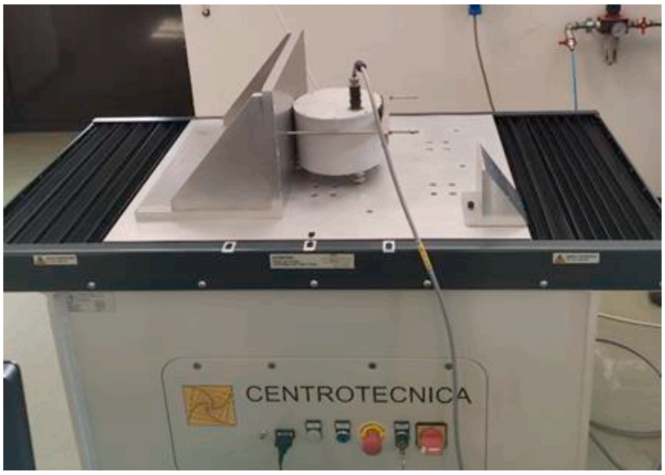

Fig. 1. Ultra-low frequency shaking table (Lo.F.Hi.S.).

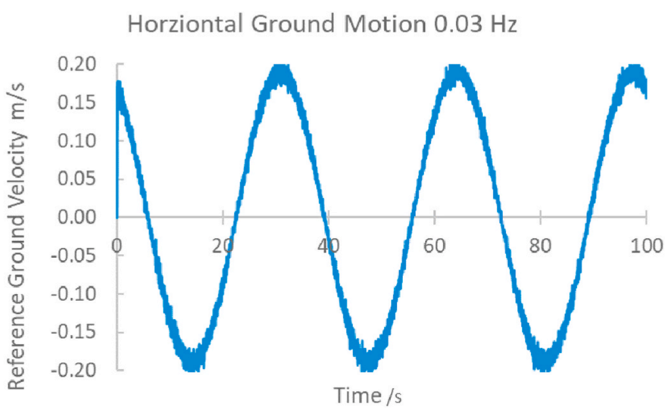

Fig. 2. Example of single frequency ground motion at 0.03 Hz.

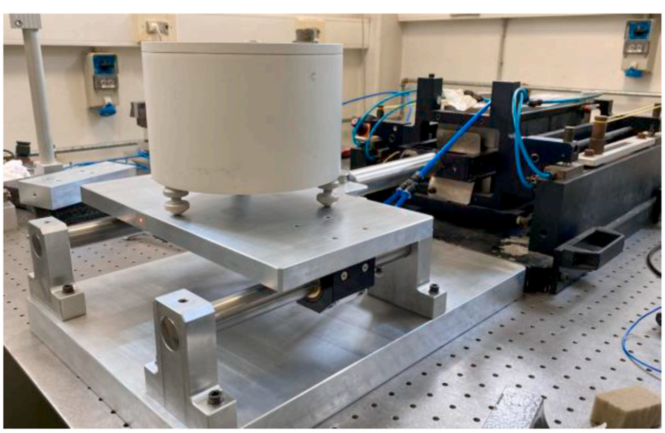

Fig. 3. Low/middle frequency vibrating table.

2. Dynamic calibration system

As stated in VIM [13], calibration is defined as the «operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties». The inherent sensitivity of the seismometer is achieved from the ratio between the electrical output signal of the seismometer, subjected to predefined ground motions, and the Laser-Doppler vibrometer primary standard reference signal. Since seismometers are sensitive to displacement/velocity amplitude of ground motions, starting from very low frequencies of oscillation, namely $\sim 10^{-3}$ Hz, the excitation system used in calibration must be able to reproduce similar motions. Moreover, the excitation system must generate high-quality ground motions, with negligible transversal motions and low background noise, and it must also be able to perform dynamic displacements by carrying on heavyweight (such as the large mass of sensors under test).

2.1. Ultra-low frequency shaking table

A specific shaking table has been designed and realized by CENTROTECNICA s.r.l., in Masate, Italy, for vibrations testing at very low frequency (nominally from 0 Hz up to 100 Hz), and it is addressed in particular for massive and bulky devices (up to 100 kg). The machine (Lo.F.Hi.S.) consists of an aluminum plate constrained to move only in the horizontal direction, up to the maximum velocity of 2.5 m/s, and maximum displacement of 258 mm. A dedicated software, developed to use the machine in displacement control mode, reads the positions from the machine in count units, 1 mm = 1000 count, reproducing the positions at intervals of 0.01 seconds. The table can be equipped with proper fixtures [14] for the correct positioning and fixing of devices on it, as shown in Fig. 1.

In operating conditions for ultra-low frequency calibration purposes, the shaking table has been characterized over a frequency range from 0.025 Hz to 2 Hz and a frequency-dependent amplitude range from 0.3 mm/s to 100 mm/s.

In Fig. 2 the graph of reproduced ground motion with a displacement of 2 mm (0.38 mm/s), at 0.03 Hz, is shown.

2.2. Low/middle frequency vibrating table

To cover a higher frequency range, namely up to 100 Hz, a suitable air-bearing table (conceived to carry on load up to 10 kg), driven by a single axis horizontal linear slide (APS ELECTRO-SEIS shaker), has been designed and realized. In Fig. 3 the test bench is shown.

2.3. Seismometer LE-3D/20s

The 3-axis seismometer investigated in this work (LE-3D/20s, produced by Lennartz electronic GmbH), is widely adopted for "classical" regional earthquake seismology, or grumblings of volcanoes, between short period and "real broadband", having a low-frequency response down to 20 seconds, and a nominal velocity sensitivity value of 1000 V/(m·s^{-1}). It is a very robust and practical device: it is not extremely sensitive to improper leveling and to temperature or pressure fluctuations [15]. The seismometer LE-3D/20s and its theoretical sensitive response, are shown in Fig. 4.

3. Calibration procedure

The calibration frequency range investigated is between 0.03 Hz and 1 Hz, by using the ultra-low frequency shaking table (Lo.F.Hi.S.), and from 1 Hz up to 30 Hz, by using the low/middle frequency vibrating table. In Table 1 frequencies and related amplitudes of the imposed

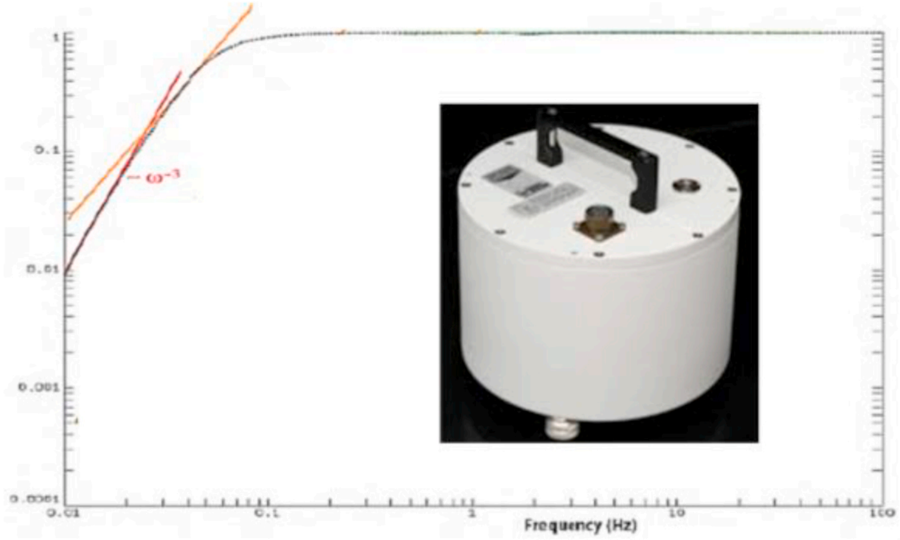

Fig. 4. Theoretical sensitive response of seismometer LE-3D/20s.

Table 1
Selected calibration conditions.

	Frequency/ Hz	Displacement /mm	Velocity /mm·s^{-1}	U /%
Ultra-low frequency shaking table	0.03	33	6.2	1
	0.05	20	6.3	1
	0.1	10	6.3	1
	0.2	5	6.3	1
	0.3	3.3	6.2	1
	0.5	2	6.3	1
	1	1	6.3	1
Low/middle frequency vibrating table	1	0.24–2.07	1.5–13	1
	3	0.06–0.65	1.2–12.3	1
	5	0.04–0.40	1.3–12.5	1
	10	0.02–0.05	1–3	1
	30	0.002–0.005	0.4–0.9	1

Table 2
Transverse motions.

	Frequency /Hz	Transverse motions/%		
		N-axis	E-axis	Z-axis
Ultra-low frequency shaking table	0.03	1.5	5.3	0.6
	0.05	1.1	1.5	0.6
	0.1	0.4	0.9	0.7
	0.2	0.3	0.1	0.6
	0.3	0.2	0.1	0.6
	0.5	0.2	0.1	0.6
	1	0.3	0.2	0.6
Low/mid. frequency vibrating table	1	0.3–1.2	0.9–1.0	0.2–0.7
	3	0.5–2.2	0.8–1.8	0.4–1.2
	5	0.7–5.5	1.0–3.3	0.7–2.7
	10	1.2–2.2	1.4–2.4	2.0–2.1
	30	15.6–91.8	3.0–7.8	18.9–93.8

Fig. 5. The seismometer on the inclined plane (2°±0.1°).

horizontal ground motions displacement and velocity, are shown. The expanded uncertainty U in percentage is related to the velocity.

As a first step, only the horizontal sensitive axes (labeled as N and E) of the seismometer are investigated. The alignment between the seismometer-sensitive axes and the reference acceleration laser beam is set through a laser tracker positioning system. The calibration is replicated by positioning the sensitive axes (N and E) at 0° and 180° with respect to reference acceleration (i.e., single horizontal axis calibration), and the occurring transverse motions on the perpendicular axes (E and Z-vertical) are monitored; hence calibration is performed at ± 45° and ± 135° (i.e., two horizontal axes simultaneous calibration), by monitoring the amplitude of occurring transverse motions on the vertical axis. As it is known, since it is not possible to rotate the seismometer to determine the sensitivity of the vertical axis, the calibration is carried out by positioning the seismometer on an inclined plate (with a tilt angle of 2°±0.1°), to derive the sensitivity of the vertical axis, as shown in Fig. 5.

It is expected that very small inclinations (at least less than 3°) do not seriously affect the functionality of the seismometer. With 2° of inclination, the velocity amplitude is weak, but not negligible along the vertical axis, being around 3.5% of the original velocity amplitude. The uncertainty due to the angle of rotation is considered within a tolerance

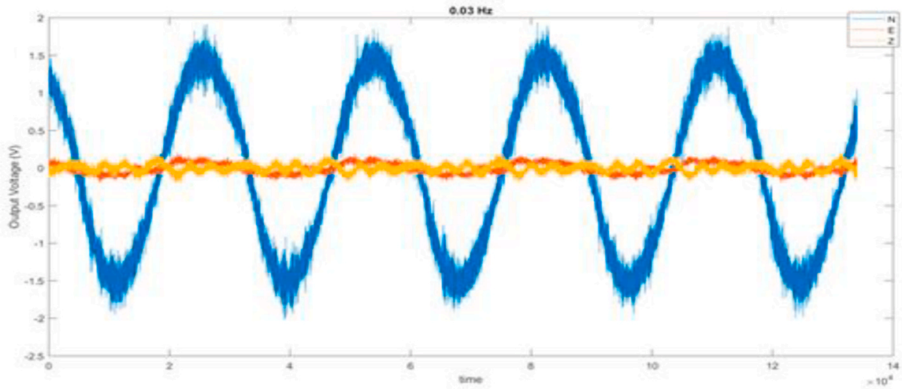

Fig. 6. The contributions of transverse motions.

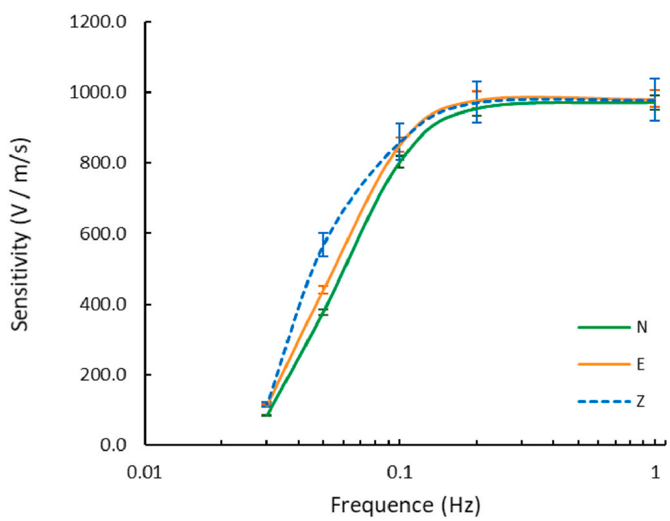

Fig. 7. Sensitivity of N-axis, E-axis, and derived Z-axis.

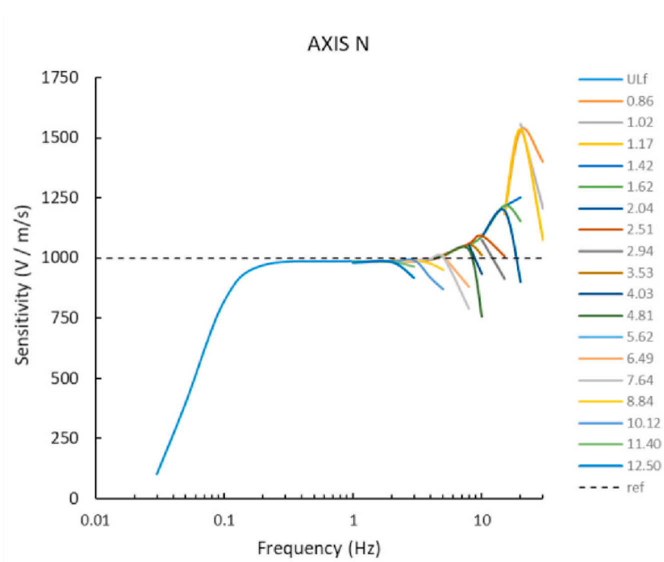

Fig. 8. Sensitivity of N-axis, from 0.03 Hz to 30 Hz.

of ±1°, and inclination within a tolerance of ±0.1°

4. Calibration results

Once verified both the background electric noise (in static conditions), and the amplitude of transversal motions for each sensitive axis as a function of frequency, with respect to the reference ground motion, the calibration is performed. The electrical noise is ~10 mV for the 3 sensitive axes. The contributions, in percentage, of transverse motions (determined along with perpendicular directions with respect to the reference ground motion), are shown in Table 2.

As observed from the experimental evidence, the contribution of transverse motions can seriously affect measurements above 10 Hz, thus it can be considered as the upper frequency limit of the seismometer effectiveness. In the frequency range below 10 Hz down to 0.03 Hz, transverse motions are on average below 1%, except few points. By way of example, the main contribution of transverse motions on E-axis (red curve) and Z-axis (yellow curve), with respect to N-axis (blue curve), observed at 0.03 Hz, is depicted in the graphs of Fig. 6.

The sensitivity is preliminarily determined for the two horizontal axes only, on the plane perpendicular to the gravitational field (with the vertical axis parallel to *g*), as previously described. Finally, the calibration is performed with the seismometer on the inclined plane (2°±0.1°). To assess the method suitability, several replications on 3 different inclined planes (with 1°, 2° and 3° of tilt angle) were previously performed. The main sensitivities *S* of the 3 axes, with respect to the reference velocity of the horizontal ground motion, is calculated according to geometrical laws, from the following relations:

$$\left\{ \begin{aligned} S_N &= \frac{V_{out,N}}{v_{ref}} \cdot \frac{1}{\cos\alpha\cos\omega} \\ S_E &= \frac{V_{out,E}}{v_{ref}} \cdot \frac{1}{\cos\alpha\sin\omega} \\ S_Z &= \frac{V_{out,Z}}{v_{ref}} \cdot \frac{1}{\sin\alpha} \end{aligned} \right. \tag{1}$$

where, V_{out} is the tension of the electrical output signal of the seismometer and v_{ref} is the reference velocity, measured using Laser-Doppler vibrometer (see Table 1); inclination angle is $\alpha = 2°$, and the rotation angle is $\omega = 45°$ (or reciprocals and/or opposites).

In the graph of Fig. 7, the sensitivity values of the N-axis (green curve), E-axis (yellow curve), and Z-axis (dotted blue curve), are depicted. Calibration results are in agreement with the expected theoretical sensitivity response (see Fig. 4).

On the contrary, experimental results from 1 Hz up to 30 Hz show an

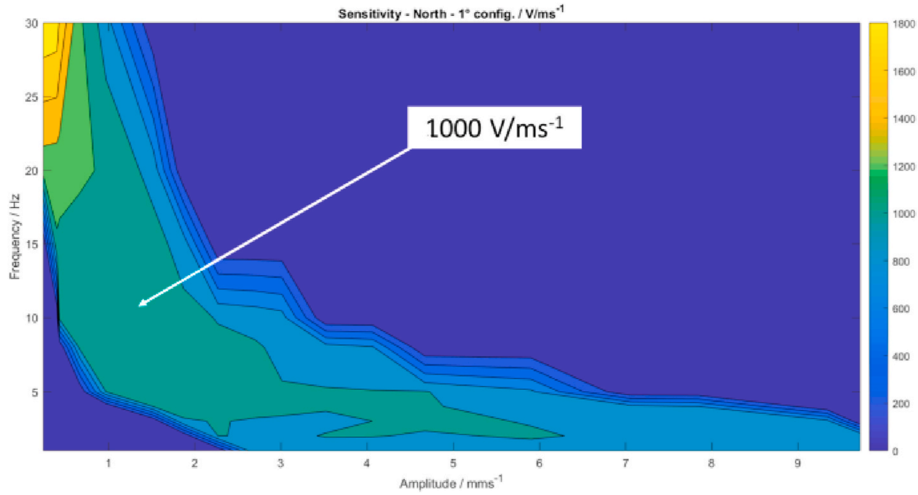

Fig. 9. Sensitivity of N-axis, from 1 Hz to 30 Hz, within the amplitude range from 0.1 mm/s to 10 mm/s.

"unclear" frequency-velocity dependence, as shown in the graph of Fig. 8, for N-axis. Similar responses are observed for both Z-axis and E-axis.

The variations of the seismometer sensitivity, can be represented as a function of frequency and velocity, as shown in the graph of Fig. 9. The following "map" allows to identify the actual sensitivity-dependence within the amplitude and frequency ranges investigated.

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