SEISMOMETERS CALIBRATION: COMPARISON BETWEEN A RELATIVE ELECTRICAL METHOD AND A VIBRATION EXCITER BASED ABSOLUTE METHOD

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Abstract :

Considering the vibration metrology field, seismometers calibration is a challenge because of low frequency, and the heavy mass of the sensors. The CEA designs short period horizontal and vertical ground velocity measurements single axis seismometers, uses, and maintains them in operational condition. Their response is calibrated with an electrical method during their operational life to ensure that they fulfil their technical requirements. Thanks to the PTB multi-component exciter we calibrated an horizontal and a vertical short-period seismometers as well as a STS-2 according to the ISO 16063 standard method. The author presents a comparison of the two methods and the associated results.

Keywords : seismometer, calibration, STS-2.

1. INTRODUCTION

1.1 The context

Thanks to its implication in several monitoring geophysical network and its participation to the CTBTO (Comprehensive Nuclear Test-Ban Treaty Organization), the DASE (Departement Analyse, Surveillance, Environnement) of the CEA (The French Atomic Energy Commission), uses and maintains in operational conditions many short-period and broad band seismometers. These instruments have to satisfy some technical requirements and performances associated with the users specifications. For instance, the CTBT specifies a tolerance of ± 5 % on the velocity sensitivity value and 5° on the phase. In order to verify or to adjust the sensors, a dedicated metrology laboratory is working in that field. Among the set of measurement operations, the parameters of the velocity transfer function are determined.

1.2 The CP seismometers description

The concerned seismometers are the vertical CP ZM500 [1] and the horizontal CP HM500 [2] seismometers. They are passive short-period velocity sensors designed by the CEA. They comprise a permanent magnet and a mobile rigid arm to which a weight of 700 g is attached. The measuring coil is located at the end of the arm. Considering the CP ZM500, this moving assembly is hinged on the base by quenched steel points resting on sapphires. For the CP HM500, the moving assembly is link to the base with a couple of crossed spring blades.

An integrated adjustable electronic low noise amplifier is used to obtain 4 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 weight is 11 kg for both seismometers.

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,

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

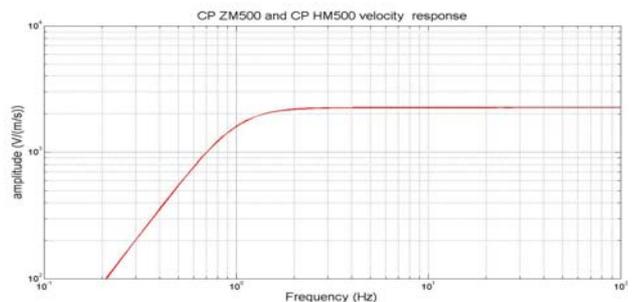The nominal amplitude velocity response on the Figure1 is shown

Figure 1. CP ZM500 and CP HM500 nominal amplitude velocity response.

Figure 2. CP ZM500 vertical and CP HM500 horizontal seismometers.

1.3 The STS-2 seismometer description

The STS-2 is a 13 kg velocity seismometer [3] developed by Streckeisen Company. It is a broad band sensor [240 s ; 16 Hz] with three reconstructed axis X,Y, Z. The transducers use capacitive plate sensors, with a seismic mass and a feedback control loop. The nominal velocity sensitivity value is 1500 V/ m·s⁻¹ at 1 Hz.

Figure 3. STS-2 seismometer.

1.4 The metrology challenge

We can summarize the calibration as an operation that establishes a relation between a reference quantity value provided by a measurement standard and the corresponding indication of a measuring result provided by the calibrated device itself. As the seismometers measures ground motions, the calibration standard should be a known ground motion and the result the seismometer electrical signal output. The application of that definition is difficult. Standard ground motion means to have high quality displacement mechanical systems with no parasitic motions (yaw, roll, pitch), low frequency control, accurate and traceable to SI displacement or velocity measurement sensors, and a stable metrological loop that guarantees the alignment between the reference sensor and the seismometer axis all over the translation. Combining all these requirements, we need an absolute calibration method. That method is available and well controlled for accelerometers, but difficult to transpose to seismometers like the CP and STS-2. Consequently, to by-pass this situation, the external forces and accelerations are transferred to internal electromechanical force generated in a calibration coil. Knowing the relation between the current in the coil and the equivalent ground acceleration, calibration becomes an electrical method [4].

Our seismic metrology activity is based on the electrical method and sensor comparison between a reference one and that to be verified. The seismometers measured at PTB are our laboratory references. The laboratory temperature is controlled at 23 °C ± 2 °C. The seismic noise was taken into account with an active isolation table under the seismometer and a mechanical support united with the basement of the building. To improve thermal stability for STS-2 we used a passive thermal enclosure.

2. ELECTRICAL CALIBRATION

2.1 The CP electrical circuits

The CP ZM and CP HM include the same two electrical circuits. One is dedicated to the ground motion measurement and the other one to calibration.
The electrical ground motion measurement circuit is composed of a transducer made of a permanent magnet and a 30 000 turns coil, in parallel with a set of adjustable resistances corresponding to the damping resistance. This circuit is directly connected to the non-inverting input of a preamplifier assuming to be totally resistive. The

calibration circuit is composed of a 200 turns coil, covered by the measurement coil and a set of resistances. The calibration coil is completely inserted in the magnet. The calibration circuit behaves like a current generator when a voltage is applied to its input.
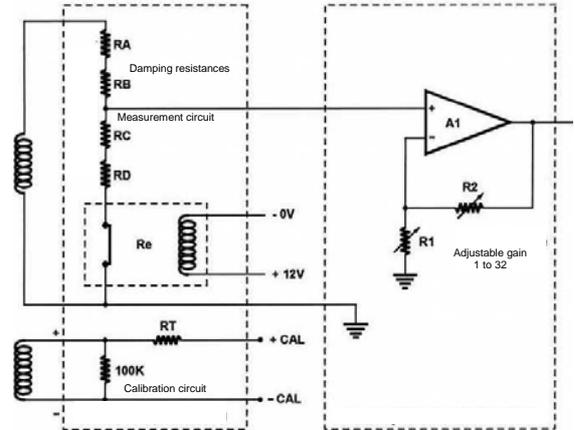

Figure 4. CP Electrical configuration.

2.2 The method

The same method is applied to the CP ZM, the CP HM and the STS-2 seismometers but the equipments are different.
The calibration is based on an acceleration excitation of the mobile part with an external electrical reference signal generated within the calibration circuit.

The CP ZM and CP HM excitation and measurement chain is composed of a 36570A Dynamic Signal Analyzer with a FFT mode analysis configuration in order to get the signal amplitude, phase, pole and zero. The external reference voltage is generated by the source output of the analyzer. The excitation signal waveform parameter is a periodic chirp. The seismometer output signal is sent to the input of the analyser.
The STS-2 excitation and measurement chain is composed of the identical digitizer and controller used in a vault for operational calibration.
When the seismometer is in a vault or cave installation on its base plate, a remote connection calibration is made possible thanks to a command and control system available on the digitizer associated with the seismometer. Such a digitizer integrates some calibration features like a 1 Hz sine wave and a MLS pseudo random signal for the whole bandwidth measurement.

2.3 The results

The CPZ and CPH sensors response on the [0.2 Hz; 100 Hz] bandwidth with the Signal Analyzer or the controller are identical and is presented in Fig. 5.
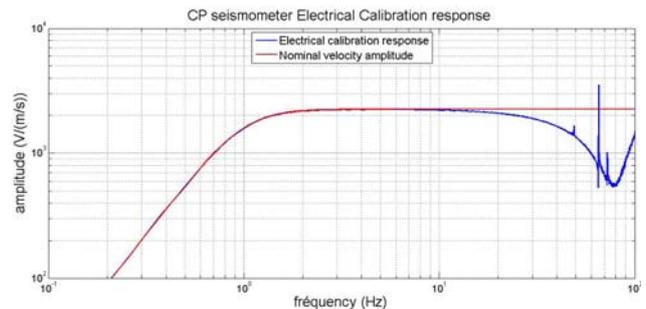

Figure 5. CP response with the electrical calibration method.

Between 0.2 Hz and 7 Hz, the measured velocity response agrees with the nominal value. The estimated expanded uncertainty of measurement is 1.8 %. At 10 Hz, the sensitivity deviation reaches 2 %. Above 10 Hz, the amplitude decreases strongly up to 80 Hz and then increases. The physical origin of this deviation has been investigated. The self-capacitance and coupling capacitance phenomenon of the solenoid coils are the main contributors [5][6]. In an ideal system with no capacitor coupling between the coils and in the coils the calibration coil produces a current, and the induced electromagnetic force moves the arms and the measuring coil which induced the output signal whatever the frequency. Here, the coils design induces at the same time a self-capacitance effect in each coil, and a coupling in the multi-layer turns inside the measuring coil and between the two superimposed coils.

The electrical circuit in Fig.4 was modelled with a capacitor located between the two solenoids. The resulting effect is lowering the high-pass corner frequency of the velocity sensitivity and increasing the damping as measured.

Considering the STS-2, the electrical calibration is based on a pseudo random MLS order 13 sequence. The velocity sensitivity measurement in the bandwidth [0.25 Hz; 100 Hz] is shown in Fig 6 with the nominal data sheet velocity sensitivity given by Streckeisen. The measurement result at 0.4 Hz is 1500 V/m·s^{-1}. The measured response and the nominal one have a good agreement up to 20 Hz.
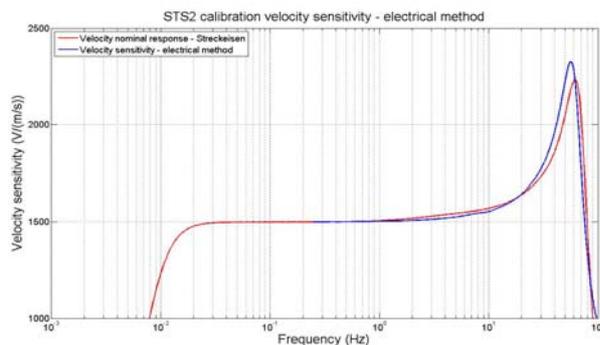

Figure 6. STS-2 response comparison with the electrical calibration method and the nominal response from Streckeisen.

3. MECHANICAL CALIBRATION

The mechanical calibration principle uses an exciter or shaker associated with a mobile table carrying the seismometer. A metrological loop including the reference sensor which measures the displacement or the velocity of the seismometer, and the adjustable supports to eliminate the alignment and the Abbe errors is associated with care to the mechanical vibration chain. No vibration, thermal drift, mechanical strain may disturb the metrological loop. Commercial exciter systems exist to carry load up to 11 kg or more in the horizontal direction, but none of them is able to carry such a load in the vertical direction. The maximum vertical payload is 8 kg with the APS600 [7] for example.

3.1 The PTB mechanical device

The mechanical calibration was carried out using the multi axis exciter available at the PTB [8]. This device offers a heavy load capacity, a frequency bandwidth capability down to 0.5 Hz, three orthogonal axis motions fully in accordance with our seismometers and an XYZ reference measuring coordinate system with three laser vibrometer sensors traceable to the SI.

3.2 The method

The CP horizontal and CP vertical axis of the seismometer was excited to rectilinear sinusoidal vibrations. The seismometer was put onto the vibration platform of the vibration exciter onto its three screwing legs to adjust its horizontal attitude. For the horizontal seismometer, the angular alignment of the instrument was made according to the orientation of the three axis of the multi-component vibration exciter.

For the vertical and the horizontal axis a non-contact reference measurement of the motion of the vibration platform through the seismometer hood was performed by a laser Doppler interferometer using its analog velocity output.

For the STS-2, after axis alignment and horizontal levelling, the three axis of the exciter allows a complete three axis calibration sequence without any action on the seismometer. The lower excitation frequency that can be achieved is 0.5 Hz.

The output voltage of the seismometer and the vibrometer were simultaneously sampled by a data acquisition board and the magnitude signal was evaluated using the sine approximation method.

The magnitude of the voltage sensitivity of the seismometer was calculated from the ratio of the magnitude of the output voltages of the seismometer and the velocity reference from the vibrometer.

The calibration method is in accordance with the respective standard *ISO 16063-21:2003* [9]. The velocity output of the applied vibrometers are traceable to the primary acceleration standards of PTB.

Figure 7. Short period CP ZM500 seismometer on the PTB vibration table.

Figure 8. Three axis STS-2 seismometer on the PTB vibration table.

3.3 Calibration results

The CPZM500 and CPHM500 calibrations were done at the following exciting frequencies 1 Hz, 2 Hz, 5 Hz, 10 Hz, 20 Hz, 50 Hz and 100 Hz. For both seismometer, the response is a flat-velocity beyond 2 Hz and starts to increase close to 100 Hz due to the mechanical resonance at 400 Hz. At 10 Hz, sensitivity value is 2277 V/m·s^{-1} and 2312 V/m·s^{-1} at 100 Hz.
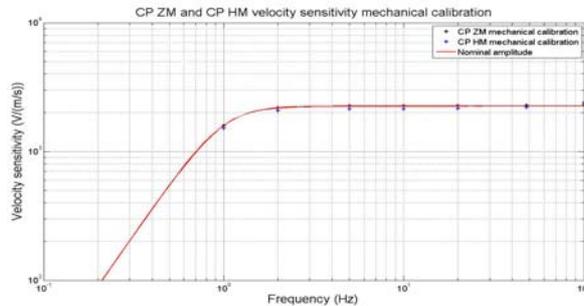
Figure 9. CPH and CPZ sensitivity calibration with the mechanical method and their nominal response.

The STS-2 was calibrated according to its three axis sensitivity Sx, Sy and Sz at 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, 10 Hz, 20 Hz. The Sz has a very low deviation with the nominal response given by Streckeisen. Sx and Sy have a maximum deviation value of 1.5 % with the nominal value at 0.5 Hz.
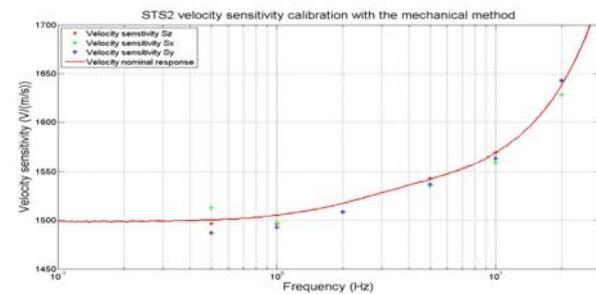

Figure 10. STS-2 three axis sensitivity calibration with the mechanical method and the nominal response by Streckeisen.

Whether it is for the CP or the STS-2, the relative measurement expanded uncertainty is estimated to be 1 %.

4. METHODS COMPARISON

The following graphs show the measurements of the CP ZM and the STS-2 velocity sensitivity with the two methods. For the CP ZM, up to 5 Hz, the two methods deviation was less than 2 % but increased for higher frequencies.
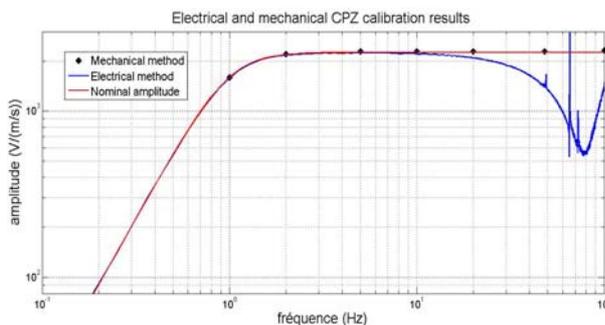

Figure 11. CP ZM sensitivity calibration: Electrical and mechanical methods

Considering the STS-2, the two methods gave very good agreement with a deviation less than 0.5 % except at 5 Hz and 10 Hz where the deviation was about 1.5 %.
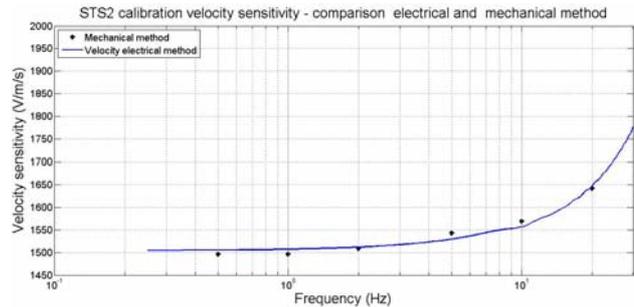

Figure 12. STS-2 Z axis sensitivity calibration: Electrical and mechanical methods

5. CONCLUSION

CEA calibrated some short period and broad band seismometers with two different methods. One uses an electrical excitation and the second one uses a mechanical vibration exciter. The electrical method introduces artefacts in the CP and the STS-2 sensitivity measurement at higher frequencies. The *ISO 16063-21* standard mechanical method and the PTB calibration device is perfectly adapted for large seismometers like CP and STS-2 for frequencies calibration from 0.5 Hz to 100 Hz. This method is to be considered as the reference method in laboratory, but cannot be transposed for the in situ applications where electrical calibration remains for low frequencies the best one for a relative follow-up. The calibrated sensors are from now used in our laboratory as reference sensors for relative signal comparison and coherent analysis between seismometers.

6. REFERENCES

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