Relative Calibration of Inertial Seismometers

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Abstract - This paper discusses technical problems of performing an accurate electrical sine-wave calibration of seismograph systems. This topic is well known in the seismic scientific community, however it has been presented to a lesser extent to engineering research and industrial circles. The purpose of the paper is to identify the unsolved technical questions related with calibration of seismograph systems. Finding exact solutions is beyond the purpose of this paper, considering the complexity of research and design work required.
Index Terms: Calibration, metrology and standards.

I.   Calibration Methods of Seismographs

Data collection from a large geographical area, namely from worldwide distributed seismographs, is a very actual scientific and technical challenge. The aim of scientists is to have a high station-density network, providing good geographical-resolution information. Data collected by a wide area data acquisition network is used to build an extensive database and processing the data to detect seismic motions, to accurately locate the source of the motion and to predict future changes of the monitored environment.

Wide area seismographic data acquisition systems (Figure 1) consist in measuring points (seismographic sensor and transducer, signal conditioner, D/A and A/D converters or digitizers, data communication device and power system), digital long-distance communication network (VSAT or Internet based communication) and data acquisition and processing centres. The confidence regarding the acquired data is basically determined by the first element of the above-mentioned information chain: the analogue signal based seismographs accuracy.
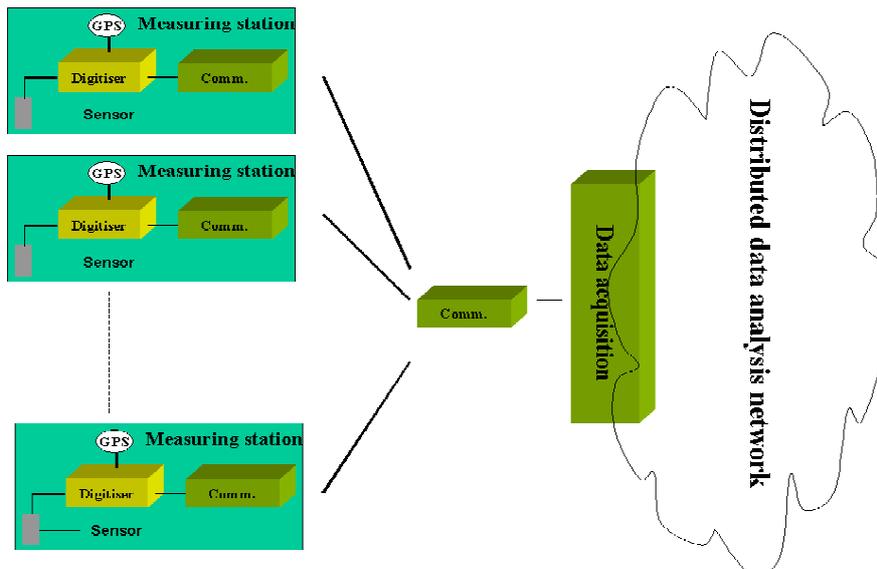

Fig. 1.   Block diagram of a seismograph network

Seismographs measure ground motion for determining important information such as earthquake epicentre, earthquake magnitude, for conducting refraction surveys, remote sensing of explosions, etc. Seismographs provide invaluable data for scientists in this field – from here the ever-increasing number of installed seismograph systems and networks. Seismographs include a seismic sensor and a recording device. There are two types of seismic sensors: inertial seismometers and strainmeters. Inertial seismometers measure ground motion relative to an inertial reference (a suspended mass), while strainmeters or extensometers measure the motion of one point of the ground relative to another. The seismometer is a mechanical-electrical transducer modelled as a mass-and-spring mechanical pendulum and a coil. The current or voltage variation in the coil is linear to the angular acceleration of the mass relative to the coil.

The output of the seismograph must be linear to the measured parameter in the operating frequency band. The linearity is represented by the transfer function of the seismograph. As with any transducer an exact determination of the transfer function is crucial for the precise analysis of measured data. The transfer function can either be derived from precise measurement of parameters of physical components of the system or from mechanical or electrical calibration experiments. The calibration of a seismograph system consists of determining the relationship of the output of the system with the input, when the input is known. The input of the seismograph system is known when the inertial mass is moved with a known force.

In design or manufacturing environment usually both methods can be used. Methods used for determining the transfer function of the seismometer in laboratory environment include:

1. **Mechanical calibration** using a shaking table, when the seismometer is placed on a high-precision mechanical shaking table simulating ground motion. The system input in this case is considered to be the simulated ground motion produced by the shaking table while the output is the recorded electrical signal produced by the seismometer.

2. **Electrical calibration**, when an analogue electrical signal is input in the calibration coil of the seismometer and the generated output is recorded. The input calibration signals could be pulses, step functions, random binary signals, white noise and sine-waves of different frequencies. The seismometer response is calculated using different methods depending on the type of the calibration signal. During electrical calibration the ground motion is simulated with an electromagnetic force generated in a calibration coil applied to the mass of the seismometer. Figure 1 presents the block diagram of electrical calibration of the seismometer.
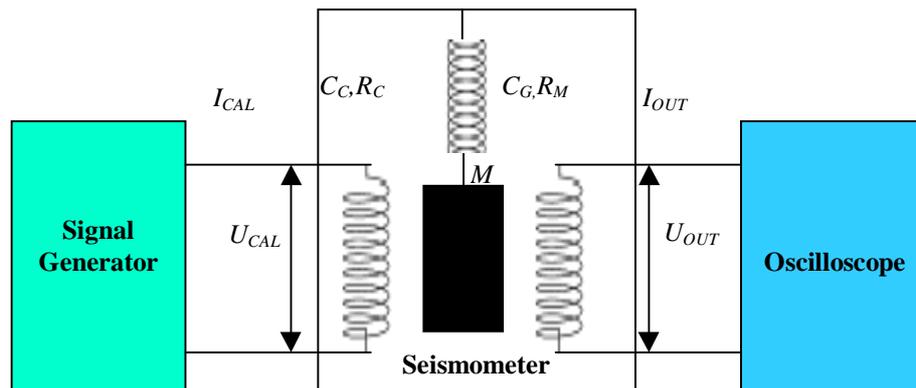

Fig. 2.   Block diagram of electrical calibration of seismometers

Seismographs (systems composed of seismometer, digitiser and acquisition software) require periodic calibration following their field-installation (on ground surface, in borehole or bottom of the ocean) without disconnecting components of the system. The only feasible method for determining the system's transfer function following the installation is electrical calibration. This paper discusses questions regarding the electrical sine-wave calibration of inertial seismometers.

II. Sine-wave Calibration of Seismographs

The most common calibration method used after the installation on the field is sine-wave calibration. The sine-wave calibration is an electrical calibration when a precise sine-wave with known frequency and amplitude is input in the calibration coil of the seismometer. The advantages associated with sine-wave calibration include simplicity and efficiency. A calibration with sine-waves therefore permits an immediate check of the system transfer function, without any mathematical modelling.

Most digitizers (data acquisition blocks) used in the field of seismic instrumentation can generate calibration sine-wave, therefore, no additional equipment required for performing sine-wave calibration. In sine-wave calibration no pre-processing or post-processing of the input and output signals are required. The response of the seismometer and the generator constant of the main coil are calculated by comparing the output electrical signal of the seismometer (in frequency and amplitude) to the current fed to the calibration coil.
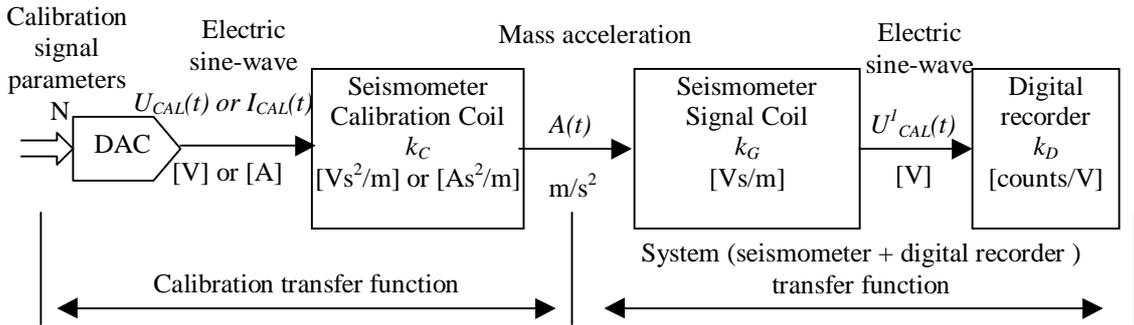

Fig. 3.   Stages of calibration

As shown on Figure 3., for calculating the system transfer function, the following parameters should be taken in consideration:

    a.   The amplitude of the calibration signal:
            Voltage, when the calibration signal is generated by a voltage source $\{U_{CAL}(t) \text{ [V]}\}$
            Current, when the calibration signal is generated by a current source $\{I_{CAL}(t) \text{ [A]}\}$
    b.   The total input impedance of the calibration circuit seen by the digital-to-analog converter generating the calibration signal – if the calibration signal is generated by a voltage source. $\{R_C \text{ [Ohms]}\}$, as the reactive component of the impedance can be neglected at the very low operation frequencies of the seismometers;
    c.   Factor of proportionality between the current in the calibration coil and the generated equivalent ground acceleration of the mass – known as the calibration coil motor constant k_C and usually expressed in $[\text{As}^2/\text{m}]$.

Relation between the calibration current and the acceleration of the mass caused the electromagnetic field generated by this current:

$$A(t) = I_{CAL}(t) / k_C .$$

(1)

If a voltage source is used this formula becomes:

$$A(t) = U_{CAL}(t) / (k_C R_C).$$

(2)

The signal coil generator constant (seismometer's sensitivity) k_G [Vs/m] can be calculated from the relation between the acceleration of the mass caused by the electromagnetic field generated by the input current of the calibration coil and the seismometer output voltage:

$$k_G = U_{OUT}(t) / \int A(t) \, dt$$

(3)

The integrator is included in the feedback circuit of the seismometer in order for the output voltage to be proportional with the ground velocity. By repeating the above procedure for a number of different frequencies in the pass-band of the system (e.g.: 0.001 – 50 Hz) and for a few frequencies outside of the pass-band for determining the 3dB-points and the cut-off region, the transfer function of the seismometer-digitizer system can be plotted and stored. The larger the number of frequency points the higher the accuracy of the derived amplitude response curve. The system sensitivity and the transfer function are then compared to those calculated from factory or theoretical values and the differences are taken in consideration during analysis of real ground motion (seismic data).

III. The Accuracy of the Calibration

The calibration accuracy is characterized by the error between the transfer function obtained with calibration and the actual transfer function of the system. The accuracy of a calibration operation depends, typically, on the following factors:
- The accuracy of the calibration signal generator (I_{CAL} or U_{CAL});
- The accuracy of the calibration coil motor constant (k_C);
- The accuracy of the calibration circuit.

A. Accuracy of the calibration signal generator

The calibration signal generator consists of all digital and analog circuits that transform the parameters included in the calibration command issued from the user interface of the system into the actual electric sine-wave signal, with user-specified amplitude and frequency. As mentioned above most digitizers used in seismic instrumentation have an integrated calibration signal generator consisting of a digital to analog converter and auxiliary circuitry. The parameters of the calibration signal generator integrated in the digitizer can be measured with good accuracy in the factory. It is usually documented on the unit test sheet and does not change considerably during years of operation.

B. Accuracy of the calibration coil motor constant

The sensor calibration circuit consists, typically, of a coil with an input impedance or coil resistance, R_C, and a calibration constant, k_C. As mentioned above the motor constant of the seismometer's calibration coil quantifies its capability of moving the mass with a desired acceleration when a specified current is flowing through the coil. The calibration coil motor constant is given in [As^2/m] and represents the ratio between the calibration current and the acceleration of the mass under the electromagnetic force generated by the coil when the calibration current is applied to it. The coil also has an inductance (L_C), but this is negligible at typical pass-band frequencies (0.001–50 Hz) of seismographs. As with the calibration signal generator, the parameters of the calibration coil are measured with good accuracy in the factory and are recorded on the calibration sheets accompanying the unit. However, the calibration coil motor constant is believed to change over years of operation due to aging of material, temperature changes, improper transportation, etc. Then this factor is a real error source and must be managed by multi-annual re-calibration in special laboratories.

C. Accuracy of the calibration circuit

The calibration circuit consists of all elements and connections between the calibration signal output of the digitizer and the calibration coil of the seismometer. While the parameters of the calibration signal generator and the calibration coil can be determined in the factory, the quality of the digitizer-seismometer connection depends on the quality of workmanship during the field installation. Poor cable quality ("noisy" connections, cold solder joints, poor shielding, etc.) can considerably affect the accuracy of the calibration signal fed into the calibration coil. In case of borehole seismometers, for instance, the analog cable between the seismometer and the digitizer can have lengths of over 50 meters. It is important, therefore, to determine the effect of the calibration circuit on the accuracy of the calibration signal following field-installation.

IV. Method of Increasing the Accuracy of the Calibration Process

A method of determining the accuracy of the calibration signal consists in digitizing the calibration signal before is fed to the calibration coil. This method is known in the field of seismic instrumentation as "digitizer relative calibration" and requires the use of a loop-back circuit. The calibrator is first

looped back to the digitizer channel and the digitized calibration signal is recorded in the system. The calibrator is then connected to the calibration coil of the seismometer and the generated seismometer output signal is digitized by the same digitizer channel. Finally the seismometer generator constant is calculated from the amplitudes of the recorded signals.

The closer is the loop-back circuit installed to the calibration coil the better the accuracy of the measurement. The authors of this paper propose to install the loop-back circuit inside the seismometer, thus allowing for performing digitizer relative calibration remotely, after the installation on the field of the seismometer, without the need of additional equipment and without disconnecting cables.
The loop-back circuit is shown on figure 4. The R_{LB} resistor is inserted in the loop-back circuit to limit the calibration signal, input as single-ended signal in the digitizer channel. The inserted resistor and the input resistance of the digitizer channel will form a voltage divider with gain G. The gain of this voltage divider should be selected to limit the input signal below a level saturating the common mode rejection circuit of the digitizer channel.
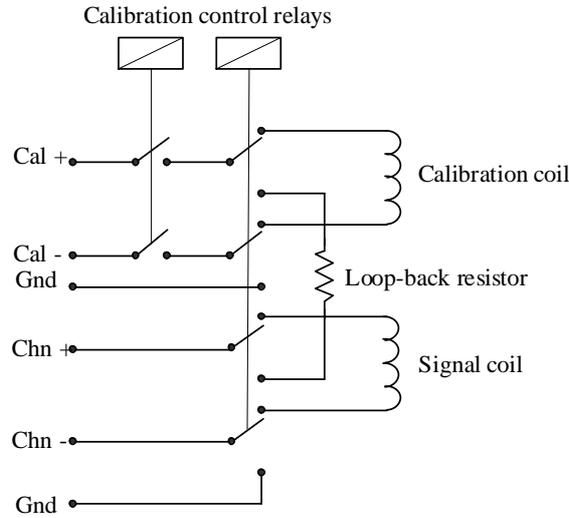

Fig. 4. Conceptual diagram of calibration loop-back circuit installed inside the seismometer

In the conceptual diagram shown on figure 4. one relay is used to connect the calibration lines to the calibration coil, while the second one to switch the calibration lines from the loop-back resistor to the calibration coil. The digitizer would control both relays, the calibration command in this case including not only the parameters of the calibration signal but control bits for the relays.

As first step of this calibration process the loop-back circuit is connected to the calibration signal generator. Figure 4. shows the equivalent system diagram with the feedback circuit connected to calibration circuit.
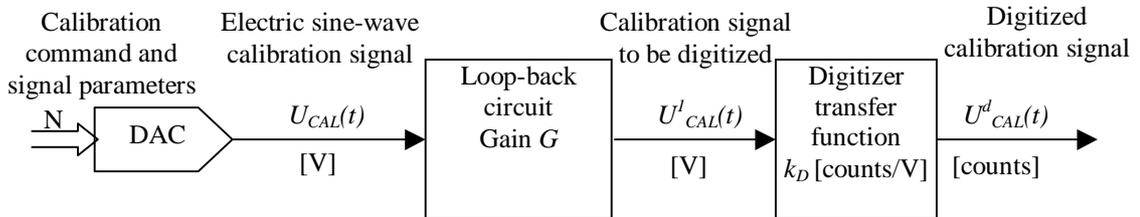

Fig. 5. Equivalent system diagram with feedback circuit

The digitized calibration signal is:

$$U^d_{CAL} = G\, k_D\, U_{CAL} \tag{4}$$

where 'G' represents the gain of the feedback circuit. In the second step the calibration coil of the seismometer is reconnected to the calibration circuit and the same signal is fed into the coil.
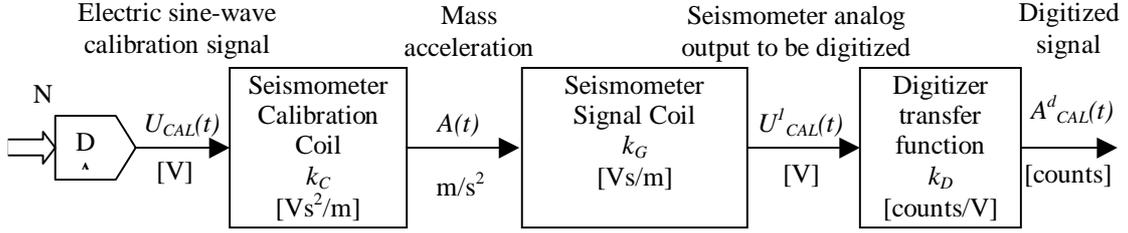
Electric sine-wave calibration signal	Mass acceleration	Seismometer analog output to be digitized	Digitized signal

N → D → $U_{CAL}(t)$ [V] → | Seismometer Calibration Coil k_C [Vs²/m] | → $A(t)$ m/s² → | Seismometer Signal Coil k_G [Vs/m] | → $U^l_{CAL}(t)$ [V] → | Digitizer transfer function k_D [counts/V] | → $A^d_{CAL}(t)$ [counts]

Fig. 6. Equivalent system diagram with calibration coil connected

The digitized seismometer output is:

$$A^d_{CAL} = k_D\, C_G\, U_{CAL} / (2\,\pi f\, k_C). \tag{5}$$

Finally, from equations (4) and (5) it can be calculated the generator constant of the signal coil:

$$k_G = 2\,\pi f\, G\, k_C A^d_{CAL} / U^d_{CAL}\,, \tag{6}$$

which is just the seismometer transfer function:

$$H_s(f) = 2\,\pi f\, G\, k_C A^d_{CAL} / U^d_{CAL}\,. \tag{7}$$

The A^d_{CAL} and U^d_{CAL} amplitudes can be precisely measured, and the gain of the loop-back circuit (G) is precisely known. Therefore, the accuracy of this calibration depends only on the accuracy of the calibration coil motor constant (k_C).

V.   Conclusions and Contributions

The contribution of the authors is the proposal to make the loop-back circuit for digitizer relative calibration as integral part of the seismometer. This requires relatively minor design changes of existing seismometers. Adopting the relative calibration method the sources of error associated with the digitizer sensitivity, the calibration signal generator and the calibration circuit are eliminated. It is believed, that this calibration can provide an accuracy better than 5%, what is considered adequate acceptable for most seismic applications. Installing the loop-back circuit inside the seismometer, close to the calibration coil, digitizer relative calibration can be performed not only in laboratory environment, but allows for remote calibration after field deployment of equipment, without the need of disconnecting cables and the need of additional equipment.

Further increase of calibration accuracy can be achieved by measuring the electromagnetic field created by the calibration current flowing through the calibration coil. With this method the remaining error factor, that is: the uncertainty of the calibration coil motor constant could be eliminated. However, this method requires further circuits and devices to be integrated (installed, tested and experimented) in the seismometer, which might considerably increase the cost of today's seismometers.

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