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ORIGINAL ARTICLE

Adaptation of the S-5-S pendulum seismometer for measurement of rotational ground motion

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Abstract The Russian electrodynamic seismometer model S-5-S has been adapted for the measurement of rotational ground motion. The mechanical system of the original S-5-S seismometer consists of electrodynamic sensing and damping transducer coils mounted on an asymmetrical double-arm pendulum. This pendulum is suspended on a footing using two pairs of crossed flat springs, which operate as the axis of rotation. The pendulum is stabilised by an additional spring. The S-5-S can be used either as a vertical or as a horizontal sensor. The adaptation of the S-5-S seismometer described below involves removal of the additional spring and installation of an additional mass on the damping arm. Strain gauge angle sensors are installed on one pair of the crossed flat springs. The main dynamic parameters of the rotational seismometer created in this way, i.e. the natural period and damping, are controlled electronically by feedback currents proportional to the angular displacement and angular velocity, both fed to the damping transducer coil. This new seismometer, named the S-5-SR, enables measurement of the rotational component of ground motion around the horizontal or the vertical axes. The output signal from this S-5-SR seismometer can be proportional either to rotational displacement or rotational velocity.

Keywords Rotational ground motion · S-5-S seismometer · Experimental measurement · Mining-induced seismicity

1 Introduction

The ground motions that are produced by earthquakes can be completely described by six components of motion, i.e. three translational components and three rotational ones, and by deformation (e.g. Båth 1979; Teisseyre et al. 2006; Lee et al. 2009; Trifunac 2009). Rotational components have been known for several centuries. However, it is only during the last decades that greater attention has been dedicated to precise measurements of these. Although rotational components have usually small values, several studies have shown the importance of these components in seismological analyses and engineering applications (e.g. *Bulletin of the Seismological Society of America*—May 2009; papers presented at the ESC conferences; papers at the IWGoRS workshops).

A number of different designs for sensors used to measure rotational components have been developed in the Czech Republic. Jedlička et al. (2009) introduced a strong motion fluid rotational seismograp0-runc et al. (2009) described a rotational sensor using a capacitance detector to measure angular displacement.

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Brokešová and Málek (2010) and Brokešová et al. (2012) describe a rotational sensor based on differential evaluation of signals from pairs of geophones mounted along the perimeter of a rigid disk. The progress achieved during the current Czech–USA AMVIS Grant on "Fluidal Seismo" was presented by Kozák at the IWGoRS workshops in Prague (2010).

In this paper, we describe an adaptation of the Russian electrodynamic S-5-S pendulum seismometer for direct measurement of the rotational component. This adapted seismometer is named the S-5-SR. To acquire information about the existence of a rotational component in vibrations generated by mining-induced seismic events, experimental measurements have been carried out in an area with strong mining-induced seismicity. The results of these laboratory and field tests of the S-5-SR seismometer are presented below.

2 Mechanical design of S-5-S seismometer

The original S-5-S seismometer is of the "mass-on-rod pendulum" type with sensing and damping electrodynamic transducers. It is designed for vibrations in the period range from 5 to 0.01 s. A sketch of the mechanical configuration for sensing the vertical vibration is shown in Fig. 1.

The description below and Fig. 1 were given by Aranovic et al. (1974). The components used in the construction of the seismometer for sensing vertical vibration are mounted on a chassis (9) that is fixed to two tangs (11) using four bolts (8); these tangs are situated on the base of the seismometer (10). The pendulum (1) is in the form of a two-arm lever, which has identical magnets (2) mounted at each end. Electrodynamic transducer coils (7) are fixed on the chassis (12). This pendulum is suspended on a chassis by means of two pairs of crossed flat springs (3). The pendulum is balanced by a spring (4) that is fixed between the thermo-compensator (6) and an adjustable suspension (5). The reduced length of the pendulum is 0.425 m. Changes of spring tension and/or the point of spring clamping enable the effective stiffness of the pendulum suspension to be set; the natural period (free oscillation) is defined by these adjustments (usually $T0=5$ s). Optimal damping of the seismometer is carried out by the loading resistor on the damping coil. The chassis (9) can be turned through 90° and thereby horizontal vibrations can be detected. The seismometer records both translational oscillations perpendicular to the axis of pendulum rotation and rotational oscillations round this axis because the defined axis of pendulum rotation is not situated at the centre of gravity of the pendulum.

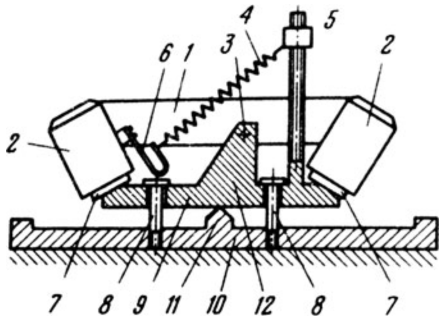


Fig. 1 Sketch showing the mechanical configuration of the S-5-S seismometer for sensing vertical vibration (Aranovic et al. 1974); numbers are explained in the text

3 The concept of adaptation

To record rotational oscillations only, it is necessary to equilibrate the pendulum so that the centre of its moment of inertia is centred in the axis of pendulum rotation. It is necessary to mount additional mass on the shorter (damping) arm of the pendulum. Simultaneously, two adjustable counterweights are mounted on the pendulum in perpendicular directions to achieve precise balancing. The thermo-compensator and original balancing spring, including their suspensions, were removed. This mechanical adaptation is shown in Fig. 2.

Free oscillations of the pendulum of the S-5-S are described by the following equation:

$$m \cdot r \cdot \frac{d^2\varphi}{\mathrm{dt}} + (\mathrm{D0} + \mathrm{De}) . \frac{d\varphi}{\mathrm{dt}} + (\mathrm{S0} - \mathrm{Sa}) \cdot \varphi = 0 \tag{1}$$

where

m	Equivalent moving mass of moment of inertia of pendulum
r	Equivalent radius of moment of inertia of pendulum
D0	Natural mechanical damping moment of pendulum

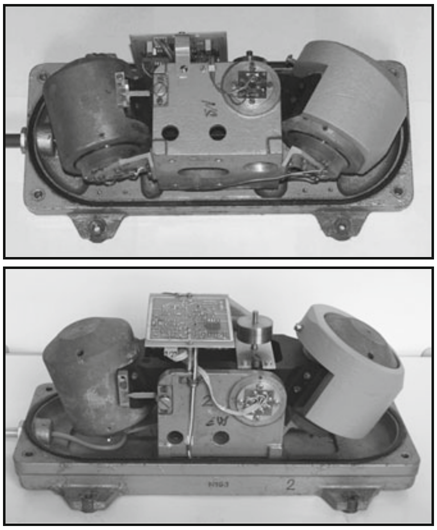


Fig. 2 Adapted pendulum of the S-5-SR seismometer (showing additional mass on right arm); configuration for rotation around vertical axis above, configuration for rotation around horizontal axis below

De	Damping moment caused by damping EDT
S0	Natural mechanical stiffness of suspension of pendulum
−Sa	Negative moment generated by astatic spring suspension.

Basic parameters, i.e. the natural period T0 and damping constant b are defined as follows:

$$\mathrm{T0} = 2 \cdot \pi \cdot \sqrt{\frac{m \cdot r}{(\mathrm{S0} - \mathrm{Sa})}} \tag{2}$$

$$b = \frac{\mathrm{D0} + \mathrm{De}}{2 \cdot m \cdot r} \tag{3}$$

After the adaptation described above, only the stiffness S0 of two pairs of crossed flat springs governs the stiffness of the pendulum suspension. In spite of an increase in equivalent moving mass, the natural period decreases to the value T0=3.3 s. It is not possible to damp the adapted system optimally, even by a resistive load in the circuit of the damping electrodynamic transducer (denoted in the following text by the abbreviation DET). After making the mechanical adaptation described, the component for adjusting the zero position of the pendulum is absent. However, the natural period, damping and zero horizontal position can be adjusted electronically. Both the moments De and −Sa can be induced by feedback currents in the coil of the DET. The current for generation of the moment De (proportional to angular velocity $d\varphi$/dt) can be derived from the signal produced by the sensing electrodynamic transducer (denoted in the following text by the abbreviation SET). A current proportional to angular displacement φ is needed for the generation of the moment −Sa. For this reason, it is necessary to add an additional sensor for detecting the pendulum position—this is the angular displacement transducer (denoted in the following text by the abbreviation ADT).

The flow chart of the electronic circuit is shown in Fig. 3. The ADT is constructed as a strain gauge bridge installed on one pair of crossed flat springs of one pendulum suspension. The design of this strain gauge sensor is described in detail by Kaláb and Knejzlík (2000). The angular displacement signal is an output from the A1 amplifier, while the angular velocity signal is an output from the A2 amplifier. The constant md [N.A^{-1}] is defined as the constant of the DET and rd as the effective force of the damping arm.

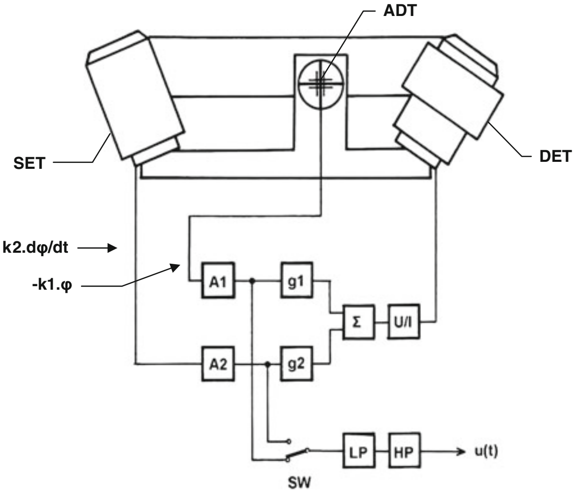


Fig. 3 Flow chart of electronic circuits. *DET* damping electrodynamic transducer; *SET* sensing electrodynamic transducer, *ADT* angular displacement transducer; *k1* sensitivity constant of ADT; *k2* sensitivity constant of SET; *A1* amplifier of rotational displacement signal; *A2* amplifier of rotational velocity signal; *g1* gain control of rotational displacement feedback signal (natural period setup); *g2* gain control of rotational velocity feedback signal (damping setup); *Σ* summing network; *U/I* voltage-to-current converter (equivalent conductance *G*); *SW* selector of measured variables (either rotational velocity or rotational displacement); *LP* low pass filter (e.g. three-pole Bessel, fH=30 Hz); *HP* high pass filter (e.g. one-pole, fL= 0.005 Hz; DC offset removing); *u(t)* output signal

Then, the electronically generated stiffness Sa can be expressed as:

$$\mathrm{Sa} = -\mathrm{d1} \cdot \mathrm{A1} \cdot G \cdot \frac{\mathrm{rd}}{r} \cdot \mathrm{md}. \tag{4}$$

The value of the stiffness moment Sa, as well as the value of T0 can be set-up by d1 value using the resistance trimmer as a voltage divider g1. Depending on the polarity of the angular velocity, it is possible to either enlarge or reduce the output signal of A1.

The damping moment De can be calculated from equation:

$$\mathrm{De} = \mathrm{d2} \cdot \mathrm{A2} \cdot G \cdot \frac{\mathrm{rd}}{r} \cdot \mathrm{md}. \tag{5}$$

The value of moment De resulting in damping of the pendulum of the adapted S-5-SR seismometer can also be set by the d2 value using the resistance trimmer as a voltage divider g2.

To achieve dynamic balancing of the pendulum, it is necessary to mount the S-5-SR seismometer on a flexible pad, e.g. foam rubber. Oscillations of the pendulum are excited by AC current connected to the damping coil (f ~5 Hz). Transverse oscillations are measured using the minimum biaxial accelerometer (Fig. 4). By the adjustment of counterweights, the pendulum has to be balanced to minimise transverse oscillations.

The type of signal measured can be selected using the switch SW. The signal given by angular displacement is present on the output of A1 and signal of angular velocity on the output of A2. Behind the SW, the signal is filtered by high pass (HP) and low pass (LP) filters. The HP filter has a frequency limit of about 0.01 Hz and it is used mainly for removing DC offset from the measured signal. The LP is a Bessel type two-pole low pass filter with a frequency limit of 25 Hz. The typical frequency range of the S-5-SR is 0.2–25 Hz.

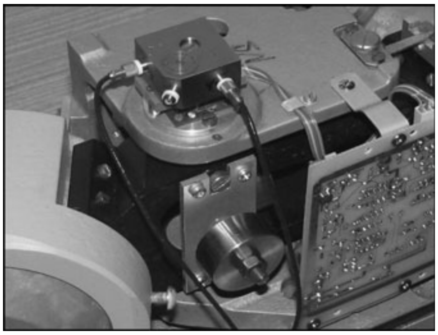


Fig. 4 Dynamic balancing of S-5-SR seismometer using a biaxial accelerometer

4 Laboratory tests of the S-5-SR

Basic parameters of the adapted S-5-SR seismometer in the configuration used for measurement of the rotational component of ground motion around vertical axis were measured on a test vibration table located at the Geophysical Institute of the ASCR, Prague (Fig. 5). This vibration table enables either translational or rotational oscillation to be generated.

The sensitivity constants for angular velocity and angular displacement and also spurious sensitivity to translational oscillation were tested using stationary amplitude harmonic oscillation 50 μm (peak–peak). The amplitudes of output signals were measured using a Brüel & Kjær Spectral Analyzer Type 2031. The sensitivity constant for angular velocity $k(d\varphi/\mathrm{dt})$= 52.6 Vs rad^{-1} was obtained over a range of oscillation velocity up to 10 mrad s^{-1}. The clamp amplitude of angular velocity is limited by inhomogeneous

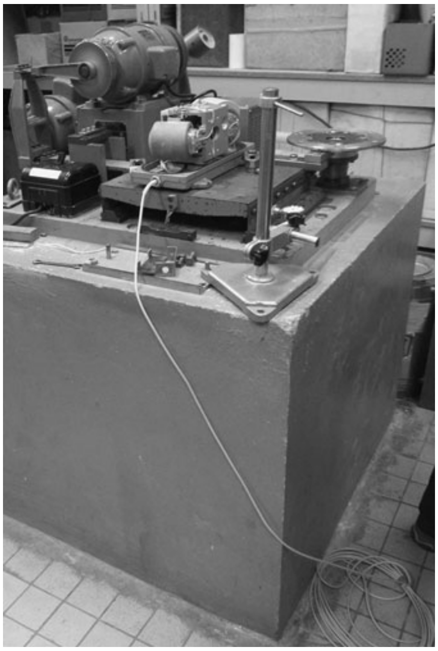


Fig. 5 Laboratory tests on the S-5-SR seismometer using the vibration test table located at the Geophysical Institute of the ASCR, Prague

magnetic fields in the SET. The sensitivity constant $k(\varphi)=1{,}393\ \mathrm{Vrad}^{-1}$ was measured outside the angular displacement channel.

The sensitivity constant kp=1.1 mV/Hz was measured for spurious sensitivity to translational oscillation of different frequencies at stationary amplitude 50 μm (peak–peak). During all tests, the pendulum of the seismometer was oriented perpendicular to the direction of mechanical oscillation of the table.

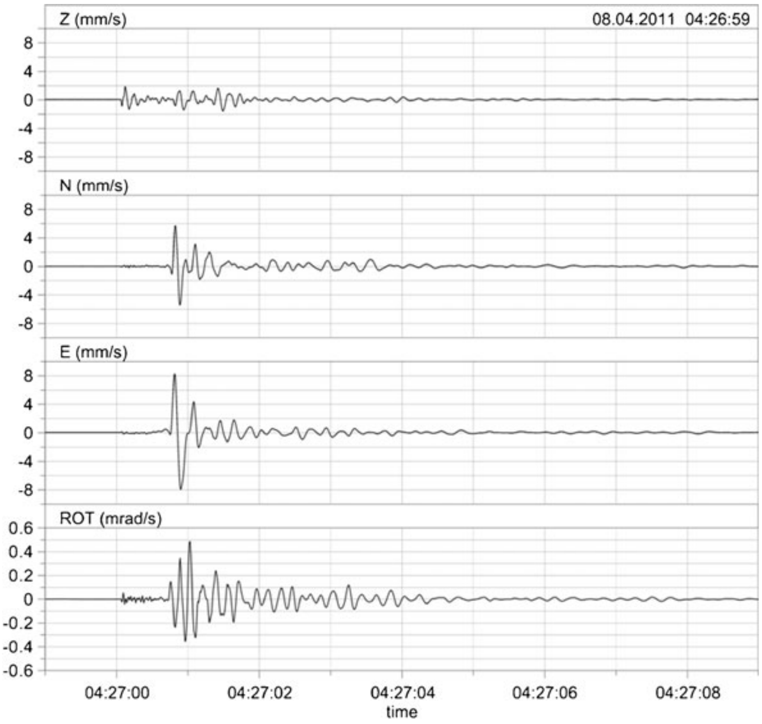
The signal ratios of angular velocity to spurious translation Rt were calculated from the results of translation measurements. For the given radius of rotation (132 mm) and the double amplitude 50 μm of oscillations of the SET, theoretical amplitudes of the equivalent rotation signal were calculated for individual frequencies. The ratio Rt was calculated as the quotient of this theoretical value of angular signal to the measured spurious signal. The signal ratio Rt determined by the method described above decreases with frequency from 70 dB for 2.5 Hz to 39 dB for 25 Hz. This effect is probably a consequence of incomplete dynamic balancing of the seismometer pendulum and spurious oscillation generated by the suspension of the pendulum and also by other parts of the seismometer. The spurious oscillations of the vibration table are not precisely defined. Peaks are observed in spectra of the measured signals that do not represent multiples of the excitation period and they can be generated by the spurious effect of the gear in the vibration table. Nevertheless, the value of Rt >40 dB is in the frequency range below 12.5 Hz.

To estimate maximum sensitivity of S-5-SR, frequency spectrum of noise has been measured using Narrow Band Spectrum Analyzer Brüel & Kjær type 2031. The first prototype of S-5-SR, configured for measurement of rotation rate around vertical axis, has been installed on the silent place. Maximum measured noise level for frequency range below 0.5 Hz matched 1.1 μrad/s. In excess of 0.5 Hz, the noise level was under 0.1 μrad/s. It was not possible to determine the level of self-noise more precisely because of the relatively high levels of seismic noise at places where measurements were made.

5 Results of experimental field measurement

The Karviná Region of the Upper Silesian Basin (Czech Republic and Poland) is an area where underground exploitation of black coal has taken place on a large scale (e.g. Martinec et al. 2006). This region is very well known as an area of intensive mining-induced seismicity. Mining-induced seismic events are similar in character to weak natural earthquakes; however, these events are

Fig. 6 Example of wave patterns produced by a mining-induced seismic event in the Karviná Region (see text). Local time is shown on the horizontal axes (one scale division is 1 s)



closely connected in space and time with current mining activities. Gibowicz and Kijko (1990) described the characteristic parameters of this type of seismic event. The strongest rockburst, at a magnitude $M=3.8$, occurred in 1983 at the ČSA mine in the Karviná District. As many as 50,000 events are registered per year in the Karviná Region, of which about 100–500 events release energy higher than 9×10^{3} J (local magnitude equal to about 1). Seismic activity is monitored by a specialised institution—Green Gas of the company OKD. Experimental investigation has shown that the seismic velocity component of the most intensive shocks exceeds the value 10 mm s^{-1}; the value of the acceleration component reaches up to 500 mm s^{-2} (e.g. Kaláb and Knejzlík 2002, 2006).

In the mines here, only longwall retreat faces are used, either with caving and/or the low-pressure stoping method. The mine workings are situated at depths of 700–1,000 m. This exploitation is manifested as negative effects on the surface of the terrain, mainly by motions of large masses of ground (continuous and non-continuous deformations of surface), changes of hydrogeological conditions (irrigation, dewatering) and induced seismicity (vibrations of fundamentals) (e.g. Kwiatek et al. 1998; Kaláb 2004). The seismic effect on the surface structures in the Karviná Region is monitored using solitaire seismic stations operated by the Institute of Geonics, Green Gas DPB-OKD joint-stock company and INSET Ltd.

To test the application of the S-5-SR seismometer and to verify the existence of rotational ground motions during intensive mining-induced seismic events in Karviná Region, one prototype of the rotational seismometer has been installed in a large building in Doubrava village. The seismometer was anchored to the concrete basement in a cellar, and it is configured to detect angular velocity around vertical axis. Wave patterns are digitally recorded using seismic instrumentation of the PCM3-EPC4 type (Knejzlík and Kaláb 2002). The frequency range of the seismic channel is 0.5–30 Hz, sampling frequency is 100 Hz and the dynamic range is 120 dB. Seismic station operated

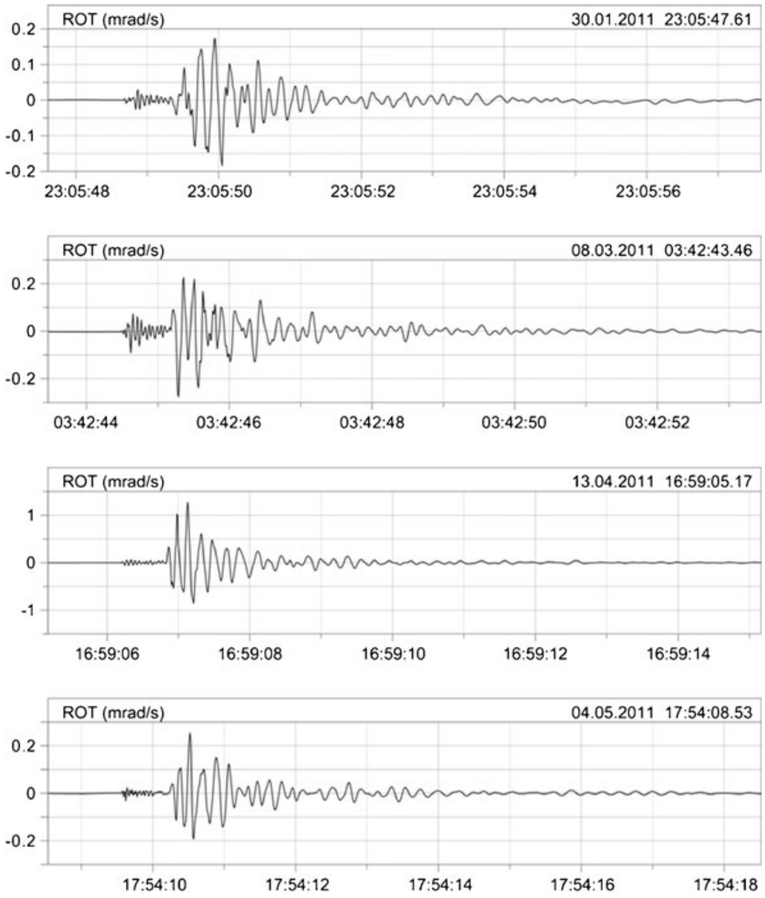


Fig. 7 Four examples of rotational components around vertical axis recorded during mining-induced seismic events occurring in the Karviná Region. Local time is shown on horizontal axes (one scale division is 1 s)

by the company INSET Ltd. Ostrava is installed at the same site, and consequently, both sets of data can be interpreted together and compared. This station is equipped by sensors with natural frequency of 1 Hz and seismic recorder MIO-16L-9, and sampling frequency is 1 kHz.

Examples of wave patterns are shown in Fig. 6; from the top downwards, three component records of translational components (vertical, horizontal longitudinal and horizontal transversal, all in millimetres per second are depicted based on the records of INSET Ltd. Ostrava) together with the rotational component ROT around vertical axis (in millirads per unit). The time axis is the same for all components. The transverse component of the INSET station is perpendicular to the pendulum of the S-5-SR seismometer.

To illustrate more records of rotational velocity around vertical axis from this area, four other records are summarised in Fig. 7. All the mining-induced seismic events presented were very intense with seismic energy of more than 10^5 J (approximately local magnitude 1) at hypocentre distances of about 2 km. Wave patterns shown in Figs. 6 and 7, and many other records, point to the existence of rotational oscillation. The shape of wave pattern of the ROT component is different from that of wave patterns of both translational components. Inputs of significant rotational oscillation are usually associated with the S-wave group. It is necessary to state that the character of these wave patterns can probably be markedly influenced by the response of buildings.

6 Conclusion

The Russian pendulum seismometer S-5-S can be adapted for measurement of the rotational components of seismic motion around both the vertical and horizontal axes. The output signal can be proportional either to rotational velocity or rotational displacement. The clamp amplitude is limited to ±0.015 rad due to the inhomogeneous magnetic fields of the electrodynamic transducers used in the original S-5-S seismometer. The typical frequency range of the adapted S-5-SR seismometers is 0.2–25 Hz. The sensitivity constant for angular velocity $k(d\varphi/\mathrm{d}t)=52.6\ \mathrm{V\,s\,rad^{-1}}$ was obtained for a range of oscillation velocity up to 10 mrad s^{-1}. The level of self-noise was estimated to be in the order 1 μrad s^{-1}.

Experimental field measurement using the S-5-SR seismometer was started in December 2010. This seismic station is located in Doubrava village in the Karviná Region where there is intensive mining-induced seismicity. The wave patterns recorded show the existence of rotational ground motion in this area. The character of this rotational component is different from records of translational components; however, it is not possible to carry out detailed interpretation of rotation movements at present because the seismometer is installed in a building and the response of this structure to seismic events has not been determined.

Adaptation is comparatively easy and cheap. However, because the setting of parameters, and especially balancing of the pendulum, is complex, the S-5-SR seismometer above all is most suitable for stationary seismic stations.

Utility model named “Seismometer for seismic measurements of rotational ground motion”, registered with the Industrial Property Office of the Czech Republic, no. 21679 (31-01-2011), was accepted. The next stage of research will be focused on the investigation of parasitic features (especially of spurious sensitivity to translational vibrations) and on the development of microcomputer-based circuits for the automatic control of natural period and damping.

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