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Usefulness of the fiber-optic interferometer for the investigation of the seismic rotation waves

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In the paper new areas of the fiber-optic Sagnac interferometer applications are discussed and proposed. Because this system detects the absolute rotation, its application is directly designed for detection of the seismic rotation waves which are rotational events existing in the seismic waves. In most cases those waves are extracted from recordings of differential seismic signals. However, all differences in responses of the seismometers cause disturbances which obscure these hidden components as it is for two antiparallel pendulum seismometers (TAPS) system. The presented device, named fiber-optic rotational seismometer (FORS), is free from this disadvantage and may be used for other rotational seismometer calibration, as well as for direct seismic rotation waves detection. The paper describes the design based on a well-known optical gyroscope configuration but with its optimization for its optimization for detection the absolute rotation, only. The obtained results have been the source of TAPS work improvement by applying the data smoothing by a spline function. Moreover, the first application of FORS for recording rotational parts existing in the seismic events has shown that they probably propagate with different velocity than classical earthquake waves.

Keywords: rotation waves detection, optical fiber sensor, interferometry, filter design.

1. Introduction

A study of seismic waves has been found to be one of the most effective ways for prediction of the earthquake mechanism, because such waves have some advantages in comparison to other physical phenomena associated with earthquakes [1]. Firstly, the high resolution and accuracy are attainable as seismic waves have the shortest wavelength of any wave that can be observed after passing through structures inside the Earth. Secondly, seismic waves undergo the least distortion in waveform and the attenuation in amplitude.

Generally speaking, there are three types of seismic waves, which can exist in the Earth. Waves that propagate inside the Earth are called bulk seismic waves; they can be *P*-waves or *S*-waves. *P*-waves are also called compressional or longitudinal waves and *S*-waves are also called transverse or shear waves. For *P*-waves, the particle motion is in parallel with the wave propagation direction, while for *S*-waves, the particle motion is perpendicular to the wave propagation. There are two polarisations of *S*-wave: *SH*-waves and *SV*-waves. The former has all the motions in horizontal plane of the Earth, while the latter has all the motions in the vertical plane of the Earth. Waves that propagate over a free surface of an elastic body are called Rayleigh wave or surface waves.

As one can see, the above classic seismological approach describes only the ground particles motion related to displacements. The other kind of the ground particles motion can be associated with the rotational effects caused by the earthquakes or by the interaction between seismic waves and micromorphic properties of rocks [2–4]. Initially, these effects have been explained by the inertia properties of objects situated on the Earth surface when hit by the seismic body waves [5]. Recently such events are treated as the seismic rotation waves (SRW) which appear in the case of a non-ideal elasticity due to defect content (the non-symmetric dislocations) in a medium [6] or due to internal structure of a medium (micromorphic or micropolar media) [7, 8]. The interest in these waves is connected mainly with important seismic information included in them. For example, they give accurate data for arrival times of *SH* waves, because the rotational component around the vertical axis is sensitive to *SH* waves, although not to *P-SV* waves. A vertical heterogeneous, isotropic, elastic medium is the first-order approximation of the Earth's interior, so records of the rotational component around the vertical axis should give a clear *SH*-wave onset [9]. Classical separation of *SH* waves from *P-SV* waves from recorded translation motions, needs to rotate two horizontal components into radial and transverse components. To do this, knowledge about the incident directions of seismic waves is needed. Moreover, some further advantages can be expected, too.

However, recording SRW needs a new instrumentation techniques, because conventional seismographs are inertial sensors of linear velocities [10, 11]. For this reason the new kind of rotational seismometer consisting of two antiparallel pendulum seismometers (TAPS) [8] or two antiparallel suspension coil seismometers (TASCS) [12], has been proposed. Depending on their constructions they may record the distortion (space derivatives of displacements) and/or the components of rotations. The second one has been used with some success for the detection of rotational waves during seismic events of 29.11.1998, $14^{h}10^{m}31.96^{s}$, $\varphi = 2.07$S, $\lambda = 124.89$E, $M = 8.1$ and of 05.04.1999, $11^{h}08^{m}04.06^{s}$, $\varphi = 5.26$S, $\lambda = 149.58$E, $M = 7.4$ [13]. Unfortunately, the simulation work [14] showed that the rotational motions are small comparing with the amplitude of the translational motions. Hence, extremely high sensitivity to translational motions of the conventional seismometer used in construction of the mentioned above rotational one can be limitation of its accuracy. Moreover, there exists a serious problem with their proper calibration, because in fact it is a set of two independent devices and rotational components are obtained in the indirect way as a difference in their action [15, 16].

From the above reason the idea of the seismic rotation waves recording based on the Sagnac effect [17] in optical system seems to be an attractive proposition. The main advantage of such system is the measurement of the absolute rotation rate around any axis perpendicular to the optical path plane, without sensitivity to the uniform linear motion or distortion [18]. The comparison of standard seismograms and a ring laser as a sensor for rotational events has shown some advantages of the latter [19], mainly in its extremely high sensitivity [20]. However, such ring laser is as expensive as a motionless device. Therefore, in this paper the relative cheap version of an optical rotation sensor made with the use of the fiber-optic technique is presented and discussed. The described sensor is based on a configuration well-known from the classic fiber-optic gyroscope (FOG) system [21]. However, the basic system optimisation for a detection of the rotation only without conversion for angular changes distinguishes this system from gyro applications [22]. On the other side, the compact system construction makes the device movable, which is advantageous in comparison with the ring laser system. Thus, the main paper content is the fiber-optic rotational seismometer designed for investigation of TAPS as well as for detection of SRW. On this base the results of a new method of TAPS calibration and some conclusions drawn from the first probe of the SRW registration simultaneously by the TAPS and the FORS are also presented.

2. Main principle of taps operation

Figure 1 shows TAPS based on two seismographs situated at the common axis and connected in parallel, but with opposite orientations [13]. In the case when ground motion contains displacement $w(t)$ and, possibly, a rotation motion $\alpha(t)$, the SEM recorded by each seismograph contains a component of displacement $\pm w$ and the rotation motion α multiplied by a proper length of pendulum l:

$$u(t)_i = \pm w(t) + l\alpha(t) \begin{cases} + & \text{for } i = R \text{ (right seismograph),} \\ - & \text{for } i = L \text{ (left seismograph).} \end{cases} \tag{1}$$

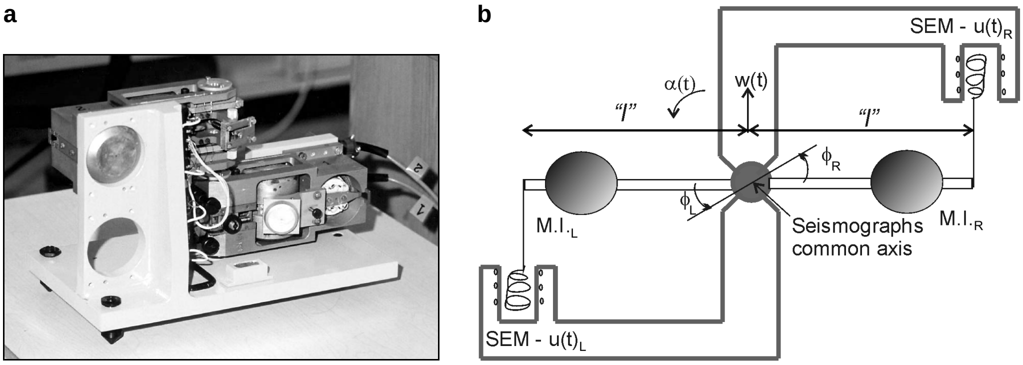

Fig. 1. General view (**a**) and scheme (**b**) of the TAPS system. Parameters: M.I. – moment of inertia, ϕ–seismograph turns, index L, R – left and right seismograph, respectively.

In the case of identical two seismographs the rotation motion $\alpha(t)$ can be obtained from the sum of two recorded SEM u_L and u_R as:

$$a(t) = \frac{u(t)_R + u(t)_L}{2l}. \tag{2}$$

However, the proper TAPS operation assumes *identical* characteristics of seismographs used for its construction. Because the expected rotational seismic events are very small, any differences in seismographs can affect the TAPS operation. This aspect should be carefully and throughly investigated in laboratory as well as in the seismic station conditions. In the first place the system calibration is possible but many noises existing in such place connected with the urban activity require further investigation of the TAPS in the seismic station.

3. Design of the fiber-optic rotational seismometer

The application of the fiber-optic Sagnac interferometer (FOSI) as the fiber-optic rotational seismometer (FORS) may be an attractive proposition for the TAPS calibration as well as a recorder of SRW. The main advantage of such system is the dependence of its sensitivity only on rotational motion, however the system must be optimized for seismic area of operation. From the above reason the special construction of an optical part of the system as well as signal processing is required. According to the optical part of the system the main parameter is maximum sensitivity (in the range of 10^{-7}–10^{-10} rad/s), so the sensor loop should contain a long section of the optical fiber wound in the shape of a loop with maximum radius and extremely high power optical sources. Compatibility with a standard seismic recording unit – KST, appropriate band of detection and the sampling scheme are the main parameters for the constructed signal processing unit. These requirements make main differences between the FOSI application as FOG and FORS system.

From the above reason the existing construction of FOG has been adopted for introductory investigation of its usefulness for SRW detection according to the scheme shown in Fig. 2.

This system, named FORS-I, uses 1.0 mW light source which operates at wavelength $\lambda = 1300$ nm and a sensor loop with radius $R = 0.1$ m containing

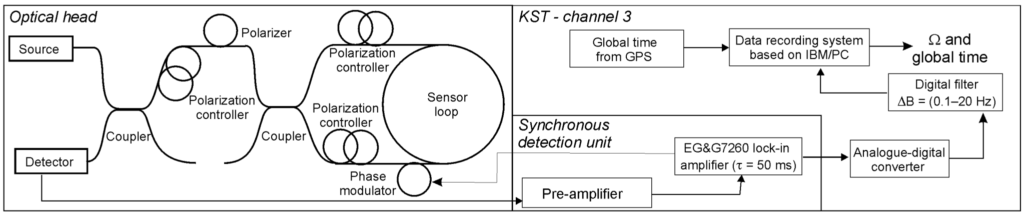

Fig. 2. General scheme of the FORS construction.

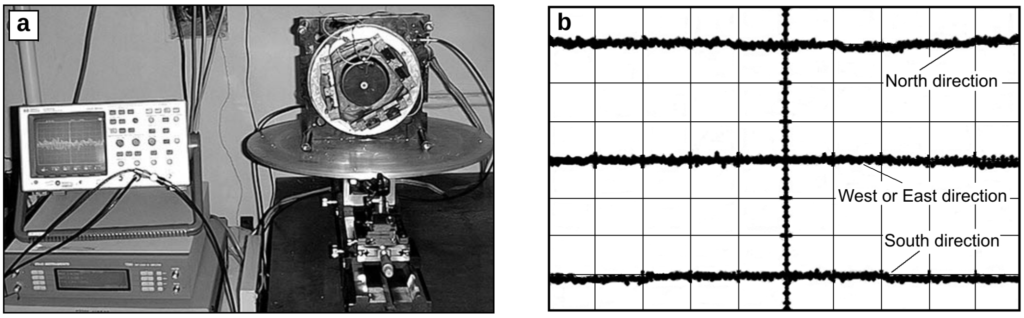

Fig. 3. FORS-I positioned in W-E direction (**a**), and oscillogram of electronic signals from the FORS-I during system calibration (**b**) [23].

$L = 400$ m PANDA fiber. The detection unit, based on a lock-in amplifier 7260 (EG&G), realises the synchronic detection through the phase modulator operating at 147.7 kHz. Because the calculated total optical loss was about 30 dB, the theoretical system sensitivity connected with the noise level is equal to 6.8×10^{-7} rad/s/Hz^{-2} [23]. The practical system calibration has been made basing on the constant Earth rotation component detection for Warsaw latitude ($\varphi = 52°20''$), as it is widely described in [23]. Because the Sagnac effect detect only the absolute rotation speed in the plane of an interferometric loop [18], the FORS-I placed in the North or the South direction should give the signal of rotation $\Omega_E = \pm12.86$ deg/h, and in direction West-East (see Fig. 3**a**) equals null deg/h. The calibration procedure gives the signal equal to 400 mV and 20 mV for the FORS-I placed in the North/South and the West/East direction, respectively, as shown in Fig. 3**b**. These data have been used for the calculation of FORS-I sensitivity as equal to 2.3×10^{-6} rad/s which is twice worse than the expected for this system in the applied detection band. The main source of this error is the occurrence of polarisation parameters fluctuations of the used light source [24]. Finally, the standard seismic recording unit KST has been used for the data processing. The analogue-digital converter samples the signal with frequency 1 kHz and after re-sampling stores it with frequency $f_s = 100$ Hz.

The drift phenomenon is a well-known problem for the FOSI application as an optical gyroscope, because all FOG systems give angular position as a result of time integration of the detected rotation speed. Therefore, the final system accuracy is very sensitive to the integration process. The system's sensitivity grows with narrowing integration time but drift minimisation needs an opposite operation – it is widening [21]. Hence, the drift, connected with the constant component of the output signal, has an influence on final FOG accuracy and must be taken into consideration. The application of the FOSI as the FORS, where final parameter is rotation speed directly obtained from Sagnac phase shift [18], does not require the integration process. It gives a possibility to eliminate the drift influence on the system accuracy by a suitable choice of an output signal band. The digital filter included in the KST provides such a selection because its lower frequency equal to 0.1 Hz generally eliminates environmental fluctuation of the FOSI [25], whereas the upper frequency equal to 20 Hz is just equal to frequency put by a lock-in system (for time constant $\tau = 50$ ms used by lock-in). It is worth mentioning that the above frequency band is connected with the expected frequency characteristic of rotational seismic waves [26].

4. Laboratory test of TAPS and FORS-I work

The FORS-I system has been initially used for the TAPS investigation. Figure 4**a** shows the TAPS and the FORS-I placed on the rotation table in such a way that the rotational event is dominated by displacement ($w \ll la$). The rotation with a speed equal to the Earth rotation for Warsaw latitude (*i.e.*, about 12.86 deg/h) gives 400 mV signal generated in KST the in-phase signals from the TAPS channels. These data have been used for the evaluation of the rotation components according to relation (2) with additional TAPS left channel equalisation by the following method [27]:

$$u_L^{'} \to u_L \sqrt{\frac{\sum u_R u_R}{\sum u_L u_L}} \,. \tag{3}$$

The results presented in Fig. 4**b** show good conformities of the TAPS and the FORS-I for the above events, however the TAPS system seems to generate worse response to rotation. As one can see the rotational signal obtained from the TAPS is fuzzed, whereas the signal from the FORS-I is very smooth. These results show advantages of the direct method of rotation measurement by the FORS in comparison with the differential method realised by the TAPS. Hence the sources of disturbances in the TAPS work should be analysed and some methods of their minimization should be proposed, too.

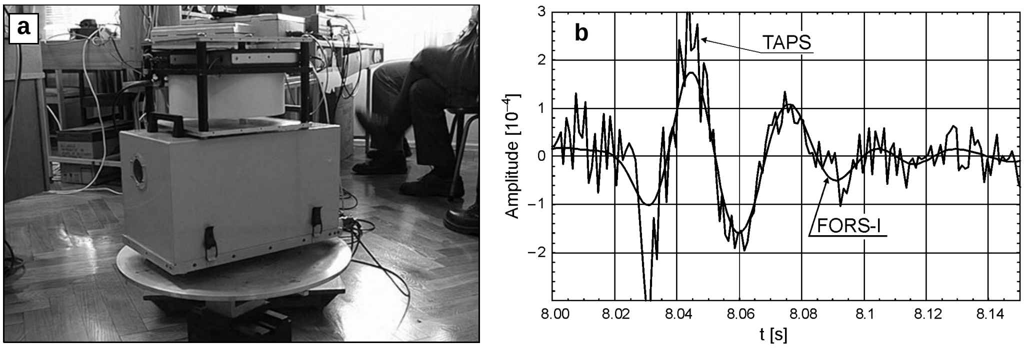

Fig. 4. Rotation table with the TAPS (bottom box) and the FORS-I (top box) (**a**), and the comparison of output signals from the FORS-I and the TAPS after proper numeric processing (**b**) [23].

4.1. Estimation of the main error sources in the TAPS operation

Probably, the non-identical characteristics of two seismographs used in the TAPS construction are the main source of this fluctuation. The applied channel's equalisation method described by Eq. (3) seems to be too weak. It should be noticed that correlation like (3) is not adequate to the presented data, because it minimizes the mean square of the sum u_L and u_R, which contains the anticorrelated rotational components $l\alpha$; thus relation (3) minimizes at the same time both the errors and rotations, destroying the latter. Moreover, our simulation analysis [24] has shown that this procedure can be ineffective, especially if the TAPS system components have different attenuation characteristics. In such situation the existing finite components sensitivities connected with signal sampling procedure used during the data recording generate error signal, as shown in Fig. 5. In this simulation the difference between left and right seismographs attenuation $\Delta\beta$ equal to 0.05 has been assumed. Moreover, two seismographs as elements with a different noise level have been considered.

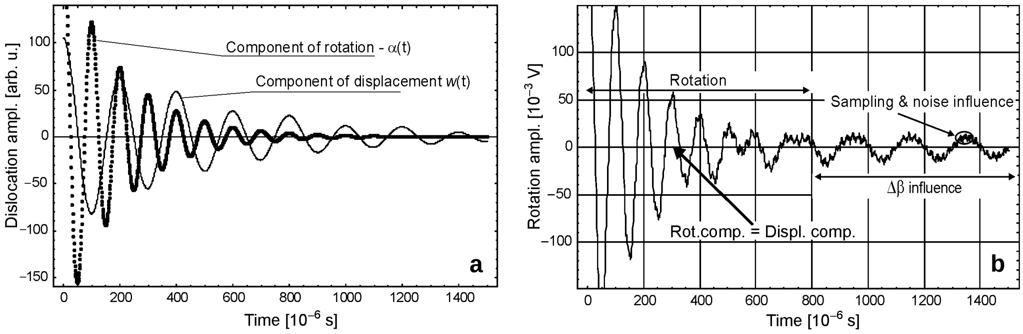

Fig. 5. Simulated rotational and displacement components of a seismic event (**a**) and rotation signal detected by the TAPS (**b**) [24].

As one can see the main error signal exists in the region, where the rotational events have small amplitude in comparison with the displacement. Because, in fact, it is the expected region of the rotational seismic event, the method of the TAPS calibration is a crucial problem for credibility of its operation.

4.2. New method of improvement of the data recorded by the TAPS

The reasons signalized in the latter section have led to other methods of the TAPS performance improvement proposed recently, applying, for example, the filtering procedure in the FFT domain [15] or the time-domain [16]. However, these methods use the so-called test positioning of the TAPS (the seismographs of the system are turned so as to make them situated in the parallel-parallel position), that generally changes the conditions of the TAPS operation. From this reason the other procedure of the recorded data processing has been proposed [28]. Generally, this procedure is based on smoothing by the spline functions [29, 30]. The recorded digital data $\mathbf{Y} = \{Y_i,\, i = 0, \ldots, N\}$ with sampling equal to Δt is smoothed by the spline function

$$S(t) = a_j\tau^3 + b_j\tau^2 + c_j\tau + d_j \qquad (j\Delta t \le t \le (j+1)\Delta t,\ \tau = t - j\Delta t, j = 0, \ldots, N-1) \tag{4}$$

in this way the functional

$$F[S] = p\int_0^{N\Delta t}[S''(t)]^2\mathrm{d}t + \sum_{i=0}^{N} p_i[S(i\Delta t) - Y_i]^2 \ \ (p \ge 0, p_i > 0) \tag{5}$$

reaches its minimum. It should be emphasized that there exists a relation between the parameter p of the above functional and error mean-square ε [29] defined as:

$$\varepsilon = \frac{\sqrt{\dfrac{1}{N+1}\sum_{i=0}^{N} p_i\Big[Y_i - S(i\Delta t)\Big]^2}}{\sqrt{\dfrac{1}{N+1}\sum_{i=0}^{N} p_i Y_i^2}}. \tag{6}$$

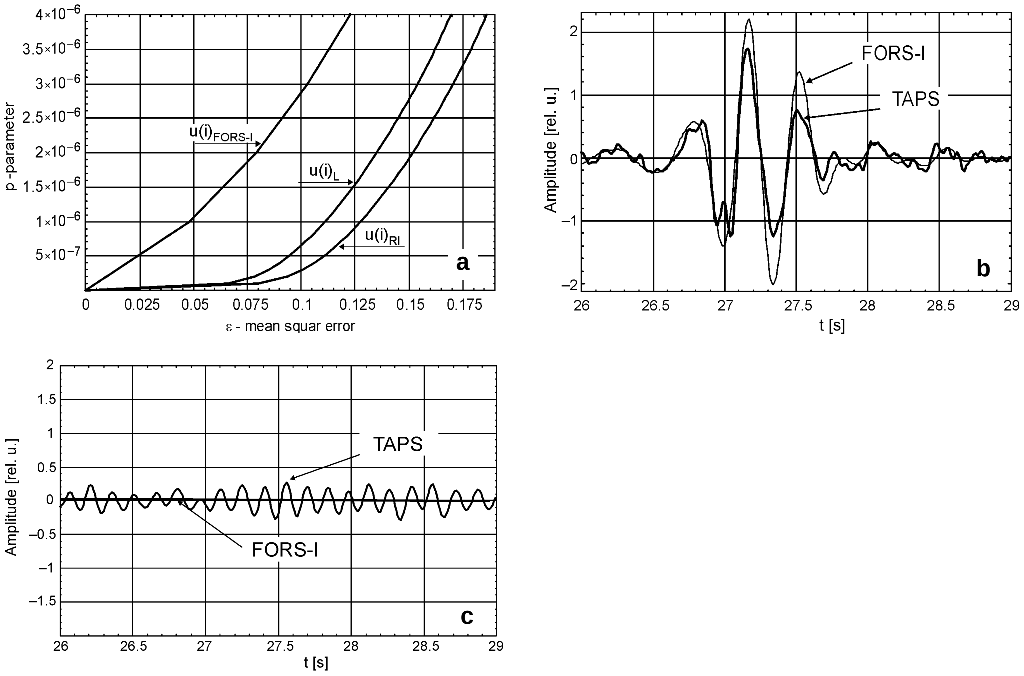

Fig. 6. Dependence between ε and p for the TAPS and the FORS-I (**a**), the rotational component recorder during the test presented in Fig. 4**c** after smoothing (**b**) and recorded by TAPS additional displacement effect (**c**).

This relation calculated for $p_i = 1$ ($i = 0, ..., N$) [29] by implementation of the falsi method [31] is shown in Fig. 6**a**. As one can see the smoothing procedure generates an error of one order greater in magnitude for TAPS than for the FORS-I.

The effectiveness of this method for the improvement of rotation events recorded by the TAPS (in comparison with the method presented in Fig. 4**b**) is shown in Fig. 6**b**. For the spline function the parameter p equal to 5×10^{-6} has been chosen as optimum for smoothing. It is high enough for rotational component smoothing without decreasing the really existing displacement (see Fig. 6**c**) [28]. It should be noticed that rotational events have been one order higher in magnitude than the displacement ones. Such situation is possible during laboratory tests only; in practice the relation between these events is reversed [14].

5. Results of seismic events recorded by Książ standard seismic observatory

The described above set of the FORS-I and the TAPS have been mounted in Książ (Poland) standard seismic observatory in order to record the rotational seismic events. This station consists of two parts: the ground platform for sensor mounting placed on a stable rock and the remote data recording room containing the KST. The correctness of the FORS-I operation has been achieved basing on the forced rotational events and their recording by the KST unit [24].

The first result related to the seismic event recorded by the above system is shown in Fig. 7 [32]. It was a small earthquake from Silesia mines region recorded on

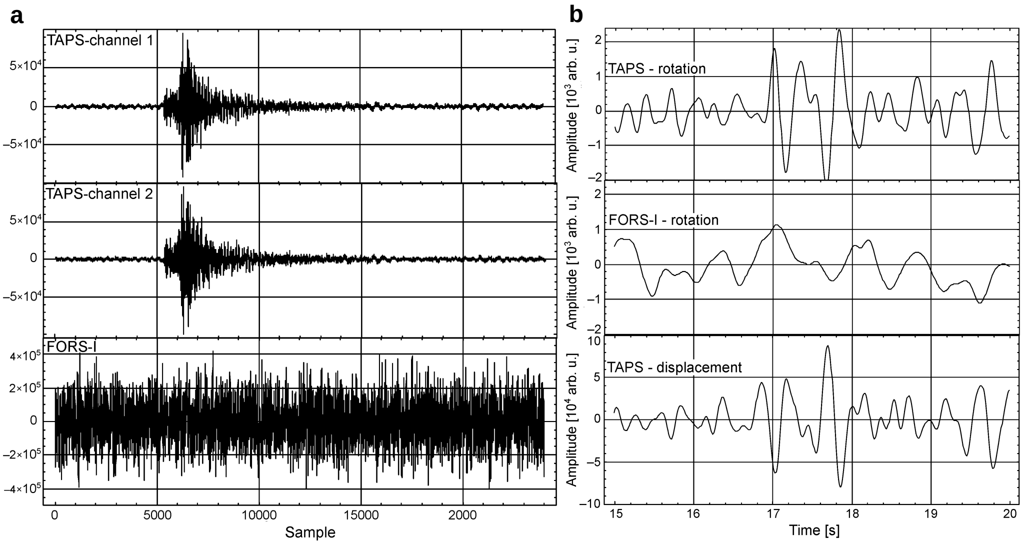

Fig. 7. Seismic events recorded by the TAPS and the FORS-I on 28.12.2001 9^h33^m in Książ (Poland); signals from the KST (**a**) and calculated rotational (by TAPS and FORS-I) and displacement (by TAPS) components (**b**).

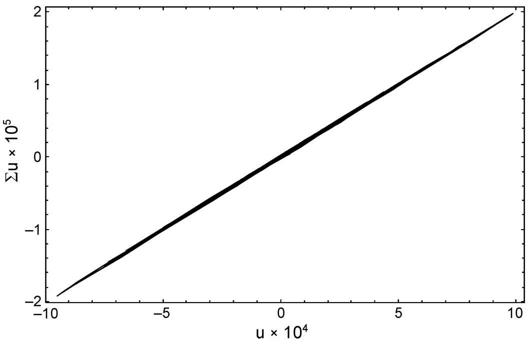

Fig. 8. Relation between channels sum Σu and indication from one of channels u for seismic event recorded on 28.12.2001 at 9^h33^m in Książ [32].

28.12.2001, at 9^h33^m. An interesting fact is that the FORS-I has not registered rotation correlated with linear motion characteristic of this earthquake which two channels from the TAPS have shown (Fig. 7**a**). After application of the numerical processing described in Sec. 4.2 the TAPS gives the rotational component, whereas the FORS-I has not confirmed it (see Fig. 7**b**). It should be pointed out that the calculated rotational component is about two orders of magnitude smaller than the displacement one, as it is shown in Fig. 7**b** (bottom picture). The investigation based on these data shows that probably this seismic event contained the linear displacement only. If these conclusions were true, then observed by TAPS rotational component would be connected only with the difference between the attenuations of the left and right seismometer ($|\beta_L| \neq |\beta_R|$). Basing on the data presented in Fig. 7**b**, it is calculated to be smaller than a few percent. Obviously it would be true if the FORS-I operated correctly during this event with suitable sensitivity on rotation events.

Absence of the rotational component, which is observed by the FORS-I system, can be confirmed in another way, too. As shown in Fig. 8, the relation between calculated from the TAPS rotation (Σu – TAPS's channels sum) and the linear motion detected by one of its channels u, for these seismic events, has only linear dependences. It seems that rotational components recorded by TAPS were completely phase correlated with component of displacement. Such situation may be in conflict with general expected characteristic of rotational seismic waves [26].

6. Conclusions

The idea and the first experimental results of the FOSI application for detection of the SRW presented in the paper are very promising for several reasons. Firstly, the presented FORS system is designed to detect absolute rotation, which is probably impossible to realise in another way. It seems that the data obtained are clear for identification. Moreover, the FORS as a system operating in real time gives immediate information about such events, which is an additional advantage. Secondly, it can be used for the investigation of other kinds of rotational seismometers, for example, the

TAPS. The presented results of the investigation have become an impulse for a new method of data analysis recorded by the TAPS. This method, based on smoothing by the spline function, gives more clear results of rotational events measured by the TAPS system.

The first results obtained in Książ are very interesting, because, in contrast to the earlier results analysis, presented in the paper, they have shown that expected RSW do not exist in the recorded by TAPS linear displacement connected with this earthquake. This conclusion should be confirmed by further studies. Two different approaches should be adopted. In the first, the recording data procedure used by KST should be improved due to continuous monitoring of TAPS and FORS action. Such approach gives an opportunity to compare their indications in the time for the investigation of the possible time relation between the displacement and rotational events in the earthquakes. Secondly, the new FORS system with higher sensitivity should be used. Such device named FORS-II is now under construction. It should provide a sensitivity of 8×10^{-8} rad/s, mainly applying fiber length equal to 11000 m in 0.63 m diameter sensor loop as well as high power SLED with 5 mW in a single-mode optical fiber. The authors have confidence in the effectiveness of the FORS-II system. However, it should be emphasized that recording of the seismic rotation waves is connected with waiting for the strong earthquakes. Unfortunately such events appear seldom and unexpectedly, so the designed FORS-II system should work continuously in a long period of time.

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