Chapter 2

Measurement of Rotational Events in Regions Prone to Seismicity: A Review

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Abstract

On the basis of the explanation of rotational seismology as an area of study, a modern approach to the seismic rotation in various continuum models is summarized. The aim of this chapter is to formulate the fundamental requirements for rotational seismometer. Consequently, a review of all existing technologies of rotational seismometers including mechanical, electrochemical, magnetohydrodynamical, as well as optical type solutions is discussed. The analysis of their parameters that considers technical requirements enforced by rotational seismology has indicated an optical instrument using a Sagnac interferometer as the best solution. Fibre-Optic System for Rotational Events & phenomena Monitoring (FOSREM) with its main parameters and features is described as an example of such solution. Moreover, the example of rotational events recorded in Książ observatory, Poland, using mechanical rotational seismometers and FOSREM is presented. There are data for M = 3.8 earthquake near Jarocin, Poland on the 2012.01.06 at 15:37:56 at a distance of about 200 km from Książ. Although the used devices have totally different designs, the results obtained using FOSREM and the results calculated by mechanical devices show compatibility in rotational signals.

Keywords: theory of rotational events, rotational seismometers, rotational seismic data processing, rotational seismic data acquisition

1. Introduction

Mutual rotation or twisting of monumental blocks around a vertical axis as a result of seismic activity has been observed for nearly 300 years. The distortion of the San Bruno obelisk after the February 5, 1783 Calabria earthquake, intensity XI-XII MCS, is cited as the first illustration of these phenomena [1, 2], and now it is a symbol of seismic rotational effects. Starting with that event, we can find a large number of other examples of observed rotation effects resulting from historical earthquakes where the description of 12 majors ones (VII-XI MSC) can be found [3]. The shallow, catastrophic 2009 l'Aquila earthquake was a source of more than hundreds of evidenced rotational effects. Its analysis [4] revealed a tectonic dependence of their distribution and the influence of substrate. From the above, positive correlations have been found between rotation effects, damage and soft lithology of the site where buildings are located.

However, the term 'rotation' has several meanings in seismology. Displacement of rocks, soils and various objects during an earthquake in the focal area and its vicinity, and reversible rotational oscillations in the seismic wave field are called 'seismic rotations.' The historical explanation of observed seismic rotations based on mechanical models can be found in [5, 6], whereas Section 2. summarizes their explanations on the basis of continuum models.

Recently, it is believed that rotational signals contain additional information, valuable for studies on wave propagation, and that the rotational ground motion is an important source of excitations in the engineering structures. Therefore, increasing interest in rotational motions' measurement has emerged. From seismological point of view, it is an area of a rotational seismology which according to [7] becomes an emerging field for the study of all aspects of a rotational ground motion induced by earthquakes, explosions, and ambient vibrations. This domain is very interesting for researchers from a wide range of geophysical disciplines, including broadband seismology, strong motion seismology [8], earthquake physics [9, 10], seismic hazards [11], seismotectonics [12], geodesy [13], and for physicists using Earth-based observatories for detecting gravitational waves generated by astronomical sources [14–16]. Additionally, it is interesting for researchers of earthquake engineering, where seismic behavior of different engineering structures is investigated [17] to search for their optimal seismic design [18].

However, rotational seismology needs a new methodology and new instruments for more reliable recordings. A rigorous analysis of existing classical solutions delivered from instruments for seismological investigation [19] shows their limited usefulness for rotational events recording, mainly because of their sensitivity to linear motions, as well. For the abovementioned reason, in Section 3, we have summarized the main types of rotational seismometers that now exist, with comments on their usefulness. This description shows that a new approach taking advantage of the von Laue-Sagnac effect [20] is the most promising one. Finally, in Section 4, recent results regarding rotational events' detection, which are obtained in Poland, based on such approach are presented and discussed.

This chapter presents the description, the principle of operation, and the comparison of main technical parameters regarding requirements of rotational seismology. This will help seismologists and earth scientists involved in seismic studies to choose the best method for analyzing problems related to seismic rotation.

2. Seismic rotation in various continuum models

In all continuum models mentioned in this section, the wave motion, possibly with rotations, comes from the integration of motions and deformations of numerous small bodies, which form the given continuum. Exterior conditions or forces play only a minor role with the exception of a discontinuous surface. There exists a tension between two types of solid material's mechanical features such as rock mass and soil. In the first case, the continuous material can translate rectilinearly in its body. A mechanical impulse is translated in a medium as the elastic wave in two simultaneous ways: as compressional-dilatational deformations—the longitudinal wave and transverse shape distortions—the transverse wave. In the second case, both the continuous and grainy solid matter can also be translated into rotational motions in which we distinguish a rotation (named also rigid rotation, or simply a turn) and a symmetric-shape distortion—the shear. It should be underlined that in the elastic theory, there is no place for a rigid rotation, as it would introduce a complicated deformation state around the small body which turns. This theory explained so many phenomena; as a result, the idea of rotation was not accepted.

Recently, it becomes clear that the S-waves comprise rotations of axes perpendicular to the wave propagation. For the plane wave, a suitable relation was found by Igel et al. [21] joining this rotation velocity to transverse acceleration and phase velocity. Rotation curves were very similar to signals of a horizontal acceleration divided by twice the phase velocity (all measured in SI units). The relation was confirmed with a simple geometrical consideration of motions [22, 23]. The same results were found also in the seismic near field, where the spherical wave front was taken as a sufficient approximation [24, 25]. This aspect of the measured oscillations leads to one of the reasons to study rotations—the phase velocity may be easily assessed in this way. The same relation is valid for a love-type surface wave. Since measurements usually proceed on the Earth's surface, rotations about horizontal axis, as in Sv and Rayleigh waves, are not amenable to this method. Finally, various reasons can be found for the presence of rotations also in a P-waves' part of a seismic event trace. For instance, it must be noted that in reality, far from ideal conditions, P-waves are not entirely longitudinal, as well as S-waves bear not only shearing deformations.

It must be noted that this geometrical aspect of rotation does not solve all the problems. Microscopic motions and deformations may not be uniform and not have the same sense. Possible modes of their propagation have been formulated within the vast area of micromorphic studies (including micropolar variant of theories) led by mathematicians and physicists [26]. This branch of science is also named the generalized continuum theory. This trend, initiated by Cosserat brothers in 1909 [27], started to flourish decades later with works of Eringen [28], Nowacki [29, 30], and others. In the micromorphic approach, solid material is taken consisting of numerous small (not infinitesimal) bodies, often called shells, which are capable of deformations and rotations. Various modes of passing them from one body to the other have been proposed [31], and this leads to the independent rotational waves' concept [32, 33]. Individual small body in the undeformed state is usually seen as a cube; each of its sides may react not only to a vector of stress but also to their couple. Couple stress denotes a noncentric interaction between small bodies: a pair of forces act on the body's surface and their moment "tries" to distort or rotate the body. This theoretical small body is treated, in some works, as anisotropic layered entity [34].

In some works, joints between small bodies are treated as important elements in the deformation/propagation process. Among the particle-based numerical studies, there are such in which neighboring particles (small bodies) are linked by elastic bonds "…which can transfer elastic forces, both attractive or repulsive" and break if the distance between the pair exceeds a certain threshold. Such model allows shearing, twisting, and bending interactions between two bonded particles. Used in simulating fracturing, this model facilitates realistic results [35].

The contemporary studies on generalized elasticity can be found in the works of Grekova [36] as well as in the works of Neff et al. [37], which finally concluded that the rotations that are treated as antisymmetric motions/deformations should also be presented. Review on the topic has been prepared by Hadjesfandiari and Dargush [38], which concluded that when an elastic wave propagates through the medium considered in accordance with generalized elasticity concepts, its elements undergo angular motions. Despite the fact that the micromorphic approach is more visible in acoustics or in the studies on various materials than in the geophysics, recent [39–41] search for laboratory confirmation of the micromorphic concepts of seismic rotation yielded sound results, as well.

Original theory of rotational components of a seismic field has been developed by Teisseyre. Starting from elastic continuum with defects [42], he constructed a model of rotations and shears' generation and propagation on the base of constitutional bonds between the antisymmetric part of stresses, density of self-rotation nuclei and the stress moments. Finally, a linear continuum theory, incorporating asymmetric (symmetric plus antisymmetric) stress field, as well as shears and rotations, was introduced [43–45]. In this theory, rotation and shear propel each other. Developing stages of abovementioned theories helped to popularize the rotational seismology in the sciences and resulted in the monographs by [9, 10]. Teisseyre works also accomplished field studies with the use of original microarray of sensors [46–49].

Near-field rotation effects were explained by the action of a nonlinear deformational bend-rotation wave [50]. Several studies point to the possibility of rotational soliton waves (pulses) generated during an earthquake in the focal area, then propagating slowly along fault and triggering new events [51].

Beside verifications of theoretical concepts, dynamic measurements of a real earthquake wave field are urgently needed. These should be best done with special devices enabling detection and recording of rotational motions. Such devices generally named the rotational seismometers or seismographs appeared relatively not long ago, and description of their current state is given in the following section.

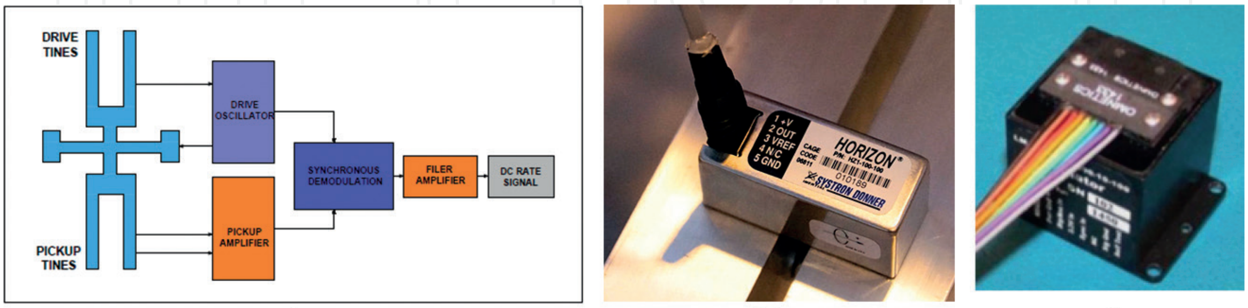
3. Current state of rotational seismometers

The main thing regarding the practical construction of a rotational seismometer is a proper description of the fundamental parameters required for such sensor. The general scope of such parameters for a rotational seismometer, which is used for recording signals connected with rotational seismic effects was formulated only 5 years ago in 2012 by [52] as the following four requirements: (1) independently; (2) assures portable size as well as stable work under changing ambient conditions (temperature, humidity, vibration, pressure,…); (3) uses independent power supply that assures autonomous work; and (4) protects measuring rotation rate with an amplitude of the order of 10−7 rad/s at a frequency range between 0.01 and 0.1 Hz. Moreover, (1) the device should be completely insensitive to linear motion or has possibility to measure linear and rotational movements, and the similar requirements were also described for an earthquake engineering area of rotational seismology interest; the first three were the same and only the last one differs in a measuring range containing amplitude up to a few rad/s at a frequency range up to 100 Hz [53].

A formulation of main requirements for rotational seismometers regarding the rotational seismology is useful for a review of available current solutions in this area. Generally, all used devices can be classified as mechanical, acoustical, electrochemical, and optical devices.

The mechanical systems were historically first used, and they can detect rotation in two ways: directly and nondirectly. The directly rotation detecting systems represent modern mechanical rotational sensors based on a highly miniaturized technique named micro electro-mechanical systems (MEMS). Originally, this technique was developed for manufacturing integrated accelerometers for airborne applications. Rotational seismometers in this technique, usually called MEMS gyro, resemble microelectronic systems in terms of size and production methods. MEMS gyros use the Coriolis effect, and each type of these sensors currently uses vibrating proof masses, which generally vibrate at a high frequency. If the sensor rotates in an inertial space, a Coriolis force is induced on the proof mass. The Coriolis effect generates a vibration in an orthogonal plane, and amplitude of the orthogonal motion can be detected. One can distinguish the following technological structures of MEMS gyros [54]: tuning fork gyros (TFG), hemispherical resonating gyro (HRG) or wine glass resonator gyro, vibrating-wheel gyros, and Foucault pendulum gyros. The biggest advantage of these devices is their mass production at low cost with a small form factor. Systron Donner Inertial (USA), using this technology, manufactured a compact, high reliability, solid-state angular rotation sensor named Horizon™ [55]. It uses vibrating quartz tuning tines to sense rate, acting as a Coriolis sensor, coupled to a similar fork as a pickup to produce the rate output signal (**Figure 1**). Aligned with their support fixtures and frames, these paired tines are fabricated from thin wafers of single crystal piezoelectric quartz.

Another company, Gladiator Technologies Inc., offers six models of MEMS gyros, which are very small, portable and of ultra-low power consumption (see **Figure 1c**) [56]. Nevertheless, the products by both abovementioned companies do not fulfill requirements for entirely rotational seismology as shown in the study, and their parameters are listed in **Table 1**. They are suited solutions as an additional device, which can be used for laboratory investigation, mainly for a rotational seismology engineering application (see example [57]).



a) b) c)

Figure 1. MEMS gyros: (a) scheme of operation, (b) the Horizon™ MEMS angular rate sensor HZ1-100-100, and (c) Gladiator Technologies Inc. model G200D [56].

Parameter	Unit	HZ1–200-100 [55]	G200D [56]
Axial		Uniaxial	Triaxial
Sensitivity[1]	rad/s/√Hz	4.4×10^{-4}	8.7×10^{-5}
Maximum rate	rad/s	3.49	5.23
Frequency band	Hz	>60	Bandwidth 200
Operating temperature	°C	−40 to +71	−40 to +85
Calibration (S.F. dev. from 20/22°C)	%/°C	<0.08	<0.05
Shock survival	g	200	500
Power supply	VDC	8–12	3.1–5.5
Supply current	mA	<20	<300
Power consumption	W	0.24	0.30
Weight	kg	<0.06	<0.031
Dimensions (L × W × H)	mm	58.3 × 25.3 × 25.3	25.4 × 25.4 × 25.4

[1] An output noise for SNR = 1 also defined as a resolution @ 1 Hz in (rad/s).

Table 1. The main parameters of the rotational sensors in the MEMS technology.

The mechanical systems working in an indirect way use defined pairs of classical seismometers. The first of them named Rotaphone based on commercially available geophones arranged in parallel pairs has been mounted on a rigid frame. They have been applied to record seismic events induced by natural sources (weak earthquakes with measured rotation about 10^{-6} rad/s) and anthropogenic sources (blasts with measured rotation about 10^{-3} rad/s) [24, 59–61]. They can be described as a recording system of ground velocity and rotational rate at a point. In order to obtain the rotational rate accurately, special gradients of the ground velocity wave field have to be measured. In 2010, a system named 6DOF (six-degree-of-freedom, see **Figure 2a**) was developed containing eight horizontal and one vertical geophones SM-6 (Sensor Nederland, B.V.), and it was mounted onto a cubic-shaped metal frame. It gives the possibility of recording three Cartesian components of ground velocity and three rotation rate components about Cartesian axes. Finally, the system named Rotaphone-D used 16 (eight horizontal and eight vertical) SM-6 geophones mounted around disc with a separation of the paired geophones of 0.4 m, as shown in **Figure 2b** [58]. The separating distances were chosen to correlate with a specific wavelength of interest. Data from **Table 2** show that Rotaphone is close to fulfilling

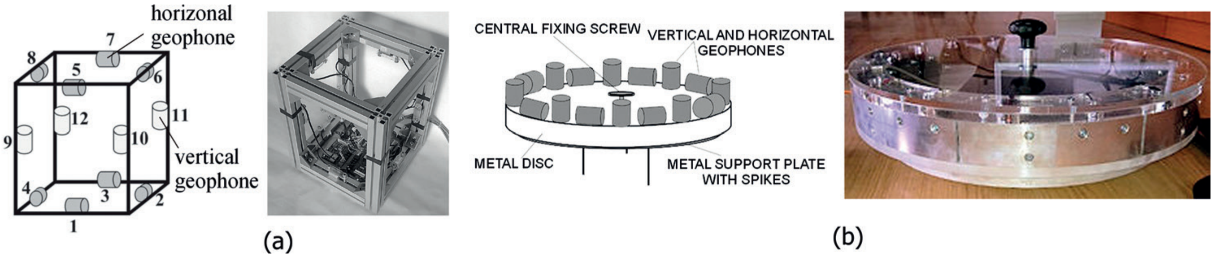


Figure 2. Schematic and general view of Rotaphones: (a) 6DOF prototype II [24] and (b) Rotaphone-D [58].

Parameter	**Unit**	**Rotaphone**	
		6DOF [24]	**D [58]**
Frequency range	Hz	2–60[1]	2–80[1]
Sampling frequency	Hz	250	250
Sensitivity[2]	rad/s	2.16×10^{-9}	3.77×10^{-9}
Maximum rate	rad/s	2.87×10^{-1}	3.17×10^{-2}
Dynamic range	dB	120	120
Operating temperature	°C	−20–40	−40–100[3]
Weight	kg	9.5	15.3
Dimensions (L × W × H)	mm	350 × 350 × 430	445[4] × 112
Natural frequency	Hz	4.5	4.5
A/D converter (dynamic)	Type (Bit)	4 × Tedia (28)	1 × EE & S (24)

[1] The instrument generally operates in a high-frequency range (above the natural frequency of the sensors used).

[2] Understood as an expression for the smallest signal that can be resolved ([19] p. 79).

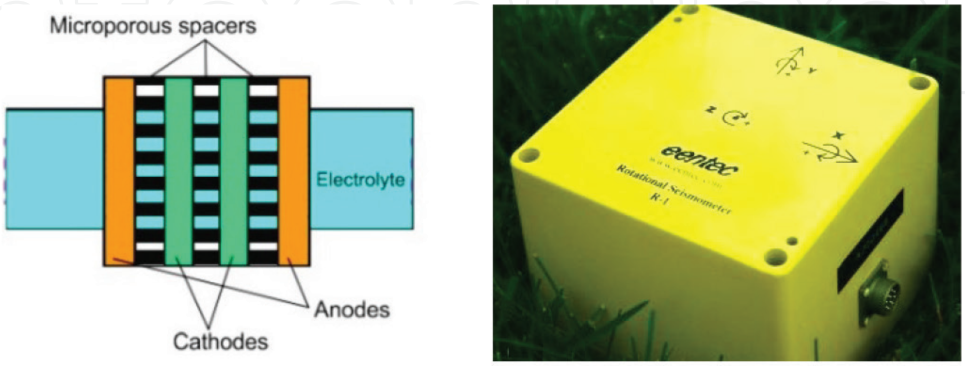
[3] Data for geophone SM-6.

[4] Disc diameter.

Table 2. The main parameters of Rotaphone rotational seismometers.

the requirements for seismological applications. However, their frequency ranges are still too narrow, and they should be treated as short-period systems. The other type of mechanical rotational seismometer operating in an indirect way named TAPS is described later.

The electrochemical rotational seismometers use molecular electronic transfer (MET). One can point out R-1 and R-2 from Eentec (USA) as representative in this group. Sensor construction is based on the electrochemical transducer contained in a channel filled with an electrolytic solution [63]. It includes four fine platinum mesh electrodes separated by microporous spacers (**Figure 3**). The fluid motion is converted into an electrical signal by using the ions' convective diffusion in electrolyte. The rotational seismometer has a toroidal channel filled



a) b)

Figure 3. The electrochemical rotational seismometer: (a) schematic diagram of the MET transducer and (b) the Eentec R-1 [62].

with electrolyte. If the sensor rotates, liquid is forced through the MET sensor placed across the channel, converting liquid motion into electrical output. The parameters of R-1 and R-2 (see **Table 3**) are very close to fulfilling all technical requirements for entirely rotational seismology for both seismological and engineering applications.

Nevertheless, measurements carried out in the last decade showed reasonable results only for higher frequencies. The test with model R-1 showed its linear sensitivity equal to 6×10^{-5} rad/s/(m/s^2) and a 2% cross-axis sensitivity [65]. The calibration quality casts also doubt in lower frequency range (<1 Hz) [66] since the frequency response does not have a flat shape, and at frequencies above 1 Hz, the dynamic range is only 80 dB [56]. Moreover, the measurement [52] in a temperature range of 20–50°C revealed deviations in the scale factor from the nominal value equaling 27 and 18% for R-1 and R-2, respectively, which suggests that this technology needs to be improved. In spite of the abovementioned disadvantages of the electrochemical seismometers, the R-1 model has recorded several hundreds of local earthquakes and two explosions in Taiwan [67].

The sensors designed by Applied Technology Associates (USA) [68] represent another technology with fluid. These devices operate based on the physical principle named magnetohydrodynamics (MHD). The main part of the sensing is a rotational proof mass containing conducting fluid as well as a permanent magnet that is fixed to the sensor case (**Figure 4**). The case-fixed magnetic flux moves through the inertially fixed conducting fluid with relative velocity as the case is rotated with the angular velocity Ω. This relative velocity between the magnetic flux and the fluid conductor generates a radially oriented electric field. This interaction or the MHD effect produces a voltage difference between the electrode surfaces that may be amplified by a transformer or other active electronic amplifier configurations. The signal (voltage output) is proportional to the angular rate Ω [70].

Parameter	**Unit**	**R-1 [62]**	**R-2 [64]**
Axial		Triaxial	Triaxial
Sensitivity[1]	rad/s/√Hz	1.2×10^{-7}	0.6×10^{-7}
Maximum rate	rad/s	0.10	0.40
Dynamic range	dB	110	117
Frequency band (extended)	Hz	0.05–20 (0.03–50)	0.03–50 (0.01–100)
Scale factor[2]/optional	V/rad/s	50/ 2×10^2	50/5–2×10^2
Operating temperature	°C	−15 to +55 (extended −45 to +55)	
Shock survival	g	200	200
Power supply	VDC	9–14	9–18
Power consumption	W	0.28	0.54
Weight	kg	1.0	1.5
Dimensions (L × W × H)	mm	120 × 120 × 90	120 × 120 × 100

[1] An output noise for SNR = 1 also defined as a resolution @ 1 Hz in (rad/s).

[2] Understood as the gain of the instrument ([19] p. 79).

Table 3. The main parameters of rotational seismometers R-1, R-2.

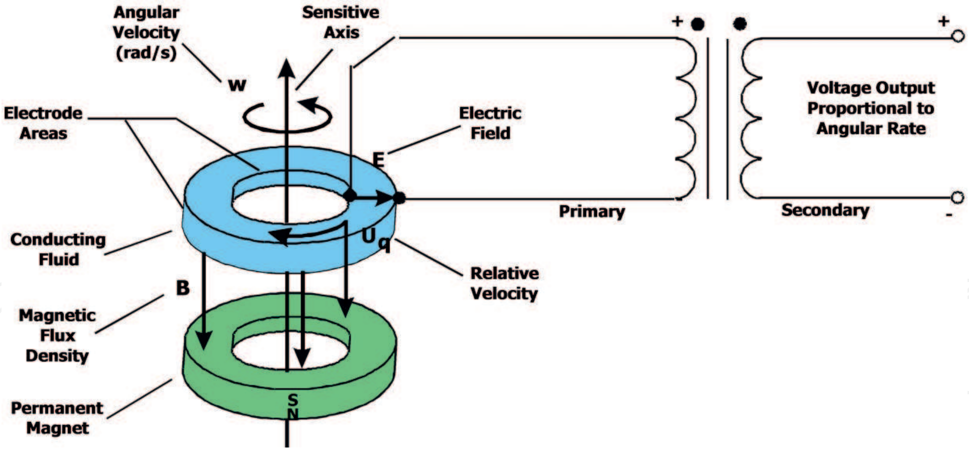


Figure 4. Principle of magnetohydrodynamics effect of a conductive fluid in the presence of a magnetic field [69].

At ATA website, one can find two models of angular rate sensors: ARS-14 and ARS-15 (**Figure 5a** and **b**), where ARS-14 is able to measure angular motions as low as 30 nanoradians. Nevertheless, it should be emphasized that the sensor construction in MHD technology limits the frequency bandpass because the lower corner frequency is a function of parameters such as conductive fluid and fluid proof geometry. The upper value of a frequency bandwidth is usually determined by a signal processing unit. The ATA model Proto-SMHD (**Figure 5c**) which can be found in [69] is interesting because it is the device suited for microseismic signal detection. Nevertheless, in the literature, there are no examples of these sensors application for recording effects connected with rotational seismology.

The last group is the optical systems operating based on the Sagnac effect [72] (more precisely, the von Laue-Sagnac effect). They are interferometric devices which use light for rotation detection. For the abovementioned reason, they have nonfrequency dependence of an output signal. The optical rotational seismometer exists in laser (RLG) or fiber (FOG) technology.

The ring laser gyroscopes (RLGs) detect the Sagnac beat frequency of two counter-propagating laser beams, which are propagated along a rectangular or triangular perimeter (**Figure 6a**). In the RLG, two coherent laser beams of an equal wavelength are generated. They are introduced into the system, and they circulate around the closed cavity in opposite directions. If the whole

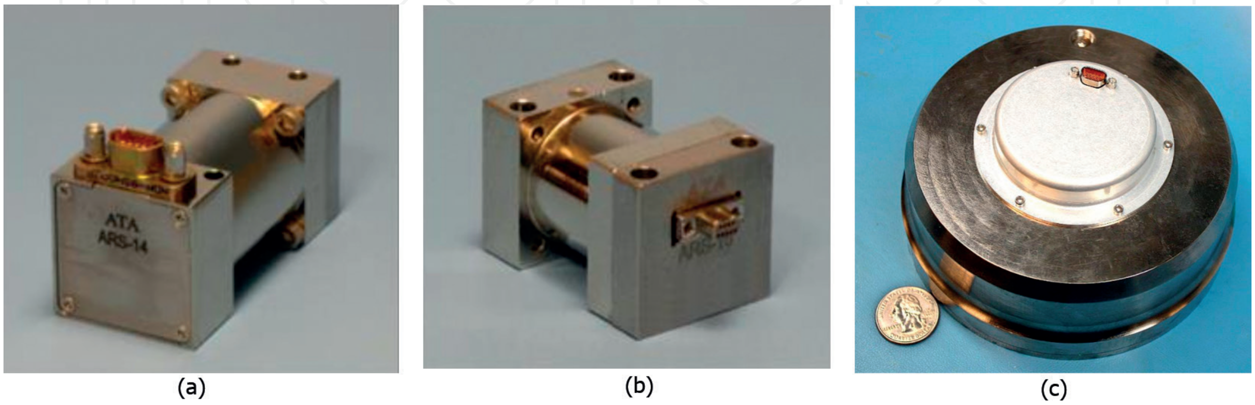


Figure 5. Various models of angular rate sensors by ATA: (a) ARS-14, (b) ARS-15 [69], and (c) Proto-SMHD [71].

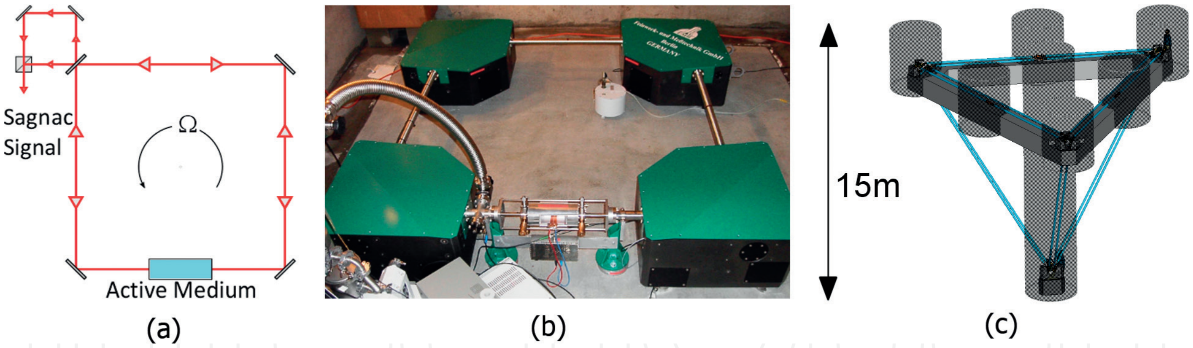


Figure 6. The ring laser gyroscope: (a) principle of operation, (b) GEOSensor [73], and (c) ROMY project—schema of the construction [74].

system rotates, the effective cavity length between the counter-propagating laser differs and a frequency splitting of two counter-propagating optical waves is obtained. The Sagnac frequency, δf, is described as:

$$\delta f = \frac{4A}{\lambda P} n\Omega \tag{1}$$

where A and P are the area and perimeter enclosed by the beam path, respectively; λ is optical wavelength of the laser oscillation, Ω is vector of angular velocity at which the instrument is turning; n is normal vector to the laser beam plane.

The RLGs have been applied for the rotational seismic events recording since the 1990s. The first ring laser gyroscope named “C-I” was assembled in the University of Canterbury in New Zealand in 1988–1990, and their parameters can be found in [75]. The next version was the ring laser “C-II” [76]. Its cavity with an area of 1.0 m^2 was equipped with an ultra-high vacuum between metal flanges and a solid piece of Zerodur (glass ceramic with a low thermal expansion coefficient). The ring laser gyro with an area of 16 m^2 and named ring laser “G” was assembled at Wettzell, Germany in 1998–2001. The bigger ring laser gyro named “UG-1” is installed in Cashmere Cavern, New Zealand. Its laser cavity has an area of 367 m^2. Especially, for seismological application, the ring laser “GEOsensor” has been designed and assembled at Wettzell, Germany. The “ROtational Motions in seismologY (ROMY)” [74] is a big project under the leadership of Igel. During the project, an apparatus consisting of four individual triangular ring lasers arranged in the shape of a tetrahedron with 12 m of length on each side (**Figure 6c**) will be used. The ROMY’s constructors expect sensitivity in the range between 0.02 and 0.05 × 10^{-12} rad/s [74]. **Table 4** summarizes the fundamental parameters of various RLG systems. As one can see, there are not so many installations of RLGs, mostly because of their high cost and high sophistication involved in installation. They are very sensitive to external local disorders such as temperature, noise or pressure. Due to their dimensions and special isolation, they are unable to be transported.

Regarding the practical application of the optic rotational seismometer in fiber technology, the authors have knowledge only about one, other than their solution described in the next section, from iXBlue (France) named blueSeis-3A. Its parameters are available on web page http://www.blueseis.com as: portable, three-component system with 0.01–100 Hz broadband,

RLG name	Area (m²)	Sensitivity (rad/s/√Hz)
C-II	1	7.2×10^{-10}
G	16	9.0×10^{-11}
UG1	367	4.7×10^{-12}
GEOsensor	2.56	4.5×10^{-11}
ROMY	249	$(0.02–0.05) \times 10^{-12}$

Table 4. The sensitivity of different RLG systems used for rotation detection.

low noise <20 nrad/s/√Hz, high dynamic range, Plug & Play, no calibration needed, maintenance-free, embedded digitizer, GNSS time stamping, and so on.

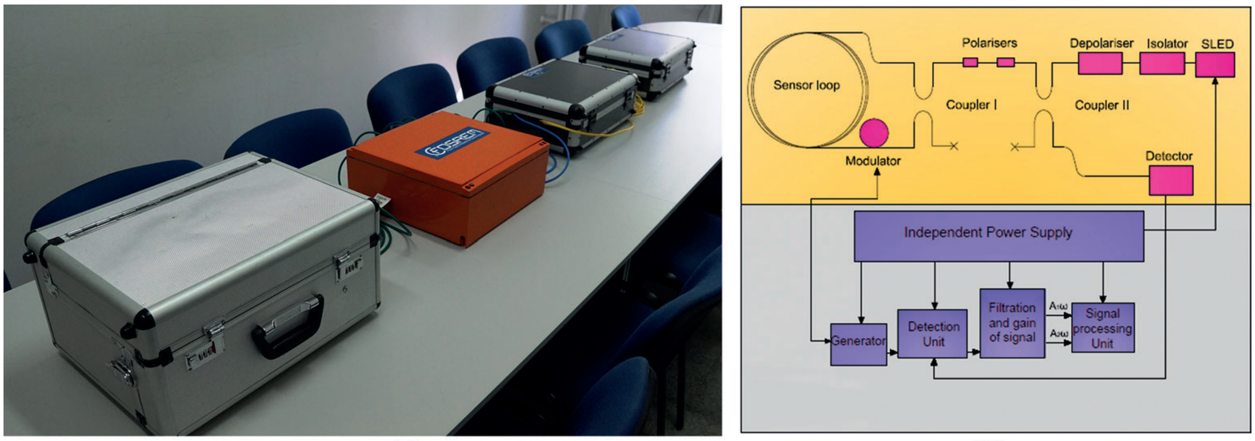
4. Comparison of results obtained from measurements using optical and mechanical rotational seismometers

Finally, in this section, we compare results obtained from two rotational seismometer systems installed for a continuum measurement in Książ, Poland seismological observatory—the Fibre-Optic System for Rotational Events& phenomena Monitoring (FOSREM) based on a fiber-optic gyroscope and the Twin Antiparallel Pendulum Seismometers (TAPS) based on microarray of mechanical seismometers.

FOSREM is a new version of Autonomous Fibre-Optic Rotational Seismometer (AFORS), which was used between 2007 and 2017 in Książ. Each FOSREM contains three basic parts, which work interdependently: rotational seismometers FOSREM-XX type, data transmission unit (DTU), and power communication unit (PCU), see **Figure 7a**. The heart of the FOSREM—the rotational seismometer FOSREM-XX type—contains an optical head for generating the phase shift proportional to the detected rotation rate as well as the electronic part for data processing (**Figure 7b**). The optical head is constructed according to a so-called minimum configuration of FOG [77]. The light beam emitted by the source SLED is halved by the coupler and propagated to the sensor loop where two beams are propagating in the opposite direction. The sensor loop has been constructed by winding of 5 km SMF-28e + fiber in a double-quadrupole mode on a 0.215 m duralumin circular frame with attenuation equal to 0.35 dB/km@1310 nm [78]. The two polarizers mounted in line between two couplers assure the same optical path for the both counter-propagating waves. In order to shift the operating point to quadrature point of operation, the phase modulator at the end of the sensors loop was applied. The detected rotation rate is obtained by a specially designed system of filters (see **Figure 7b**), which properly select and amplify the first ($A_{1\omega}$) and the second ($A_{2\omega}$) amplitude of harmonic detected output signal u(t). The electronic part calculates the rotation rate Ω. Applying the following equation [79]:

$$\Omega(t) = S_o \tan^{-1}\left[S_e u(t)\right] = S_o \tan^{-1}\left[S_e\left(\frac{A_{1\omega}}{A_{2\omega}}\right)\right], \tag{2}$$

S_o and S_e are optical and electronical constant of the interferometer, respectively.



(a) (b)

Figure 7. FOSREM: (a) from left: rotational seismometer FOSREM-SS, FOSREM-BB, data transmission unit (DTU), and power communication unit (PCU); (b) schematic diagram of FOSREM-XX, top—optical head, bottom—electronic part.

In order to continuously collect data, the special software has been applied which enables the recording of only values of signals, which gained the assumed level of event [79]. The DTU enables a synchronic data recording from up to three rotational seismometers with their collection on a local disc as well as a transfer to PCU via fiber link. The PCU transmits the recorded data using Internet or GSM/GPS to a dedicated server FOSREM with a rate up to 100 Mbps. Furthermore, PCU enables the device to run for a minimum of 12 h.

Table 5 summarizes the main parameters of three fiber systems used by our team. They differ in sizes, mechanical protections, and measuring range. AFORS and FOSREM-SS are suited for seismological investigation, but they cannot be applied for an engineering application because they have limited detection of the maximum rotation rate. FOSREM-BB due to the optimized optical part and the special software solution allows for the rotation rate detection in a wider range of signal amplitude up to 10 rad/s.

AFORS and FOSREM may work even when tilted; moreover, when used in continuous mode, they may record the tilt. They are portable, easy to assemble, as well as fully remotely controlled via Internet. It makes them as suitable devices to work with in a continuous mode for a very long period of time (weeks, months, and even years). For these reasons, AFORS (in 2007) and two FOSREM-SS (in 2017) have been mounted in seismological observatory in Książ in order to gather data connected with rotational seismic events.

As a reference system, the TAPS has also been mounted in Książ. TAPS is a mechanical rotational sensor constructed by a group from Institute of Geophysics PAS, Poland [80]. It is a set of two antiparallel pendulum seismometers (SM-3 type, Russia) mounted at one axis and connected parallel with opposite orientations (**Figure 8**). If the ground motion includes the displacement $u(t)$ and the only vertical rotation $\Omega(t)$, the electromotive force (EMF) $f(t)$ recorded by each SM-3 contains the component of displacement $\pm u(t)$ and the rotational motion $\Omega(t)$ multiplied by the proper length of the pendulum l [80]:

$$f_{L,R}(t) = \pm u(t) + l \cdot \Omega(t), \tag{3}$$

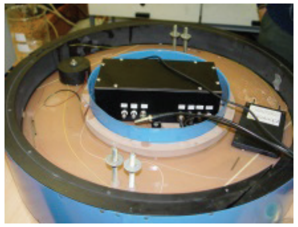
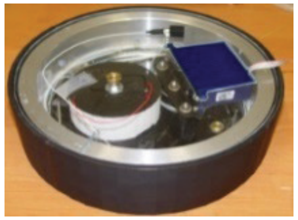
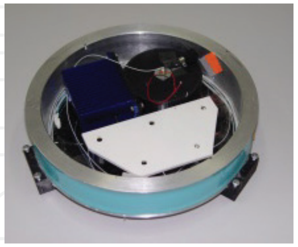
	Unit	**AFORS**	**FOSREM-SS**	**FOSREM-BB**
Picture of the optical head				
Optical losses	dB	14.47	16.89	16.37
Theoretical sensitivity	rad/√Hz	4×10^{-9}	2.18×10^{-8}	2.06×10^{-8}
Frequency bandpass	Hz	0.83–106.15	DC–328.12	
Accuracy in bandpass	rad/s	$(0.48–6.1) \times 10^{-8}$	$3 \times 10^{-8}–1.6 \times 10^{-6}$	
Angle Random Walk	rad/√Hz	1.2×10^{-8}	3.2×10^{-8}	4.9×10^{-8}
Bias instability	rad/s	1.1×10^{-8}	1.6×10^{-8}	0.8×10^{-8}
Dimension	mm	$700 \times \phi = 160$	470 × 360 × 230	360 × 360 × 160
Weight	kg	~18	~10	
Operating temperature	°C	0–50		
Measuring range	rad/s	$4 \times 10^{-9}–6.4 \times 10^{-3}$	$2 \times 10^{-8}–0.06$	$2 \times 10^{-8}–10$

Table 5. The main parameters of rotational seismometers AFORS and FOSREM type.

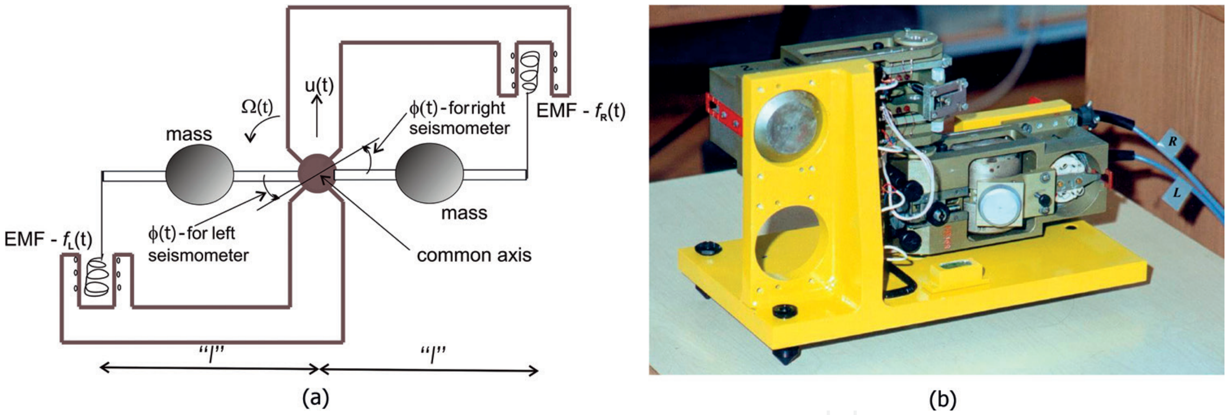


Figure 8. The TAPS rotational seismometer: (a) scheme [81] and (b) general view. ϕ(t) is the angle of rotation for a given pendulum.

where the signs "+" and "−"represent right (R) and left (L) seismometers, respectively. From the above, the rotational and translational components can be obtained from the sum and difference of two recorded signals, respectively as:

$$\Omega(t) = \frac{1}{2l}\left[f_R(t) + f_L(t)\right] \text{ and } u(t) = \frac{1}{2l}\left[f_R(t) - f_L(t)\right]. \tag{4}$$

Due to the rotational rate determination from the sum of the measured signals, the inaccuracies and difficulties can be observed. If the two antiparallel seismometers are precisely the same, the sum of the signals is proportional to the rotation rate. Taking into account the practical aspects of the pendulums, they are never identical. There is a difference in measured signals, which is widely described in [81]. As a result, it causes noise in the measurements of one order of magnitude greater for TAPS than for SM-3. In practice, the attenuation characteristic differences of the pendulum seismometers equal to a few per cent can generate a false rotational signal, especially if the rotational component is small in comparison with the translation one. There are different solutions for eliminating this problem, unfortunately with limited efficiency. Nowadays, one can find the records obtained by TAPSs including rotational motions during earthquakes [46, 82, 83] and seismic activity connected with artificial detonation in mine regions [84–87]. Unfortunately, this system does not fulfill the requirements for seismological applications of the rotational seismology due to the limited frequency bandpass as well as the measuring range.

In order to illustrate the rotational phenomena in the seismic wave field, we present in **Figure 9** seismograms of seismic events recorded in Książ. This earthquake was felt around Jarocin town and radiated the seismic field with clean rotational components. The distance to the source was of about 200 km. We show the unfiltered diagrams of the whole waveforms, but with a low-pass filtration which cut the spectrum at about 12.5 Hz. We decided to use these analyses in order to remove a high-frequency noise. The presented data allow for the comparison of rotational signals obtained by two different devices—TAPS and AFORS which have totally different idea of design. The compatibility between these two sensors is disturbed by differences in their spectral characteristics [86]. Unfortunately, we have observed noncorrelation between TAPS and AFORS for the same set of recorded events. For this reason, we decided to install in Ksiaż two FOSREM-SS in order to obtain more precise data.

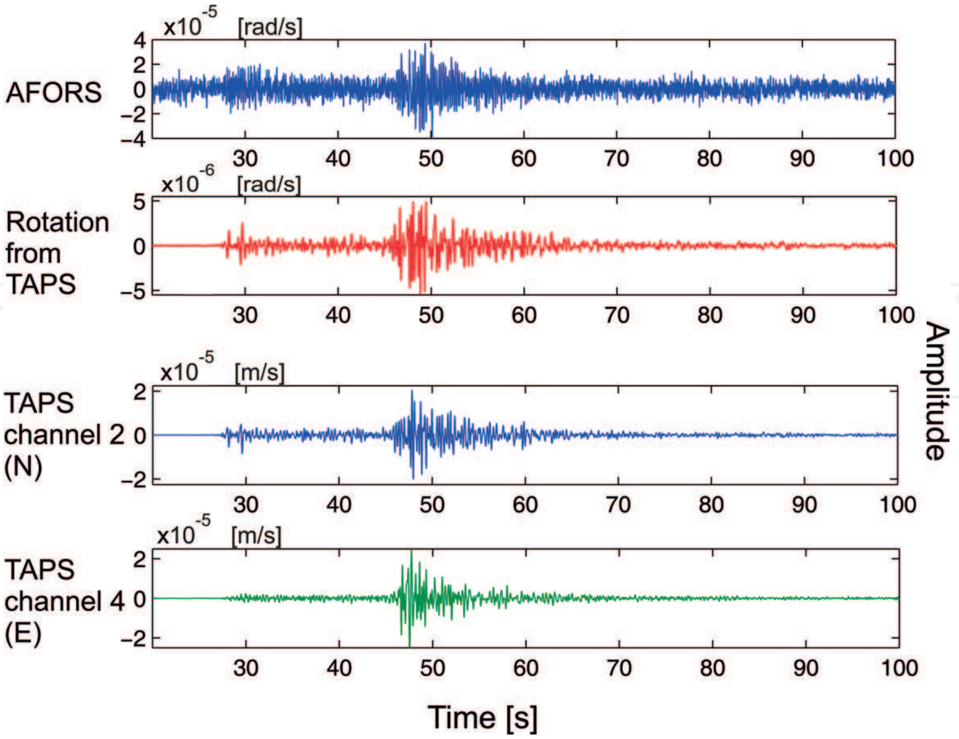


Figure 9. M = 3.8 earthquake near Jarocin, Poland, 2012.01.06, 15:37:56. The uppermost window shows a rotation signal obtained from the AFORS. Plots of the rotation labeled "from TAPS" were obtained with the array method—two TAPSs were used.

5. Conclusions

Several advanced technologies of rotational sensors began to develop due to rapid increasing interest of rotational seismology. Nevertheless, the strict requirements for this scientific discipline are not fulfilled in many cases. From the presented review, it is clear that probably technologies based on optical interferometer are the most promising ones. However, it can be concluded that theoretical and mainly experimental studies of the rotational seismology are still in the initial state of development. Future works should be channeled toward acquiring a large amount of reliable experimental data recorded by different devices regarding rotational events from long distance sources (earthquakes generated in natural ways) as well as from short distance sources (the shocks generated in an artificial way—the explosions in a mine region). Such data are very handy for the confirmation of any theoretical investigation in the area of rotational seismology.

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