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Corresponding Author	Family Name	**Leugoud**
	Particle	
	Given Name	**Robert**
	Suffix	
	Organization	
	Division	
	Address	St. Louis , MO, USA
	e-mail	rleuogoud@eentec.com
Author	Family Name	**Kharlamov**
	Particle	
	Given Name	**Alexei**
	Suffix	
	Organization	
	Division	
	Address	St. Louis , MO, USA
	e-mail	
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ORIGINAL ARTICLE

Second generation of a rotational electrochemical seismometer using magnetohydrodynamic technology

Q1 **Robert Leugoud · Alexei Kharlamov**

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Abstract Rotational seismometers have many applications. Some require a low self noise with a lower clip specification. Others require many different bandpass specifications, from very low to higher frequencies. The principles of the eentec second-generation R-2 electrochemical triaxial rotational seismometer can achieve many features for various applications. Combining the use of the sophisticated magnetohydrodynamic (MHD) technology increases the current and future features. Principles of the MHD technology used and the many advantages it has in a rotational seismometers are described.

Keywords Rotational seismometer · eentec · 6 DOF seismometers · R-1 · R-2

1 Introduction

The past years have witnessed revolutionary changes in rotational seismology resulting from the combinations of greatly enhanced capabilities of geophysical instrumentation and appearance of first commercially available field rotational seismometers. Such sensors could be employed in areas of high seismicity, where the translational and rotational motions have comparable orders of magnitude. This is especially true for the near zones of strong shallow earthquakes. The measurement of this frequently observed rotational motion in the vicinity of the epicenters of strong earthquakes will be extremely valuable in earthquake engineering, since buildings and other structures are generally quite vulnerable to torsional stresses.

A variety of angular sensors are commercially available. Some of these feature quite excellent resolution, with a frequency band extending to DC. Rather than being true rotational seismometers, such devices are, in fact, very low frequency accelerometers that measure the tilt of their foundation relatively to the local gravity vector. With any single-point measurement, gravity is indistinguishable from any other inertial acceleration. These instruments are inherently incapable of separating pure rotation from horizontal accelerations.

A natural method of measuring "pure rotations" would be to use two identical vertical seismometers (or accelerometers) placed a certain distance from each other, so that the rotational motion can be derived from the difference between the two outputs. Interestingly enough, the concept for a pendulum-based rotational seismometer and its use to correct horizontal seismic signals was put forward a century ago by Prince Boris B. Golitsyn. Starting with Golitsyn's early experiments, and in many subsequent attempts, the resolutions attained were very poor, since even the smallest differences between the two instruments can lead to large errors. Indeed, it was shown that in order to achieve a tilt measurement accuracy of even

R. Leugoud (✉) · A. Kharlamov
Q2 St. Louis, MO, USA
e-mail: rleuogoud@eentec.com

10^{-7} rad, the maximum acceptable difference between the two seismometer's (or accelerometers) characteristics must be about $10^{-4}\%$, a consistency which is practically impossible to realize.

There are also a few "true" rotational sensors, i.e., those which measure angular motion and are insensitive to translational accelerations. The best known and most accurate types are discussed in the following subsections.

1.1 Magnetohydrodynamic angular rate sensors

The typical passband for these sensors is from several hertz to about 1,000 Hz (Applied Technology Associates). Its angular resolution at the low cutoff frequency is ~10^{-7} rad It is unlikely that this device's passband can be extended even to a period of 100 s.

2 MEMS-based gyros

These instruments, based on a micromachined sensor design, are specified to put out a signal proportional to the angular velocity in the 0 to 100 Hz band, with a resolution of about 10^{-5} rad/s. The instrument's sensitivity to translational acceleration is specified as 10^{-4} rad/s/g, which is several orders of magnitude less than the desired value. In addition, the manufacturer's specified short-term stability (0.05% over 100 s at constant temperature) and long-term stability (1% over 1 year) are inadequate for seismic applications.

2.1 Fiber optic rate gyroscope

While having better short and long term stability than microelectromechanical (MEMS)-based sensors, their resolution in angular velocity is comparable to the above sensors, although large lab units are quite accurate.

2.2 Electrochemical or molecular-electronic sensors

In the core of such seismometer (Abramovich et al. 1999) is an electrochemical transducer, which is shown in Fig. 1. The transducer is generally contained in a channel (1) filled with a specially prepared electrolytic solution. It consists of fine platinum mesh electrodes — two anodes (2) and two cathodes (3) — separated by thin, microporous polymer spacers (4). This stack is tightly held together by housing (5). The motion of the fluid caused by an external acceleration must be converted into an electrical signal. One way of achieving this is by using the convective diffusion of the ions in the electrolyte.

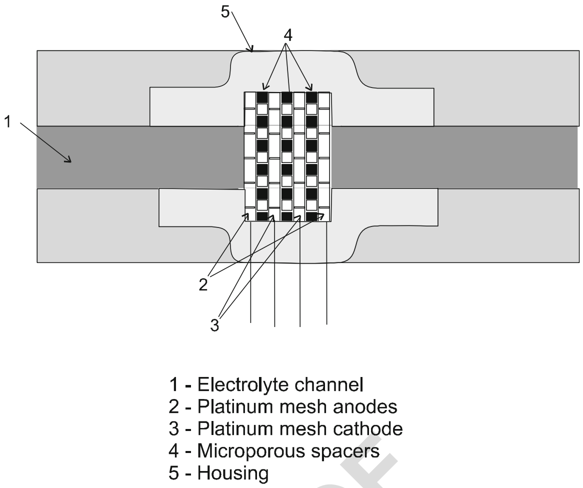


Fig. 1 Electrochemical transducer

When a small dc offset is applied between the anodes and cathodes, the flow of ions of each type is given by the following expression:

$$j_a = -D \cdot \nabla c_a + q_a \cdot c_a \cdot \mu \cdot E, \qquad (1)$$

where D is the diffusion coefficient, μ is mobility, c_a is the concentration of active ions, and E is the electrical field vector. Since the strong electrolyte is an excellent conductor, the electric potential drops rapidly in the vicinity of the electrodes, and there is no electric field, E, in the bulk of the fluid. The second term in Eq. 1 can therefore be ignored. Thus, the application of a bias voltage results only in a concentration gradient. This is in contrast both to conductors, in which the current is driven by the external electric field, and to semiconductors, in which both the field and the concentration gradient determine the currents.

An external acceleration, a, along the channel creates a pressure differential, ΔP, across the transducer, which forces the liquid in motion with a volumetric velocity, v. This flow of electrolyte entrains ions and causes an additional charge transfer between the electrodes:

$$j'_a = v \cdot c_a \qquad (2)$$

The total current from active ions, in the presence of acceleration, will thus be:

$$j_a = -D \cdot \nabla c_a + v \cdot c_a \qquad (3)$$

The transducer thus generates an electrical signal in response to an input motion. The symmetric geometry of the transducer cell (two anodes and two cathodes in opposite direction) ensures its linear behavior over a wide range of input signals (Abramovich et al. 2001).

With a highly concentrated electrolyte, the electric field is non-zero only in a narrow boundary layer adjacent to the electrodes. In this case, the electric current is fully determined by the diffusion. If such a transducer cell is incorporated into a toroid completely filled with liquid (Fig. 2), no translational acceleration will put the fluid in motion but an angular acceleration around the axis of the toroid will cause the liquid to move. This simple device is completely indifferent to any translational motion.

The rotational sensor (Fig. 2) used in the eentec R-1 seismometer consists of an electrolyte-filled ceramic toroid 1 with a velocity-output electrochemical transducer 2; the bulb 3 is necessary to compensate for temperature expansion of the electrolyte.

Electrochemical transducers are characterized by a very high conversion coefficient of mechanical motion into electrical signal. That is why the electronics noise plays a noticeably smaller role in the total signal-to-noise ratio than in rotational sensors mentioned above. In addition, this results in low power consumption, typically several times smaller than in any other rotational seismometers.

Rotational seismometers have many applications. Some require a lower self-noise or higher clip level specification. Others require many different passband specifications, from very low to higher frequencies, or flatter velocity response. R-1 seismometer was the first field rotational seismometer, not very flexible, has limited passband from 20 s to 20 Hz, limited dynamic range and clip level (Fig. 3). And, in addition, each sensor has to be individually calibrated on a special rotational shake-table, leaving the end customer without an option of checking its response in the field, like in all translational seismometers that have calibration coil and input. For this reason the R-2, a second generation rotational seismometer was developed. It incorporated customer inputs over the years plus corrected various design problems of the original unit. This latest unit has extended dynamic range, lower noise, higher clip-level and also equipped with the Magnetohydrodynamic (MHD) calibration input. Describe below are the physical principles of its operation.

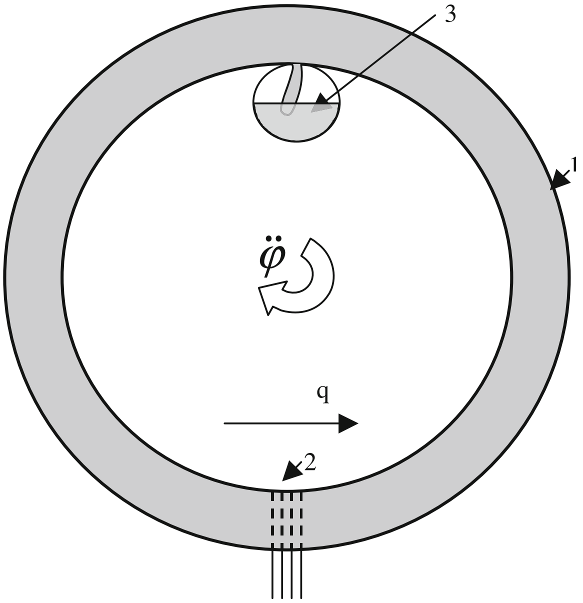


Fig. 2 Simplified sketch of an electrochemical rotational sensor

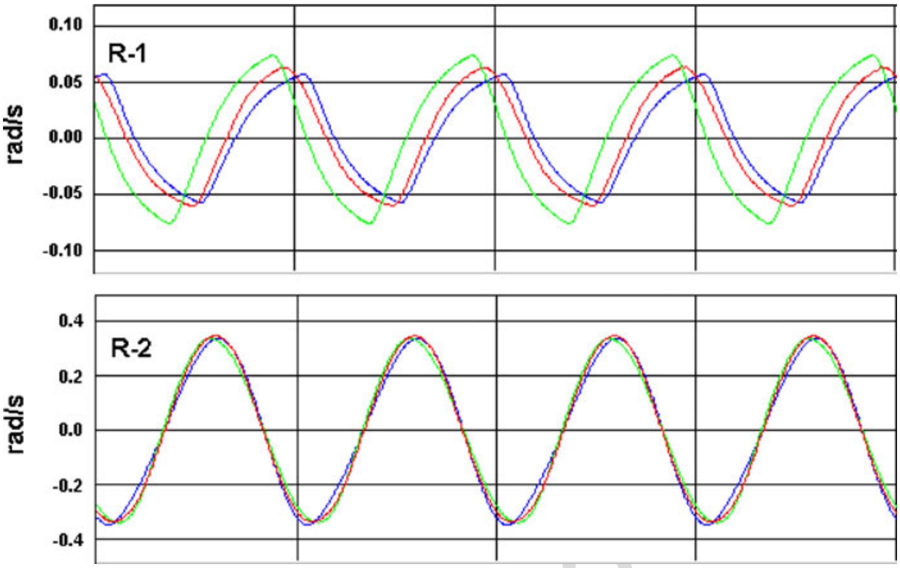


Fig. 3 Outputs about clip level of a typical R-2 compared to R-1 (20 Hz sine wave)

3 Noise and clip level

The power spectral density (PSD) of the self noise of the electrochemical rotational seismometer in terms of the angular acceleration $\ddot{\phi}$ can be described in the equation

$$\left\langle \ddot{\phi}^2 \right\rangle_\omega = \frac{2R_hkT}{(2\rho S)^2} \tag{4}$$

where S is the effective area circumscribed by the sensor, R_{h} is the hydraulic impedance of the sensor channel, k is Boltzmann's constant, ρ is the electrolyte density, and T is temperature.

Increasing the size of the sensor substantially increases the packaging required. The R-1 was designed many years ago with the help from M. Trifunac, V. Graizer, and V. Kozlov determining the optimal size versus noise because the size of the toroid directly effects the sensitivity and noise. It was determined at that time the optimal sensor size and packaging for field use. This resulted in a small compact triaxial rotational seismometer, light weight, with ease of manufacturing allowing to handlers produce a low-cost unit. This was a very delicate balance.

The clip level of the electrochemical rotational sensor is limited by the nonlinearities in the transducer cell which occur when the pressure differential of the electrolyte across the cell exceeds the certain limit sacrificing laminar flow. This pressure ΔP described as follows

$$\Delta P = 2 \cdot \rho \cdot S \cdot \ddot{\phi} \tag{5}$$

In R-2, the sensor size was reduced S to about of 1/4 of the R-1. This should result in 4-fold (12 dB) increase of the clip level from 0.1 to about 0.4 rad/s.

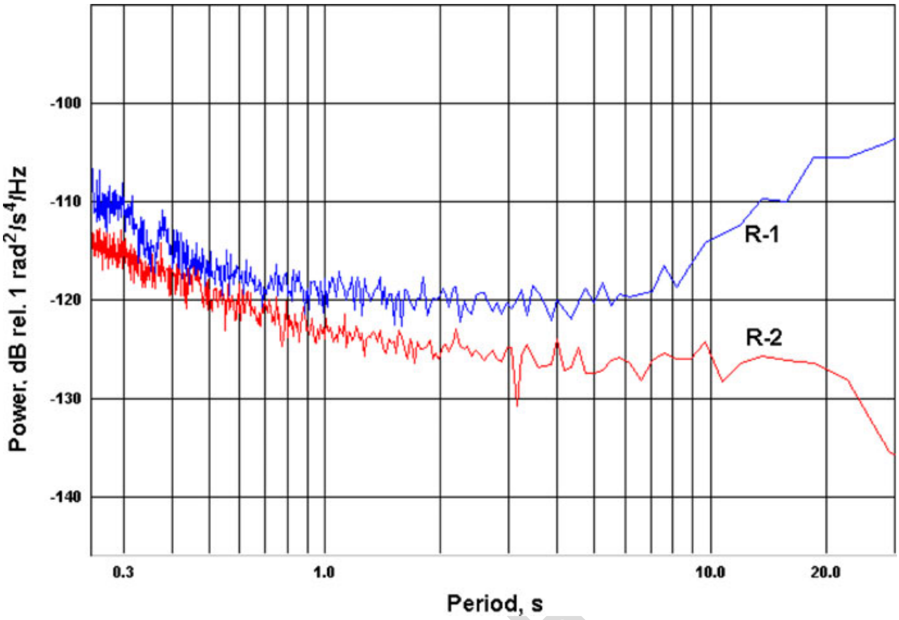
Experimentally measured outputs of three R-2 sensors (green, blue and red curves) and three R-1 sensors close to their clip levels are shown in Fig. 4. The responses were obtained using rotational shake-table driven by a 20-Hz sine wave. As one can see from the picture, the R-2 sensors produce good signals with about 2% THD at 0.35 rad/s, while the R-1 sensors produce significantly distorted signals with THD >10% at only 0.06 rad/s. It is also worth mentioning that at high drive amplitudes R-2 sensors have more identical response compared to R-1.

The reduced size or the toroid, according to Eq. 4, would affect the noise if the R_{h} of the transducer cell remained the same. A novel transducer cell with low hydraulic impedance R_{h} had to be developed. In R-2's case, the only limiting factors in the reduction of R_{h} are the practical physical dimensions of the transducer cell and the sensor itself. For a single channel in the transducer cell, the hydraulic impedance can be found using the Poiseuille's expression, with l as the length of the cell, η is the electrolyte viscosity and R is the radius of the channel:

$$R_h = \frac{8 \cdot \eta \cdot l}{\pi \cdot R^4} \tag{6}$$

Since R_{h} changes as the fourth power of the channel radius, significant potential for improving the resolution lies in achieving the maximum practically possible expansion of the channel cross-section. The

Fig. 4 Self-noise of a typical R-2 sensor (red curve) compared to R-1 (blue curve)



transducer cell in the R-2 has only 1/64 of the hydraulic impedance of the original cell used in the R-1, which resulted in about 6-dB noise reduction in the same passband. Experimentally measured PSD of the noise of a typical R-2 sensor is shown in Fig. 4. The real noise improvement proved to be in accordance with theoretical calculations at mid-range periods. The short-period noise of the R-2 is found to be better or the same as of the R-1. The major noise reduction is observed at long periods and may be attributed to the lower noise electronics developed for the R-2.

4 Passband and calibration

R-1 rotational seismometer has the passband limited from 20 s to 20 Hz and each sensor has to be individually calibrated on a special rotational shake-table. Extension of the range to 100 s or to 100 Hz would result in building a new rotational shake-table capable for calibration in the extended range. That shake-table has to have its mechanical resonance over 100 Hz while being capable to provide at least 5-fold increase of the magnitude at low frequencies compared to an old one. No currently known calibrator comes close to providing the required specifications, nor is there any obvious design that would.

Calibration of the very broad band (VBB) rotational seismometer requires a radically new approach. All modern translational VBB seismometers are equipped with a calibration coil that eliminates the need of a shake-table for the production and gives the user an option of checking the response in the field via a calibration pulse which is implemented now in almost all digital recorders.

Obviously no calibration coil and magnet could be integrated into the sensor shown in Fig. 2 to force the electrolyte into motion. However there exists a close physical principle called the inverse MHD effect, whose action depends on the force applied to a current-carrying conductor in a magnetic field, with the electrolyte being the conductor. When a current I flows through the electrodes, the volume force, applied to the electrolyte is proportional to the vector product $I \times B$, where B is the magnetic induction. This force causes the ions in the electrolyte to flow through the transducer cell, entraining the liquid as well. This flow q_{cal} is essentially equivalent to that caused by the inertial forces and can be related to I and B via the following simple expression:

$$q_{cal} = \frac{(B \times I_{cal})L}{sR_h} K \tag{7}$$

The proportionality coefficient, K, depends on various properties of the transducer, primarily the electrode configuration and the non-uniformity of the magnetic field, L is the distance between MHD electrodes, and s is the cross-section of the electrolyte channel. Figure 5 shows a

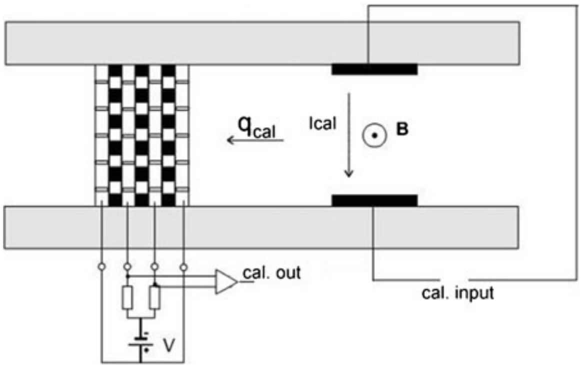


Fig. 5 Adding a MHD cell to an electrochemical transducer

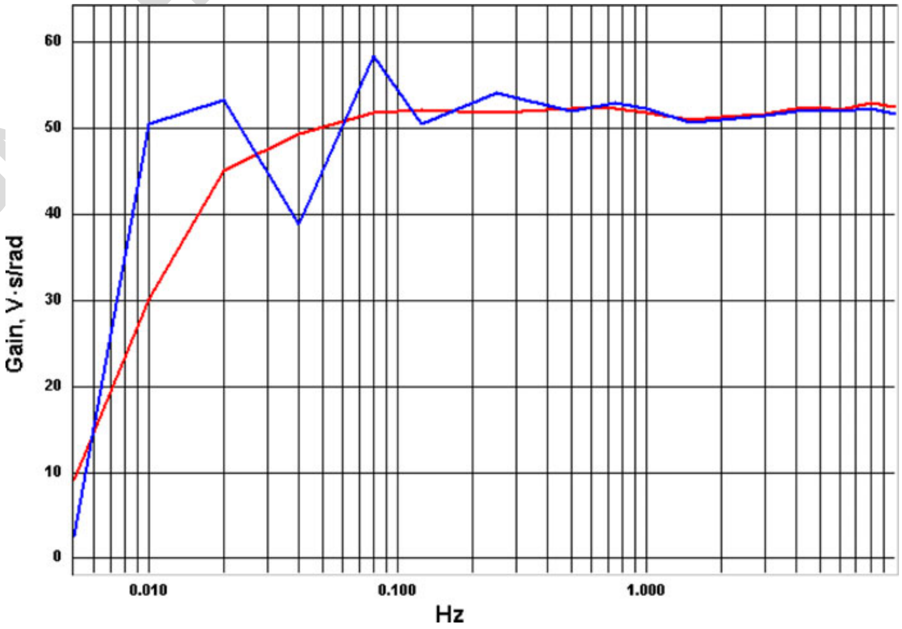
simplified sketch of an R-2 rotational transducer equipped with MHD calibration cell. The sketch does not show the magnetic system explicitly, since the magnet's poles are parallel to the drawing's plane and located in front of and behind it. The magnetic field in Fig. 5 is designated by the symbol ⊙ (indicating that it is directed toward the viewer).

Despite the apparent simplicity of Eq. 7, it does not in itself prove that the required calibration force may be achieved using reasonable levels of the magnetic field and electric current. It is also unclear whether such MHD cell may be implemented subject to the manufacturability and low cost limitations. A review of magnetic materials revealed that some rare earth magnets can provide very strong local fields. Preliminary calculations (Kharlamov and Panferov 2001) indicated that such fields, in conjunction with currents of about several milliamperes, should generate forces equivalent to rotational velocity close to the projected clip level of the new instrument.

Technical implementation of an MHD calibrator was difficult since the MHD cell and the electrochemical transducer share the same volume of the electrolyte that is a good conductor with very complex and nonlinear volt-ampere characteristics (Kharlamov and Kozlov 1998). A special current generator has been developed for the R-2 seismometer that eliminates any leakage currents between MHD cell and the electrochemical transducer as well as protects all electrodes from overvoltage that may lead to decomposition of the electrolyte. This allows for the extension of the R-2 passband to 100 s–100 Hz range and providing all rotational sensors with the very accurate (1%) and simple calibration like the coil and magnet used in translational seismometers.

Comparison of the calibration curves of a typical R-2 sensor obtained from the shaketable (blue curve) and MHD (red curve) is shown in Fig. 6. As displayed from the graph, at 0.5 Hz and higher frequencies both methods of calibration give very close (within 1%) values of the gain of the sensor which proves that MHD calibration works and is at least as accurate as

Fig. 6 Shaketable calibration (blue curve) vs. MHD calibration (red curve)



the shaketable. On the other side, at 0.1 Hz and lower frequencies the shaketable starts introducing calibration errors, the lower the frequency, the higher the error. This is primarily due to the fact that the shaketable has limited angle of the rotation and cannot generate clean signals with the angular velocities above the levels of the ambient noise. And it is worth mentioning that any shaketable adds the noise and parasitic signals which may affect the accuracy of measurements. On the contrary, MHD calibration is free from this limitation and is capable to generate very clean and strong signals even at longest periods, starting from DC.

5 Original design

The original design of the R-1 was constructed with a ceramic toroid. Over the years, it was found that the ceramic experienced micro-fractures at around 4 to 5 years, regardless of shelf time or field use. Also in earlier units it was found the epoxy used in the production of the sensor element had a different temperature coefficient than the ceramic toroid that sometimes led to cracks. Any crack would slowly leak the electrolyte, hence making the sensor element useless.

In 2009, all eentec's electrochemical sensors were changed to a plastic toroid. This change eliminated the problem of micro-fractures due to aging. Also, using a different adhesive to correspond with the toroid material eliminated the temperature coefficient problem. These improvements have resulted in currently deployed sensors leakage problem from about 75% for the ceramic toroid (R-1) to zero for the R-2.

6 What's next

For the second-generation rotational seismometer R-2 rotational seismometer, a number of unique technologies were developed that allow the unit to be built for various needs having very different noise, clip and passband specifications. Neither specifications of the R-2 reach the theoretical limit of the electrochemical and MHD technologies, leaving opportunities for the further improvement of eentec's rotational seismic sensors.

References

Abramovich I, Agafonov V, Daragan S, Kharlamov A, Kozlov V (1999) Development of seismic sensors on new principles. Seismic Instruments. Vol. 31. Allerton Press, New York, ISSN 0747-9239 Q6

Abramovich I, Cobern M, Kharlamov A, Panferov A (2001) Investigation of nonlinearities in vertical sensors of MET seismometers. Seismol Res Lett 72(2), ISSN 0895-0695

Applied Technology Associates, 1300 Britt St. SE Albuquerque, NM USA 87123 Q7

Kharlamov A, Kozlov V (1998) Dynamic properties of an electrochemical cell under parametric pumping. Russ J Electrochem: Interperiodica (Birmingham, AL) 34(2). ISSN 1023-1935

Kharlamov A, Panferov A (2001) Theoretical and experimental study of an electrochemical converter of a pulsing electrolyte flow. Russ J Electrochem: Interperiodica (Birmingham, AL) 37(4), ISSN 1023-1935

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