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Mechanical sensors

Dependence of Self-Noise of the Angular Motion Sensor Based on the Technology of Molecular-Electronic Transfer, on the Area of the Electrodes

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Abstract—In seismic applications, molecular-electronic transfer (MET) sensors are considered to be among the most promising instruments for the measurement of seismic-associated signals. The subject of the presented study is the MET angular motion sensor self-noise dependence on the area of the electrodes of the electrochemical signal converting cell. Sensors with a different area of the signal conditional cell electrodes have been produced, and their self-noise at frequencies <100 Hz has been studied. The results show that sensors with a larger area of electrodes have lower self-noise at low frequencies and larger self-noise at high frequencies, which agrees with the assumption that uncorrelated small-scale hydrodynamic velocity fluctuations are responsible for the sensors convective noise. The results of the study allowed us to refine the MET sensors self-noise model and refined and revealed the directions of further improvement of the MET angular sensors performance.

Index Terms—Mechanical sensors, collective noise, rotational motion, seismic sensors self-noise.

I. INTRODUCTION

On-land seismic exploration and seismological studies are based on the measurement of only translational motions, such as particle velocity. Meanwhile, the rotational motions should also be observed for a complete description of ground motions [1]–[4]. The recent development of rotational sensors has resulted in several instruments capable of directly measuring the rotational motion, which may be used for geophysical exploration [5]–[8]. Among other applications of rotational motion measurements are P- and S-wave separation, more detailed seismic field reconstruction [9], [10], removal of the ground-roll [1], structures and equipment monitoring [11], [12], etc.

Taking into an account a small level of the signals usual for seismic exploration, one of the most significant parameters for the rotational motion sensors is self-noise, which determines signal-to-noise ratio and, consequently, the accuracy of the data processing results. Among others approaches, the molecular-electronic transfer (MET) technology is considered to be one of the most prominent technologies for rotational motion measurements. The advantage of modern MET rotational sensors is a relatively low level of self-noise, combined with low manufacturing cost, high reliability, and compact size. In the most important seismic exploration frequency range between 10 to 100 Hz, the MET self-noise varies between $2 \cdot 10^{-6}$ rad/sec$^2/\sqrt{\text{Hz}}$ at 10 Hz and $3 \cdot 10^{-5}$ rad/sec$^2/\sqrt{\text{Hz}}$ at 100 Hz. These values are noticeably higher than the rotational noise in many quiet locations. The decrease in the MET self-noise of presented frequency range may significantly expand the application area of the rotational sensors.

According to the experimental data analysis and modeling [13]–[15], self-noise in the 10 to 100 Hz range is convection, which is noise described in [16]. The purpose of the efforts undertaken here was further investigation of the convection noise nature, specifically the convection noise dependence on the electrodes area of the sensing element. The experimental samples with different electrodes areas have been produced and tested. The experiments showed that for the convection noise, the power spectral density is proportional to the electrodes area. Physically, it corresponds to the situation where random convection processes at the different parts of electrodes responsible for the self-noise generation are independent from each other. The result allows us to reduce the MET rotational sensors self-noise significantly, and it clearly shows the direction for further improvement of the MET sensors performance.

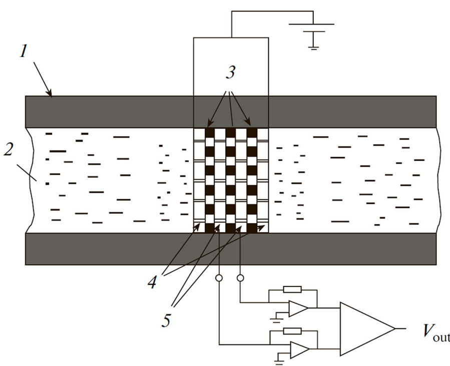

Fig. 1. Electrochemical transducer. 1: Ceramic or glass case. 2: Electrolyte. 3: Porous ceramic partitions. 4: Anodes. 5: Cathodes.

II. OBJECT OF THE STUDY

The main component of the angular motion sensor is a MET, which is a set of electrodes placed in an electrolyte solution (see Fig. 1).

The MET operating principle is that with the application of electrical voltage, electrochemical current flows in the system. In this case,

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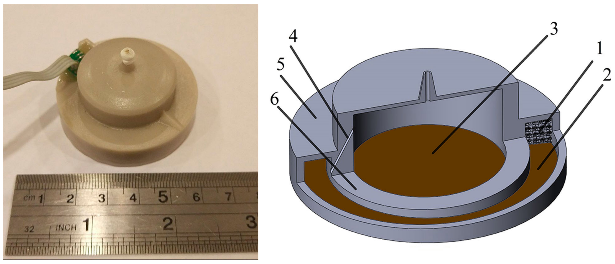

Fig. 2. Molecular-electronic transducer of angular motions. 1: Transductive element. 2: Circular channel. 3: Expansion volume. 4: Capillary. 5: Outer wall of the circular channel. 6: Wall separating the circular channel and the expansion volume.

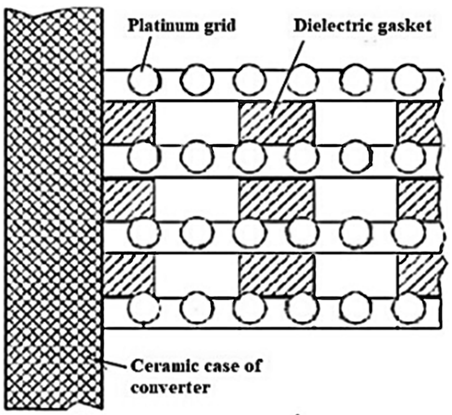

Fig. 3. Design of the MET electrode unit.

electrochemical reactions create a gradient in the concentration of the solution components and charge transfer in the motionless electrolyte is performed by ion diffusion from one electrode to another. In the presence of a mechanical signal, the electrolyte comes into motion under the influence of inertia, and, in addition to diffusion, there is a convective transfer of ions to the electrodes, which drastically changes the delivery speed of the reacting substances to the electrodes and the current flowing through the sensing element. The changes of current are proportional to the external mechanical signal.

In order to make an angular motion sensor, the transduction element is placed in a torus completely filled with electrolyte solution. Under the action of external angular acceleration perpendicular to the plane of the torus, the electrolyte in the transducer channel comes into motion, which is converted into the changes in the current in the external circuit.

III. EXPERIMENT

The molecular-electronic sensor of angular motion has the closed circular channel filled with electrolyte, and the electrodes are placed across the channel. The layout of the sensor is shown in Fig. 2. The electrodes in an MET present a platinum grid and are separated by ceramic nonconductive partitions (see Figs. 3 and 4).

In modern serial devices, the thickness of nonconductive partitions (see Fig. 4) is 120 μm, and each has 80 holes with 0.6-mm diameter. Thus, since only the area of the grid electrodes against the holes in the spacer is accessible for the electrolyte, the area of the active part of the MET electrode grid (participating in the electrochemical conversion)

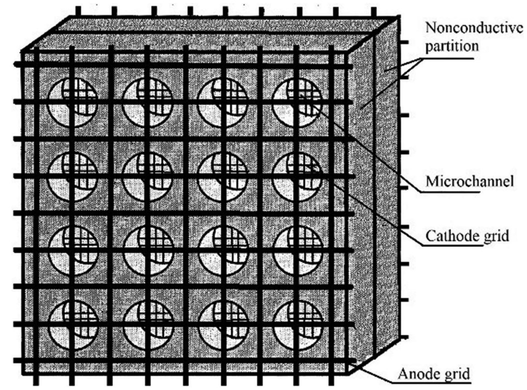

Fig. 4. Top view of the MET electrode unit.

in modern serial devices could be defined as the sum of 80 holes cross-section area and is 22.62 mm^2.

To perform the experiment, six molecular-electronic angular-motion transducers with different configurations of the transduction element have been produced. Two of them were serial sensors (type 1). Other transducers had nonconductive partitions 40-μm thick with the diameter of the holes of 0.25 mm. Two of them (type 2) had 67 holes and two last ones (type 3) had 22 holes. The grid parameters of the electrodes have been made the same.

The records of the analysis of the sensor noise characteristics have been obtained in a room with a low noise level and after installing the sensor on a monolithic concrete base. To improve the correlation between the sensors, two transducers of the same type have been paired together on a flat surface of the housing. The noise has been calculated as an uncorrelated component of the signal spectral density in accordance with the equation from [17], [18]

$$\left\langle |U_N(\omega)|^2 \right\rangle = \frac{\sqrt{\left\langle |U_1(\omega)|^2\right\rangle \left\langle |U_2(\omega)|^2\right\rangle}}{|W(\omega)|^2} * \left(1 - \sqrt{\frac{\left\langle U_1^*(\omega)\, U_2(\omega)\right\rangle \left\langle U_1(\omega)\, U_2^*(\omega)\right\rangle}{\left\langle |U_1(\omega)|^2\right\rangle \left\langle |U_2(\omega)|^2\right\rangle}}\right) \quad (1)$$

where $U_1(\omega)$ and $U_2(\omega)$ denote the signals from the first and the second sensor with the same parameters, respectively; $U_1^*(\omega)$ and $U_2^*(\omega)$ denote the complex conjugate signals; and $W(\omega)$ denotes the transfer function of the sensor.

As a result, the experimental graphs of the noise-frequency dependence for three different electrode grid configurations have been obtained (see Fig. 5). The horizontal axis shows the frequency in Hertz, while the vertical axis shows the square of the spectral density of self-noise in units of angular acceleration in decibels. The experiment showed that below 30 Hz, the sensor with $S_{el} = 22.62$ mm^2 has the lowest self-noise, while above 30 Hz, the sensor with $S_{el} = 3.28$ mm^2 has the highest self-noise.

IV. THEORY

It was shown in [7] that the self-noise of the angular motion sensor transducer in the range below 100 Hz is caused by thermal fluctuations of the hydrodynamic flows of the working fluid through the

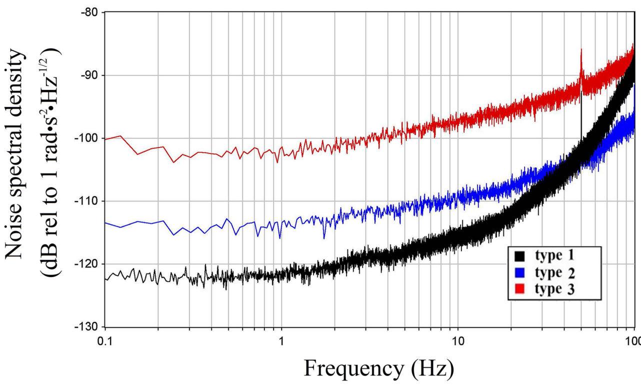

Fig. 5. Experimental dependence of noise on frequency.

transducing element and convective noise

$$\langle \varepsilon^2 \rangle_{\text{conv}} = \frac{R_h kT}{2\pi^2 \rho^2 R^4} + \frac{K(\omega, S_{el})}{|W_{\text{mech}}(\omega)|^2 |W_{el-ch}(\omega)|^2} \tag{2}$$

where R_h denotes hydrodynamic resistance, k denotes the Boltzmann constant, ρ denotes the electrolyte density, R denotes the toroid channel radius, T denotes the environment temperature, $K(\omega, S_{el}) \equiv I_\omega^2$ is the noise spectral density of the transducer output current caused by the convection, and S_{el} is the electrode surface area. Note that the noise of the readout electronic circuit, including $1/f$ noise, is not taken into account according to Brokešová and Málek [7]. Physically, it is the result of the transducer high output. To model the dependence on the electrodes area, we can naturally assume that $R_h \sim 1/S_{el}$. For $K(\omega, S_{el})$, taking into account according to Agafonov and Zaitsev [16] that with the same area of electrodes $K(\omega, S_{el}) \sim I_0^2 \sim n^2/d^2$, I_0 is the background current, i.e., flowing between the electrodes in the absence of liquid flow, n is the concentration of the electrolyte active substance, and d is the interelectrode gap. In addition, assume that convective noise is associated with random microflows of liquid near the electrodes with a characteristic correlation length much smaller than the size of the electrode. Then, $K(\omega, S_{el}) \sim S_{el} n^2/d^2$. Finally, use [19]

$$W_{el-ch}(\omega) = \frac{I}{q} = \frac{2nq_e}{\sqrt{1 + \frac{\omega^2}{\omega_d^2}}} \tag{3}$$

$$W_{\text{mech}}(\omega) = \frac{q}{\varepsilon} = \frac{2\pi R^2 \rho / R_h(S_{el})}{1 + \frac{i\omega}{\omega_h}} \tag{4}$$

where I is the output signal current, q is the flow velocity, q_e is the electron charge, $\omega_d = \frac{D}{d^2}$ is the diffusion frequency, D is the diffusion coefficient, q is the flow velocity, ε is the external angular acceleration, $\omega_h = \frac{R_h(S_{эл})S}{2\pi R\rho}$ is the hydrodynamic frequency, and S is the channel surface area.

For the calculation, the following parameter values have been used: $D = 2 * 10^{-9} \frac{\text{m}^2}{\text{s}}$, $n = 0,03 \frac{\text{mole}}{1}$, $\rho = 1500 \frac{\text{kg}}{\text{m}^3}$ (lithium iodide solution), $S = 36$ mm^2, and $R = 0.02$ m, Theoretical analysis has been carried out for three electrode grid configurations with the area $S_{el} = 22.62$, 3.28, and 1.07 mm^2. R_h and d for various electrode grid configurations are defined in [14] and are listed in Table 1.

For $S_{el} = 22.62$ mm^2, $K(\omega, S_{el})$ has been found from convective noise voltage spectral density defined by Zaitsev [14], by converting it into the units of noise current spectral density. Besides, the frequency dependence below 1 Hz was approximated by constant value according to the experimental data from [16]

$$K(\omega, S_{el}) = \frac{4.2 * 10^{-18}}{(1+\omega)^{0.55}} \text{A}^2\text{Hz}^{1,1}. \tag{5}$$

For $S_{el} =$ 3.28 and 1.07 mm^2, the values of $K(\omega, S_{el})$ and $R_h(S_{el})$ are determined on the basis of the dependencies $K(\omega, S_{el}) \sim S_{el} n^2/d^2$, $R_h \sim 1/S_{el}$, and $d = 40$ μm.

The calculated dependence of the self-noise of the angular motion sensor on frequency is shown in Fig. 6. At theoretical calculations, $W_{el-ch}(\omega)$ and $W_{\text{mech}}(\omega)$ have been defined in accordance with (3) and (4), respectively.

Table 1. Values of Parameters Used in Calculations for Three Electrode Grid Configurations.

Symbol, units	Parameter	Value Type 1	Type 2	Type 3
S_{el}, mm^2	Electrode area	22.62	3.28	1.07
d, µm	Interelectrode gap	120	40	40
R_h, $\frac{N*\text{s}}{\text{m}^5}$	Hydrodynamic impedance	$1.1 * 10^9$	$7.6 * 10^9$	$2.32 * 10^{10}$

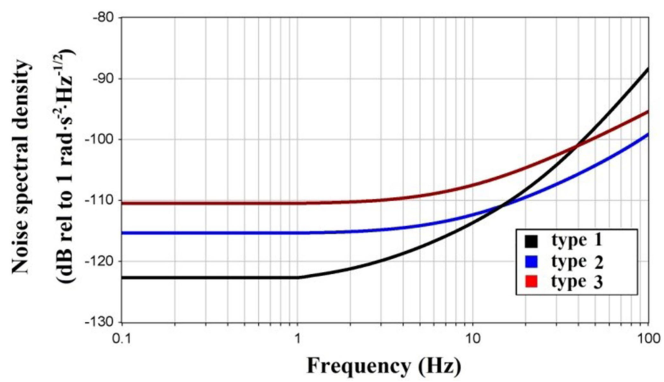

Fig. 6. Theoretical dependence of the self-noise on frequency.

As seen from Fig. 6, the results of the theoretical analysis qualitatively agree with the experimental data, and it can be concluded that the chosen model of angular motion sensor noise describes the processes leading to the occurrence of the MET self-noise with sufficient accuracy.

The graphs also show that the sensors with a larger electrode area are characterized by lower noise at low frequencies and higher noise at high frequencies when compared to the sensors with a smaller electrode area. In the frequency range from 10 to 100 Hz, the experimentally determined electrode area optimum from the point of view of its self-noise is $S_{el} =$ 3.28 mm^2, in comparison with $S_{el} =$ 22.62 mm^2, which is used at present.

In particular, the idea of two dominant mechanisms of self-noise generation, described by (2), is well confirmed. At low frequencies, the thermal fluctuations of the integral fluid flow prevail, replaced by random local convective currents in the vicinity of the converting cell electrodes at higher frequencies. Accordingly, at low frequencies, a

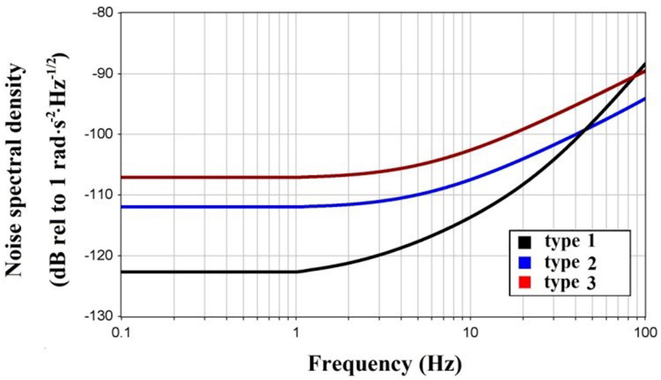

Fig. 7. Theoretical dependence of the self-noise on frequency. The influence on the viscous friction R_h between the liquid and the walls of the holes in nonconductive partition is taken into account.

sensor with a larger electrode area, capable of passing large flows of fluid through itself at a similar external action, is characterized by lower noise. At high frequencies, the additive nature of convective noise in various areas of the electrode surface becomes significant, and the sensors with the largest electrode area have a higher noise.

In spite of the qualitative agreement, there is a noticeable difference between the experimental data and the modeling results. Generally, the modeled noise for the transducer with smaller electrodes is lower than the experimental data. Physically, it could result from the assumption $R_h \sim 1/S_{el}$, which does not take into account the influence on the viscous friction R_h between the liquid and the walls of the holes in nonconductive partitions. It could be expected that this effect results in an increase of the hydraulic impedance for the transducers with smaller holes.

This effect taken into account in modeling results is presented in Fig. 7. Compared to the diagrams given in Fig. 4, the value of R_h was twice as large for the calculations for types 2 and 3 transducers. Now, the calculation results are in good agreement with the experimental data presented in Fig. 3.

V. CONCLUSION

The experimental dependence of the MET angular motion sensors self-noise on the area of the electrodes of the converting element is in good agreement with the model represented by (2), with the additional assumption that convective noise is conditioned by uncorrelated fluctuations of the liquid flow near the electrodes, which made it possible to specify the dependence of the indeterminate coefficient $K(\omega, S_{el}) \sim S_{el}$ on the area of the electrodes. The practical consequence of the performed research is the experimental proof of a lower level of self-noise for sensors with a decreased electrode area compared to the modern serial devices in the frequency range from 50 to 100 Hz, which is the most important for seismic applications.

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