A SIMPLE AND CHEAP METHOD OF MET GEOPHONES AND SEISMIC ACCELEROMETERS TEMPERATURE SENSITIVITY STABILIZATION IN A WIDE TEMPERATURE BAND

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ABSTRACT

In this paper, we propose a mathematical model and an appropriate algorithm that allows one-time measurement of the frequency response and phase response of the MET sensor under normal conditions to construct a complex transfer function of the MET at any other temperatures from the allowable range of -35 + 55 °C with the experimental accuracy not worse than a few percent. This model and the algorithm for setting up and selecting thermocompression circuits of electronic amplification and filtration circuits introduced into production practice significantly reduce the operating time of the device setup (long-term and expensive temperature measurements and verification in thermal cameras are no longer required), respectively reducing the production cost. Most importantly, the proposed method significantly improves the quality of temperature compensation due to the automated selection of individual ratings, which reduces the spread of sensitivity parameters from device to device and its stability at the temperature range edges.

Keywords: molecular electronics technology (MET), transfer function, thermocompression circuits, geophone, accelerometer, stability

INTRODUCTION

The current pace of geophysics development requires active development of new equipment that meets high requirements and is able to solve modern tasks. One of the most promising technologies for manufacturing linear motion sensors, such as accelerometers [1,2] and geophones [3], is the technology based on molecular electron transfer (MET) [4]. The scope of application of low-frequency linear motion sensors based on MET is extremely wide: geophysics [5,6], seismic exploration [7], security systems [8], construction [9], and others. This technology has several priority ways of development, one of which is the adaptation of the devices to work in extreme temperatures [10]. This limitation occurs because of the physical properties of the liquid electrolyte underlying the design of MET-based sensors [11]. One of the most effective ways is to develop an electronic thermal compensation scheme for the sensor that demonstrates the temperature curve opposite to the sensor, which requires a number of resource-intensive experiments and research, which largely determine the cost of the final product [3]. The ideas and algorithms presented in this paper can significantly simplify the production of devices, and consequently make them cheaper and more accessible on the market [12].

The main element of linear motion MET-based sensors is the electrode cell. It consists of four platinum electrodes placed in a closed volume filled with an electrolyte, Figure 1. In this system, the internal electrodes serve as cathodes, while the external ones serve as anodes. The anodes are connected to a DC power source [13].

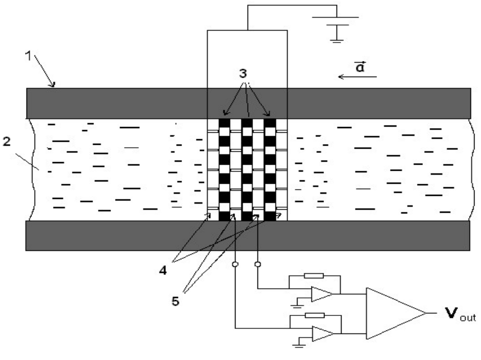


Figure 1. Schematic diagram of a molecular-electronic cell. 1-Converter housing, 2-working fluid, 3-dielectric spacers, 4-anodes, 5-cathodes (3-4-5-electrode assembly)

In the traditional design, high - concentration iodine-iodide electrolytes are most often used as electrolyte. In this study, a LiI solution with the addition of active I_2 was used. Redox reactions occur on the electrodes with the formation or absorption of electrons:

$$I_3^- + 2\bar{e} \to 3I^-; \qquad 3I^- \to I_3^- + 2\bar{e}$$

Background cathode currents are determined by the rate of supply of the active component (triiodide ions) to the electrodes. In a stationary liquid, the carrier transport is carried out by a diffusion mechanism, so the background cathode currents depend on the concentration gradient of the active component in the areas between the anodes and the cathodes, as well as the diffusion coefficient of the active carriers. In the presence of external mechanical disturbances, the liquid flows through the molecular-electronic transducer, and in addition to the diffusion, there is a convective carrier transfer, which increases or decreases the cathode currents. This change is registered by means of an electronic circuit, thereby fixing the external disturbance.

The parameters of the system described above depend on the temperature, which is caused by the hydrodynamic and electrochemical properties of the electrolyte. With decreasing temperature there is an increase in viscosity and decrease in diffusion coefficient, which affects the sensitivity of the instrument.

It was experimentally established that the sensitivity of a serial MET-based sensor was reduced when the ambient temperature was lowered. Specifically, the frequency response of the MTSS-1001 model geophone was compared with the GS-20DX reference electrodynamic geophone in a wide temperature range (+ 25 °C to - 35 °C). The sensors were placed in a thermal chamber M-60/100-120 KTH-T, where the required temperature was set up. In the created environment, the sensors were exposed to external influences and their response was recorded by the ADC. Signal spectra were constructed from the received responses, and the signal value was measured for the frequency with the maximum amplitude. Comparing these maxima, the numerical dependence of the geophone sensitivity relative to the reference sensor was calculated as a function of temperature. According to the results of the experiment, it was found that the sensitivity of the serial MET sensor significantly decreases in the low temperature region, especially below -20 °C., figure 2.

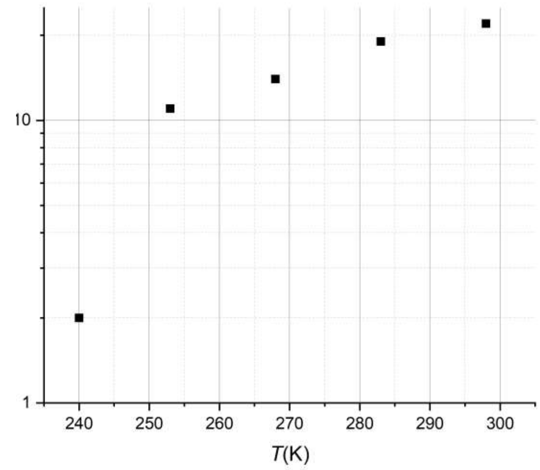


Figure 2. Relative sensitivity of the sensor depending on the temperature

TRANSFER FUNCTION

The previously developed theoretical model from [3] was used to work with the transfer function of the MET-based sensor, the expression of the transfer function:

$$W = \frac{A}{(1+\frac{\omega_1^2}{\omega^2})^{1/2}(1+\frac{\omega_2^2}{\omega^2})^{1/2}(1+\frac{\omega^2}{\omega_e^2})^{1/2}(1+\frac{\omega^2}{\omega_d^2})^{1/4}} \quad (3)$$

The values A, ω_d, ω_e, ω_1, ω_2 will be approximation parameters and can be found from the experimental data.

The previously described temperature dependence of sensitivity is well described by this model: approximation frequencies depend on the diffusion and viscosity coefficients, which, according to [3], have exponential dependence on temperature.

$$\omega_1 = \frac{\alpha}{R_h S_{CH}}\sigma^2 \sim \frac{1}{\nu(T)}, \quad \omega_2 = \frac{R_h S_{CH}}{\rho L} \sim \nu(T), \omega_e = \frac{bD}{d^2} \sim D(T), \quad \omega_d \sim D(T) \quad (5)$$

Thus, the transfer function of the sensor also has an exponential dependence on temperature.

VERIFICATION OF THE THEORETICAL MODEL AND DEVELOPMENT OF A NEW RESEARCH ALGORITHM

The experimental data (Amplitude to Frequency Response) in a wide temperature range were used in the study of the electronic thermal compensation system (+ 70 °C to - 35 °C) as it was measured in [3].

To use the analytical model described above, it is necessary to calculate the approximation parameters of the studied transducer. This can be done based on the experimental data. It is most convenient to use the frequency response curve at a temperature close to room temperature. The approximation parameters are calculated using the method of least squares (MLS). When substituting them into equation (3), the frequency response constructed from this equation will have the smallest discrepancy with the experiment.

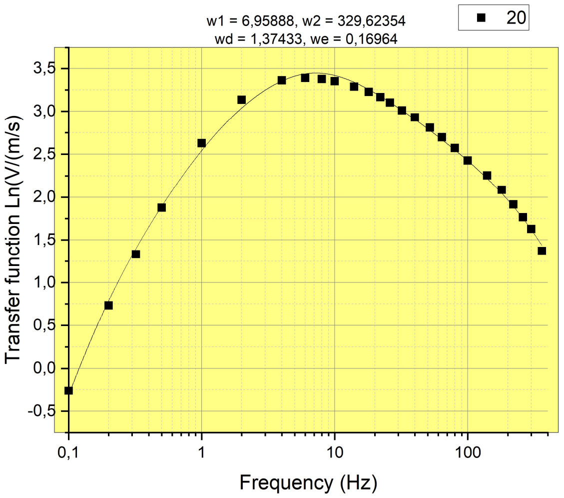


Figure 3-finding the approximation parameters using MLS

To simplify the calculations, software with internal MLS algorithms can be used. Origin 2019 Pro was used in this work. The parameter that determines the temperature dependence of the viscosity and diffusion coefficients is the activation energy E_a. Knowing it, the parameter values can be received (and therefore the frequency response curve can be built) for any temperature. The activation energy value was obtained in [3] by several experimental methods. However, the frequency response curves for different temperatures calculated using this value differed significantly from the experimental data.

In some of the previous works, a different analytical model was used, for which the mechanical and electromechanical subsystems of transfer function were described by different temperature dependencies, that is, they had different activation energies. Based on this work, the activation energies were calculated using MLS from the range from 1230 to 3620 kT. Found values are as follows:

$$\mathrm{E_1 = 1870kT}; \qquad \mathrm{E_2 = 3350kT}$$

To test the obtained values of the activation energies, an experiment was conducted with a new sample. For it, the frequency response was measured in the range from -20°C to +20°C.

The experiment was conducted in a thermal chamber. An external signal with pre-set parameters is transmitted to the sensor via a digital-to-analog converter. For this device it was a sinusoid in a wide frequency range from 0.1 Hz to 660 Hz. In the feedback system, an electromagnetic coil is installed. When the calibration signal flows through it, it affects the magnetic core attached to the membrane on the sensor body. The motion of the core initiated the acceleration of the electrolyte in the cell, and hence the appearance of a signal current. The currents were converted to a voltage signal after passing through the electronic conversion circuit. The obtained response was returned to the computer via the ADC.

Then the developed algorithm was used to construct the frequency response curves from the same range. The curves constructed using the set values of the activation energies are approximated with a high accuracy to the experimental data (Figure 4).

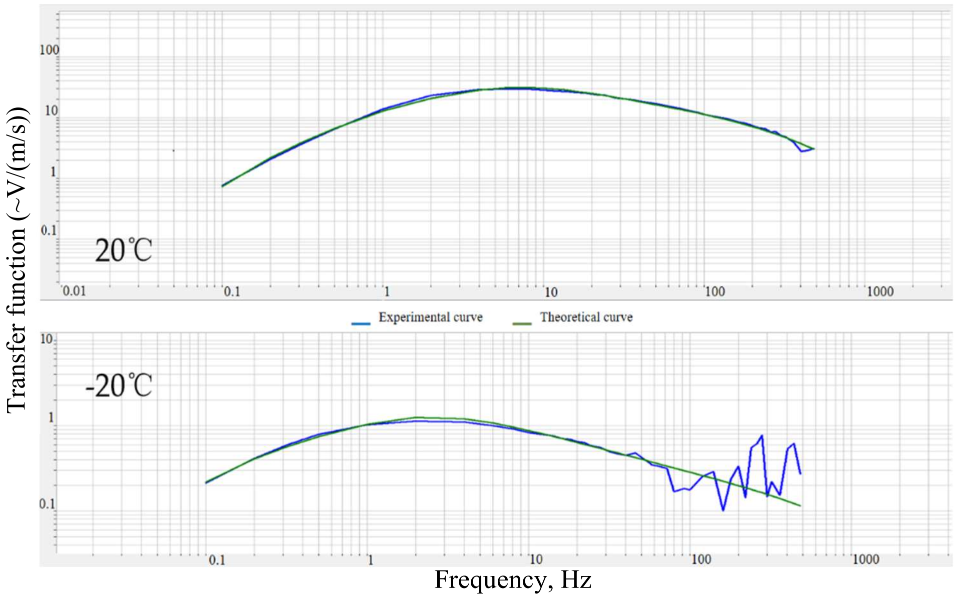


Figure 4. Comparison of frequency response curves for different temperatures based on the experimental data and using a theoretical model.

Now it is possible to build a curve that accurately describes the transfer function of the sensor for any temperature (Figure 5).

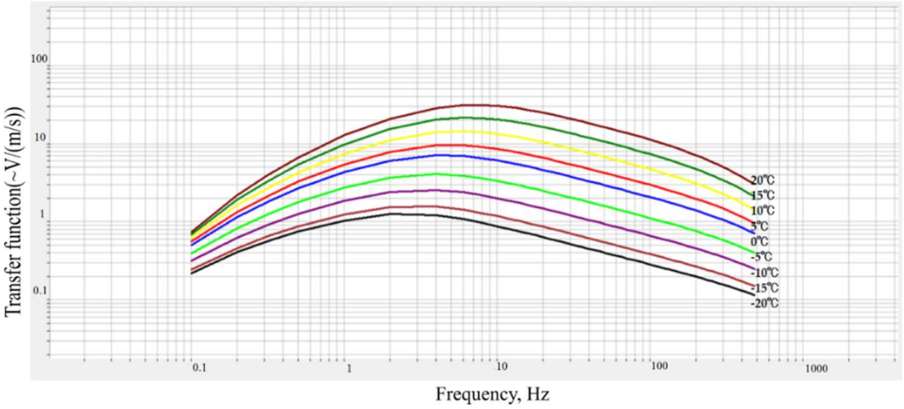


Figure 5. Family of analytical frequency response curves in the range + 20 °C to - 20 °C.

INVESTIGATION OF THE TEMPERATURE BEHAVIOR OF THE PHASE CURVES

The next stage was to find out the temperature behaviour of the Phase to Frequency Response (PFR) for the MET-based devices. The existing formula (3) of the transfer function describes only the amplitude to frequency response of the transfer function. Knowing the amplitude of a complex function, it is not difficult to find it:

$$Z = \frac{A}{(1+\frac{\omega_1}{i\omega})(1+\frac{\omega_2}{i\omega})(1+\frac{i\omega}{\omega_e})(1+\frac{i\omega}{\omega_d})^{1/2}} \tag{6}$$

In the course of its verification, by comparing the experimental and theoretical PFR curves, their overlap was found to have a large percentage of discrepancy. To eliminate the discrepancy, the effect of formation of a double electric layer in the dielectric was considered. When a solid comes into contact with an electrolyte solution, a number of processes occur that lead to the accumulation of charge by the surface, mainly absorption and dissociation of the surface groups. Near the charged surface, the concentration of ions changes: the ions of the opposite sign are drawn to the surface from the solution and the ions of the same sign with the surface charge are repelled. As a result, the so-called double electric layer is formed in the "solid-electrolyte" system. In the absence of thermal motion of the particles, the structure of the double electric layer is similar to that of a flat capacitor with ≈ 50 uF. Let us express the current I flowing from the anode to the cathode.

$$I = I_0 + U_{DL} \cdot i\omega_0 C \quad U_{DL} = -IR \tag{7}$$

Where I_0 is the current flowing inside the layer, $R \approx 3$ Ohms is the resistance of the electrolyte, and U_{DL} is the voltage of the double layer. Solving system (7) by simple mathematical calculations, find:

$$I = \frac{I_0}{1+i\omega_0 RC} \tag{8}$$

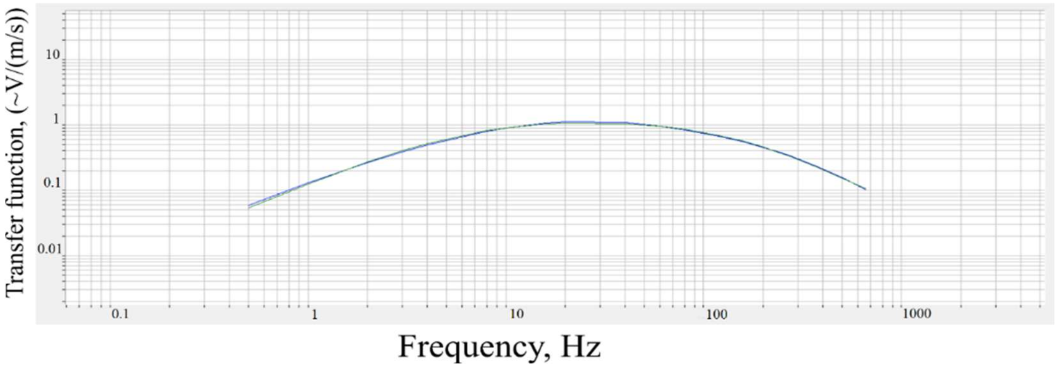
It is necessary to estimate the value of the frequency that affects the cathode current:

$$\omega_0 = \frac{1}{RC} = \frac{10^6}{150} \approx 6.6 \cdot 10^3 \qquad \omega_{DL} = \frac{\omega_0}{2\pi} \approx 1kHz \tag{9}$$

Thus, name the value of ω_{DL} as frequency of the double layer and introduce it into the complex transfer function:

$$Z = \frac{A}{(1+\frac{i\omega}{\omega_{DL}})(1+\frac{\omega_1}{i\omega})(1+\frac{\omega_2}{i\omega})(1+\frac{i\omega}{\omega_e})(1+\frac{i\omega}{\omega_d})^{1/2}} \tag{11}$$

The transfer function of the form (11) is the desired one. Figure 6 illustrates the accuracy of approximation by the model (11).



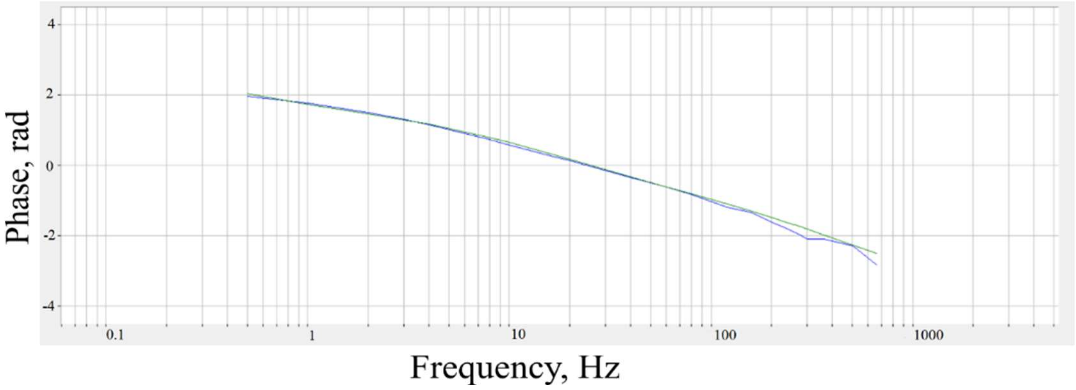


Figure 6. The comparison of theoretical and experimental frequency response upper figure and lower figure

CONCLUSION

In the course of the work, the dependence of the sensitivity of linear displacement sensors based on MET was studied. The formula for the transfer function of the device was clarified, taking into account the contribution of the double electric layer, and a new frequency was introduced. As a result of the assessment, its value was equal to 1 kHz. As a result of the refinement, the behaviour of the phase-frequency response was corrected depending on the temperature. These corrections set the vector for further actions in the development of an electronic thermal compensation scheme, for which the behaviour of the phase characteristic plays a crucial role. It was found that mechanical and electromechanical subsystems of transfer function were described by different temperature dependencies, that is, they had different activation energies. An algorithm was developed and tested to reduce the time and resources spent on temperature experiments during the study.

This algorithm is already used in practice, significantly reducing the time of manufacturing and testing, which greatly reduces the cost of the final products and projects.

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