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The temperature dependence of amplitude-frequency response of the MET sensor of linear motion in a broad frequency range

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Abstract - This paper is the first to present the experimental results on the measurement of amplitude-frequency characteristics of linear motion sensors based on molecular-electronic transducers in a wide frequency and temperature range. The analytical dependence of the temperature behavior of the amplitude-frequency characteristic of the studied sensor type in the 0.1–443 Hz band and the –35 / (–15)° C to + 70° C bands fully consistent with the experimental data has been presented for the first time. The verification of the theoretical model for the experimentally found approximation parameters has been performed. Different methods have been used to find the activation energies of the components of electrolyte solutions of several types.

Index Terms **— molecular electronics, accelerometer, geophone, temperature sensitivity, activation energy, transfer function.**

I. INTRODUCTION

The development of modern methods of geophysical monitoring imposes ever higher requirements on instrumental means of recording seismic signals [1], which poses the task of finding new technologies for sensors of primary information [2, 3]. Molecular-electronic technology (MET) measurers [4, 5] are used in such areas as land and offshore seismic prospecting [6, 7], monitoring of building structures [8], navigation [9,10], world ocean studies [11,12] and even the study of medical and sport science [13]. The advantages of modern sensors based on MET are high sensitivity, low level of self-noise combined with low production costs [14]. At the same time, devices based on the liquid inertial mass also have traditional disadvantages. First of all, it is a relatively narrow operating temperature range, limited by the boiling and freezing temperatures of the electrolyte.

However, there are already such electrolytes that allow devices based on MET transducers to operate in a fairly wide range of temperatures, which is from –40 to +60 degrees Celsius, which is sufficient for use in almost any terrain. Since the MET transducers transfer characteristics are determined, among other things, by the type of electrolyte used, which implies that its viscosity and diffusion coefficient vary quite intensely with temperature, the MET transducers transfer characteristics significantly depend on the temperature [15]. Of course, it is possible to significantly reduce the influence of ambient temperature by special thermostatic housings and devices, but this significantly increases the power consumption of the device and weight and size parameters, which sharply limits the area of application. Therefore, when designing final measuring instruments, special attention is currently being paid to the methods of compensating the temperature drift of the amplitude-frequency response (AFR) [16]. To do this, it is essential to know precisely the characteristics behavior of the MET transducers of various types in the entire temperature range.

The complexity of studying the MET transducers characteristics is conditioned by the fact that the complete transfer function is determined by both mechanical and electrochemical subsystems [17]. At that, both components of the transfer function have a rather complicated frequency and temperature dependence. Moreover, many converter parameters affect both the mechanical and the electrochemical subsystem simultaneously.

The objectives of this study are to try to expand the existing knowledge of the temperature dependence of the amplitude-frequency response of the MET sensors of linear movements in the extended towards the low-frequency direction range; to build a clear analytical model describing experimental patterns; its experimental verification in a wide range of temperature changes, study of the temperature dependences for different types of electrolytes used in traditional MET devices [18].

II. TRANSFER FUNCTION OF MOLECULAR-ELECTRONIC CONVERTER

In this work, the MET sensors of linear motions (velocities or accelerations) have been studied. By their physical nature, all the meters based on the MET are accelerometers. The importance of developing accelerometers based on new physical principles is confirmed by numerous publications, including [19,20]. while the amplitude frequency response of the MET sensor can be expressed in units of the measured speed in a certain

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frequency band. The basis of the operation of all devices based on the MET is the process of convective diffusion of ions in electrolyte solutions. In the liquid electrolyte solution is immersed converting cell, consisting, as a rule, of 4 electrodes (two pairs of anode-cathode). Some potential difference (<1 V) is applied to the anodes, which triggers oxidation-reduction reactions on the electrodes. At the anode, an excess number of current carriers is formed, at the cathode these carriers recombine and they are few. As a result, in each pair between the anode and the cathode in a stationary state, a gradient of the current carrier concentration is established, which changes when the liquid moves, leading to variations in the current on the signal electrodes (cathodes) of the device, see diagram (Fig. 1). A detailed description of the principles of operation of such devices is presented in [21, 22]. Traditionally, linear sensors based on MET are equipped with magnetic force feedback [23], which ensures the stability of characteristics. A diagram (Fig. 2) shows the tradition scheme of linear motions MET sensor construction. On the figure 1 and 2 – are anodes and cathodes, 3 – electrolyte, 4- elastic membranes, used as a restoring force, 5 and 6 - magnet and coil for electromagnetic feedback organization. At the same time, for the purposes of this study, the feedback was not used and was opened, and the elements of its design were used to perform calibration effects on the sensor (for more details, see Section III).

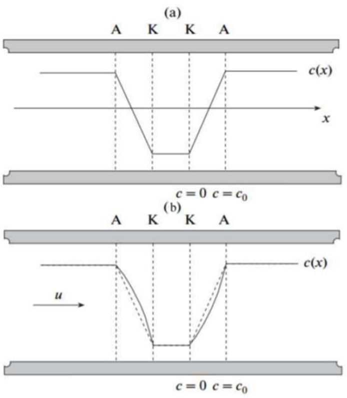

Fig. 1. Distribution of the current carriers concentration in the converting cell. c(x) is the steady state concentration of ions; (a) distribution without mechanical motion; (b) the distribution of concentration c(x) varies under the oncoming flow of liquid; u – fluid flow rate. A – anodes, K – cathodes.

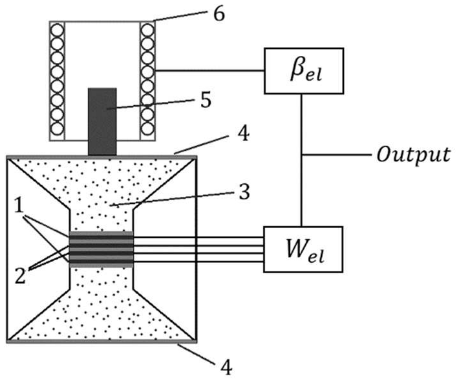

Fig. 2. Schematic representation of the MET sensor with magnetic-force feedback: 1 - anodes; 2 - cathodes; 3 - electrolyte; 4 - membranes; 5 - magnet; 6 - electromagnetic coil.

In general, for MET, the conversion of surface movement into electric current looks like a two-step process: a) conversion of external acceleration into the liquid flow through a transducer (determined by the properties of the mechanical subsystem), b) conversion of the liquid flow into current on the transducer electrodes (determined by the properties of conversion efficiency and by the electrochemical subsystem). In this connection, the transfer function of the MET transducers can be defined as follows:

$$W = W_{mech} \cdot W_{el-ch} \tag{1}$$

where W_{mech}, W_{el-ch} denote the transfer functions of the mechanical and electrochemical subsystems, respectively.

A. Transfer function of the mechanical system.

In accordance with [24], to calculate the transfer function of a mechanical system, the following equation can be used:

$$W_{mech} = \frac{Q}{V} = \frac{\rho L \omega^2}{\sqrt{\left(\frac{\rho L}{S_{CH}}\right)^2 (\omega^2 - \omega_0^2)^2 + R_h^2 \cdot \omega^2}}, \tag{2}$$

where Q denotes the volume liquid flow through the transducer generated by the measured mechanical signal, V denotes the liquid velocity in the channel, L denotes the channel length, S_{CH} denotes the channel area, ω_0 denote the mechanical frequency, ρ denotes the electrolyte density. $R_h = \frac{\Delta p}{Q}$ is the hydrodynamic resistance of the transducer. Since the electrode node makes the main contribution to the total hydrodynamic resistance of the system, for all practical calculations it should be assumed that Δp is the pressure difference at the edges of the electrode node. In the particular case when flexible membranes are used as an elastic element, the natural frequency is calculated as follows [25]:

$$\omega_0 = \sqrt{\frac{\alpha}{\rho L}\sigma},$$

where α denotes the membrane bulk stiffness , $\alpha = {}^{2\Delta p}/_{\Delta V}$, where Δp is the pressure difference from the two sides of the membrane, provided that a volume ΔV flows through the node, the coefficient 2 indicates that 2 membranes are used, $\sigma = {}^{S_{eff}{}^2}/_{S_{CH}{}^2}$, S_{eff} is the membrane effective area.

As a rule, converters have very high R_h and the resonance is well damped. In this case, the following expression can be used instead of (2):

$$W_{mech} = \frac{A_0}{\left(1 + \frac{\omega_{me\quad,1}^2}{\omega^2}\right)^{\frac{1}{2}} \left(1 + \frac{\omega_{mech,2}^2}{\omega^2}\right)^{\frac{1}{2}}}, \tag{3}$$

$$\omega_{mech,1} = \frac{\alpha}{R_h S_{CH}} \sigma^2, \quad \omega_{mech,2} = \frac{R_h S_{CH}}{\rho L}$$

where A_0 is the converter sensitivity at a very high frequency. The main part of the frequency range of velocity sensors based on MET usually lies between $\omega_{mech,1}$ and $\omega_{mech,2}$.

It is easy to see that the higher is the R_h and the greater is the S_{CH}, the wider frequency range of the sensors can be achieved.

B. Transfer function of the electrochemical system.

The calculation of the transfer function of the electrochemical system is described by the system of Navier-Stokes equations, non-compressibility of the liquid and convective diffusion [17]:

$$\begin{cases} \frac{\partial \vec{v}}{\partial t} + (\vec{V}\,\nabla)\vec{V} = -\frac{\nabla p}{\rho} + \nu \Delta \vec{V} \\ div(\vec{V}\,) = 0 \\ \frac{\partial c}{\partial t} + (\vec{V}\,\nabla)c = D\Delta c \end{cases},$$

where $\vec{V}$ is the flow velocity, p is the pressure, c is the active electrolyte ions concentration, D is the diffusion coefficient, ν is the liquid viscosity, ρ is the electrolyte density.

The first equation in the above system is the Navier-Stokes equation, the second one is the condition of the liquid incompressibility, and the last one is the equation of convective diffusion, under the assumption that a high concentration of background electrolyte is created and the contribution of migration to charge transfer is insignificant. As the boundary conditions, the ‘sticking’ condition is usually used - the liquid velocity on a solid surface is zero, the absence of the normal component of current on dielectric surfaces, and the condition for concentration on electrodes: in the saturation mode on cathodes $c = 0$. All these assumptions were used to find the transfer function of MET transducer.

For a known concentration distribution, the currents through the electrodes can be found [17] according to the expression:

$$I = -Dq \oint_S (\nabla c, \vec{n}) dS, \qquad (4)$$

here integration is performed over the electrode surface S, $\vec{n}$ is a unit vector normal to the surface, q is the charge transferred through the electrode in a unit reaction.

Using numerical and analytical methods, various cell configurations can be calculated. The choice of a particular method depends on the geometry of the electrodes and the required accuracy.

C. Mesh electrodes.

Currently, electrode nodes for MET transducers are manufactured out of platinum mesh. According to [15], where one of the types of rotary motion meters based on the MET has been studied, having an electrochemical subsystem similar to the studied sensor type, in the case when the distance between electrodes is of the order of the channel size, the electrochemical transfer function can be approximated by the following expression:

$$W_{el-ch} = \frac{qc_0}{\left(1 + \frac{\omega^2}{\omega_{el-ch}^2}\right)^{1/2}} \qquad (5)$$

where $\omega_{el-ch} = bD/d^2$, D is the diffusion coefficient, d is the distance between the electrodes, b is the parameter depending on the electrode system geometry, c_0 is the equilibrium concentration.

Putting (3) and (5) into (1) and considering [17], get that for practical calculations of the MET transducer transfer function, the following functions can be used:

$$W = \frac{A_0}{\left(1 + \frac{\omega_{mech1}^2}{\omega^2}\right)^{\frac{1}{2}} \left(1 + \frac{\omega_{mech2}^2}{\omega^2}\right)^{\frac{1}{2}}} \cdot \frac{1}{\left(1 + \frac{\omega^2}{\omega_{el-ch}^2}\right)^{\frac{1}{2}} \left(1 + \frac{\omega^2}{\omega_D^2}\right)^{\alpha}}, \qquad (6)$$

where $A_0, \omega_{mech,1}, \omega_{mech,2}, \omega_{el-ch}$, ω_D and α are the approximation parameters. These parameters can be calculated both from theoretical considerations and selected in the process of experimental studies. The theoretical value of $\omega_D \sim D/R^2$ is shown according to [15]. The theoretical value of the parameter $\alpha = 1/4$, which corresponds to the dependence $W \sim 1/R^{3/2}$ at high frequencies, which has been obtained from [26] and verified in a series of experiments for converters of various types.

D. Temperature dependence of electrolyte parameters.

The rate of ion transport in an electrolyte is determined by its diffusion coefficient and viscosity. They significantly affect the MET transducers conversion parameters. According to the Frenkel theory from [27], the viscosity of a simple liquid depends on the temperature as follows:

$$\nu = A \cdot \exp\left(\frac{E_a}{kT}\right). \qquad (7)$$

Here E_a is the electrolyte activation energy, $A = kT/\pi\omega_0 r\sigma^2$, where r is the molecule radius, σ is the interparticle distance, ω_0 is the molecular frequency.

In this case, the diffusion coefficient is related to viscosity the following way:

$$D = \frac{kT}{6\pi r\nu} = \frac{\omega_0\sigma^2}{6} \exp\left(-\frac{E_a}{kT}\right). \qquad (8)$$

It is obvious from (7) and (8) that viscosity and diffusion coefficient strongly depend on temperature, and, while viscosity decreases exponentially with the temperature increase, the diffusion coefficient increases exponentially. Since the process of convective diffusion is determined by these qualities of the electrolyte, the temperature change has a strong influence on the MET transducers characteristics. It should be comprehensively studied to determine methods and approaches to reduce the temperature sensitivity of the final products based on MET.

III. MEASUREMENT METHOD

To study the temperature dependences, the following setup was used, Fig. 3:

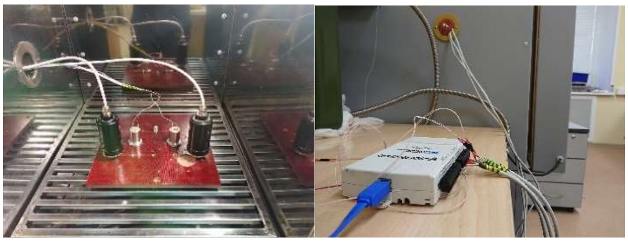

Fig. 3. The setup diagram of the study of the temperature dependence of the MET devices (two MET sensors in thermo-chamber (black ones), DAC NI6212 out of chamber collect the data to the PC).

The studied MET linear displacement sensors have been placed vertically in a heat chamber. Temperature regimes were created by the heat chamber M-60 / 100-120 KTX-T. For the purity of experiments, electrical circuits have been brought outside.

To obtain the amplitude-frequency characteristics of the device with open-loop feedback, the National Instruments NI-6215 data acquisition system has been used. Calibration was carried out as follows. Device feedback was open. The specified signal was fed through the DAC to the electromagnetic coil in the feedback loop. The force created by the action of the coil field on the magnetic core created the acceleration of the liquid in the electrode node. The change in the ion concentration gradient created a current on the MET transducers electrodes, which, after passing through the electronics with a known transfer function, was converted into a voltage signal. That signal, recorded using a data acquisition system, was fed to a PC.

Further, for each frequency, the spectrum of the signal from the sensor was plotted. The maximum of this spectrum was divided by the same maximum signal from the generator. From the points thus obtained, the amplitude frequency response of the instruments was obtained in units of applied acceleration. The instruments were calibrated using sinusoidal signals in the range from 0.1 to 443 Hz at various temperatures. To convert the characteristics into units of speed and compare them with theoretical models in the spectral region, it is sufficient to multiply the values of the experimental amplitude frequency response by the appropriate frequency.

Also, dependencies of the values of background currents on temperature have been taken. For this, voltage drops on resistors R in the cascade of signal conversion from current to voltage have been measured (Fig. 4).

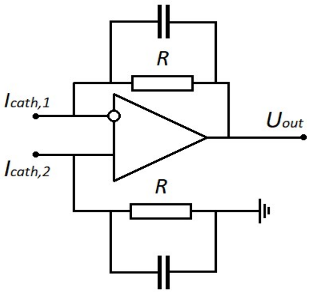

Fig. 4. Circuit of the current-voltage converter cascade.

As noted above, in this study sensors that were filled with different electrolytes have been investigated. To do this, 2 devices were filled initially with an aqueous solution of *KI*, with a concentration of 4 mol/l, with the addition of I_2, with a concentration of 0.1 mol/l. Experimental works have been carried out with these devices in the temperature range from -15°C to + 70°C. After that, the devices were refilled with an aqueous solution of *LiI* with the addition of I_2 at the same concentrations, and similar experimental works have been carried out in the temperature range from - 35°C to + 70°C. Thus, we have achieved the use of the same mechanical subsystem and could compare the dependences of electrochemical subsystems on temperature.

IV. OBTAINED RESULTS

For each device, transfer functions of devices have been obtained with increments 5°C. The examples are presented in Figures 4 and 5.

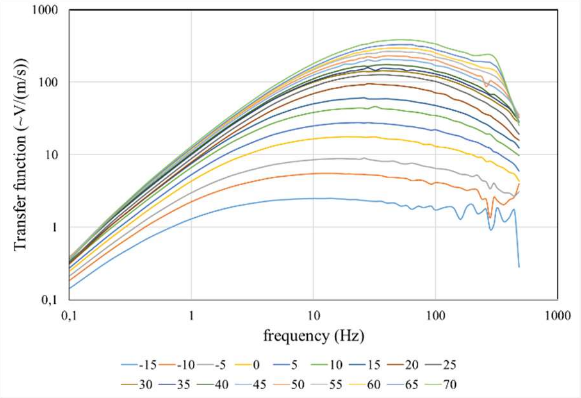

Fig. 4. The amplitude frequency response family for one of the KI-based sensors from -15°C to + 70°C

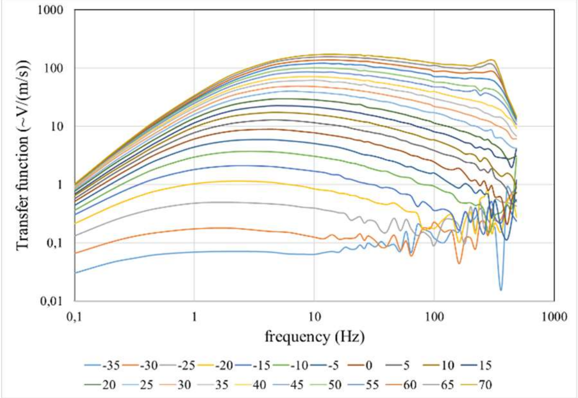

Fig. 5. The amplitude frequency response family for one of the sensors on the basis of LI from -35°C to 70°C

It is clearly seen that the amplitude frequency response of the MET devices changes significantly with increasing temperature, and the nature of the changes is not linear, both in the frequency and temperature range.

At the same time, the dependences of the background currents on temperature for the same linear displacement sensors have been obtained. They are shown below in Fig. 7.

It can be concluded from Figure 7 that it is obvious that the background currents have a dependence similar to the exponent on temperature. The close dependencies of the background currents of the devices with the same electrolytes confirm the identity of the devices.

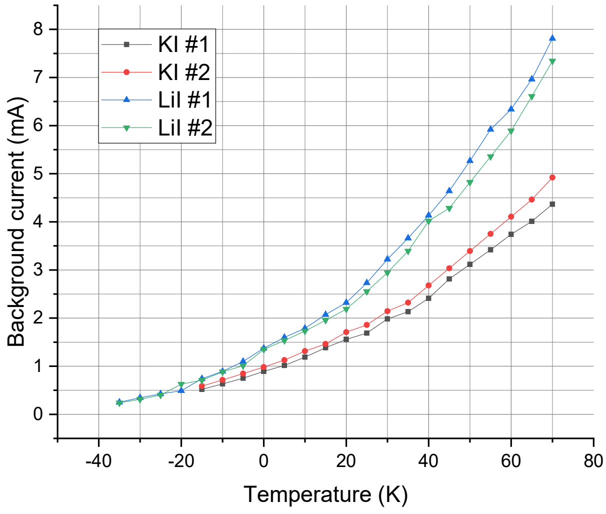

Fig. 7. The dependences of background currents on temperature for the tested sensors in both fillings.

V. INTERPRETATION OF RESULTS

First consider the behavior of the recorded characteristics at high frequencies. Perform calculations similar to those done in the previous study [16], but already for two types of electrolytes. As a result, obtain a strict correspondence of the results with previous studies. In particular, dependences of $ln(W)$ on $1/T$ based on the presented data have been constructed for each of the frequencies at temperatures from 0^oC to 50^oC. Each color line illustrates the value of $W(\omega)$ at the same frequency ω ω for different temperatures in the range of 80 - 403 Hz (Fig. 8 and Fig. 9).

A linear approximation for each array of experimental points will give a slope for each frequency $\alpha = T \cdot \ln(W)$. According to (6), $\alpha = const$ at $\omega >$ 100 Hz, which strictly corresponds to the experimental results. In this case, the transfer functions of the MET devices have a constant temperature dependence for both types of electrolytes, similar to [16]:

$$W = W_0 \cdot \exp\left(\frac{\alpha}{T}\right) \tag{9}$$

Thus, for the high-frequency range, the results from [16] got verified and supplemented with new information for the electrolyte based on LiI. Temperature compensating circuit at high frequencies for it can be calculated using similar methods.

As noted above, the model from [16] is however reliable only in the high frequency range and at temperatures above 0°C. To get rid of the restrictions imposed on (9), an approximation has been made in accordance with the theoretical model (6) proposed in Section II:

$$W = \frac{A_0}{\left(1+\frac{\omega_{mech1}^2}{\omega^2}\right)^{\frac{1}{2}}\left(1+\frac{\omega_{mech2}^2}{\omega^2}\right)^{\frac{1}{2}}} \cdot \frac{1}{\left(1+\frac{\omega^2}{\omega_{el-ch}^2}\right)^{\frac{1}{2}}\left(1+\frac{\omega^2}{\omega_D^2}\right)^{\alpha}},$$

where $A_0, \omega_{mech,1}, \omega_{mech,2}, \omega_{el-ch}$, ω_D and α are the approximation parameters.

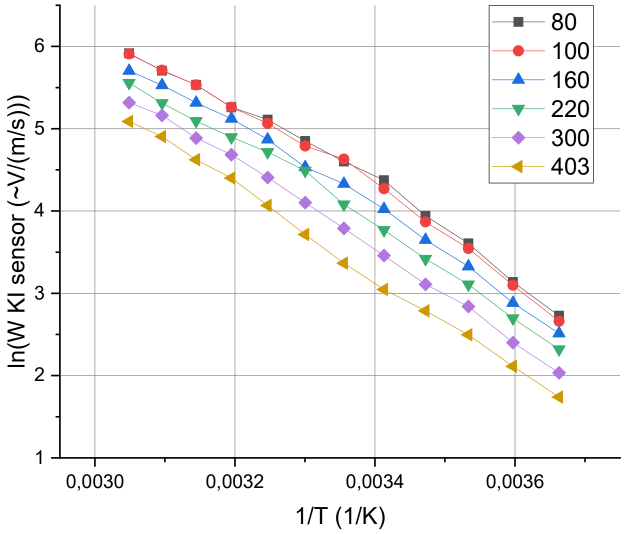

Fig. 8. Dependencies $\ln(W_{KI\ sensor})$ on $1/T$ from 0,1 Hz to 403 Hz.

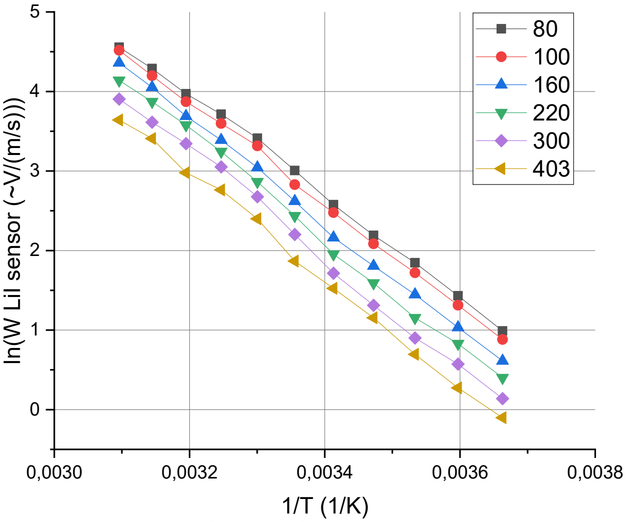

Fig. 9. Dependencies $\ln(W_{LiI\ sensor})$ on $1/T$ from 0,1 Hz to 403 Hz.

Approximation has been carried out in the program Origin 2018 on a logarithmic scale using the method of least squares.

It has been found out that the parameter A_0 almost does not change with a temperature change, and the parameter α received a scatter of values from 0.24 to 0.27, which well agrees with the theoretical value 0.25 [17]. Further selection of the approximation parameters has been carried out with fixed A_0 and α. Figures 10 - 12 show typical approximations of sensor characteristics.

It is worth noting that at low temperatures at the highest frequencies, the set gain and bitness of the ADC have not always been enough to remove the amplitude frequency response points, which did not significantly affect the reliability and verifiability of the models and experimental data.

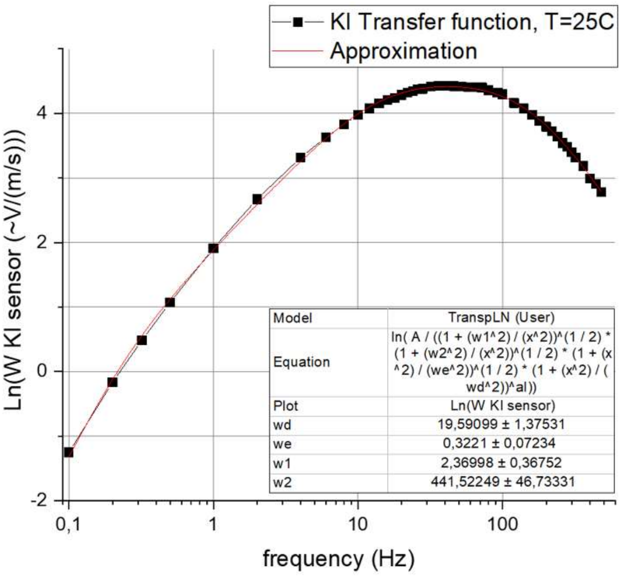

Fig. 10. Approximation of the transfer function for one of the KI-based sensors at 25ºC.

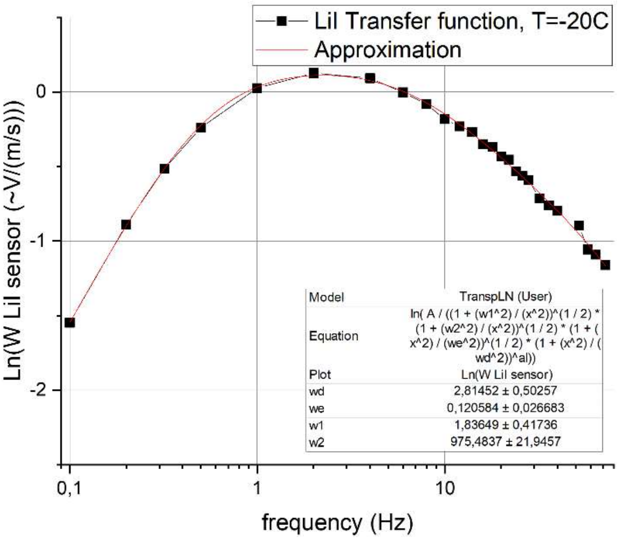

Fig. 11 Approximation of the transfer function for one of the *LiI*-based sensors at -20°C.

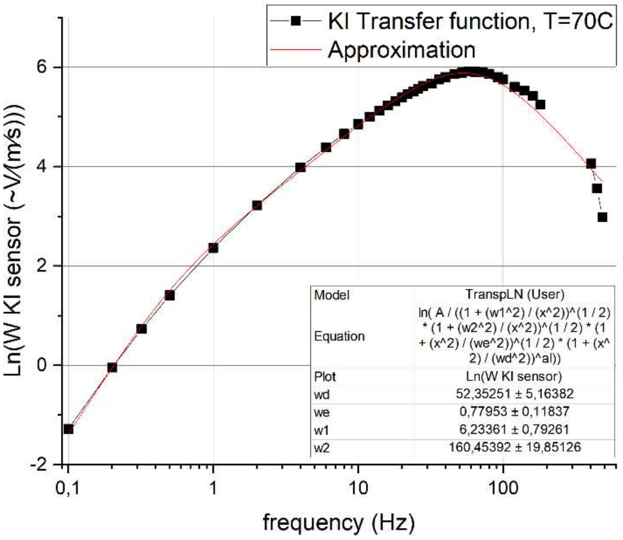

Fig. 12. Approximation of the transfer function for one of the KI-based sensors at 70°C.

Thus, for each of the transfer functions taken at each temperature, values $\omega_{mech,1}$, $\omega_{mech,2}$, ω_{el-ch} and ω_D have been obtained, that is, according to the experimental points for each temperature, approximation parameters have been given to adhere clearly to the AFC of the theoretical analytical dependence proposed in (6).

VI. VERIFICATION OF RESULTS

According to the theoretical model from Section II, each of these parameters is associated with temperature-dependent viscosity and diffusion coefficients, such as:

$$\omega_{mech,1} = \frac{\alpha}{R_h S_{CH}} \sigma^2 \sim \frac{1}{\nu}$$

$$\omega_{mech,2} = \frac{R_h S_{CH}}{\rho L} \sim \nu$$

$$\omega_{el-ch} = b \frac{bD}{d^2} \sim D$$

$$\omega_D \sim D$$

in turn, the diffusion coefficient D and the liquid viscosity ν exponentially depend on temperature (7) and (8).

To test the theoretical model and the obtained approximation coefficients of the experimental data, construct on a logarithmic scale $\omega_{mech,1}$, $\omega_{mech,2}$, ω_{el-ch} and ω_D from the inverse temperature (1/T), in Figures 13 – 14 examples of such dependencies for ω_D are given. It can be seen that the experimental points strictly lie on the linear dependence, which is fully consistent with the model of temperature behavior from (7) and (8). The angular coefficient of such dependences must correspond to the activation energies E_a of the corresponding ions of the corresponding electrolyte divided by the Boltzmann constant k.

Similar dependencies have been constructed for the remaining approximation parameters $\omega_{mech,1}$, $\omega_{mech,2}$, ω_{el-ch} and ω_D and the angular coefficients of the straight line for each of the characteristic frequencies corresponding to the activation energy has been calculated similarly. The results are shown in Table 1.

The table shows that, within the error limits, the activation energies coincide well with each other for each approximation parameter, which is a good verification of the correctness of the chosen mathematical model of the temperature behavior of the MET sensors in the 0.1 - 483 Hz frequency band.

Note that the activation energies for the 'electrochemical' coefficients (ω_{el-ch} and ω_D) in all cases turned out to be slightly higher than for the 'mechanical' coefficients ($\omega_{mech,1}$, $\omega_{mech,2}$). It happens because when considering the indicated effects of diffusion and viscosity, different ions of the electrolyte solution are important. Since the current carriers in the MET transducers, which is determined by the diffusion coefficient (4), are only triiodide ions (I_3^-), so the activation energy of these ions corresponds to the electrochemical subsystem. Whereas viscosity enters already as a parameter of the mechanical system and the averaged energy of activation of all molecules and solution ions plays a significant role here: water molecules H_2O, iodine ions I^-, K^+ ions (or Li^+), triiodide ions I_3^-.

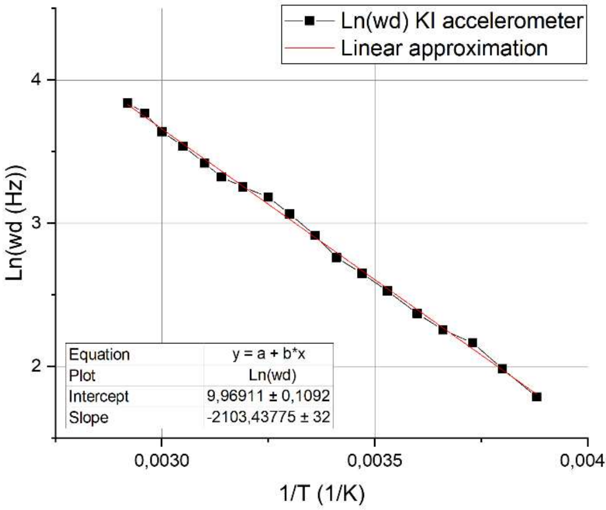

Fig. 13. Angular coefficient approximation for ω_D for one of the *KI*-based sensors.

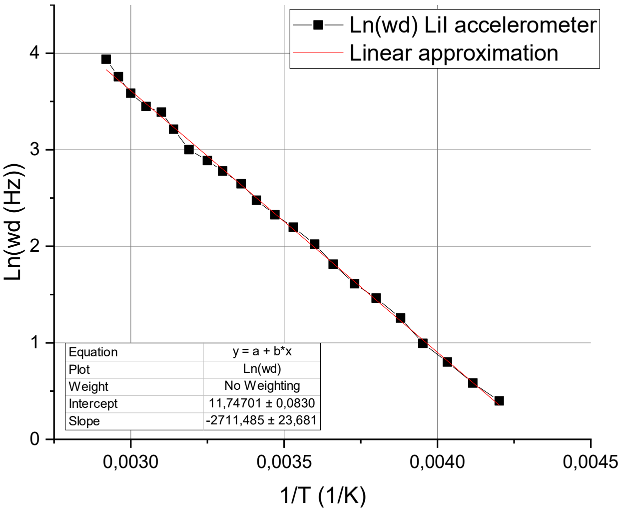

Fig. 14. Angular coefficient approximation for ω_D for one of the *LiI*-based sensors.

Angular coefficients, E_a/k (^0K)				
Parameter	KI #1	KI #2	LiI #1	LiI #2
ω_D	2168±27	2103±24	2711±31	2698±33
ω_{el-ch}	2133±28	2090±19	2612±21	2594±35
$\omega_{mech,1}$	1989±39	1922±43	2420±47	2297±51
$\omega_{mech,2}$	2018±54	1934±51	2412±62	2251±50

Table 1. Activation energies found from approximation coefficients

Remember that in Section IV we obtained the dependences of background currents on temperature, Fig.7. In accordance with (4), background currents also have a temperature dependence proportional to the diffusion coefficient. The dependence of background currents on temperature on a logarithmic scale should be linear, and the angular coefficient should be the same as that obtained from the ω_D and ω_{el-ch} dependences. In Figure 15, the corresponding patterns have been constructed.

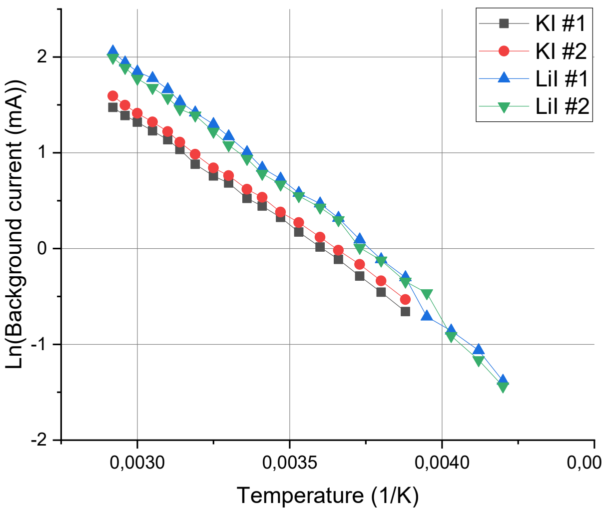

Fig. 15. The approximation of the angular coefficient for the background current of *KI*- and *LiI*-based sensors. The *x*-axis shows the reverse temperature (1/K), the *y*-axis shows the background current value, the scale is logarithmic

Angular coefficients, E_a/k (^0K)			
KI #1	KI #2	LiI #1	LiI #2
2184±28	2102±24	2626±33	2567±39

Table 2. Triiodide (I_3^-) activation energies, found from background currents

Comparing the results of Tables 1 and 2, we see that the activation energies obtained for the parameters depending on the diffusion coefficient for the triiodide ions (I_3^-) are very close to each other, which indicates the correct choice of the model and full agreement with the experiment.

The electrolyte viscosity and the activation energy of the ions of a 4-molar *KI* solution can be measured independently of the sensor operation with a conventional viscometer, with the possibility of thermoregulation of the selected volume. In this work, the "ВПЗ-3" viscometer has been used (Fig. 16).

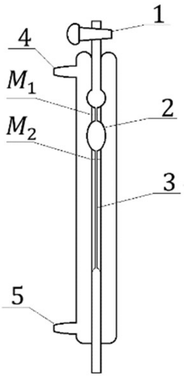

Fig. 16. The «ВПЗ-3» viscometer diagram: 1 - tap, 2 - measuring tank, 3 - capillary tube, 4 and 5 - taps for connecting to a thermostat, M_1 and M_2 - tags.

To measure the viscosity, the viscometer is filled with electrolyte through the valve (1), then the valve (1) is sealed. The thermostat is connected to (5) and the cavity around the capillary tube is filled with water of a known temperature. Drain for the circulation of water is performed through (4). After holding the device at the given temperature, the valve (1) opens and the time of electrolyte flow between the marks M_1 and M_2 is measured. After several measurements, viscosity is calculated from the average electrolyte flow time using the formula presented in the device instructions:

$$\nu = k \cdot t \cdot \rho,$$

where ν is the liquid dynamic viscosity (10^6 Pa·s) $k = 0{,}1074$ (mm/s^2) is the viscometer constant , t is the average fluid flow time (s), ρ is the liquid density (g/cm^3). The density was measured by weighing 100 ml of each electrolyte: $\rho_{KI} = 1{,}5$ g/cm^3 and $\rho_{LiI} = 1{,}41$ g/cm^3. The Figures 17 - 18 show diagrams of logarithms of viscosity on inverse temperature, approximated by a linear function.

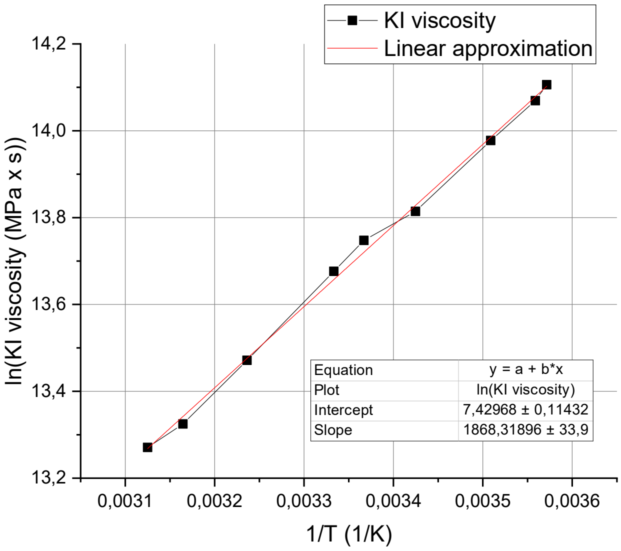

Fig. 17. Approximation of the *KI* electrolyte viscosity coefficient.

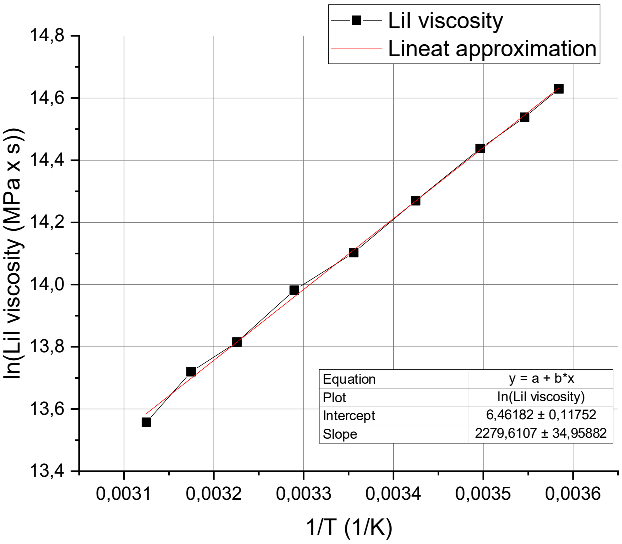

Fig. 18. Approximation of the *LiI* electrolyte viscosity coefficient.

This way, angular coefficients E_a/k have been obtained using direct measurements of the electrolyte's viscosity from temperature, presented in Table 3.

Angular coefficients, E_a/k (^{0}K)	
KI	LiI
1868±34	2280±35

Table 3. Activation energies of 4-molar solutions of *KI* and *LiI*, found from viscosity coefficients.

When comparing Tables 1 and 3, it can be seen that the values of the energies obtained for the parameters depending on the viscosity coefficient for 4-molar solutions of *KI* and *LiI* coincide within the limits of measurement error. Therefore, the proposed theoretical model (6) has been fully confirmed.

The results of this study are in good agreement with the latest results of studies of the transfer characteristics of molecular electronic meters at elevated temperatures and pressures [28].

CONCLUSION

According to the results of this work, temperature dependence of the MET transducer amplitude-frequency characteristic can be described by a well-known explicit analytical dependence containing simple power and exponential functions, which opens up the possibility of direct and precise circuit thermal compensation of final products based on molecular electronics principles.

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