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Molecular Electronic Linear Accelerometers. Preliminary Test Results

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Abstract—The paper focuses on the accuracy characteristics of linear motion meters based on molecular electronic technology. Zero bias stability in terms of Allan variance and power spectral density is experimentally determined for the linear accelerometers. Harmonic distortions depending on the input amplitude are measured.

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Currently the inertial navigation is aimed at development of small-sized systems measuring the motion parameters. The traditional technologies can't cater for the market needs as regards the cost of these measurement systems combined with their weight and dimensions, power consumption, dynamic parameters and accuracy, determined by the tasks to be performed. Therefore, new components—sensors with the desired characteristics—are to be found. A step forward in the development of small-sized measurement systems is the application of molecular electronic technology.

Conventionally, molecular electronic devices have been employed in various fields of applied seismology. It is caused by an extremely high sensitivity and low self-noise of molecular electronic transducers (MET). The task of this research is to create MET-based small-sized linear motion meters for the applied problems of inertial navigation and motion measurement.

MET sensor consists of a transducing electrode cell (Fig. 1), located in a dielectric case filled with a concentrated electrolyte solution. Usually the iodine-iodide electrolyte is used [1]. A small potential drop (<0.9 V) is applied to the electrodes situated in the solution, and reversible electrochemical reactions occur at the electrodes. Then the distribution of active component concentration is established in the system. The charge is transferred between the anode and cathode under the absence of external action by the diffusion of electroactive ions in the electrolyte solution, and the electron interchange only is performed at the electrodes: the electron is taken from the cathode and transferred to the outer circuit at the anode. The current flowing through the electrodes is completely defined by the diffusional component: $j = -neD\nabla C|_{\text{electrode}}$, where C is the active ion concentration, e is the electron charge, D is the active ion diffusion constant, n is the number of electrons involved in the single reaction at the electrodes. Under the presence of hydrodynamical flows the convection transfer is added to the diffusion one, which causes the system current step-up or step-down depending on the liquid flow direction. Current variations determined by the appearing hydrodynamical flows are MET output signals.

Using the elastic membranes installed at the channel ends, a device for the measurement of inertial motions along the channel axis can be formed, see [2–5]. The device drawback, however, is its inability to measure the constant acceleration.

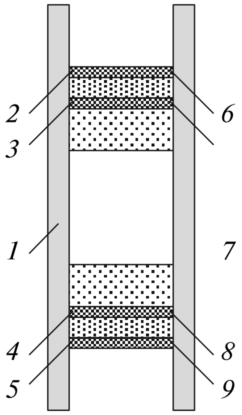

Fig. 1. MET cell: *1*—ceramic case, *2*, *3*—anode and cathode of the first electrode pair, *4*, *5*—anode and cathode of the second electrode pair, *6*, *7*, *8*, *9*—permeable dielectric spacers.

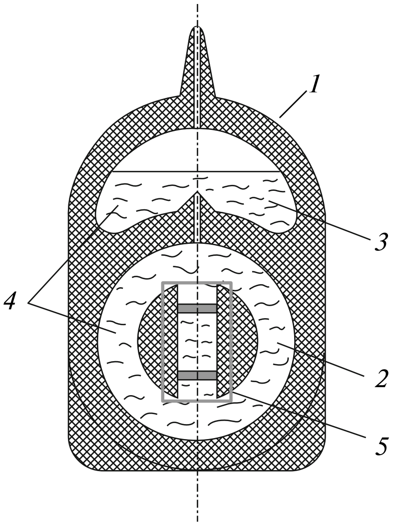

Fig. 2. Structural diagram of MET linear accelerometer.

The problem can be solved using MET design under study, shown in Fig. 2. The transducer is a ceramic case *1* with a working *2* and expansion *3* volumes filled with electrolyte *4*. The transducing electrode cell *5* is immersed in the working volume (see Fig. 1). The highly concentrated solution of potassium iodide KI (base electrolyte) and iodine I_2 is used as electrolyte. In the excess of iodide the iodine converts to triiodide, a very soluble complex compound (electrocative ions) as follows: $I_2 + I^- \longrightarrow I_3^-$. In the electrode cell used the distance between the electrode couples (between the cathodes) is rather big as compared to the anode-to-cathode distance.

One can easily note that in this design the liquid flow through the transducing cells occurs also under constant acceleration, which provides high sensitivity of this accelerometer up to 0 Hz. As mentioned before, the performance characteristics of a linear accelerometer can be simply optimized for the specific technical problems by the adjustment of accelerometer geometry and hydrodynamic resistance of a transducer. It should also be said that the sensitivity of this sensor does not depend on the direction of sensitivity axis in space.

One-dimensional Larcam model [1, 2] is one of the first theoretical models describing the principle of diffusional transducers. In the later theoretical research works [3–5] various 3D configurations of molecular electronic cells were modeled which made it possible to closely describe the mechanisms and main features of signal conversion in different frequency ranges. However only the flows for the electroactive ions were analyzed in these works, which is insufficient for the comprehensive description of a transducer under study, as both the active ions and the base electrolyte are responsible for the density variation in its transducing channel.

In view of the above it became clear that one should not only successively account for the transducing cell geometry, which is in general a complex 3D structure, but also consider the flows of all kinds of ions in the solution.

For the theoretical description of a similar MET a model shown in Fig. 3 was proposed and analyzed. The model geometry is simplified up to the single rectangular channel where the electrodes are located on dielectric steps. Electrolyte is considered to be electrically neutral, and its volume does not depend on the ion concentration.

Navier-Stokes equation and the diffusion-convection equation describing the system behavior were solved numerically using the values of physical magnitudes characterizing the electrolyte and cell geometrical dimensions representing the real values for the prototype cell.

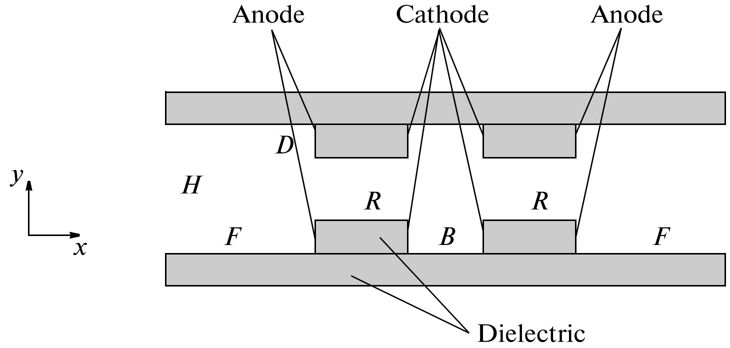

Fig. 3. Model of a MET linear accelerometer sensor; *H*—channel height, *D*—electrode height, *F*—distance between the channel end and anode, *R*—thickness of dielectric step, *B*—inter-cathode distance.

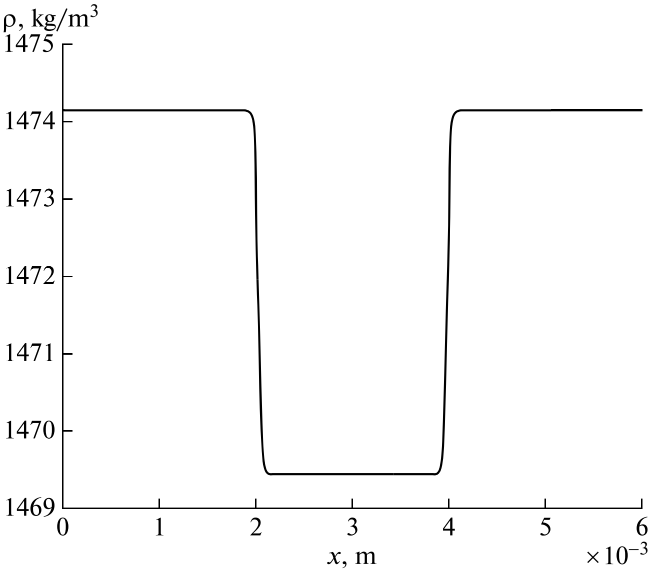

Fig. 4. Electrolyte density distribution under constant acceleration $a = 1$ m/s^2.

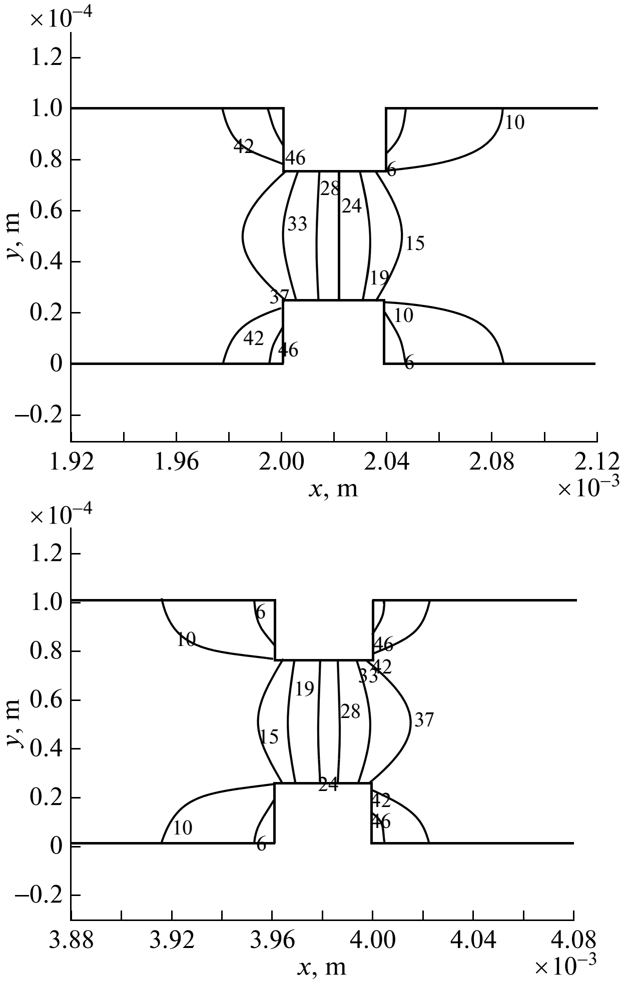

Fig. 5. Concentration distribution for active ions I_3^- at the left and right electrode couples under acceleration $a = 0.1\sin(2\pi ft)$ m/s^2 at $t = 12$ s.

The main result was the obtaining of electrolyte density distribution and concentration distribution for all ion types (Figs. 4, 5).

The calculations show that the electrolyte density mainly degrades between the anode and cathode of a corresponding couple both in motionless case and under external acceleration, whereas electrolyte density in inter-cathode space differs from the density outside MET by 0.3%.

The proposed theoretical model accounts for the electrical field effect on the processes in molecular electronic cell, and the numerical solution of equation systems qualitatively fits the experimental results.

If the devices under study are compared with the other ones, the primary parameters defining the data generation accuracy are the harmonic distortion, self-noise and zero bias drift: these errors can't be eliminated by the calibration of parameters in mathematical models for the navigation systems. This research focuses on these characteristics of MET meters, and compares the obtained noise characteristics with those of navigation parameters sensors produced by the world leading manufacturers.

There are several stochastic methods to describe various noise processes which determine the inaccuracy of generated navigation data. Among them is the analysis of noise characteristics in the terms of power spectral density in frequency domain and time sequence analysis to determine the system self-noise as averaging time function. Nowadays it is common practice to determine the zero bias stability using the time sequence analysis—Allan variance method [6]. This algorithm was specially developed to study the stability and noise of synchronization systems. However, it can be easily adapted for the systems with any output parameter other than time [7]. To calculate Allan function the noise signal record is divided into different number of parts with the same averaging time T. Variation for each averaging time is determined by the formula

$$\sigma^2(T) = \frac{1}{2(n-1)}\sum (y(T)_{i+1} - y(T)_i)^2,$$

where $\sigma(T)$—Allan function, $y(T)$—averaged value of the recorded signal at the i-th part, n—number of parts. After the calculations the Allan function is plotted against averaging time in log-log scale.

As the zero bias stability is determined under no external disturbing signal in heat-stable conditions,

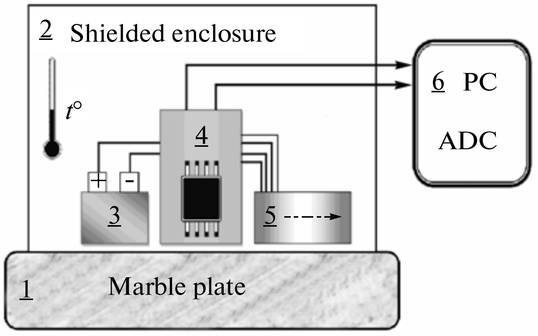

Fig. 6. Test setup for noise measurement of MET motion meters.

the following test setup (Fig. 6) was used to study noise parameters and bias instability of MET meters. The units under test *5* were put under the dome of enclosure *2*, where the constant temperature was maintained during the test. The sensor sensitivity axis was in the horizon plane. Correcting electronics *4* and power unit *3* were also located under the enclosure dome. The enclosure was installed in a room isolated from the external seismic effects. External data acquisition system *6* converted the sensor analog signal to the digital one with sampling rate 80 Hz. To analyze the noise parameters the sensor signal was recorded for a long time (~10 h) under no external effects and under constant temperature. Then Allan variance was calculated as a function of averaging time T using the expression given above.

Results of test data processing for MET miniature linear accelerometers are presented in Fig. 7. By the zero bias instability the value corresponding to the minimum Allan function of averaging time in acceleration units (μg) is meant. The given data demonstrate that the best zero bias stability can be obtained with the averaging time approximately 500 s. The zero bias instability is 2.5 μg (2.5×10^{-5} m/s^2).

Meters of motion parameters are used in various navigation systems depending on their zero bias values (see table) [8]. Therefore, miniature MET linear accelerometers can be applied in all the groups of navigation systems, up to strategic ones.

Another accepted stochastic method to describe the device noise characteristics is the power spectral density (PSD) $S_\Omega(f)$ which is related with Allan variance $\sigma(T)$ by the formula $\sigma^2(T) = 4\int_0^\infty S_\Omega(f)\frac{\sin^4(\pi f T)}{(\pi f T)^2}df$, where T is the averaging time, f is the frequency.

Allan variance is proportional to the full power of noise signal that passed through the filter with a transfer function of the form $\sin^4(x)/(x)^2$. The filter width obviously depends on the averaging time T. Therefore Allan variance as a function of averaging time T provides identification and numerical estimation of various noise contributors in the sensor data. However, *PSD* is a more universal method to analyze the noise.

Figure 8 presents the test results in terms of PSD for MET linear accelerometer, with PSD of 35 $\mu g/\sqrt{\text{Hz}}$.

The next part of the paper focuses on nonlinear distortions in the signals of MET sensors. The values of harmonic distortions are determined by the amplitude of spurious harmonics, occurring in the signal spectrum of a sensor under sinusoidal input.

The nonlinearities of linear accelerometers were investigated as follows. Using the calibration bench providing harmonic oscillations at a certain frequency,

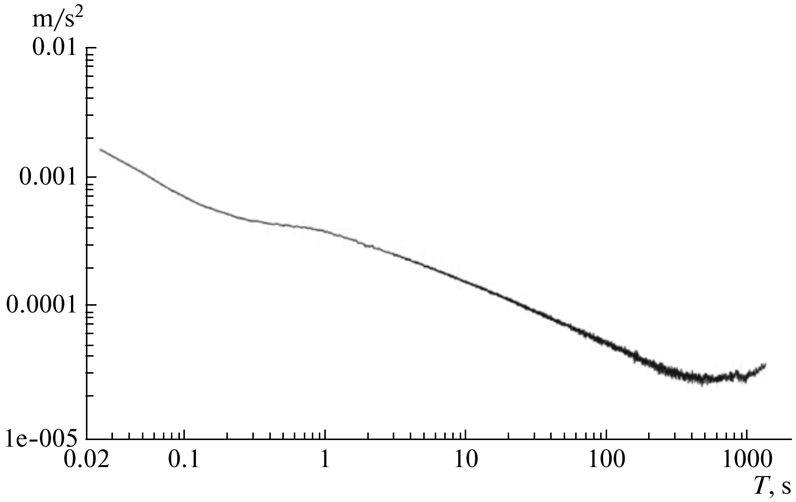

Fig. 7. Allan variance for MET linear accelerometer.

Accelerometer application depending on zero bias values

Application	Zero bias
Strategic	<1 μg
Navigation	10–50 μg
Tactical	0.1–1 mg
Industrial	10–100 mg

a sine signal with amplitude 0.8–3 mm/s^2 was formed at 10 Hz frequency and the amplitudes of the first, second and third harmonics of the output signal were taken. The test made it possible to find the dependence of output signal harmonic distortions on the input amplitude. The measurement results are given in Fig. 9.

The test showed the level of nonlinear distortions to be rather low. The relative value of spurious harmonics in miniature MET linear accelerometer does not exceed 1% under accelerations below 2.8 m/s^2. Both the second and the third harmonics grow as the input amplitude is increasing. It is connected with the nonlinear performance of the calibration bench under input amplitudes above 3 m/s^2.

For comparison purposes below are given the zero bias and self-noise values of MEMS accelerometers which are marketed by the manufacturers as high-precision motion parameters meters to be used in inertial measurement units:

—A35 Accel (Gladiator Technologies, Inc., USA), ~0.25 mg, 25 $\mu g/\sqrt{Hz}$;

—7290A (Endevco Corporation, USA), ~10 mg, 5 $mg/\sqrt{Hz}$;

—CLX02TG3 (Crossbow Technology, Inc., USA), ~10 mg, 20 $\mu g/\sqrt{Hz}$;

—QA-3000 (Honeywell International Inc., USA), ~4 mg, 10 $\mu g/\sqrt{Hz}$.

The analysis of results and characteristics of devices chosen for comparison shows that MET linear accelerometers exceed the best of MEMS rivals in the studied frequency range (0–100 Hz) and successfully compete with other meter types in self- noise, zero bias stability and level of harmonic distortions.

The key differences of MET sensors from the other inertial sensors that are advantageous for the batch production are as follows: the inertial mass is a liquid (electrolyte solution flowing through the transducer) and no moving fine mechanics subject to wear-out and possible damage, which makes the performance more reliable. It is the liquid inertial mass and the properly selected parameters of transducer (electrode assembly) that define high sensitivity and low self-noise of such devices in low and ultra low frequency ranges.

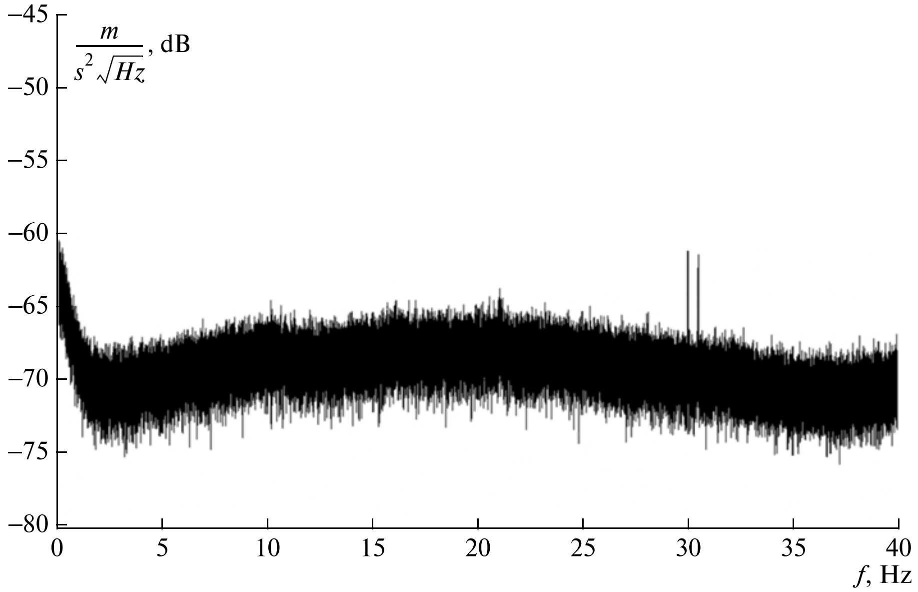

Fig. 8. PSD of MET linear accelerometer.

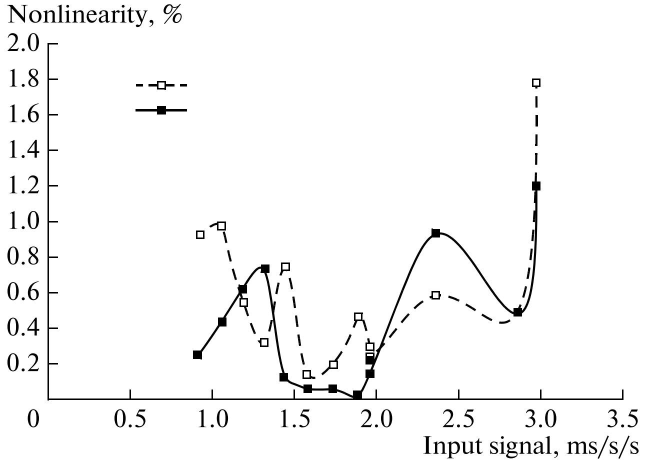

Fig. 9. Dependencies of the 2nd (row 1) and 3rd (row 2) harmonics on the input amplitude (relative to the first harmonic).

The paper data demonstrate that the new types of low-cost miniature inertial motion meters based on molecular electronic technology can be applied to achieve accuracy of navigation parameters estimation acceptable in a broad range of applications.

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