# Small, Low-Power, Low-Cost Sensors for Personal Navigation and Stabilization Systems.


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## BIOGRAPHY

Dr. Kozlov holds the position of Senior Vice President in charge of Research & Development at Met Tech, Inc. He received his Ph.D. in Physics from Moscow Institute of Physics and Technology in 1974 and his Doctor of Science in 1988 from the same Institute. He is a world authority in the research and development of inertial sensors based on the technology of Molecular Electronic Transducers. Dr. Kozlov is a Professor and chair in the Division of Molecular Electronics at the Moscow Institute of Physics and Technology. His research focuses on the fields of fluid mechanics in porous structures, kinetic phenomenon in solids, physical properties of electrolytic solutions, molecular electronics, and phenomenon of the liquid /metal interfaces, seismic instrumentation and devices for intentional navigation systems. Dr.Kozlov`s cross-disciplinary background has allowed him and his group to develop and commercialize anew type of broadband three-component seismometers based on molecular - electronics transducers. Since 2000, he has focused on the development of IMU for railroads, vehicles and personal inertial navigation systems. He has more than 300 professional publications.

Vadim Agafonov received his MS in General Physics in 1989 and a Ph.D. in Physics of Semiconductors and Dielectrics in 1993 from Moscow Institute of Physics and Technology. He plays a leading role in the experimental aspect of R&D work and makes a significant contribution to the advancement of the theoretical foundation of molecular electronics. He has published over 30 scientific and technical articles.

Mr. J. Bindler holds undergraduate and graduate degrees in Engineering from the Minsk Polytechnic Institute and an MBA in Finance and International Business from New York University's Stern School of Business.

Currently, Alexander Vishnyakov is a Ph.D. candidate at Moscow Institute of Physics and Technology. In 2003, he received a bachelor's degree at Moscow Institute of Physics and Technology and a master's degree from Moscow Institute of Physics and Technology in 2005. His areas of scientific interest are: molecular electronics, kinetic phenomenon in electrolytes and metal electrodes, Inertial Navigation Systems, development of signal conditioning circuits for molecular-electronic sensors, and MCU-based mixed-signal circuits for inertial motion units.


## ABSTRACT

The first decade of the 21st century has been labeled by some as the "Sensor Decade." With a dramatic increase in sensor R&D and application over the past 15 years, sensors are certainly poised on the brink of a revolution similar to that experienced in microcomputers in the 1980s. Tremendous advances have been made in sensor technology and many more are on the horizon. Sensor designers are working hard to minimize the size of devices without sacrificing their performance characteristics. Efforts to minimize linear acceleration systems and gyros for inertial navigation systems are mostly concentrated around MEMS technology. This technology satisfies some of the requirements for inertial navigation systems. However, the cumulative errors of MEMS-based devices are still too high for most navigation applications. The desired parameters for INS are at least an order of magnitude better than current devices based on MEMS technology.

This article reports on the development of linear and angular accelerometers based on the proprietary molecular-electronic technology. The technology utilizes liquid not only as an inertial mass but also as one of the main elements in the conversion of mechanical motion into electric current. The amplification process is similar to that in a vacuum triode. Therefore, it is possible to achieve signal amplification close to $10^8$. As a result, we have been able to develop a product line of inertial sensors demonstrating wide frequency and dynamic range and sensitivity that is two orders of magnitude better than MEMS devices of the same size.

**MOLECULAR-ELECTRONIC TRANSDUCER – PRINCIPLES OF OPERATION AND NOISE CHARACTERISTICS**

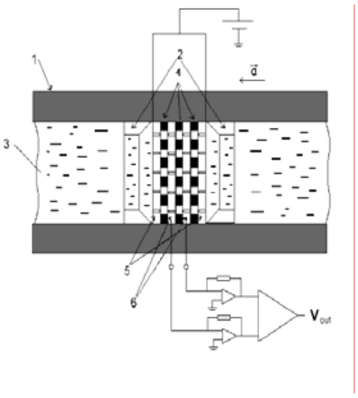



**Fig. 1** MET Cell.

1 – Ceramic tube; 2 – Clamping rings;

3 – Electrolyte; 4 – Punched dielectric

spacers; 5 – Anodes; 6 – Cathodes.

A key diagram of the MET cell is shown in **Fig. 1**. Spacers *4* with punched holes are installed inside of a ceramic tube *1* filled with electrolyte *3*. Thin wires connect the transducer electrodes, *5* & *6*, with the external electronic circuit. Electrodes located between the spacers *6* precede as cathodes; the outer electrodes *5* as anodes. The symmetrical geometry of the cell is important for ensuring its linear behavior over a wide range of signals. When a voltage source V is connected, after a short settling time a quiescent electric current starts flowing between two pairs of electrodes and in the external bridge circuit.

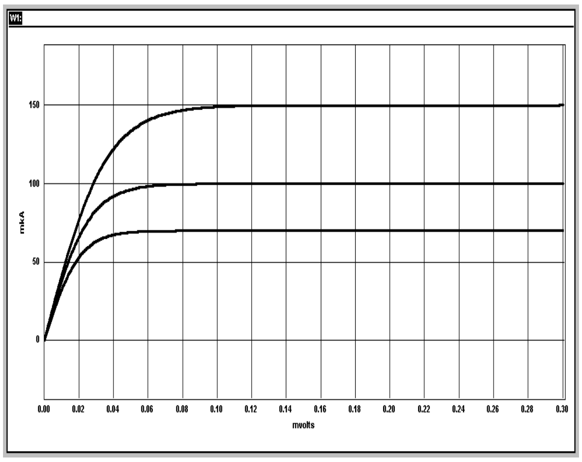



**Fig. 2** The Current-Voltage Output Characteristics of the MET System.

The middle curve corresponds to the absence of external acceleration. Top and bottom curves correspond to the different directions of applied acceleration shown in **Fig. 2**. These characteristics are very similar to those of a vacuum pentode, where the role of the control grid voltage is played by the liquid movement bringing the electrical charges to the electrodes. As does a pentode, a MET provides extremely high power gain ($>10^8$).

Acceleration causes a pressure differential to be formed across the cell. This pressure difference causes a flow of electrolyte, with volumetric flow rate q, between the electrodes. The flow entrains charge carriers (ions), raising their concentration on one set of the electrodes and reducing it on the other. This results in a change of the electric current in the external circuit. The electrical signals at the output of the cell therefore change as a function of the input mechanical motion. The symmetrical arrangement of the cell is required for improvement of the linearity and expansion of the dynamic range. Taking into account that the amplitude of the second harmonic is proportional to the square of the input signal, the second harmonic will be removed when the two parts of the cell are connected in the opposite polarity.

The transfer function of the molecular electronic cell depends on its geometrical parameters, such as the diameter of the holes in the punched spacers and the diameter of the wire used during the mesh manufacturing. In practice, it is possible to design the molecular electronic cell with the frequency independent transfer function and with the frequency dependent ~ 1/ω transfer function. When the transfer function is frequency independent, the output signal is proportional to the external acceleration. If the transfer function is proportional to 1/ω, the output signal of the molecular electronic cell corresponds to the velocity. For better understanding, it is necessary to keep in mind that electrical current is generated by the molecular electronic cell proportional to a volumetric flow of the electrolyte across the cell. Since the volumetric flow of the electrolyte in accordance with Navier–Stockes equation is proportional to the pressure drop across the cell, the output signal is proportional to the external acceleration. The relationship between pressure drop $\Delta p$ across the cell and external acceleration is the following:

$$\Delta p = \rho \cdot l \cdot a_{ext},$$

where $\rho$ is electrolyte density, $l$ is the length of the cell, and $\alpha_{ext}$ is the external acceleration.

This transducer is used as a sensitive element in both linear and angular sensors. The operation mode depends on the assembly used. In linear sensors, it is generally similar to that used in

MEMS and includes an inertial mass (liquid mass in MET sensors: 0.9 grams for the angular sensors and 0.4 grams for linear) and damping elements. Both linear and angular accelerometers have no mechanical oscillating system, and they do not need the elements providing the restoring force. As a result, these accelerometers can operate from DC. Angular accelerometer schematic assembly is shown in **Fig. 3**. The sensor consists of an electrolyte-filled toroid *1* with a molecular electronic transducer *2*, described above. The bulb *3* is necessary to compensate for temperature expansion of the electrolyte in the temperature range -65 ÷ +85 °C.

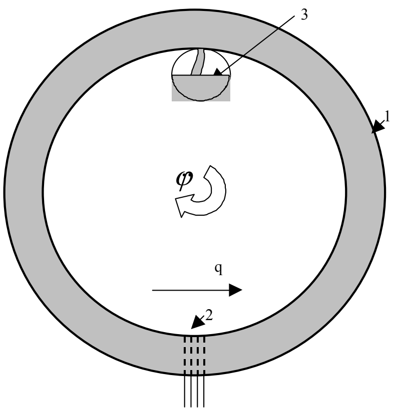



**Fig. 3** Simplified Sketch of a

MET Angular Sensor.

The angular accelerometer operates in the following manner. If the angular acceleration is applied as shown by the arrow in **Fig. 3**, the fluid in the toroid starts to flow. As a result, the electric current appears at the output of the molecular-electronic transducer. The amplitude of the electric current is proportional to applied angular acceleration. The transfer function of an angular accelerometer is a constant from DC up to 300 Hz. The upper limit of the cutoff frequency is defined by the distance between electrodes. The less the distance between electrodes, the wider the frequency range. For example, when the thickness of the spacer is 30 microns, the upper cutoff frequency is equal to 300 Hz. When the thickness of the spacer is decreased 3 times, the upper cutoff frequency is increased 9 times. This frequency range is sufficient for modern inertial navigation systems [14]. There are no obvious limitations to the upper cutoff frequency reaching several dozens of kHz. The same relationship is true for linear sensors.

Molecular-electronic technology allows for developing not only the angular accelerometer but also the rate sensor. In this case, the transfer function should be proportional 1/ω. The most common way to obtain this transfer function is to use the electronic circuit design. Our angular accelerometers are uniquely suited for this purpose because of their low self-noise parameters. At the same time, we have designed a DC-sensitive MET rate sensor based on Carioles effect. MET transducers internally generate high-gain electronic response for the mechanical motion. This feature allows the devices to overcome the main disadvantage of existing micro-machined transducers, which suffer from low signal level that is close in strength to electronic self-noise.

The self-noise of the molecular-electronic transducer is defined by the hydrodynamic impedance $R_h$ of the molecular-electronic cell, shown in **Fig.1**. More accurately, self-noise is defined by the diameter of the holes in the spacers, the step of the mesh, and the diameter of the mesh wires. The spectrum density of the self-noise expressed in terms of acceleration is defined by the following expression:

$$\left\langle \ddot{\varphi}^2 \right\rangle = \frac{R_h \cdot T \cdot k_b}{4 \cdot \pi^4 \cdot \rho^2 \cdot R^4},$$

where $k_b$ is Boltzmann's constant, $T$ is the absolute temperature, $\rho$ is the density of electrolyte, and $l$ is the length of the cell. The typical value of $R_h$ is equal to $10^8$ N* sec/m$^5$. The typical value of $R_h$ can be varied by two or three orders of magnitude, in both increasing and decreasing directions.

It is important to note that the spectrum density of noise in the molecular-electronic cell looks like white noise; in other words, it does not depend on the frequency. On the other hand, the higher value of the hydrodynamic impedance, the maximum measuring acceleration, is higher. As a result, molecular-electronic technology has great potential in regard to decreasing self-noise levels and increasing dynamic range.

Assuming the self-noise is flat, the angular error after the period $t$ of the autonomous operation can be estimated using the following expression:

$$\Delta\alpha_{1hour} = \sqrt{\frac{R_h \cdot T \cdot k_b \cdot t^3}{3 \cdot (2\pi)^6 \cdot \pi^2 \cdot \rho^2 \cdot R^4}}$$

For example, at room temperatures for *t=1 hour*, the angular error will be close to 1°/*hour*, for $R_h$ = *3*10$^{10}$ N*s/m$^5$* and *R=5 mm.* If $R_h$ = *10$^8$ N*s/m$^5$* , the one-hour angular error will be less than 0.1 °/*hour*. Independent measurements of the angular errors performed by Motorola and at Russia's Federal State Unitary Enterprise CSRI "Elektropribor" confirmed these calculations.

## LINEARITY TESTS

Special tests have been performed to estimate the linearity of the molecular-electronic sensor and its sensitivity to vibrations. During these tests, the amplitude of the input signal varied in a wide range for the constant frequency of the signal. The output signals were measured using a spectrum analyzer. To evaluate the influence of the vibrations, tests were performed at frequencies of 800Hz and amplitude 350 rad/sec$^2$.

The test results are presented in the following tables. First column is the amplitude of the input signal; the second column is the output signal in dBs, relative to 7.5 mV. The third column contains the output acceleration of the sensor, which was calculated by dividing the sensor output signal by the gain, determined in the previous test.

***Sample # 1***

| ε, rad/s$^2$ | A, dB | $\varepsilon_s$, rad/s$^2$ |
|---|---|---|
| 400 ± 40 | 58.44 | 417.8 ± 20 |
| 300 ± 12 | 56.00 | 315.5 ± 20 |
| 250 ± 12 | 54.38 | 261.8 ± 15 |
| 200 ± 12 | 52.19 | 203.5 ± 12 |
| 150 ± 12 | 49.38 | 147.2 ± 10 |
| 100 ± 12 | 46.25 | 102.7 ± 5 |
| 100 ± 4 (switching to another frequency range) | 45.94 | 99.1 ± 5 |
| 80 ± 4 | 44.06 | 79.8 ± 4 |
| 60 ± 4 | 41.56 | 59.8 ± 3 |
| 40 ± 4 | 38.13 | 40.3 ± 2 |
| 20 ± 4 | 32.19 | 20.3 ± 1 |

***Sample #2***

| ε, rad/s$^2$ | A, dB | $\varepsilon_s$, rad/s$^2$ |
|---|---|---|
| 300 ± 12 | 61.88 | 289±15 |
| 250 ± 12 | 60.31 | 242±15 |
| 200 ± 12 | 58.44 | 195±12 |
| 150 ± 12 | 55.94 | 146±10 |
| 100 ± 12 | 52.88 | 103±5 |
| 100 ± 4 (switching to another frequency range) | 52.81 | 102±5 |
| 80 ± 4 | 50.94 | 82±4 |
| 60 ± 4 | 48.44 | 62±3 |
| 40 ± 4 | 45.0 | 41±2 |
| 20 ± 4 | 39.06 | 21±1 |

The accelerations achieved during the calibration are presented in the left column; in the right column are presented the accelerations measured by the sensor.

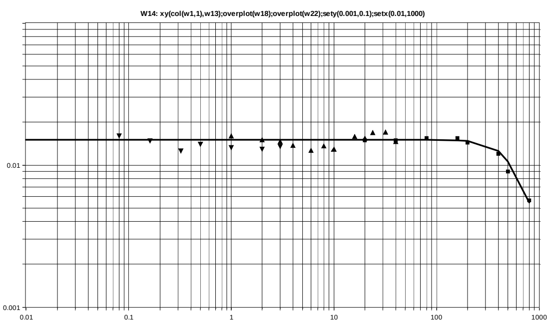
It is easy to see that in the entire range of the input signals, errors introduced by sensor non-linearity are below experimental accuracy and, certainly, do not exceed 3% in the full range.

## FREQUENCY RESPONSE

Frequency response tests have been performed using two shake tables; the first one is optimized for low frequencies below 40 Hz, the second one for a 20-800 Hz frequency range. An additional electronic preamplifier has been used at very low frequencies.

The results of the tests are summarized in the pictures below.

***Sample #1***




***Sample # 2***

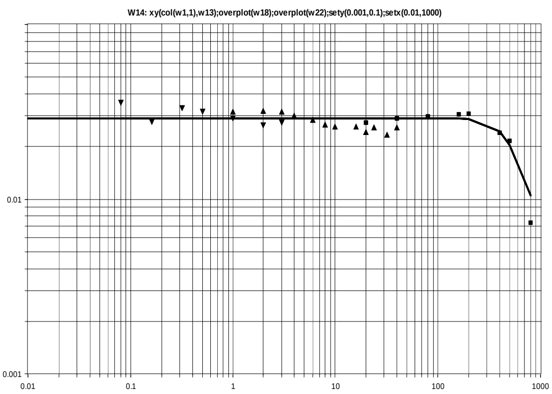



**Fig. 4** Gain-frequency characteristics of the microsensors over the 0.01-1000 Hz frequency range; horizontal axis – frequency, Hz; vertical axis – sensitivity, V/(rad/s2); ■ – characteristic determined in the 20-800 Hz; ▲– data found in the 1 – 40 Hz range, reduced to the primary sensor gain,▼– data found in the range 0.08-3 Hz, reduced to the primary sensor gain.

We must emphasize that all materials used in the MET transducer are complementary with modern volumetric manufacturing microelectronic technologies; a simple geometry of the transducer can be easily reproduced in micro scale using existing microelectronic technology and is extremely suitable for mass production. The effects of scaling the MET transducer downward to a smaller size are beneficial, since they result in a larger high-frequency conversion factor at higher frequencies and very low power consumption.

In **Fig. 4** and **5** are samples of the molecular-electronic linear accelerometer and angular accelerometer.

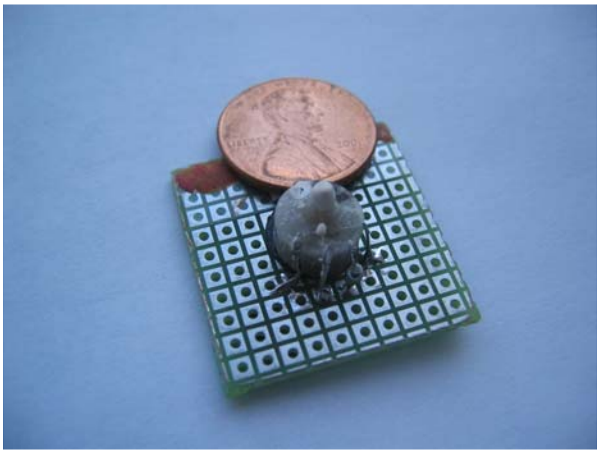


**Fig. 5** Example of molecular-electronic angular accelerometer.

**Fig. 6** Example of the molecular-electronic linear accelerometer.

Based on the aforementioned devices, a simple IMU was recently developed, designed, and tested. The results of the tests are shown in **Fig. 7** and **8**.

**Fig. 7**. The real path of the vehicle. Top view.

## CONCLUSION

As follows from the presented data, molecular-electronic technology enables the development of linear and angular accelerometers, as well as rate sensors, with performance characteristics that are orders of magnitude better than MEMS.

MET angular accelerometer could be used to correct bias stability errors of low-cost MEMS IMU. MET rate sensors and linear accelerometers will be used as components of high-performance IMUs.


## ACKNOWLEDMENTS

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