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Research Article

Precession Azimuth Sensing with Low-Noise Molecular Electronics Angular Sensors

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This paper describes the use of MET-based low-noise angular motion sensors to precisely determine azimuth direction in a dynamic-scheme method of measuring the Earth's rotational velocity vector. The scheme includes sensor installation on a rotating platform so that it could scan the space and seek for the position of the highest Earth's rotation vector projection on its axis. This method is very efficient provided a low-noise sensor is used. A low-cost angular sensor based on MET (molecular electronic transduction) technology has been used. The sensors of this kind were originally developed for seismic activity monitoring and are well known for very good noise performance and high sensitivity. This approach, combined with the use of special signal processing algorithms, allowed reaching the accuracy of 0.2°, while the measurement time was less than 100 seconds.

1. Introduction

The information about body position in space is essential for the solution of a number of tasks, such as vehicles navigation, antennae positioning in communication systems and geodesy, construction of pipes and underground tunnels, target indication, and mobile objects maintenance. Herewith the body position in space is defined by two independent directions, which are gravity vector at a certain point of the Earth's surface and azimuthal angle found from the true north heading.

The task of angle detection at which the chosen body axis is positioned relative to the Earth's gravitational vector at a certain point in space is quite easy and can be solved successfully with the use of high precision accelerometers. High precision identification of the chosen body axis relative to the local north heading (azimuth measurement) is a much more complex task.

Azimuth measurement with certain accuracy can be performed with the help of modern magnetometers [1]. To calculate the true azimuth, it is necessary to know the region magnetic declination, which primarily makes the method notoriously imprecise. Besides, any local magnetic fluctuation leads to static error in azimuth calculation. Even the most modern and precise digital magnetometers have limiting accuracy of 10 mR (milliradians) and require, often, time-consuming and relatively complex calibration [2, 3]. Therefore, in case of any magnetic disturbances or magnetized bodies the use of compass to define the true north heading is ineffective.

Azimuth measurement has been performed for a long time by the position of stars and other celestial objects. Modern astronavigation equipment is widely used at orbital vehicles and other space vehicles and missions [4]. Two of the most common methods to observe celestial objects are well known, and these are the method of hour angle measurement

[5] and the method of zenith distance identification [6]. By means of long-term follow-up and averaging of results, the methods of astronomic navigation can achieve high precision of true azimuth measurement, where the precision is about second decimal places of degrees. Nevertheless, the main problem of common usage of astronavigation is the access to clear sky and observation of remote celestial objects.

The use of differential satellite signals to define the object positioning in space is the modern way to find the true azimuth. Currently, fully featured Global Navigation Satellite Systems (GNSS) feature the American Global Positioning System (GPS) and the Russian Global Navigation Satellite System (ГЛОНАСС). As a rule, GNSS uses two main positioning methods, which are absolute (direct reception of satellite signal) and relative (with the use of premounted lighthouses). The absolute method includes object coordinates reception with lower precision; that is why it is used in navigation, while the relative one provides higher precision and is used directly for positioning. The ways of defining azimuth are also classified into static and kinematic, depending on whether the satellite receiver was moving during the measurements or not. Both methods require at least two signal receivers, simultaneously observing the same satellites to provide vector calculation between the signal receivers [7]. The main problem of satellite systems, especially from the military point of view, is that the satellite signal is not always available and it can be lost or forcedly turned off.

The modern way to define true azimuth is based on so-called gyrocompassing, which is direct measurement of Earth's angular velocity projection vector on horizontal plane at a given point of surface [8–10]. As a rule, such systems use one or several angular velocity or acceleration sensors with or without additional equipment to define the horizon level. At the present time, there are two main widely spread methods, which are static and dynamic. They have been thoroughly described in [11–13].

The possibility to use inertial measurements of Earth's angular velocity with the dynamic method arouses considerable interest. The principle of method is to place angular motion sensor (angular accelerometer or gyroscope) on a platform which changes its position in space in a certain known way. Most frequently, the platform traverses, which is orthographic to the sensor sensitivity axis. In that case, both Earth's angular velocity vector projection on sensor sensitivity axis and its output signal change periodically with the movement. Amplitude and phase of the corresponding changes have the information about Earth's rotation axis, which allows defining the true north heading [14]. This method is patented [15, 16].

The main advantage of the dynamic method is the signal shift from 0 Hz to rotational speed, related to Earth's rotation, which allows eliminating errors related to low-frequency driftage of the measuring equipment. The method could be quite effective if a low-noise angular motion transducer is used. With that, presently available angular motion sensors, including microelectromechanical [17] and fiber-optic [18] ones, do not allow getting the necessarily high precision in use, which is connected to quite high self-noise of the corresponding equipment and low signal-noise ratio, which can be achieved experimentally. The use of more precise and, correspondingly, more expensive gyroscopes [19] considerably discredits the method idea as it does not result in the equipment cost-cutting.

Qualitative increase of the method precision can be achieved by the use of brand new, more sensitive, and exact angular motion sensor. Angular motion transducers are usually used as such sensors as they are based on the principles of molecular electronic technology which has been widely developed in recent years [20]. Self-noise of such equipment is tens of times lower than fiber-optic gyroscopes noise and hundreds of times lower than the best micromechanical analogs, which allows getting qualitatively better precision parameters [21, 22].

2. Materials and Methods

2.1. The Operating Principle of Angular Motion Sensors Based on Molecular Electronic Technology. Angular motion sensors based on molecular electronic transducer (MET) exploit the electrochemical principle of mechanical signal record, as well as liquid inertial mass. MET is a system of electrodes immersed in electrolyte solution with reversible oxidation-reduction reactions on the electrodes. The transducer may use different binary electrolytes which provide reversible oxidation-reduction reactions, such as iodine-iodide, ferro-ferricyanide and so forth.

High precision of the signal record is provided by means of conflict of two charge transfer mechanisms, which are diffusion and convection ions delivery with electrolyte flow which occurs under mechanical signal influence. Electromigration does not play a key role in the charge transfer due to high concentration of so-called background electrolyte, which does not enter into reaction on electrodes.

General design of MET is schematically shown in Figure 1. The chemical reaction rate on MET electrodes is considerably higher than the rate of reacting chemicals delivery to them. Under electric potential difference, the system has constant electrochemical current (so-called background current), determined by diffusional ions transfer between the electrodes. In the presence of external mechanical signal on the device body, the electrolyte flows mechanically and the additional convective ions transfer between the electrodes is created. The system receives additional (to the background) electrical current, which is proportional to the external mechanical signal.

The design of angular motion sensor based on MET is shown in Figure 2. Molecular electronic transducer is placed into a toroidal dielectric channel completely filled with electrolyte, which provides the sensor sensitivity to rotational movements in toroid plane. To compensate temperature-related volume changes [25], the sensors have expansive volume.

To solve the task of longitude direction measurement, molecular electronic angular motion sensor (2) is placed on a platform (1) which can rotate at a certain constant angular velocity ω_1 in a way that sensitivity axis to the angular motion is orthogonal to the platform rotation angular velocity vector $\vec{\omega}_1$ (Figure 3). The platform rotation axis is adjusted heading

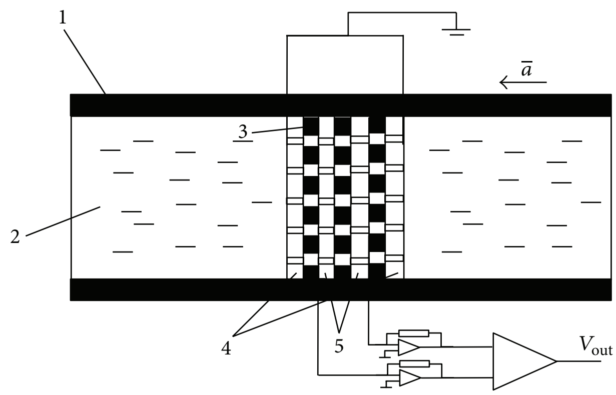

FIGURE 1: Molecular electronic transducer. 1: ceramic or glassy pipe; 2: electrolyte; 3: porous ceramic spacers; 4: anodes; 5: cathodes; a: external mechanical acceleration; V_{out}: output signal.

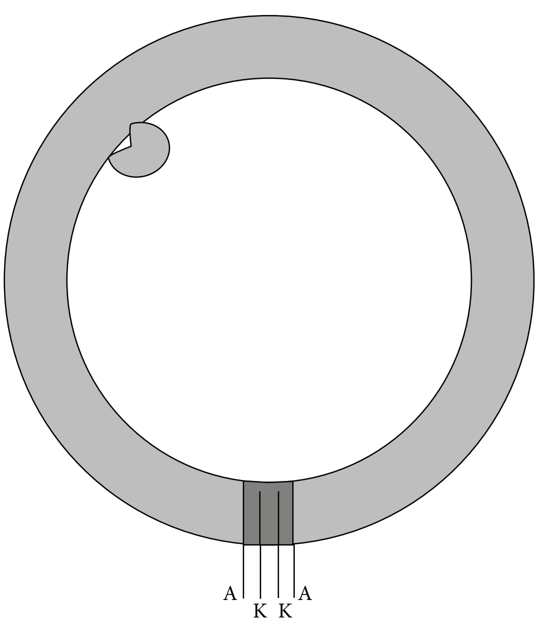

FIGURE 2: Angular motion sensor design: A: anodes; K: cathodes of the sensor electrode transducer.

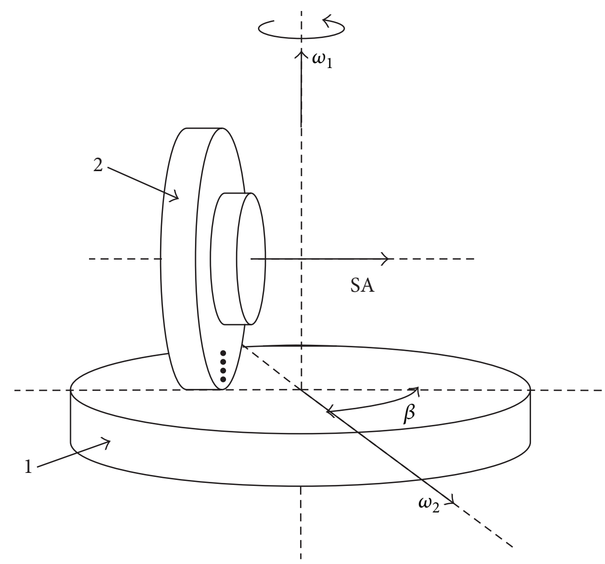

FIGURE 3: The experimental setup: 1: platform, 2: angular motion sensor, SA: angular motion sensor sensitivity axis, ω_1: platform rotation speed, ω_2: the projection of the Earth's rotation on the horizontal plane; $\beta = \omega_2 t$: the angle between the sensor sensitivity axis and the projection of the Earth's rotation on the horizontal plane.

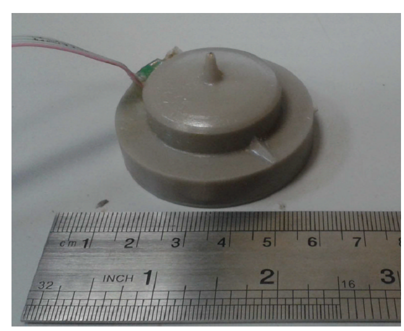

FIGURE 4: Photo of MET 50 mm.

gravitational vector. At that, Earth's angular velocity $\vec{\Omega}_E$ has a component $\vec{\omega}_2$ on the platform plane surface (where there is the sensor) and has a certain angle $\beta(t)$ with the sensor sensitivity axis [15].

With the platform rotation, the horizontal projection of Earth's rotational velocity vector on the sensor sensitivity axis changes according to the harmonic law with frequency ω_1 of the platform rotation. At that, the angular acceleration of the sensitivity element is $\omega_2 \cdot \omega_1 \cdot \sin(\omega_1 \cdot t)$. By defining amplitude and phase of the signal with the sensor, not only the value of horizontal projection of Earth's rotational velocity at the stated latitude, but also true north heading, coinciding with the maximum of Earth's angular velocity registered projection, can be found.

To create high precision molecular electronic device to record Earth's angular velocity and to define true north heading, several samples of angular velocity sensors (based on MET 50 mm) (see Figure 4) and angular acceleration sensors (based on MET 9 mm) (see Figure 5) have been produced.

Table 1 shows the main parameters used in the study of molecular electronic angular motion sensors.

During the studies of the device model to define true north heading as rotating platform, single-axis motion simulator ST 1144C produced by Actidyn SA was used. It was mounted inside the setter 750T30/4 Climats manufactured by the BLM Sinergy (Figure 6). The rotation accuracy of the platform stand at preset angle was $3 \cdot 10^{-4}$ degrees. The used single-axis motion simulator was equipped with high precision angle rotation sensor with resolution of 10^{-5} degrees. The single-axis motion simulator was positioned in

Table 1: Technical parameters of molecular electronic angular motion sensor.

Parameter	Molecular electronic angular motion sensor	Molecular electronic angular accelerometer
Transducer diameter	50 mm	9 mm
Output signal type	Analog, nondifferential, proportional to angular velocity	Analog, nondifferential, proportional to angular acceleration
Photo (Figure 4 MET 50 mm; Figure 5 MET 9 mm)	See Figure 4	See Figure 5
Service band	30 sec – 20 Hz	0–50 Hz
Transduction coefficient	50 B/(rad/sec)	0.5 B/(rad/sec^2)
Maximum bandpass flatness in service band	±0.4 dB	±0.5 dB
Maximum output signal	±5 V	±10 V
Maximal measured signal with harmonic distortions of <2%	0.01 rad/sec	5.2 rad/sec^2
Noise spectral density in the frequency range of 0.01–3 Hz [23, 24]	$7.5 \cdot 10^{-7}$ rad/(sec$^2 \cdot \sqrt{\text{Hz}}$)	10^{-4} rad/(sec$^2 \cdot \sqrt{\text{Hz}}$)
Operating temperature range	−12–+55°C	−12–+55°C
Maximum error of temperature compensation in service band	<10%	<3%
Possible installation angle	Any	Any
Mass	50 g	8 g
Power	12 V	12 V
Input	5 mA	1.4 mA

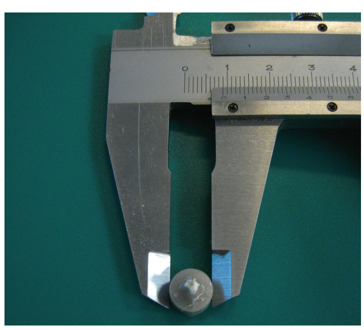

Figure 5: Photo of MET 9 mm.

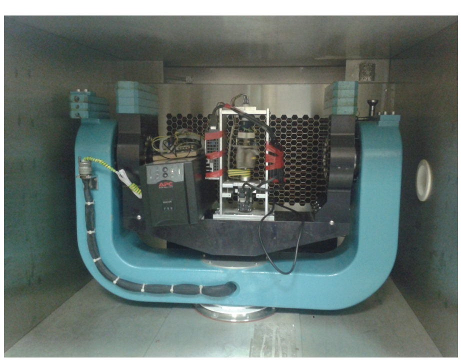

Figure 6: The experimental installation to define true north heading based on molecular electronic angular motion sensors.

the laboratory space in a way that zero position azimuth of high precision platform sensor was 254.23° with imprecision not more than 0.02°. The steadiness of the table rotation at the given angular velocity is ~10^{-3}%.

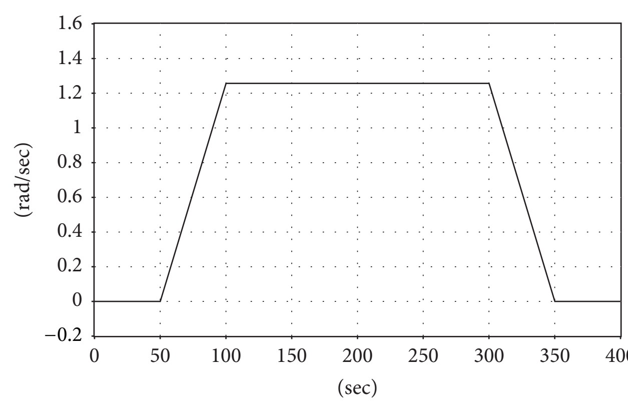

Figure 7: Typically ST 1144C rotational velocity profile.

To perform the research, ST 1144C platform was brought into motion with the given speed profile (see Figure 7), with sections of smooth acceleration, constant speed maintenance, and smooth deceleration. The cycle was then repeated with the platform counter rotating. To determine the signal phases experimentally, ST 1144C motion sections with constant angular velocity were chosen, since in the platform acceleration and deceleration sections the useful signal is mixed with the sensor response to the motion of the irregularly rotating platform.

The signal of molecular electronic angular velocity or acceleration sensor modulated to the platform rotational rate and the signal of high precision sensor of the stand position were registered by 24-bit data collection system E-24 L-Card. Based on the readings of the motion simulator angular sensor, the current platform position heading north at any time point was found.

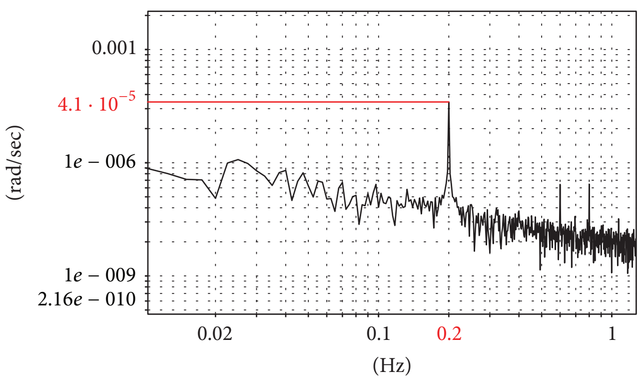

FIGURE 8: The sensor signal spectrum (MET 50 mm) at the platform rotation, log-log scale.

At that, the following measurement method was used, which, on the one hand, excludes the necessity to find the sensor signal initial phase, which, for a range of reasons, may be difficult to perform at the necessarily high precision, and, on the other hand, considerably increases the general precision of the method itself. The method implies alternate clockwise and contraclockwise platform rotation with consequent addition of the received signal phases at the stand rotational rate. Suppose the molecular electronic device is fixed on the platform, so the sensor sensitivity axis is aligned along some (zero) direction, azimuth of which has to be found. Start rotating the platform clockwise at a certain angular velocity and make a total number of turns N. Angular velocity sensor will record the signal modulated to the platform rotational rate. Analyze the data by calculating fast Fourier transform. The spectrum amplitude at the platform rotational rate gives the value of Earth's rotational velocity projection on the sensor sensitivity rotation plane, while the signal phase has the information about the unknown azimuth and is $\varphi_{\text{по}} = \varphi_1 + \varphi_0$, where φ_1 is the unknown azimuth measured relative to the initial position of the sensitivity axis and φ_0 is defined by the sensor phase characteristic. Start rotating the platform at the same rotational rate again, this time counterclockwise, and make the same number of turns N in the opposite direction. This time the signal phase at the platform rotational rate is $\varphi_{\text{п}p} = -\varphi_1 + \varphi_0$, while φ_0 is the same. To eliminate the unknown angle φ_0, find the difference between the recorded values: $\varphi_{\text{по}} - \varphi_{\text{п}p}$. Therefore, the unknown azimuth is the semidifference between the recorded phases at clockwise and counterclockwise platform rotation $\alpha_{\text{north}} = (\varphi_{\text{по}} - \varphi_{\text{п}p})/2$.

Figure 6 shows the experimental installation, while Figure 8 presents the spectrum corresponding to the signal recorded by molecular electronic sensor. At the platform rotational rate, the signal spectrum is at its maximum. The maximum, which is normalized to the angular sensor sensitivity, shows the horizontal projection of Earth's rotational rate at the certain latitude measured by the molecular electronic sensor. The phase difference corresponding to this maximum gives the information about the unknown azimuth heading at clockwise and counterclockwise rotation.

Below the experimental results of azimuth measurement with the device model to define true north heading with the help of molecular electronic angular velocity sensors (MET 50 mm) and angular acceleration sensors (MET 9 mm) are shown. The latitude of the laboratory device is 55.93° (Dolgoprudny, Moscow Region), while the corresponding projection of Earth's rotational rate at the stated latitude is $4.08 \cdot 10^{-5}$ rad/sec.

The study included a set of experiments, which differed in the platform rotation rate. The duration of each measurement was 100 seconds. Eight different samples of molecular electronic angular velocity and acceleration sensors were measured. The results of the statistical study of dispersion of experimentally measured angles heading north are shown in Table 2.

For miniature MET 9 mm, the error in measurement of north heading may reach several degrees. Thus, miniature MET 9 mm does not possess the necessary sensitivity for high precision finding of north heading; however, due to its cost and mass-dimensional parameters it can be used in cheap household systems. At the same time, in the conditions of the performed experiments for MET 50 mm, root-mean-square error of a single measurement is 0.2°-0.3°. With that, these errors may have completely different nature. Therefore, depending on the dominating mechanisms, approaches to reduce the errors must be different. The errors of random nature can be reduced by averaging the signal and by sensors noise characteristics optimization. Inaccuracy in sensor sensitivity axis positioning can be found at calibration and it can be taken into account at data processing. That is why the further analysis was performed to identify the certain sources of errors.

In the present study, a very accurate mechanical system was used. Thus, there were no errors connected with nonideality of the mechanical system in this study. Generally speaking, the following factors may affect the accuracy of measurement:

(i) Irregularity of the platform rotation may lead to errors if the angle between the ME sensor sensitivity axis and the platform rotation axis is different from 90 degrees. In fact, the sensor, does not only measure the Earth's rotation angular velocity, but also the angular velocity projection of unevenly rotating platform on its sensitivity axis.

(ii) The platform rotation axis inclination relative to the gravity acceleration causes a change in the gravity projection on the sensor axis, which results in spurious signal due to the presence of some sensor sensitivity to linear acceleration.

(iii) Fluctuations of the rotation axis due to the bearing beats result in a change of the sensor angular position, with the angular velocity component along sensors sensitivity axis.

2.2. Modelling of Azimuth Finding Error, Determined by Self-Noise of Angular Sensor. To increase the measurements accuracy and to find the main sources of errors and to develop the methods to decrease their influence, numeric

Table 2: The experiments results for angular velocity sensor (MET 50 mm) and angular acceleration sensor (MET 9 mm).

Platform rotational rate, Hz	Earth's rotational rate projection on completion of measurements, rad/sec		Azimuth average value and root-mean-square	
	MET 50 mm	MET 9 mm	MET 50 mm	MET 9 mm
0.05	$4.12 \cdot 10^{-5}$	$5.6 \cdot 10^{-5}$	$254.22^\circ \pm 0.24^\circ$	$253.3^\circ \pm 1.2^\circ$
0.1	$4.02 \cdot 10^{-5}$	$4.6 \cdot 10^{-5}$	$254.33^\circ \pm 0.17^\circ$	$257.4^\circ \pm 2.1^\circ$
0.2	$4.16 \cdot 10^{-5}$	$4.2 \cdot 10^{-5}$	$254.36^\circ \pm 0.28^\circ$	$259.5^\circ \pm 2.8^\circ$
True values of quantities	$4.084 \cdot 10^{-5}$		254.23°	

modelling was performed. The modelling studied to what type of error in the studied signal phase molecular electronic angular motion sensor self-noise led. Further modelling was performed for molecular electronic angular velocity sensor based on MET 50 mm.

For further comparison with the experimental data, calculation experiment was performed. It modelled the described above measurements on the assumption that the only source of errors was sensor noise. Software was used to create sine wave corresponding to the number of rotations made by the real azimuth measurer, to the frequency equal to the platform rotation rate, to the amplitude equal to the Earth's rotational rate projection registered in the experiment, and to the initial phase corresponding to the initial angle of sensor sensitivity axis rotation relative to the known direction of true north heading. Later, the signal was processed by bandpass Butterworth filter with decline order completely corresponding to the sensor technical parameters from Table 1.

What is more, noise signal of molecular electronic sensor was modelled. For that, standard distribution noise signal was modelled, which is known to have frequency independent spectrum. Noise spectral power density of molecular electronic angular velocity sensor was recognized not to depend on the frequency in units of applied angular acceleration [23]. Correspondingly, the spectral density in units of the measured signal (angular velocity) must be inversely proportional to the frequency. In consideration of the foregoing, the modelling noise signal was integrated and multiplied by the scale coefficient, which was selected in a way that mean-root-square error of the modelling signal and the measurer experimental noise corresponded to each other in the stated frequency range. After that, the received random signal was summarized with sine wave, which models the influence of Earth rotation.

During modelling the spectral behavior of the virtual signal was similar to the real sensor signal spectrum. So in modelled signals both the signal of projection from Earth's rotation and the contribution from the sensor self-noise existed (see Figure 9).

During modelling, statistic study of the influence of the additional interfering signal equal to low-frequency noise of molecular electronic angular velocity sensor on the error in measuring the phase of the registered signal and the azimuth, respectively, was performed. The statistic study included both the influence of the measurement duration and the platform rotation frequency on the precision of phase finding for the developed model and for the real experiment and the comparison of the obtained data. The experimental data received in a large number of experiments with the use of one measurer was used to process the information. At that, only the platform rotation frequency and the duration of record varied. Other conditions, such as temperature, type of sensor fixation on the platform, testing frequency, and the recording equipment, remained the same.

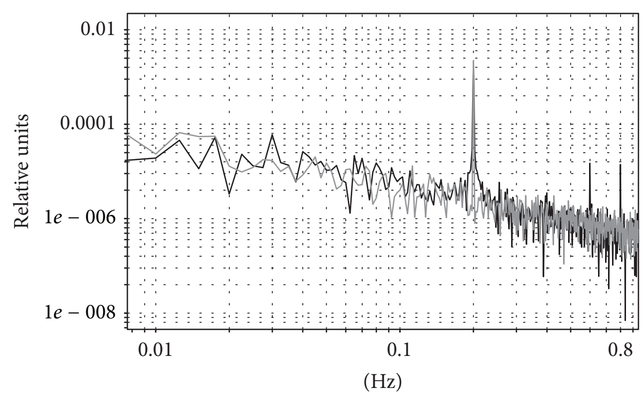

Figure 9: Spectra of real and imitating signals at modelling of azimuth measurement error, determined by the sensor self-noise (dark is the real experimental signal, light is the modelled signal, and the peak of the corresponding registered Earth's rotational rate projection is highlighted), log-log scale.

3. Results and Discussions

The study results are shown in Table 3. The first and the second columns of the table show the platform rotation rate and the record duration, respectively, while the third column shows mean-root-square error deviation in azimuth finding after modelling results (standard result deviation calculated by 15 independent productions of simulating signal); the forth column shows mean-root-square deviation from the average value of experimentally found azimuth after 15 experiments performed in identical conditions. The fifth column shows the experiment systematic error calculated in each case as the average value of 15 absolute deviation errors of the experimental azimuth from the true azimuth of the platform zero position (which is known from the platform certification by its manufacturer and is $254.23^\circ \pm 0.02^\circ$).

Table 3: The results of mathematical modelling of sensor self-noise contribution into the phase error of the studied signal compared to the experimental results of studying the possibility of high precision azimuth measurement.

Platform rotation rate (Hz)	Record duration (seconds)	Mean-root-square error in the modelling signal phase finding by 15 productions (degrees)	Mean-root-square error in experimental true north heading determination (degrees)	Experiment systematic error (degrees)
0.05	400	0.13	0.13	0.07
0.05	200	0.18	0.16	0.06
0.05	100	0.20	0.21	0.06
0.1	400	0.07	0.08	0.06
0.1	200	0.09	0.1	0.08
0.1	100	0.16	0.13	0.06
0.2	400	0.04	0.09	0.02
0.2	200	0.05	0.1	0.03
0.2	100	0.08	0.13	0.05

4. Conclusions

The presented experimental results, as well as the data of numeric modelling of angular sensor self-noise contribution into the error of azimuth finding, suggest the following conclusions.

Miniature molecular electronic angular acceleration sensor based on MET 9 mm does not have high precision of azimuth finding (2°-3°) but considering its small parameters can be treated as an alternative to portative household compasses.

The precision of true north heading determination for molecular electronic angular velocity sensor based on MET 50 mm is 0.2°-0.3° at the studied latitude ($\varphi_{\text{H}} = 55.93°$), which is close to the precision that can be achieved with modern high precision gyrocompasses.

The best precision in the stated experiment conditions is achieved at the platform rotation rate of 0.1 and 0.2 Hz. If the rotation rate decreases, the precision falls down, which can be apparently described by the increase of molecular electronic angular velocity sensor self-noise at low frequencies. At the platform rotation rate of 0.05 Hz and 0.1 Hz, the modelling results, in assumption that the only source of errors is angular rotation sensor self-noise, fully correspond to the experimental data. This result brings us to the conclusion that in this case the main error factor in true north heading determination is molecular electronic angular rotation sensor self-noise. Consequently, the methods of errors eliminating must include reduction of sensor self-noise, which can be achieved, for example, by increase of its size and by reduction of hydrodynamic resistance of the transductive element.

At the higher platform rotation rate, the modelling predicts lower value of azimuth finding error, which could be observed in a real experiment. That is apparently connected to low, achievable for this type of equipment, data sampling rate and the resulting decrease of measurements resolution for rotation angle at high rotation rate of movement simulation platform. Detailed study of the mechanisms responsible for the measurements errors at higher rotation rates must be a topic of a separate study.

Systematic error in true north heading determination in this case is lower than accidental error and is apparently conditioned by the combined effect of nonorthogonality of sensor sensitivity axis to the mounting platform, lack of perpendicularity in rotation axis, influence of angular motion sensor sensitivity to linear acceleration, and so forth. At the same time, as compared to the data from Table 2, it can have congruent quantity or even be more than accidental. As it was mentioned above, its influence can be taken into account by predetermined calibration.

On the whole, the obtained data demonstrate that the manufacturing of the equipment based on these principles, which can provide the precision of true north heading determination at 0.2 degrees or even several times better, is quite a real task.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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