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METHOD OF CALIBRATION MEMS ACCELEROMETER AND MAGNETOMETER FOR INCREASING THE ACCURACY DETERMINATION ANGULAR ORIENTATION OF SATELLITE ANTENNA REFLECTOR

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Summary. *The paper is devoted to the measurement errors investigation that arise due to the influence of MEMS accelerometers' nonlinear characteristics. They appear at large inclination angles of the antenna system support-rotary platform, as well as in the presence of a magnetic inclination, which is due to the peculiarity of the Earth's magnetic field for the magnetometer. The study was conducted to assess the possibility of using such devices to increase the accuracy of a satellite antenna control with a classic rotary platform. The experimental setup for researching the parameters of MEMS sensors allows comparison of measurement results with data obtained from precision optical encoder. The experimental results show the main sources of MEMS sensors errors. An accuracy increasing method of antenna system angular position determining using a triaxial accelerometer and a magnetometer is proposed. The main advantage of the proposed estimation vector determining approach using the least squares method is the possibility of carrying out the calibration procedure without reference to the coordinate system. The method makes it possible to get rid of the zero offset error, as well as compensate for the non-unit scale of the sensor axes and the error of the magnetometer angular orientation. This method can be used for many applications including robotics, design of unmanned aerial vehicles and many other technical systems. The proposed method makes it possible to increase the reliability and reduce the cost of such systems.*

Key words: *MEMS, angle sensor, encoder, calibration, support-rotary platform, control system, antenna system.*

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Statement of the problem. To ensure a sufficient signal level from the antenna station for normal operation of the telecommunication equipment, an important role is played by the accuracy of the antenna system (AS) pointing to Earth artificial satellite (EAS). Such systems consist of classic support-rotary platform (SRP), which includes engines responsible for the AS movement along the azimuth and elevation axes, and sensors for determining the AS angular position. Some designs include placement of angle sensors on the SRP rotation axes using transitional couplings. This design does not always ensure the correct selection of backlashes, distortions, shaft axes alignment in the antenna mechanical nodes, which leads to pointing errors and decreasing the useful signal level.

Analysis of available investigations results. Sensors are necessary to provide feedback in the actuator control system. Currently, there are a large number of gyroscopes, which can be divided into two groups: free gyroscopes that maintain their direction and angular acceleration sensors, which include MEMS accelerometers [1].

Micromechanical gyroscopes classification by measurement accuracy is shown in Fig. 1. They are characterized by high resolution, but insufficient measurement accuracy, which is associated with the temporal angle drift. The method of measuring the antenna working angles, which was proposed by the authors [2, 3], is suitable only for the Hexapod type rotating platform, which measures only the platform tilt angle. Therefore, it is proposed to use angle sensors based on

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MEMS accelerometer and magnetometer in this paper. They can be used to measure the angular positions of the classic support-rotary platforms along the elevation and azimuth axes.

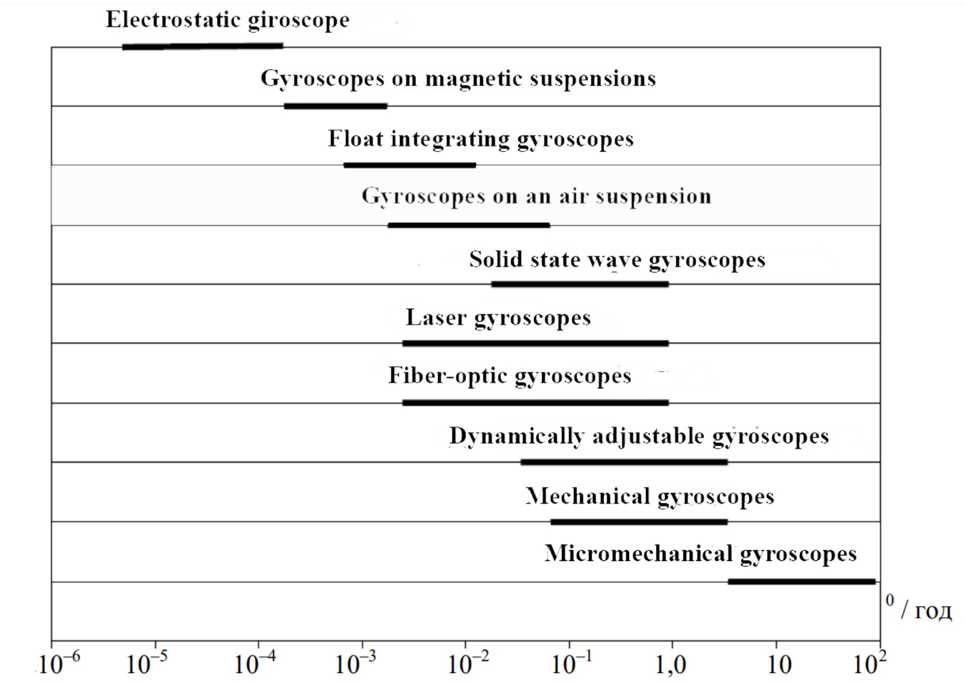


Figure 1. Gyroscopes classification by measurement accuracy

Objective of the paper. Increasing the accuracy of technical systems that use objects' spatial orientation based on MEMS accelerometers and magnetometers and estimating errors that occur when using angle sensors.

Statement of the task. Angle sensors can be installed in the reflector focus, which ensures an increase in the accuracy of the antenna orientation. To determine the angular position, sensors based on the MEMS technology of the accelerometer and magnetometer were chosen. They can be used to measure the AS position along the azimuth and elevation axes. Using this approach for measuring the angular position it is necessary to calibrate the sensor axes [4, 5].

The main error source of the MEMS accelerometer can be considered the sensor design itself. There is an inconsistency of its output values due to insufficient placement accuracy on the printed board. Moreover, the error can be caused by the displacement of the sensor coordinate system relative to the circuit board coordinate system, the axes non-unit scale and the axes non-orthogonality (Fig. 2). Magnetometers have similar errors, the main sources of which are: the magnetic inclination presence, which is due to the Earth's magnetic field peculiarity, the presence of artificial electromagnetic fields around the sensor, which are created, for example, by power cables, batteries, etc.

Due to the similarity of accelerometer and magnetometer errors, the calibration procedure can be used for both MEMS accelerometers and magnetometers. The stochastic interpretation of the procedure for identifying error parameters that are characteristic of sensors involves the application of the «sensitivity ellipsoid» concept, when the sensor response is represented as a point in three-dimensional space. The magnetometer consists of three sensitive elements, which are oriented along the measuring system coordinate axes. In practice, due to the error's presence, the points form a data cloud in an ellipsoid form with a shifted center. In order to find the correcting matrix and the zero offset, it is necessary to collect as many magnetometer output values as possible at different orientations under the external magnetic field influence of constant magnitude and direction [6].

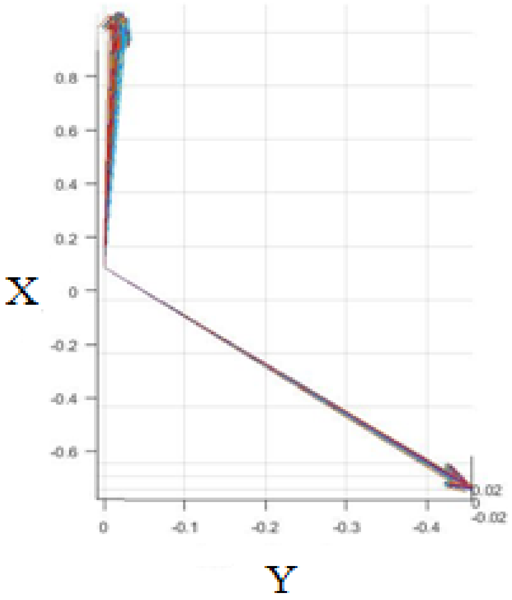


Figure 2. Non-orthogonality of the LSM303DLHS sensor axes

Thus, the calibration task consists of determining the coefficients in the transformation equation of an ellipsoid into a sphere [2]:

$$\begin{bmatrix} Ax \\ Ay \\ Az \end{bmatrix} = \left(M_{xyz}\right) \begin{bmatrix} {}^{1}/_{Kx} & 0 & 0 \\ 0 & {}^{1}/_{Ky} & 0 \\ 0 & 0 & {}^{1}/_{Kz} \end{bmatrix} \begin{bmatrix} Rx - A_{x0} \\ Ry - A_{y0} \\ Rz - A_{z0} \end{bmatrix}, \tag{1}$$

where A – is the corrected values of $X\ Y\ Z$, M – is the inequality matrix, K – is the sensitivity of each channel, R – is the sensor output data, A_0 – is the matrix correction values.

To eliminate the coordinate system offset error, it is necessary to adjust the sensor zero point placement using the determined coefficients. In this case, the sensor calibration process will have the following form [3]:

$$\overline{\mathrm{X}_{\mathrm{a}}} = \frac{1}{n}\ \sum_{i=1}^{n} X_{ia}\,,\ X = \ X_{ia} - \overline{X_a}, \tag{2}$$

where X_{ia} – are the net components of the data cloud points, X_a – is the average value, X – is the adjusting values matrix.

The vector of the model parameters estimates is determined by the least squares method, which makes it possible to minimize the sum of the squares deviations for the experimental points from the reference points [7]:

$$\vartheta = \ [X^T \ \times \ X\,]^{-1} \ \times (X^T \times Y) \tag{3}$$

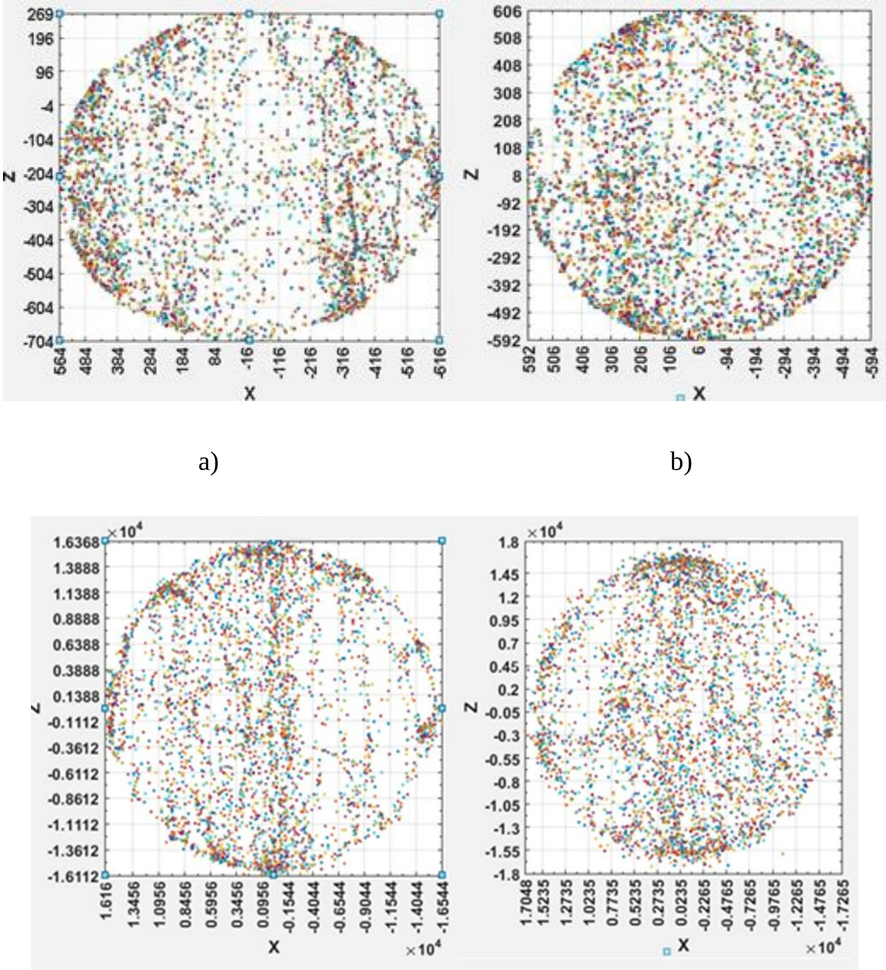
$$X = \begin{bmatrix} x_1^2 & y_1^2 & z_1^2 \\ x_2^2 & y_1^2 & z_2^2 \\ \vdots & \vdots & \vdots \\ x_n^2 & y_n^2 & z_n^2 \end{bmatrix} \tag{4}$$

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix}, \vartheta = \begin{bmatrix} 1/_{a^2} \\ 1/_{b^2} \\ 1/_{c^2} \end{bmatrix}, \tag{5}$$

where X – is the correction variables matrix, Y – is the experimental results vector, ϑ – the parameters estimation vector.

The main advantage of the estimation vector determining approach using the least squares method is the possibility of carrying out the calibration procedure without reference to the coordinate system. The proposed method makes it possible to get rid of the zero offset error, as well as compensate for the non-unit scale of the sensor axes and the error of the magnetometer angular orientation.

A visualization of the data array obtained experimentally from the magnetometer and accelerometer before and after their calibration is shown in Fig. 3. Solving the calibration task allows us to identify the ellipsoid from the data array. This makes it possible to obtain not only the zero offset, but also statistically estimate the gain coefficients and determine the sensitivity axes orientation.



a) b)

c) d)

Figure 3. «Sensitivity ellipsoid» for a magnetometer: a) before calibration, b) after calibration; and for an accelerometer: c) before calibration, d) after calibration

Description of the method. The method of obtaining angular position using the MEMS accelerometer and magnetometer is based on the use of Euler angles [8]. They define three device turns, which make it possible to change any system position to the required one. Let denote the initial coordinate system as x, y, z, and the final coordinate system as X, Y, Z. The intersection of the xy and XY planes is called the nodes line N. The system rotations by these angles are called: the angle α between the x axis and the nodes line is the precession angle, the angle β between the axes z and Z is the nutation angle, the angle γ between the axis X and the nodes line is the self-rotation angle (Fig. 4).

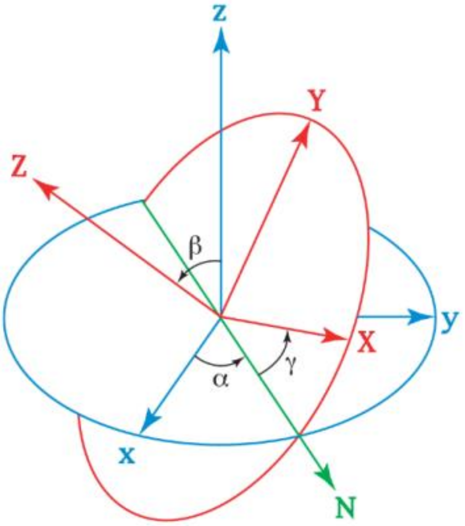


Figure 4. Euler angles

Such system rotations and its final position depend on the order in which the rotations occur. In the case of Euler angles, first there is a rotation to the angle α relative to the z axis, then a rotation to the angle β relative to the N axis, and finally a rotation to the angle γ relative to the Z axis.

$$R_z(\alpha) == \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{6}$$

$$R_X(\beta) == \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\beta) & -\sin(\beta) \\ 0 & \sin(\beta) & \cos(\beta) \end{pmatrix}, \tag{7}$$

$$R_Z(\gamma) == \begin{pmatrix} \cos(\gamma) & -\sin(\gamma)\,0 & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{8}$$

The sequence of these rotations gives the rotation matrix, which is expressed in terms of Euler angles [9]. The general solution will have the form [10]:

$$R = R_z(\gamma) \times R_x(\beta) \times R_z(\alpha) = \\ = \begin{pmatrix} \cos(\alpha)\cos(\gamma) - \cos(\beta)\sin(\alpha)\sin(\gamma) & -\cos(\gamma)\sin(\alpha) - \cos(\alpha)\cos(\beta)\sin(\gamma) & \sin(\beta)\sin(\gamma) \\ \cos(\beta)\cos(\gamma)\sin(\alpha) + \cos(\alpha)\sin(\gamma) & \cos(\alpha)\cos(\beta)\cos(\gamma) - \sin(\alpha)\sin(\gamma) & -\cos(\gamma)\sin(\beta) \\ \sin(\alpha)\sin(\beta) & \cos(\alpha)\sin(\beta) & \cos(\beta) \end{pmatrix} \tag{9}$$

After multiplying the rotation matrix by the initial angles values, the following dependence is obtained, which has the form [11]:

$$R \times \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \tag{10}$$

where x, y, z – are the initial angles values. Dependence (10) makes it possible to obtain the angles values in the moving coordinate system after rotation.

Experimental results and discussion. The measuring device was designed to determine the satellite antenna reflector orientation in space during pointing at the EAS, which is shown in Fig. 5. It allows us to investigate the parameters and make errors estimations of the MEMS accelerometer in control systems with classical support-rotary platforms. It is created based on a classic SRP, which is equipped with manual linear actuators and electronic means for comparing the obtained values with the precision optical angle sensors.

The work uses the values obtained from the LSM303DLHS sensor designed based on the STM32F3 Discovery module [12–14]. It is a compact highly efficient electronic compass module. The main characteristics of this module:

- presence of magnetic field strength measuring channels;
- 3 acceleration measurement channels;
- magnetic field strength measurement ranges: ± 1.3 / ± 1.9 / ± 2.5 / ± 4.0 / ± 4.7 / ± 5.6 / ± 8.1 Gauss;
- acceleration measurement ranges: ± 2 g / ± 4 g / ± 8 g / ± 16 g;
- 16-bit output data format;
- 2 independent programmable interrupt generators to determine free fall and movements;
- built-in temperature sensor.

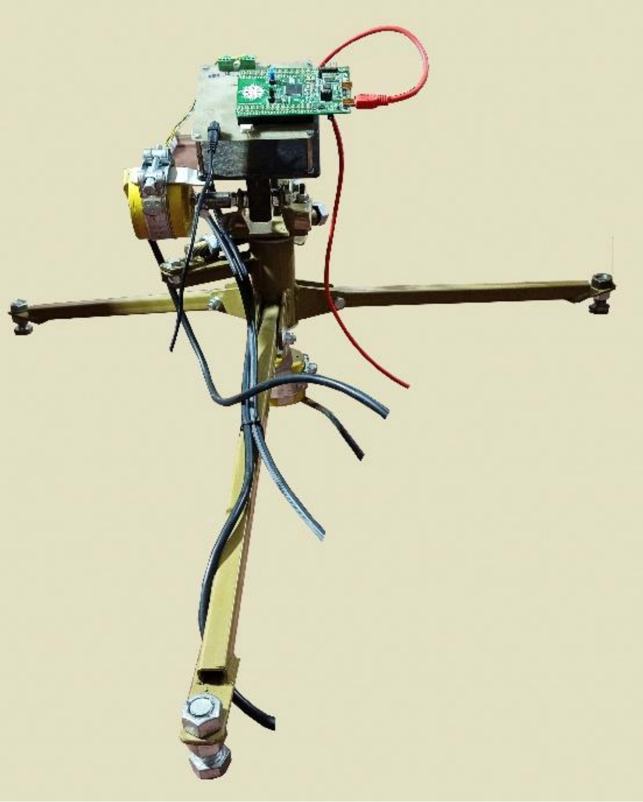


Figure 5. Measuring device for the MEMS sensor investigation based on the accelerometer and magnetometer

The angular position measuring results of the antenna support-rotary platform along the elevation axis using the investigated MEMS accelerometer were obtained. They were compared with the precision optical encoder values in the range of 0° ÷ 60°. The given graph shows that the angular position determining error after sensor calibration rises with the increasing the platform tilt angle. When angular position approaches 50°, the error value exceeds 0.5°.

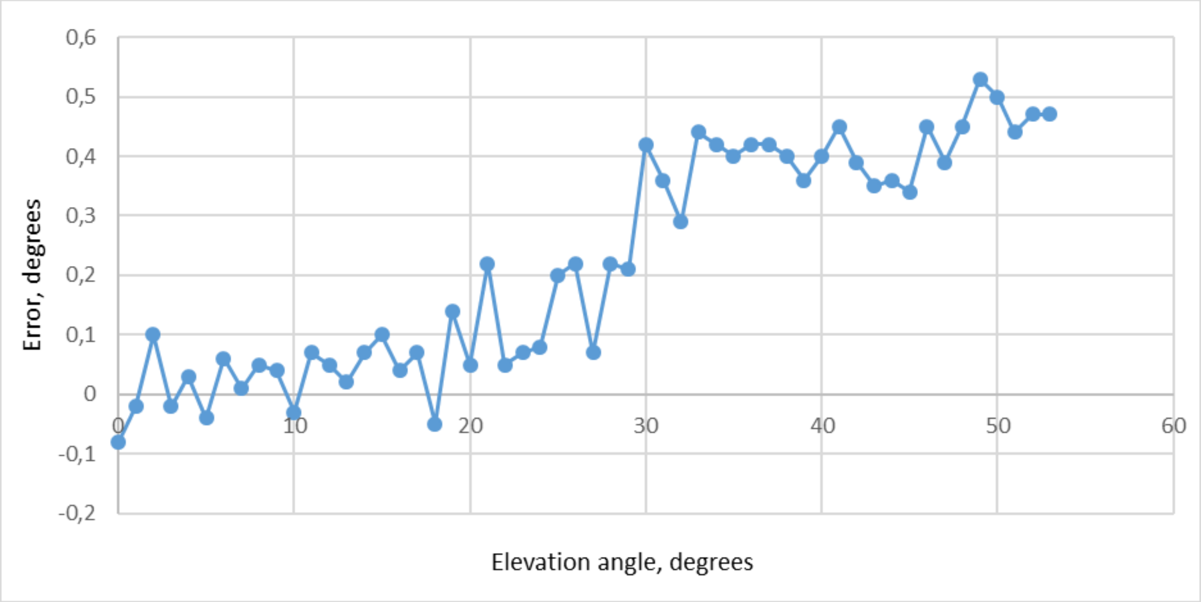


Figure 6. The discrepancy between the obtained azimuth angular position values from the MEMS magnetometer after calibration and the data from the precision optical encoder

The calculation results of the angular position along the azimuth axis for the SRP and their comparison with the precision optical encoder values [7] in the range of 0° ÷ 60° are shown in Fig. 7. It can be seen from the given graph that the angular position determining error along the azimuth axis exceeds 6°.

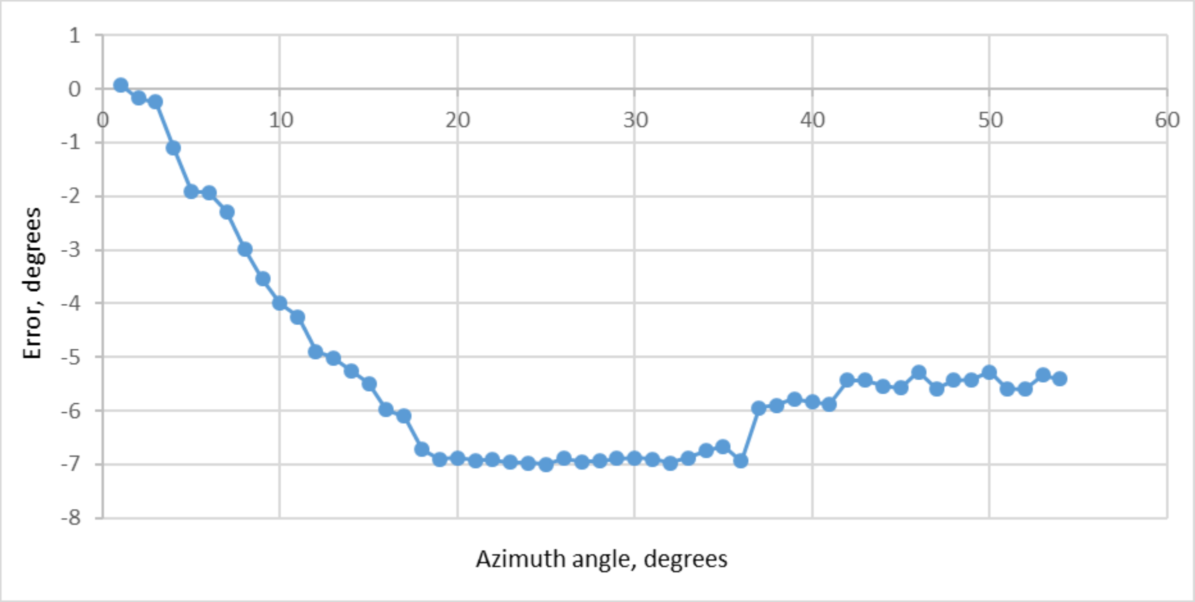


Figure 7. The discrepancy between the precision optical encoder data and the obtained values of the angular position along the azimuth axis with the MEMS magnetometer after calibration

Fig. 8. shows the time dependence of the accelerometer and magnetometer deviations from the reference values when the support-rotary platform is in a stationary state. The given graph shows a strong noise at the sensor output.

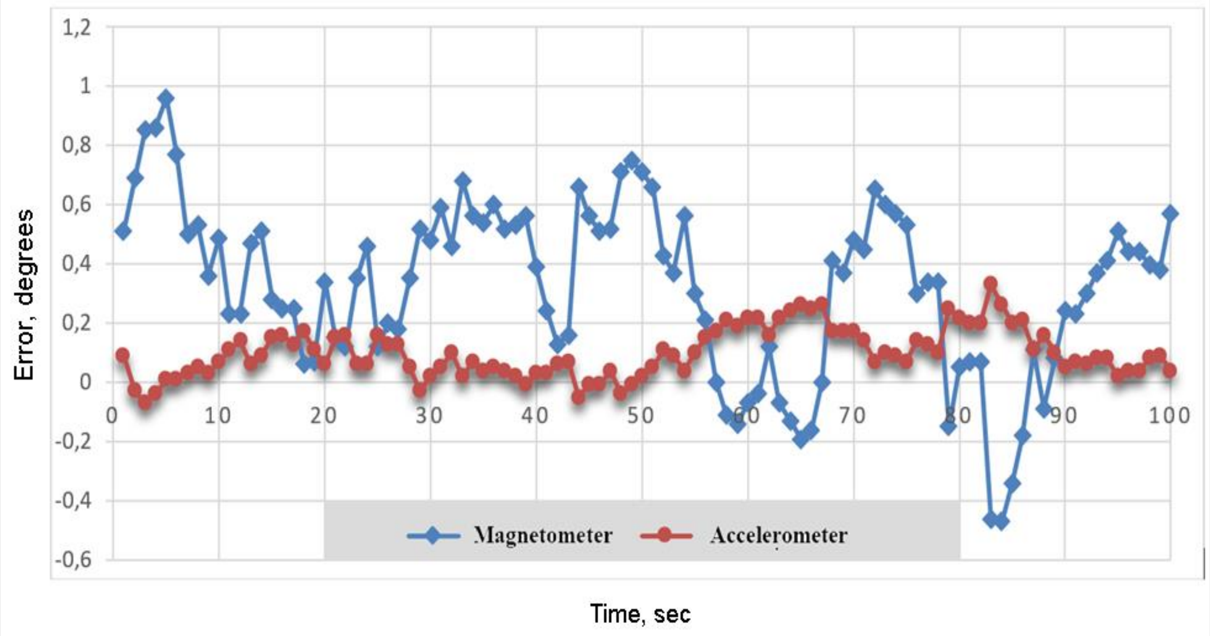


Figure 8. Noise at the output of the LSM303DHLS sensor

Conclusions. The proposed method makes it possible to compensate for the zero offset error, as well as reduce the impact of possible structural defects of attaching classic angle sensors to the antenna system axis. The main advantage of the approach to determining the estimated vector using the least squares method is that it makes it possible to carry out the calibration procedure without reference to the coordinate system. Moreover, it makes it possible to measure the current orientation of the antenna system with a parabolic reflector along the azimuth and elevation axes. The advantages of this method are low cost, design simplification of the support-rotary platform, and the possibility of use for different types of SRP. It was established that the output values are significantly affected by the Earth's magnetic field and strong noises during antenna movement, which complicate data filtering, increase the error, and reduce the system speed. Further research will be aimed at finding ways to reduce the impact of these factors.

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УДК 681.2

МЕТОД КАЛІБРУВАННЯ MEMS АКСЕЛЕРОМЕТРА ТА МАГНІТОМЕТРА ДЛЯ ПІДВИЩЕННЯ ТОЧНОСТІ ВИЗНАЧЕННЯ КУТОВОЇ ОРІЄНТАЦІЇ РЕФЛЕКТОРА СУПУТНИКОВОЇ АНТЕНИ

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Резюме. *Досліджено похибки, що виникають унаслідок впливу нелінійних характеристик MEMS акселерометрів, які з'являються при великих кутах нахилу опорно-поворотної платформи антенної системи, а також за наявності магнітного схилення, яке зумовлене впливом магнітного поля Землі на магнітометр. Дослідження проведено з метою оцінювання можливості використання таких давачів для підвищення точності керування супутниковою антеною з класичною опорно-поворотною платформою. Експериментальна установка для дослідження параметрів MEMS давачів дозволяє проводити порівняння результатів вимірювання з прецизійним оптичним енкодером у діапазоні 0° ÷ 60° по куту місця та по осі азимута. Результати експериментальних досліджень показують основні джерела похибок MEMS давачів. Запропоновано метод підвищення точності визначення кутового положення антенної системи за допомогою тривісного акселерометра та магнітометра. Проведено процедуру калібрування перед початком проведення досліджень. Основною перевагою запропонованого підходу до визначення вектора оцінювання методом найменших квадратів є можливість проведення процедури калібрування без прив'язки до системи координат. Даний метод дає змогу позбутися похибки зміщення нуля, а також компенсувати неодиничний масштаб осей давачів та похибку кутової орієнтації магнітометра. Отримання даних кутового положення з використанням показів MEMS акселерометра та магнітометра ґрунтується на використанні кутів Ейлера, що визначають три повороти системи, які дозволяють привести будь-яке положення антенної системи до необхідного. Застосування цього методу має практичне значення в робототехніці, проектуванні безпілотних літальних апаратів та багатьох інших технічних системах. Запропонований метод дає змогу підвищити надійність та знизити вартість таких систем.*

Ключові слова: *MEMS, давач кута, енкодер, калібрування, опорно-поворотна платформа, система керування, антенна система.*

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