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ACCURACY RESEARCH FOR NON-ORTHOGONAL CONFIGURATION OF INERTIAL SENSORS

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Abstract*—This article deals with accuracy research of the non-orthogonal configuration of inertial sensors based on Allan variance. The influence of changes in the measurement range of the inertial module on the Allan variance was assessed. Based on an analysis of the results of the Allan variance assessment, a procedure for choosing multi-axis MEMS sensors with identical characteristics to create an inertial non-orthogonal measuring instrument is proposed. An example of compiling a data processing algorithm for an inertial measuring instrument with a non-orthogonal arrangement of sensitivity axes based on an assembly of 3-axis MEMS sensors is given. The simulation results for numerical estimates are represented. Improvement of the accuracy of the non-orthogonal inertial measuring instruments using the Allan variance is shown.*

Index Terms—Allan variance; MEMS module; data processing; inertial sensor; non-orthogonal configuration.

I. INTRODUCTION AND PROBLEM STATEMENT

Nowadays, manufacturers of navigation and information systems are interested in creating and improving autonomous measuring instruments. This is connected with the important property of autonomy, which is characterized by the possibility to operate independently of external sources of information and energy. The efficiency of autonomy application depends on the metrological characteristics of basic sensors of information and navigation systems. Inertial sensors such as gyroscopic devices and accelerometers are the most widespread in problematics of control of the moving vehicle's motion. Among the above-mentioned measuring instruments, MEMS modules are the most widespread, especially in the area of navigation equipment for unmanned aerial vehicles [1] – [3].

Therefore, it is important to improve navigation systems based on MEMS inertial measuring instruments. One of the approaches proposed in many articles including [4], [5] is the usage of non-orthogonal configurations of MEMS inertial measuring units. In this situation, both the performance and dependability of inertial measuring instruments are sufficiently increased. The non-orthogonal sensor placement approach is well-known and a lot of fundamental and applied publications have dealt with this topic. Nowadays, the relevance of this approach is conditioned by the creation of modern inertial MEMS technologies, which provide new and wide opportunities for creating non-orthogonal configurations of MEMS sensors. If earlier non-orthogonal configurations were based on one-axis inertial sensors with high accuracy, nowadays non-orthogonal configurations of triaxial inertial measuring units of middle accuracy are of great interest for many applications including unmanned aerial vehicles industry. This trend deals with the complication of conversions between measuring and navigation reference frames and requires new approaches to creating non-orthogonal configurations of MEMS inertial measuring units. The innovation of the research represented in the article is the assessment of characteristics of non-orthogonal inertial measuring instruments based on Allan variance in contrast to the known approach based on power spectral densities.

MEMS measuring instruments are characterized by such advantages as miniature dimensions, reliability, low cost, and comparative simplicity in manufacturing. Unfortunately, these measuring instruments have some significant disadvantages including the accuracy insufficient for many applications and wide dispersion of random errors in the process of manufacturing [6] – [8]. In the general case, MEMS sensors are characterized by determined and random errors. As a rule, determined errors represent zero bias or nonlinearity. Random errors are defined by angular random walk, random noise, and drift of the angular rate [9] – [11].

The proposed realization of the non-orthogonal configuration of inertial measuring units is represented in Fig. 1. It is implemented on the basis of the compact and light module MPU-6050, which includes triaxial gyroscope and triaxial accelerometer controlled by the protocol I2C.

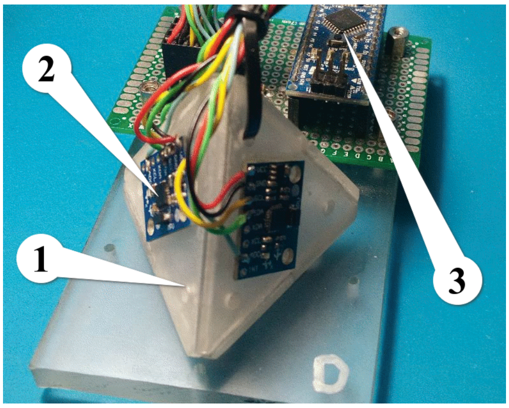

Fig. 1. The non-orthogonal configuration based on MEMS sensors: *1* is the base of non-orthogonal configuration; *2* is the inertial measuring unit; *3* is the microcontroller

The module includes also a motion processor and temperature sensor. The specific feature of the module is the availability of a 16-bit analog-digital converter. Digital outputs and the possibility to change dynamic ranges of measurement of both the angular and the acceleration are obvious advantages of the considered sensors for using in the area of navigation for moving vehicles of the wide class.

The non-orthogonal configuration of MEMS sensors consists of 4 modules MPU-6050 arranged on the facets of the trigonal pyramid. The output information is processed by the microcontroller ATMEGA328 [4].

The basic goal of the article is the accuracy characteristic of the inertial measuring instrument using Allan variances. The novelty of the proposed research is its application to the non-orthogonal configuration of inertial measuring units.nt.

II. Allan Variance Approach

For the research of the accuracy characteristics of MEMS sensors, the method of Allan variance has been used. It is known that the Allan Variance lies in the analysis of time sequences for the determination of characteristics of the noise as functions of the average time. Nowadays, this method is widely used for the research of accuracy characteristics of MEMS inertial sensors [12], [13].

The main feature of the method of Allan variance lies in the calculation of variances of a difference of neighborhood measurements instead of discrete values of a centralized random process.

The output data of an inertial sensor can be shown in the such representation [3]

$$s(t) = s_0 + \Delta s\,, \tag{1}$$

where s_0 is a constant value; Δs is time-variant centralized random process, $\Delta s(0) = 0$.

Usually, an assessment of the constant component s_0 in equation (1) can be calculated as an average value of a given random realization at the finite time interval τ [3]

$$\hat{s}_0 = \frac{1}{\tau}\int_0^{\tau} s(t)dt = s_0 + \frac{1}{\tau}\int_0^{\tau} \Delta s(t)dt\,. \tag{2}$$

The error and variance of the assessment (2) can be represented as [3]

$$ds = \hat{s}_0 - s_0 = \frac{1}{\tau}\int_0^{\tau} \Delta s(t)d\tau\,; \tag{3}$$

$$\sigma_{ds}^2 = M\left[(\hat{s}_0 - s_0)^2\right] = M\left[\left(\frac{1}{\tau}\int_0^{\tau}\Delta s(t)d\tau\right)^2\right] = \frac{1}{\tau^2}M\left[\left(\int_0^{\tau}\Delta s(t)d\tau\right)^2\right]. \tag{4}$$

Accuracy characteristics of MEMS inertial sensors can be researched on the basis of the method of Allan variance. Taking into consideration the relationships (3), and (4), the basic expression of the method of Allan variance can be given as follows [3]

$$\sigma^2_{A[ds(t)]} = \frac{1}{2\tau^2(N-1)}\sum_{k=1}^{N-1}\left[\int_{k\tau}^{(k+1)\tau}\Delta s(t)dt - \int_{(k-1)\tau}^{k\tau}\Delta s(t)dt\right]^2 \tag{5}$$

The expression (5) is insensitive to the constant component of an error.

The Allan variation (5) coincides with the assessment of the variance (4) if the following condition is satisfied [3], [12]

$$\frac{1}{2}M\left\{\left[\int_{k\tau}^{(k+1)\tau}\Delta s(t)dt - \int_{(k-1)\tau}^{k\tau}\Delta s(t)dt\right]^2\right\} = M\left\{\left[\int_0^{\tau}\Delta s(t)dt\right]^2\right\}, \tag{6}$$

for $\forall k > 0$.

Condition (6) is satisfied if $\Delta s(t)$ is the white noise, Wiener random process, or a sum of these processes. For a random sequence of signals, the Allan variance is correlated with the power of spectral density $S(f)$, which represents the full characteristic of a random process in the frequency domain [3], [12], [13]

$$\sigma_A^2(\tau) = 4\int_0^{\infty} S(f)\frac{\sin^4(\pi t f)}{(\pi t f)^2}df\,. \tag{7}$$

The expression (7) is useful for the analysis of the noise of inertial sensors based on MEMS technologies [14] – [16].

III. EXPERIMENTAL TEST

The creation of a redundant arrays of inertial meters with the non-orthogonal location of sensitivity axes requires the previous choice inertial sensors of primary information, which are characterized by discrete outputs. One of the requirements, which are given for such sensors is matching their characteristics. This requires a preliminary assessment of the sensor's metrological characteristics [17], [18].

For inertial measuring instruments based on MEMS sensors, main sources of errors are caused by the presence of noise of the different nature. The integrated assessment of these errors can be implemented on the basis of the method of Allan variance [3], [12], [13].

The application of Allan variance for the analysis of characteristics of inertial measuring instruments is widespread in areas of navigation and measuring systems. In particular, Allan variations allow us to estimate the accuracy of inertial navigation systems and their components. Nowadays, MEMS gyroscopes are widely used for the measurement of angular rates of moving vehicles. Nevertheless, any gyroscope can be subjected to different sources of noise, which can influence the accuracy of measurements [16].

The Allan variance ensures the possibility to estimate the noise characteristics of gyroscopes including the random noise, and the noise on low and high frequencies. The approach is very good for developers of inertial navigation devices. It gives the possibility to carry out the integrated analysis of sources of noise, which influences the gyroscope's accuracy, and to determine ways of decreasing appropriate errors. Finally, it is possible to optimize parameters of rate gyroscopes such as frequency of discretization and time of measurement. These actions are necessary for the achievement of the highest accuracy and stability. Moreover, this method helps to find potential problems and defects in gyroscopes and to accept measures for eliminating these disadvantages. The estimation of Allan variances for some inertial measuring instruments based on MEMS technologies has been implemented on the basis of the tested bench represented in Fig. 2.

The tested bench equipment ensures synchronous registration of noise components of MEMS arrays. The widespread low-cost inertial module InvenSense MPU-6050 has been used for designing non-orthogonal measuring instruments. For the implementation of the integrated assessment, registration of data has been carried out with different adjustments of measuring ranges (250 deg/s, 500 deg/s, 1000 deg/s, and 2000 deg/s). The technique of estimating the characteristics of separate sensors includes the following steps.

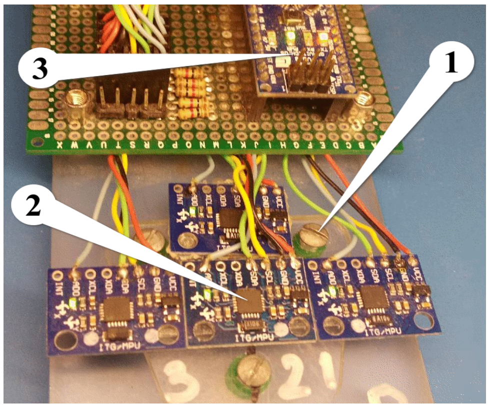

Fig. 2. The tested bench: *1* is the immovable base for sensors; *2* – inertial measuring units; *3* is the microcontroller

- After the power is switched on, time keeping has been implemented before registration of the sensor's noise. This is necessary for the stabilization of the temperature (approximately 22°C), which has been controlled by an internal thermal sensor.
- Adjustment of the sensor's internal analog-digital converter on the given measuring range has been implemented.
- For 2 hours, recording of the noise components with the discretization frequency of 100 Hz. Time of recording has been previously determined based on the typical period of operation of the studied sensors and experimental specifications by means of calculating Allan variances for different times of recording.
- Allan variance has been calculated for every axis of the triaxial MEMS sensor.

IV. TEST RESULTS

The analysis procedure represents a comparison of Allan variances for all axes of the sensor and also for different sensors. The method allows us to describe the characteristics of the noise in the measured output signal of the studied sensor. During the research, recording of output signals of accelerometers for 2 hours and gyroscopes for 4 hours was carried out. It will be observed that during the experiment, the inertial measuring module was located on the immovable base. The experimental results are represented in Figs 3 – 7.

As follows from graphical dependencies represented in Fig. 7, values of Allan variances are not essentially changed with the change of analog-digital converter resolution. This proves that the basic source of errors of the inertial module is Angle

Random Walk (ARW) and the influence of quantizing noise is insufficient. Another advantage of the application of Allan's variation is as follows.

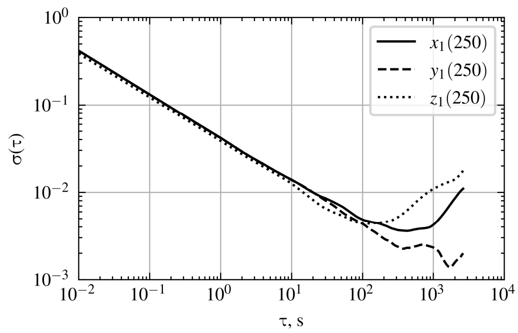

Fig. 3. The comparison of Allan variance for different axes of the gyro in the measuring range 1 (250 deg/s)

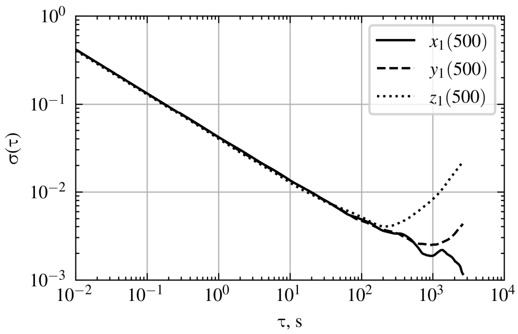

Fig. 4. The comparison of Allan variance for different axes of the gyro in the measuring range 2 (500 deg/s)

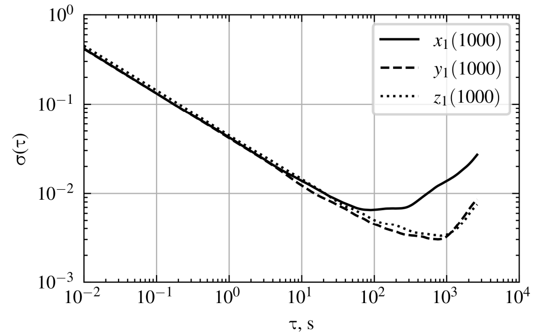

Fig. 5. The comparison of Allan variance for different axes of the gyro in the range 3 (1000 deg/s)

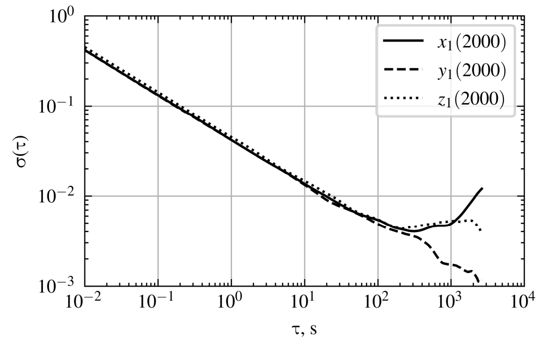

Fig. 6. The comparison of Allan variance for different axes of the gyro in the measuring range 4 (2000 deg/s)

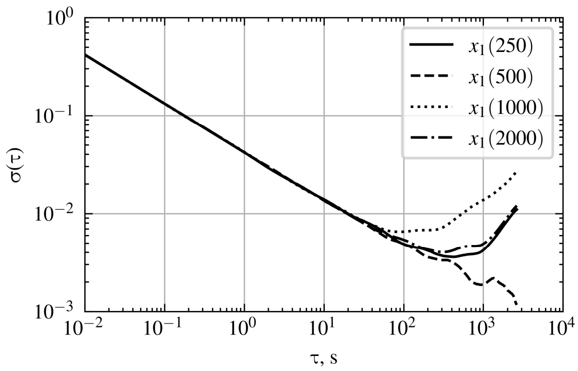

Fig. 7. The comparison of Allan variance for measuring axes of the gyro in different ranges (1 – 4)

The peculiarity of the procedure for measuring the characteristics of sensors is the possibility to estimate operating characteristics of a sensor without physical implementation and bench testing.

It is possible to carry out this operation by means of mathematical modeling of the appropriate data processing system using registered during the calibration procedure signals as input signals. The results of the modeling can also be estimated using the Allan variation.

An example of a sensor with different characteristics by axes is shown in Fig. 8.

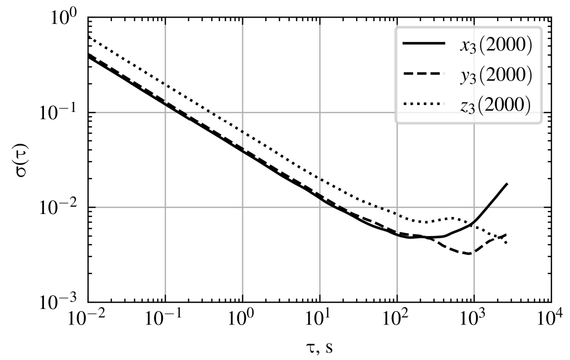

Fig. 8. Allan variances for a sensor with different characteristics by its axes

As follows from graphical dependencies represented in Fig. 8, Allan variance of the sensor by the axis *z* is different for the worse from similar variance by axes *x* and *y*. Therefore, this sensor has a defect of manufacturing and needs to be changed not taking into consideration the ability of the tested sensor for the operation.

Consider the application of the approach to the example of the non-orthogonal configuration of MEMS sensors [17], [18].

The measuring instrument consisting of inertial MEMS units with non-orthogonal measuring axes is characterized by some basic features. The orientation of the sensitiveness axes of an instrument based on MEMS sensors and a trigonal pyramid carrying out functions of the constructive unit is shown in Fig. 9.

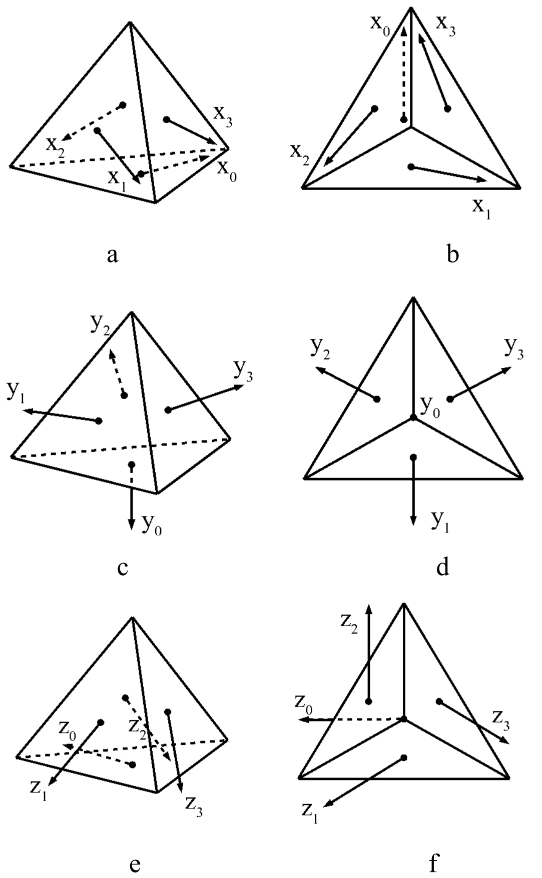

Fig. 9. Orientation of measuring axes of sensors: the face views (a, c, e) and top views (b, d, f)

One of the most important problems of processing information in non-orthogonal arrays of MEMS inertial units is the necessity to carry transformations between the navigational coordinate system connected with a moving object and the measuring coordinate system related to the measuring axes of inertial sensors. The interconnection between the above-mentioned systems of coordinates can be presented by the matrix of guide cosines. An example of such a transformation in the form of guide cosines for non-orthogonal configuration based on the trigonal pyramid is shown in Table I [17].

In Table I values of angles of rotations are determined in the following way: γ = 180 deg., ψ_0 = 120 deg., ψ_1 = 0 deg., ψ_2 = 120 deg., ψ_3 = 240 deg., ϑ = 70.5 deg.

The angle γ determined the orientation of sensitivity axes arranged on the pyramid's facets. Angles ψ_i determines the orientation of axes arranged on the lateral facets of the pyramid. The angle ψ_0 determined a tilt of the facet to the vertical axis. The angle ϑ characterizes the tilt of a slope.

TABLE I. TABLE OF GUIDE COSINES

	ω_x	ω_y	ω_z
$d_1 = \omega_x^1$	1	0	0
$d_2 = \omega_y^1$	0	$\cos\gamma$	$-\sin\gamma$
$d_3 = \omega_z^1$	0	$\sin\gamma$	$\cos\gamma$
$d_4 = \omega_x^2$	$-\sin\psi_0 \sin\psi_1 +$ $\cos\psi_0 \cos\psi_1 \cos\vartheta$	$-\sin\vartheta \cos\psi_1$	$\sin\psi_0 \cos\psi_1 \cos\vartheta +$ $\sin\psi_1 \cos\psi_0$
$d_5 = \omega_y^2$	$\sin\vartheta \cos\psi_0$	$\cos\vartheta$	$\sin\psi_0 \sin\vartheta$
$d_6 = \omega_z^2$	$-\sin\psi_0 \cos\psi_1 -$ $\sin\psi_1 \cos\psi_0 \cos\vartheta$	$\sin\psi_1 \sin\vartheta$	$-\sin\psi_0 \sin\psi_1 \cos\vartheta +$ $\cos\psi_0 \cos\psi_1$
$d_7 = \omega_x^3$	$-\sin\psi_0 \sin\psi_2 +$ $\cos\psi_0 \cos\psi_2 \cos\vartheta$	$-\sin\vartheta \cos\psi_2$	$\sin\psi_0 \cos\psi_2 \cos\vartheta +$ $\sin\psi_2 \cos\psi_0$
$d_8 = \omega_y^3$	$\sin\vartheta \cos\psi_0$	$\cos\vartheta$	$\sin\psi_0 \sin\vartheta$
$d_9 = \omega_z^3$	$-\sin\psi_0 \cos\psi_2 -$ $\sin\psi_2 \cos\psi_0 \cos\vartheta$	$\sin\psi_2 \sin\vartheta$	$-\sin\psi_0 \sin\psi_2 \cos\vartheta +$ $\cos\psi_0 \cos\psi_2$
$d_{10} = \omega_x^4$	$-\sin\psi_0 \sin\psi_3 +$ $\cos\psi_0 \cos\psi_3 \cos\vartheta$	$-\sin\vartheta \cos\psi_3$	$\sin\psi_0 \cos\psi_3 \cos\vartheta +$ $\sin\psi_3 \cos\psi_0$
$d_{11} = \omega_y^4$	$\sin\vartheta \cos\psi_0$	$\cos\vartheta$	$\sin\psi_0 \sin\vartheta$
$d_{12} = \omega_z^4$	$-\sin\psi_0 \cos\psi_3 -$ $\sin\psi_3 \cos\psi_0 \cos\vartheta$	$\sin\psi_3 \sin\vartheta$	$-\sin\psi_0 \sin\psi_3 \cos\vartheta +$ $\cos\psi_0 \cos\psi_3$

In the post-manufactured pyramid, the real values of angles are deviated from ideal values. In this case, the measurement procedure grounded on semi-natural motion using the three-degree-of-freedom tested bench (Fig. 10) is proposed. Then, it is essential to carry out an analysis of measurement data by neural network and fix numerical values of the table of guided cosines [19], [20].

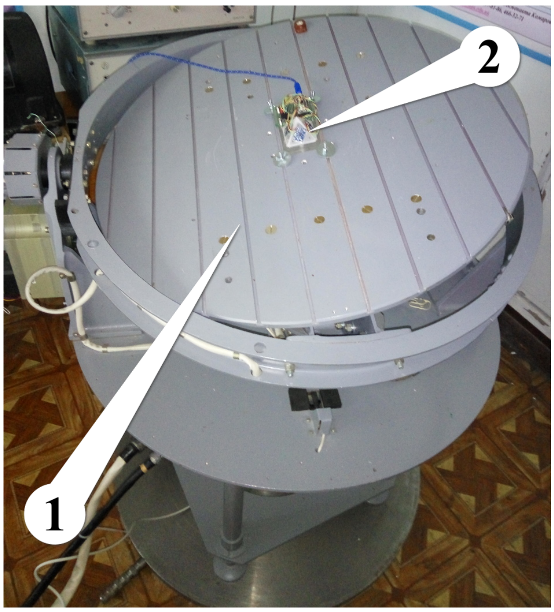

Fig. 10. Three-degree-of-freedom tested bench: *1* is the three-degree-of-freedom tested bench; *2* is the non-orthogonal measuring instrument

The angular rate of a moving object φ can be formulated in the vector form

$$\varphi = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^{\mathrm{T}}, \tag{8}$$

where angular rates ω_x, ω_y, ω_z define revolutions of the moving object in the horizontal, vertical, and lateral planes correspondingly.

Projections of the registered angle rate Ω on the sensitivity axes of separate inertial sensors based on MEMS technologies look like

$$\Omega = \begin{bmatrix} \omega_x^1 & \omega_y^1 & \omega_z^1 & \dots & \omega_x^4 & \omega_y^4 & \omega_z^4 \end{bmatrix}^{\mathrm{T}}, \tag{9}$$

where angular rates $\omega_x^i, \omega_y^i, \omega_z^i, i = 1 \dots 4$ are calculated on information about guide cosines represented in Table I.

Values of angular rates measured by means of the tested bench can be determined using transformation

$$\omega_\varphi^{\mathrm{T}} = \begin{bmatrix} \omega_\psi & \omega_\vartheta & \omega_\gamma \end{bmatrix} = \Omega^{\mathrm{T}} H, \tag{10}$$

where matrix H is the pseudo-inverse matrix of guide cosines given in Table I.

Expressions (8) – (10) represent the algorithm for processing data in the non-orthogonal configuration of MEMS sensors. Using the Allan variance method to the result of calculating the measurement noise of a non-orthogonal inertial module, the algorithm of which is given by expression (9), it is possible to estimate the characteristics of such a module [21].

A comparison of accuracy characteristics by the axis y for the separate MEMS sensor and non-orthogonal measuring device created on MEMS arrays is shown in Fig. 11.

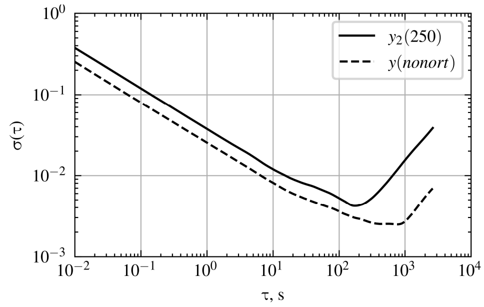

Fig. 11. Changing characteristics of Allan variances for the separate sensor and non-orthogonal configuration of MEMS arrays

As follows from the graphical dependencies represented in Fig. 11, the characteristics of the layout of the inertial module with a non-orthogonal arrangement of axes exceed the characteristics of the individual sensors from which this module is created. In particular, the ARW characteristic has been decreased 2 times. This is expected according to analytical calculations [6]. The instability of the zero bias also has decreased. The time period, after which the influence of random walk of the angular velocity will be arising, has been increased approximately up to 5 times.

V. CONCLUSIONS

The innovation of the proposed approach to using the Allan variance method consists of analyzing the accuracy of non-orthogonal measuring instruments without the use of special laboratory equipment based on numerical modeling methods based on the geometric configuration of the inertial module and Allan variances of separate sensors. There is no need for special tested equipment due to the fact that the source of the initial information of the Allan variance method is measurement noise and it is essential only to ensure the immobility of inertial sensors and stable characteristics of the external environment. This differs from the conventional approach, where the Allan variance is estimated for the device as a whole, and reduces the required time and resources for testing.

The economy in technical resources has a number of practical advantages and allows you to effectively solve a number of problems in the design of low-cost inertial modules. Based on the results of Allan's variance calculations, it is possible to comprehensively evaluate the characteristics of inertial modules and the expediency of their use for various practical tasks (for example, for orientation or navigation).

The overall level of Allan variance and, accordingly, the value of the standard deviation of the error of the inertial measuring unit for the considered non-orthogonal configuration is decreased by 2 times, which is the expected result. Another positive result is that the average start time of the influence of rate random walk increased from $2 \cdot 10^2$ to 10^3.

Further research, is planned to estimate the accuracy of the non-orthogonal inertial measuring device, which will consist of separate MEMS sensors, as well as estimate the influence of their errors on the output signals and, if necessary, reduce it by correcting the relevant weighting factors. The proposed approach will allow the use of defective sensors without significant degradation in the performances of the non-orthogonal inertial measuring instrument.

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О. А. Сущенко, Ю. М Безкоровайний. Дослідження точності неортогональної конфігурації інерціальних датчиків.

У статті виконано дослідження точності неортогональної конфігурації інерціальних датчиків на основі дисперсії Аллана. Було оцінено вплив змін діапазону вимірювання блока інерціальних датчиків на дисперсію Аллана. На основі аналізу результатів оцінки дисперсії Аллана запропоновано процедуру вибору багатоосьових MEMS-датчиків з ідентичними характеристиками для створення інерціального неортогонального вимірювального приладу. Наведено приклад складання алгоритму обробки даних для інерціального вимірювального приладу з неортогональним розташуванням осей чутливості на основі складання 3-осьових MEMS-датчиків. Представлено результати моделювання для числових оцінок. Показано підвищення точності неортогональних інерціальних вимірювальних приладів на основі використанням дисперсії Аллана.

Ключові слова: дисперсія Аллана; модуль MEMS; обробка даних; інерціальний датчик; неортогональна конфігурація.

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