ISSN 2413–9599 (Print)
ISSN 2541–870X (Online)

www.radioprom.org

DOI: 10.21778/2413-9599-2019-29-2-69-75

Identification of the noise structure of micromechanical inertial transducers of motion parameters

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The article presents the results of the analysis of the noise structure of micromechanical transducers of motion parameters – micromechanical gyroscopes (MMG) and micromechanical accelerometers (MMA) of an experimental measuring unit of strapdown inertial position navigation systems. The unit is manufactured and developed at JSC «GYROOPTICS» (St. Petersburg). It consists of a LL–MMG triad with measuring ranges of ±400°/s and an axial-type MMA triad with measuring ranges of ± 50 g. Micromechanical gyroscopes and accelerometers manufactured using modern microelectronics technologies are among the most promising microsystem technology devices that are widely used as sensors of the primary information of strapdown inertial orientation and navigation systems. The accuracy of the functioning of the inertial orientation and navigation inertial systems is significantly affected by the noise structure of the output signals of the inertial motion parameters sensors. For this reason, the urgent task of identifying the noise of micromechanical gyroscopes and accelerometers. The noise structure of the angular rate and linear acceleration transducers of the tested SINS block was identified by the Allan variance method. The output signals of the transducers were recorded in normal climatic conditions, the sampling interval was 1.0 ms, and the recording duration was 90 minutes. The processing of the output signals of the transducers was carried out on the basis of special software using the AlaVar 5.2 program. It has been established that the predominant noise components of the transducers are the random walk of the output signal – white noise and the instability of the zero signal – flicker noise. No quantization noise was detected in the output signals of the transducers. The values of the noise characteristics in Allan variance of the output signals of the angular rate transducers and the linear acceleration of the test block are compared with the noise characteristics of the most advanced modules produced by foreign companies.

Keywords: MEMS, noise, micromechanical gyroscope, micromechanical accelerometer, Allan variance

For citation:
Lestev A.M., Fedorov M.V., Evstafiev S.D. Identification of the noise structure of micromechanical inertial transducers of motion parameters. Radiopromyshlennost, 2019, vol. 29, no. 2, pp. 69–75. DOI: 10.21778/2413-9599-2019-29-2-69-75

Introduction

Micromechanical inertial transducers of angular rate and linear acceleration – micromechanical gyroscopes (MMGs) and micromechanical accelerometers (MMAs) are widely used in strapdown reference and navigation systems (SINSs and SIRSs) of mobile objects intended for various purposes. In SINSs and SIRSs, orientation angles and object coordinates are determined on the basis of integrating kinematic and navigation equations [1]. The accuracy of the functioning of inertial navigation systems is significantly affected by the noise structure of the MMG and MMA output signals used as sensors of the primary information in the navigation systems. In particular, when integrating MMG noise of white type, the standard root-mean-square deviation (RMSD) of the error in determining the orientation angle of an object increases proportionally to the square root [2] of the navigation system operation time ($t^{1/2}$). The discrete white noise in the MMA output signal at double integration leads to an error in determining coordinates, the RMSD of which increases proportionally ($t^{3/2}$). As a result, the task of identifying the noise of motion parameters inertial sensors is relevant.

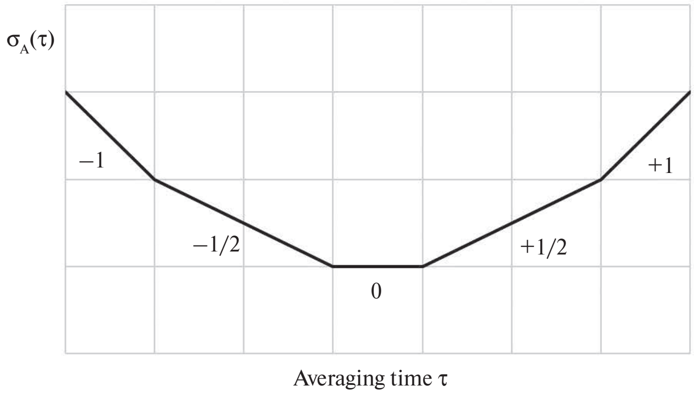

Figure 1. General view of the Allan deviation curve. Typical slopes (μ) $\sigma^2_A(\tau)$ – graph (on the scale of $\log_{10}$–$\log_{10}$): $\mu = -1$ – white noise in the angle (linear velocity) or quantization noise; $\mu = -1/2$ – white noise in angular rate (linear acceleration); $\mu = 0$ – flicker noise in angular rate (linear acceleration) – Bias instability; $\mu = +1/2$ – white noise in angular acceleration; $\mu = +1$ – trend in angular rate (linear acceleration)

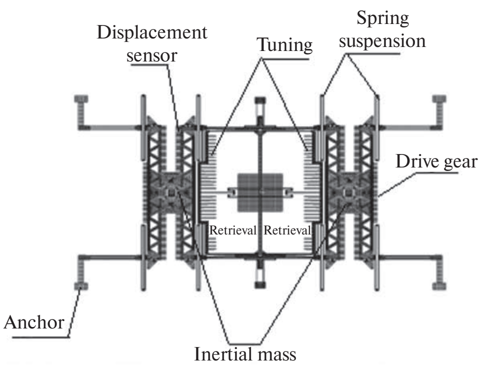

Figure 2. Geometric and finite element models of angular rate transducers' sensing element

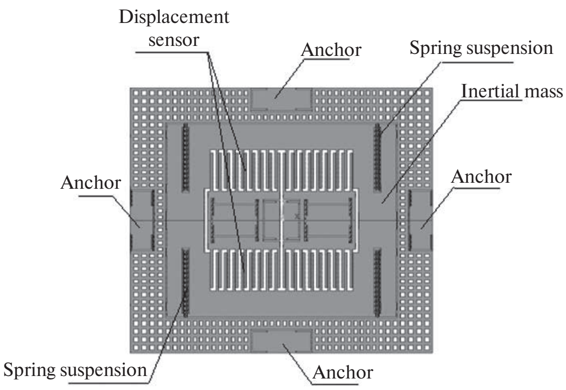

Figure 3. Geometric and finite element models of the linear acceleration transducers' sensing element

When identifying the noise structure and analyzing sensor errors, methods based on the use of Allan variance [3, 4] or Allan deviation (Allan deviation), defined as the square root of Allan variance, are widely used. The Allan variance method was proposed to estimate the errors of the cesium frequency standard for large time intervals. Subsequently, Allan variance was included in the specifications of inertial sensors of motion parameters [2, 5, 6]. Despite the fact that Allan variance is heuristic and does not have rigorous mathematical justification [7], Allan variance is included in the data sheets of MEMS gyros and MEMS accelerometers of many foreign firms [8, 9]. At present, this method has become widespread in analyzing random errors and identifying the noise structure of Russian laser and fiber-optic gyroscopes and micromechanical gyroscopes, as well as accelerometers [10–17].

Allan variance and test results

The principle of the Allan variance method is in calculating the variance of deviations of the difference between averaged values of discrete random variables generated from the measurement array of the sensor output signal

$$\sigma^2_{\mathrm{A}}(\tau) = \frac{1}{2(n-1)} \sum_{1}^{n-1} \left[\bar{U}(\tau)_{k+1} - \bar{U}(\tau)_{k} \right]^2, \tag{1}$$

where $\bar{U}(\tau)_k$ is the analyzed signal, averaged over the interval $(k\tau,(k+1)\tau)$ of time τ;

n is the number of intervals of the averaged signal.

Allan variance $\sigma^2_A(\tau)$ is related to the spectral density $S_U(f)$ of the stable random process $U(t)$ by dependence

$$\sigma^2_{\mathrm{A}}(\tau) = 4\int_0^\infty S_{\mathrm{U}}(f) \frac{\sin^4(\pi f \tau)}{(\pi f \tau)^2} df. \tag{2}$$

The article [18] proposes, and subsequent publications [10, 15, 16] use the approximation expression for $\sigma^2_A(\tau)$

$$\sigma_A^2(\tau) = R^2\frac{\tau^2}{2} + K^2\frac{\tau}{3} + B^2\frac{2}{\pi}\ln 2 + N^2\frac{1}{\tau} + Q^2\frac{3}{\tau^2}, \quad (3)$$

taking into account the following components of the output signal noise: quasi-deterministic change of the form Rt; random walk (Wiener process), described by the spectral density $S(f) = (K/2\pi)2/f$; flicker noise ($S(f) = B^2/2\pi f, f \leqslant f_0$; $S(f) = 0, f \leqslant f_0, f_0$ – cut-off frequency); white noise ($S(f) = N^2$); quantization noise ($S(f) = (2\pi f)^2 Q^2 \tau$).

A typical form of the graph of the square root of the Allan variance $\sigma_A(\tau)$ versus averaging time in a logarithmic scale is presented in Fig. 1. The solution of the identification problem using Allan variance is reduced to estimating the coefficients of R, K, B, N, Q, determining numerical values of which is performed using the method of least squares.

In this paper, the object of research is an experimental sample of an inertial measuring unit containing a triad of micromechanical angular rate transducers with measurement ranges of ± 400 °/s and a triad of micromechanical linear acceleration transducers with ranges of ± 50g. The unit was designed and manufactured at JSC GIROOPTIKA (St. Petersburg). The structures of MMG and MMA used as sensors of the primary information of the unit are based on calculations performed using the ANSYS computer system. Geometric and finite element models of the sensing element (SE) of the angular rate transducer are shown in Fig. 2, and those of the linear acceleration transducers are shown in Fig. 3.

Figs. 4 and 5 in a logarithmic scale along both axes show graphs of Allan deviations and approximating curves based on the results of processing records of

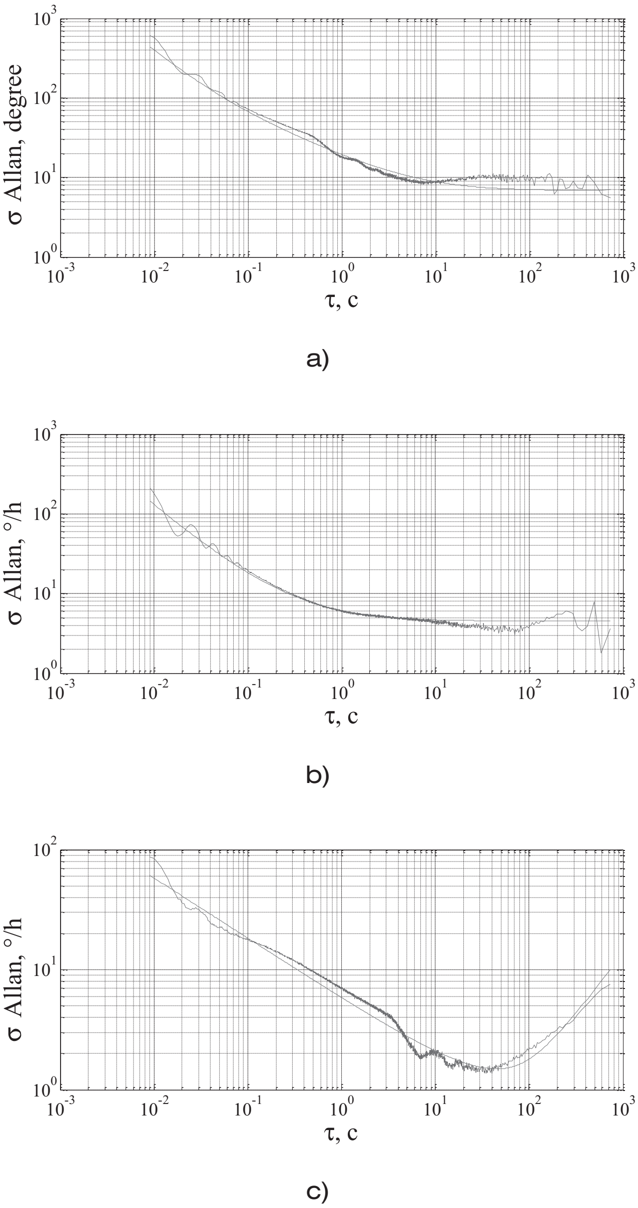

Figure 4. Allan variations of angular rate transducers measuring channels *X* (a), *Y* (b) and *Z* (c)

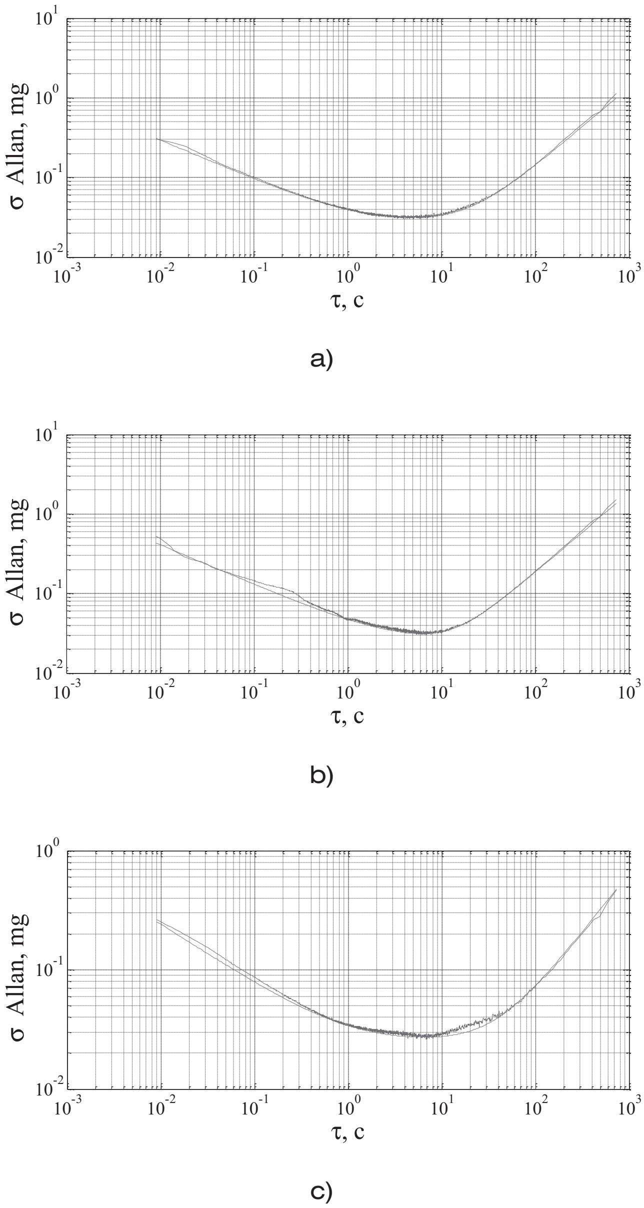

Figure 5. Allan variations of linear acceleration transducers of measuring channels *X* (a), *Y* (b) and *Z* (c)

output signals with a duration of 90 min of angular rate and linear accelerations transducers of the unit under study. The recording was made on a fixed relative to the Earth base under normal climatic conditions; the sampling interval was 1.0 ms. The processing of the output signals of the transducers was carried out using special software (M. A. Lestev, JSC GIROOPTIKA) in the C ++ programming environment using the AlaVar 5.2 program (http://www.alamath.com/alavar/). The determination of the numerical values of R, K, B, N, Q coefficients of expression (3), which characterize the intensity of the noise components of the output signals of the transducers, was carried out by the least squares method implemented by means of the MathCad computer system. The obtained values of these coefficients are shown in the table.

The Allan variance curves of angular rate and linear acceleration transducers of the inertial measuring unit contain areas with characteristic slopes «$\frac{1}{2}$» and «0», which are characteristic of white noise and flicker noise of the transducers output signals. The predominant noise components in the studied signals are a random walk (N) of the output signal – white noise and instability (B) of the zero signal – flicker noise. Quantization noise in the output signals of the gyroscopic and accelerometric channels of the measuring unit was not detected.

The specifications of inertial sensors of motion parameters manufactured by foreign companies contain the following noise characteristics: random walk of the output signal (ARW – Angle Random Walk and VRW – Velocity Random Walk), as well as zero signal instability (Bias Instability). The most accurate inertial modules manufactured by Analog Devices and Honeywell (USA) ADIS16488 (measurement ranges ± 450 °/s and ± 5 g) and HG 1700 (± 1000 °/s and ± 5 g) are characterized by the following noise parameters values: gyroscopic channels ARW – 18 and 30°/h/$\sqrt{\text{Hz}}$, Bias Instability – 6.25 and 10°/h; accelerometric channels VRW – 0.029 and 0.37 m/s/$\sqrt{\text{h}}$ and Bias Instability – 0.032 and 1.0 mg. The article [11] presents test results of the pilot batch of MMG developed by the Central Research Institute Elektropribor together with the French company Tronics Microsystems: ARW – not exceeding 36°/h/$\sqrt{\text{Hz}}$, Bias Instability – no more than 10°/h; some samples had a noise level of 7.2–10.8°/h/$\sqrt{\text{Hz}}$ and Bias instability 12°/h.

Conclusions

Using the Allan variance method, identification of the noise structure of micromechanical angular rate (range ± 400°/s) and linear acceleration (range ± 50 g) transducers of the inertial navigation system experimental measuring unit developed and manufactured by JSC GIROOPTIKA (St. Petersburg), was performed. It was determined that the predominant noise components in the output signals of transducers are random walk – white noise and zero signal instability – flicker noise. According to the results of the tests, the experimental units' MMG can be classified as micromechanical gyroscopes of the accuracy class 10°/h and MMA can be classified as micromechanical accelerometers of the accuracy class 0.05 mg. Comparison according to the Allan variance of the noise characteristics of the output signals of the micromechanical transducers of angular rate (MMG) and linear acceleration (MMA) of the experimental measuring unit manufactured by JSC

Table. The intensity factors of the noise components of the converters of angular rate and linear acceleration

Noise intensity factor	Unit of measurement	Axis X	Axis Y	Axis Z
Angular rate transducers				
R	°/h/h	0,00	0,00	0,02
K	°/h/$\sqrt{\text{h}}$	0,10	0,00	0,00
B	°/h	4,50	3,00	0,70
N	°/h/$\sqrt{\text{Hz}}$	18,00	4,00	5,80
Q	µrad	0,00	0,00	0,00
Linear acceleration transducers				
R	mg/h	0,0019	0,0026	0,0009
K	mg/$\sqrt{\text{h}}$	0,0071	0,001	0,0050
B	mg	0,0175	0,0160	0,0160
N	mg/$\sqrt{\text{Hz}}$	0,0295	0,0410	0,0240
Q	m/s	0,0000	0,0000	0,0000

GIROOPTIKA with the developments of foreign and Russian companies shows that the noise characteristics of the tested unit are close to the characteristics of the most advanced inertial modules manufactured by foreign companies and are comparable to the noise characteristics of domestic analogs.

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Submitted 01.03.2019; revised 25.03.2019; published online 27.05.2019.