UDC 629.3.025.2
DOI: 10.18372/2306-1472.69.11052

Olha Sushchenko

INERTIAL TECHNOLOGIES IN SYSTEMS FOR STABILIZATION OF GROUND VEHICLES EQUIPMENT

National Aviation University
Kosmonavta Komarova Avenue 1, 03058, Kyiv, Ukraine
E-mail: sushoa@ukr.net

Abstract

Purpose: *The vibratory inertial technology is a recent modern inertial technology. It represents the most perspective approach to design of inertial sensors, which can be used in stabilization and tracking systems operated on vehicles of the wide class. The purpose of the research is to consider advantages of this technology in comparison with laser and fiber-optic ones. Operation of the inertial sensors on the ground vehicles requires some improvement of the Coriolis vibratory gyroscope with the goal to simplify information processing, increase reliability, and compensate bias.* ***Methods:*** *Improvement of the Coriolis vibratory gyroscope includes introducing of the phase detector and additional excitation unit. The possibility to use the improved Coriolis vibratory gyroscope in the stabilization systems operated on the ground vehicles is shown by means of analysis of gyroscope output signal. To prove efficiency of the Coriolis vibratory gyroscope in stabilization system the simulation technique is used.* ***Results:*** *The scheme of the improved Coriolis vibratory gyroscope including the phase detector and additional excitation unit is developed and analyzed. The way to compensate bias is determined. Simulation of the stabilization system with the improved Coriolis vibratory gyroscope is carried out. Expressions for the output signals of the improved Coriolis vibratory gyroscope are derived. The error of the output signal is estimated and the possibility to use the modified Coriolis vibratory gyroscope in stabilization systems is proved. The results of stabilization system simulation are given. Their analysis is carried out.* ***Conclusions:*** *The represented results prove efficiency of the proposed technical decisions. They can be useful for design of stabilization platform with instrumental equipment operated on moving vehicles of the wide class.*

Keywords: bias compensation; Coriolis vibratory gyroscope; ground vehicles; stabilization system; phase detector.

1. Introduction

Characteristics of systems for stabilization of equipment operated on the ground vehicles depend essentially on their structure components. Different types of gyroscopes can be used in this case. Until now traditional electro-mechanical gyroscopes can be used in researched application due to their high accuracy and dynamics characteristics, and low noise. Usage of sensor inertial technologies is widespread trend of modern instrument making industry. Such sensors have a wide field of applications including platform stabilization [2, 3]. It is explained by low cost, and simplicity of maintenance. The modern trend of sensor design is based on inertial technologies.

The Coriolis vibratory gyroscope (the vibrating structure gyroscope) is a recent modern inertial technology, which is developed now in many countries. Its usage allows designing of inertial stabilization systems, which are characterized by the high accuracy and reliability, simplicity of maintenance, resistance to shocks, and low cost.

Usage of gyroscopes in stabilization systems requires some improvements, for example, simplification of information processing techniques, and increasing of accuracy due to bias compensation. This can be implemented by means of technical means, for example, usage of the phase detector and additional excitation unit and also algorithm of bias compensation.

2. Analysis of the latest research and publications

Review of MEMS-gyroscopes, which can be used in stabilization systems operated on the ground vehicles, is represented in [4]. The similar analysis

Copyright © 2016 National Aviation University
http://www.nau.edu.ua

of the fiber-optic gyroscopes is given in [5]. The basic features of the Coriolis vibratory gyroscope (CVG) developed by specialists of the National Aviation University (Aircraft Control Systems Department) and Kyiv Automatic Plant are represented in [6, 7]. In [6] basic advantages of CVG such as the possibility to implement measurements in some modes are considered. Automated switching of modes provides minimum errors of measurements in the wide range. The important feature of CVG is its resistance to such external disturbances as shocks. This is very important for such application as stabilization of platform with the payload operated on the ground vehicles.

The paper considers some improvements directed to the better possibilities of usage CVG in platform stabilization systems. They represent technical decisions providing simplification of information processing and bias compensation. There are some known constructions of the beam vibratory gyroscopes similar to researched in [8]. And the beam vibratory gyroscope described in [9] is the nearest to considered gyroscopes. A mode of output signal processing of this device is implemented by means of units realizing addition and subtraction of primary and secondary oscillations during change of the primary oscillations on 180^o (reverse of the primary oscillations). Further the resonance frequency amplitude is determined [9]. Exactly it includes information about an angular rate. But this technical decision has some disadvantages. Change of the primary oscillations phase is accompanied by a transient, which leads to errors of angular rate measurement. Furthermore repeated subtraction of signals increases noise, complicates information processing, and decreases reliability of the device.

3. Research aim and tasks

The aim of this paper is to develop the improved CVG and solve the following tasks.

1. To analyze modern inertial technologies and to implement grounded choice of the inertial technology, the most convenient for stabilization of platform operating on ground vehicles.
2. To simplify information processing due to measurement of difference of the primary and secondary oscillations phase.
3. To compensate bias due to detection of the axis with the minimum Q-factor and excitation of resonator oscillations along this axis.
4. To carry out simulation of the stabilization system with improved CVG and analysis of simulation results.

4. Choice of inertial technology

It should be noted that ring laser gyroscopes, which are widely used in the inertial navigation, are rarely used for platform stabilization due to large dimensions and quantization noise [2]. So, it is convenient to analyze such inertial technologies as fiber-optic, MEMS, and vibratory inertial technologies for the researched application.

Advantages of fiber-optic gyroscopes are absence of moving parts, instantaneous readiness to operation, changing sensitivity depending on length of fiber winding. However mass, dimensions, and cost can be constraints for such application as platform stabilization due to the necessity to use receiving and transmitting unit and keeping fibers polarization of transmitted radiation. Stabilization system of the researched type can also use gyroscopes designed by MEMS-technology, which are characterized by low cost and serviceability. For example, Gladiator Technologies (USA) manufactures small-size silicon two-axis MEMS-gyroscopes G20 [10] with low power consumption and long operation life. The embedded vibration isolation system provides resistance to the external vibration and shocks. Gyroscopes of such type are produced for some standard measuring ranges such as ±75deg/s, ±150deg/s, ±300deg/s. There are modifications of such gyroscope, which differ from standard ones. The important disadvantage of such gyroscope is alignment error 1 deg. The one-axis gyroscope G50Z manufactured by the same enterprise has not such disadvantage [10]. Characteristics of gyroscopes, which can be used for platform stabilization, are given in Table 1.

Characteristics of MEMS-gyroscopes represented in the third and fourth columns of Table 1 correspond to such application as stabilization of information and measuring devices operated on ground vehicles because the above stated sensors have high resistance to shocks influence. However MEMS-gyroscopes characteristics have some statistical dispersion due to manufacturing errors. Moreover ageing in such sensors has different rates. And measuring information of MEMS-gyroscopes requires compensation of zero bias. Therefore in many cases correction units of different degree of complexity are used. Usage of imbedded temperature compensation systems is widespread too.

Table 1

Characteristics of MEMS-gyroscopes suitable for platform stabilization

Parameter	GG5200	G20-075-100	G50Z-100-100 (200)
Mass, g	60	30	< 30
Time of readiness, s	< 1	-	< 0.05
Resistance to shocks, g	40	500	500
Temperature range, ^oC	-45…+85	-40…+85	-55…+100
Supply	5 V, < 200 mA	-	5 V $\pm$ 5%, 35mA
Resolution	10 deg/h or 16 bit	-	$\leq$ 0,005 deg/s
Random drift	0,2 deg/$\sqrt{h}$	0,05 deg/s/$\sqrt{Hz}$	0,014 deg/s/$\sqrt{Hz}$
Scale factor, mV/(deg/s)	25	15	20
Accuracy of alignment	$\pm$ 17 mrad	$\pm$ 1 deg	< 4 mrad
Bandwidth, Hz	100	100	50
Measuring range, deg/s	$\pm$ 360	$\pm$ 75	$\pm$ 100

CVGs have not such disadvantages. Now in Ukraine are carried tests of CVGs able to operate in three modes such as integrating, rate, and differential. Usage of such devices in the differential mode of operation allows to increase stability of the scale factor and to correct an error of the bias [7]. These advantages improve effectively the quality of stabilization and tracking processes.

Comparative analysis of such sensors as MEMS-gyroscope ADIS-16136 (Analog Devices, USA), vibratory gyroscope with the metallic resonator “Quaposon” (SAGEM, France) and CVG developed by Aircraft Control Systems department and the Kyiv Automatic Plant (Ukraine) are represented in Table 2 [7].

Table 2

Comparative analysis of parameters of CVG, ADIS-16136 and “Quapason”

Parameter	ADIS16136	“Quapason”	CVG
Measuring range, deg/s	±400, ±250, ±100	±250	±400, ±200, ±150
Sensitivity of scale factor to temperature, %/^oC (1σ)	±0,0035	±0,004	±0,0026
Non-linearity of scale factor, %	0,01	-	0,01-0,03
Repeated bias, deg/s	±0,15	-	±0,03
Sensitivity of bias to temperature, (deg/s)/^oC (1σ)	$\pm 1{,}25 \cdot 10^{-3}$	$\pm 2{,}2 \cdot 10^{-3}$	$\pm 1{,}7 \cdot 10^{-4}$
Stability of bias, deg/s	10^{-3}	(3-6) 10^{-3}	$<3 \cdot 10^{-4}$
Random drift (noise), deg/√h	0,167	0,3	0,003-0,01
Sensitivity of bias to linear acceleration, deg/s/g,1σ	0,017 (±1g)	-	0,001(±1g)
Alignment error, deg.	±1	±0,5	±(0,5-0,3)
Noise density, (1σ),deg/s/√Hz	0,00375	-	0,00187
Bandwidth, Hz	350	100	100
Temperature range, ^oC	-40 +85	-40 +85	-40 +75
Sensitivity, (deg/s)/bit; (ADC capacity)	$7 \cdot 10^{-5}$ (24)	Analog output	$6 \cdot 10^{-3}$ (16)
Supply power, W	0,6	1,0	2,5
Average nonfailure operating time, h	-	500000	500000
Resistance to shocks, g	2000,	-	400, 2 ms
Output format	SPI	-	RS-485,422

As can be seen from Table 2 almost all basic CVG parameters exceed appropriate parameters of other represented gyroscopes. Only two parameters of ADIS-16136 such as supply power and bandwidth are better than appropriate CVG parameters. This is not critical for the considered application because platform inertance and delay of motor reaction are deciding factors for successful operation of the stabilization system as a whole. The supply power 2,5 W also is not critical for the given application.

5. Improvement of CVG sensors

The paper proposes the improved beam-type CVG, structural scheme of which is represented in Fig. 1. It includes beam resonator 1, drive and sense electrodes 2, 3, 4, 5, unit of primary oscillations excitation 6, and phase detector 7 [11].

Principle of operation of this sensor is as follows. One input of the phase detector 7 is connected with the primary oscillations sense electrode 2 and another input is connected with the secondary oscillations sense electrode 3. A signal proportional to rotation angular rate is read from the phase detector output. Such a construction provides simplification of information processing due to measurement of difference of primary and secondary oscillations phases. This simplifies signal processing and its transformation into the digital form, decreases manufacturing cost, and increases reliability of the sensor.

A signal of secondary oscillations taken off from the electrode gives information about the angular rate of beam rotation Ω. It can be described by the following expression

$$Y(t) = K\Omega_0 \sin \omega_r t + A_q \cos \omega_r t = \\ = \sqrt{(K\Omega)^2 + A_q^2} \cos(\omega_r t - \varphi), \quad (1)$$

where A_q is an amplitude of the quadrature signal; K is the gyroscope scale factor.

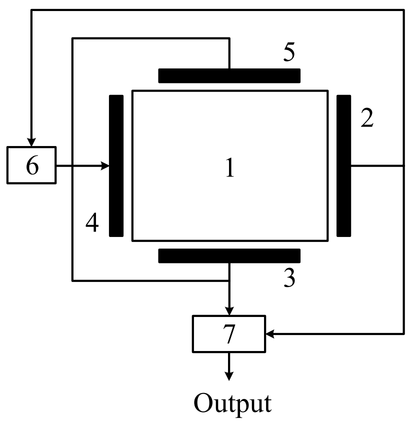


Fig.1. Structural scheme of vibratory gyroscope with the phase detector

Further signal (1) enters to the input of the phase detector. The output signal of the phase detector represents a signal of the phase difference φ [11]

$$\varphi = \text{arctg}\frac{K\Omega}{A_q} \approx \frac{K}{A_q}\Omega \text{ for } \Omega << 1. \quad (2)$$

The expression (2) defines the signal proportional to Ω for small angular rates.

The further improvement of CVG construction lies in bias compensation due to detection of axis of minimum Q-factor and excitation of resonator oscillations along this axis. This leads to simplification of information processing due to measurement of difference of the primary and secondary oscillations phases. A process of bias compensation can be explained by the structural scheme represented in Fig. 2 [12].

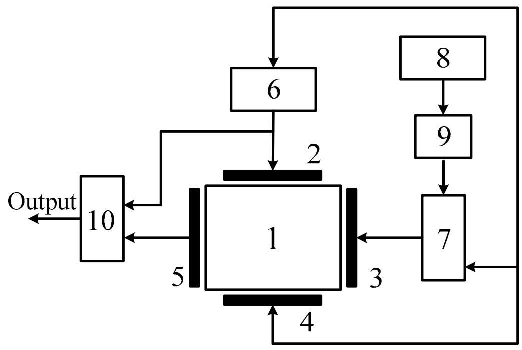


Fig. 2. Structural scheme of CVG with bias compensation

CVG shown in Fig. 2 includes beam resonator 1 with drive and sense electrodes 2, 3, 4, 5, the first excitation unit 6, which gives the drive signal of changed amplitude A_1 on the electrode 2, the second excitation unit 7, which gives the drive signal of changed amplitude on the orthogonal electrode 3, peak detector 8, which determines maximum of output signal amplitude of the second excitation unit 7, unit 9, which gives an amplitude of oscillations of the second excitation unit, and the phase detector 10. Represented CVG operates in the following way. After energization the unit 6 gives signal of oscillations $X_1(t)$ excitation on the electrode 2. The signal functions on the resonance frequency ω_r of the beam resonator with the constant amplitude A_1, which can be described by the following expression

$$X_1(t) = A_1 \cos(\omega_r t). \quad (3)$$

Reaction of the beam resonator, which operates on the first mode of oscillations, on the excitation signal (3) for the beam resonator can be represented in the following way

$$X_{1res}(t) = B_1 \cos\theta_\tau \sin(\omega_r t), \quad (4)$$

where θ_τ is an angle between oscillations axis and direction of the minimum Q-factor axis; B_1 is an amplitude of resonator oscillations. It should be noted that B_1 in (4) depends on excitation amplitude A_1, resonator Q-factor, and electrode transfer constant.

The second excitation unit 7 gives the excitation oscillations $X_2(t)$ on the orthogonal electrode 3. The signal also functions on the resonance frequency ω_r of the beam resonator with the changed amplitude $A_2(t)$, which looks like

$$X_1(t) = A_1 \cos(\omega_r t). \quad (5)$$

Reaction of the resonator on the excitation signal (5) leads to oscillations

$$X_{2res}(t) = B_2(t)\cos(\theta_\tau - \pi/2)\sin(\omega_r t) = \\ = B_2(t)\sin\theta_\tau \sin(\omega_r t) \quad . (6)$$

The signal $B_2(t)$ also depends on excitation amplitude $A_2(t)$, resonator's Q-factor, and electrode transfer constant.

Resulting primary oscillations of resonator $X(t)$ is superposition of the two oscillations described by (4), (6).

$$X(t) = X_{1res}(t) + X_{2res}(t) = B_1\cos\theta_\tau \sin(\omega_r t) + \\ + B_2(t)\sin\theta_\tau \sin(\omega_r t) = \\ = \sqrt{B_1^2 + B_2^2}\cos(\theta_\tau - \theta)\sin(\omega_r t), \quad .(7)$$

here $\theta = \mathrm{arctg}(B_2 / B_1)$. In (7) θ is an angle of the vibration wave turn relative direction of the drive electrode 2. This direction defines direction of the resonator oscillations.

So, change of the amplitude $A_2(t)$ leads to change of the amplitude $B_2(t)$. As can be seen from (7) the vibration wave rotates. When direction of the vibration wave axis will coincide with the axis of minimum Q-factor, the excitation signal achieves maximum B_{2tax} to keep stable the resulting amplitude of resonator oscillations. When oscillations axis will coincide with the axis of minimum Q-factor, the peak detector 8 fixes this amplitude value and transmits this value of unit 9 to the second excitation unit 7. Then unit 8 fixes maximum amplitude of excitation $B_{2\max}$, and unit 7 gives the signal of fixed amplitude on the electrode 3. It should be noted that bias of vibratory gyroscopes can be determined by the following relationship

$$d = \frac{\omega_r}{4k}\left(\frac{1}{Q_1} - \frac{1}{Q_2}\right)\sin[n(\theta_\tau - \theta)], \quad (8)$$

here Q_1, Q_2 are maximum and minimum Q-factors; n is a number of oscillations mode; k is a constant depending on resonator geometry. For $k = 1$, $n = 1$, the expression (8) can be rewritten in the following form

$$d = \frac{\omega_r}{4}\left(\frac{1}{Q_1} - \frac{1}{Q_2}\right)\sin[n(\theta_\tau - \theta)]. \quad (9)$$

It means that bias (9) is equal to zero if direction of oscillations will coincide with the direction of the minimum Q-factor.

The Coriolis force arises, when angular rate Ω is acting along axis parallel to beam longitudinal axis. This force causes the secondary oscillations $Y(t)$ along the axis perpendicular to the axis of the primary oscillations. In this case, this force arises under the angle $\theta_\tau + \pi/2$ to axis of the drive electrode 2. The signal of secondary oscillations, which is read from the electrode 5 and includes information about beam rotation angular rate, can be represented by the following expression

$$Y(t) = K\Omega_0\cos(\theta_\tau - \theta)\sin\omega_r t + \\ + A_q\cos(\theta_\tau - \theta)\cos\omega_r t = \\ = \sqrt{(K\Omega)^2 + A_q^2}\sin(\theta_\tau - \theta + \pi/2)\cos(\omega_r t - \varphi) = \\ = \sqrt{(K\Omega)^2 + A_q^2}\cos(\theta_\tau - \theta)\cos(\omega_r t - \varphi), \quad (10)$$

here A_q is an amplitude of the quadrature signal; K is the scale factor.

Further signal described by (10) is given on the first input of the phase detector 10. And the signal described by (3) from the first excitation unit enters on the second input of the phase detector. When $\theta = \theta_\tau$ and $\cos(\theta_\tau - \theta) = 1$, the output of the phase detector 10 will represent a phase difference φ

$$\varphi = \mathrm{arctg}\frac{K\Omega}{A_q} \approx \frac{K}{A_q}\Omega, \text{ for } \Omega << 1, \quad (11)$$

which is proportional to the angular rate Ω for small values. A_q in the expression (11) always is not equal to zero because it characterizes errors of beam manufacturing, for example, different thickness of a beam.

Scale factors of such CVGs are usually equal to 0,01…0,02 V/(deg/s), values of A_q are approximately equal to 0,04…0,5 V. It means that $K / A_q \le 0{,}5$. Therefore the equality (11) is satisfied for small Ω. For $\Omega \le 0{,}2$ rad/s (11,5 deg/s) the error of angular rate measurement $\Delta\Omega$ will is equal to nonlinearity of function arctg(x)

$$\Delta\Omega \le \frac{1}{3}\left(\frac{K}{A_q}\Omega\right)^3 \le \frac{1}{3}(0{,}1)^3 \approx 0{,}0003\,\text{rad} \approx 0{,}017\,\text{deg/s}. \quad (12)$$

The expression (12) is true for most of considered stabilization systems modes. It should be noted that for high-precision stabilization system the maximum angular rate is not more than 1 deg/s. Then measurement accuracy in correspondence with (12) will not exceed $1{,}3\cdot10^{-5}$ deg/s (approximately 0,05 deg/h).

6. Analysis of simulation features and results

Results of simulation carried out on example of the horizontal channel of stabilization system [14] are given in Figures 3, 4.

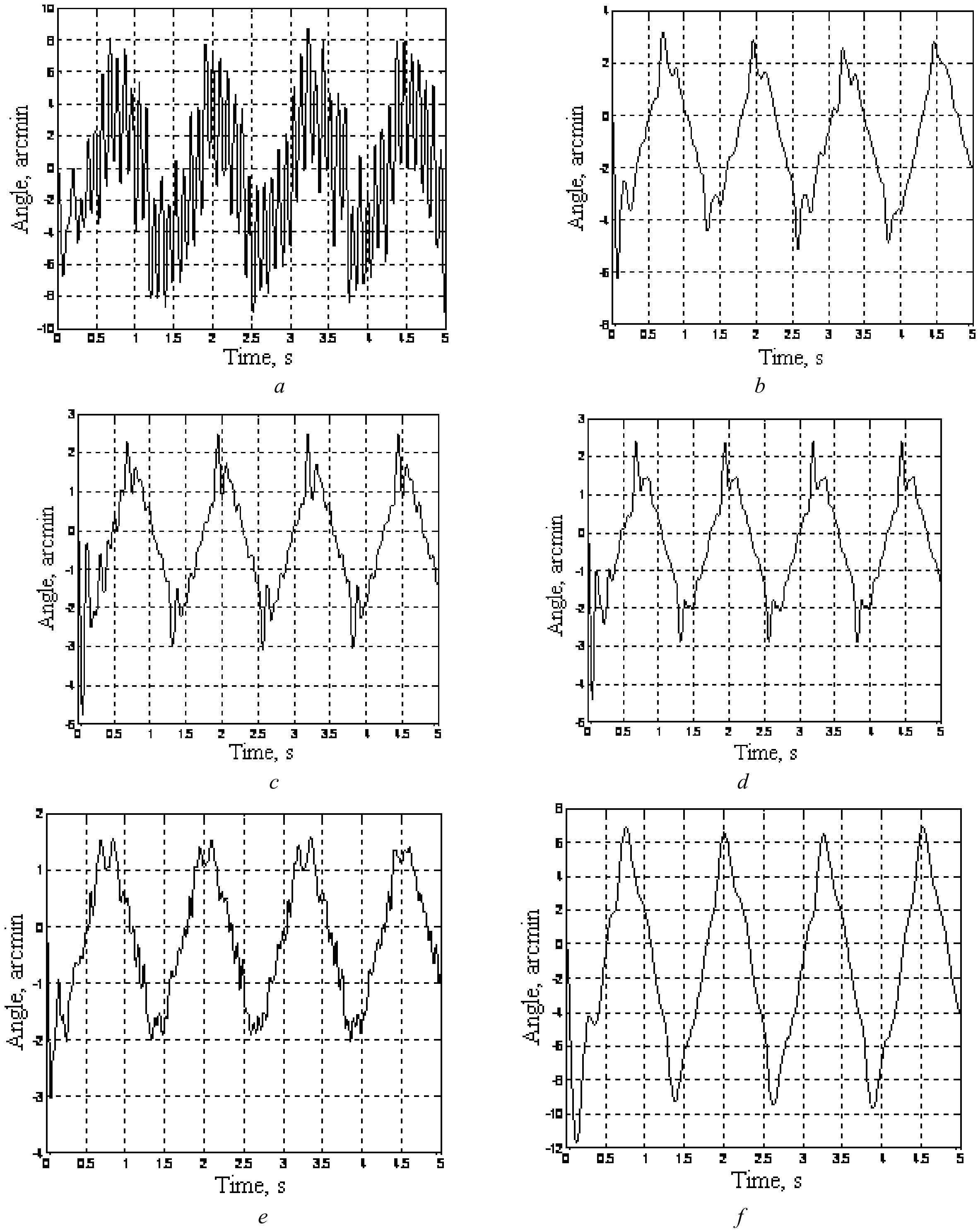
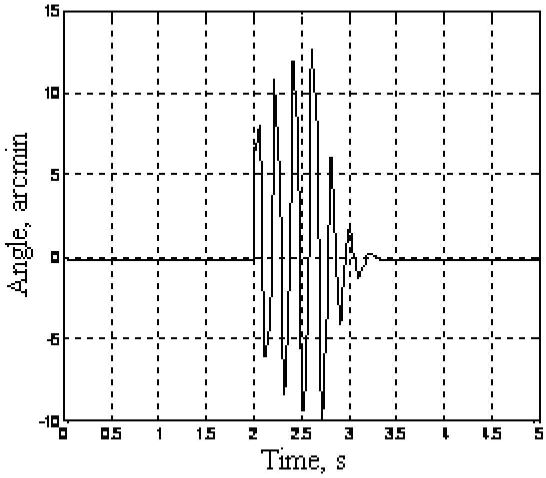
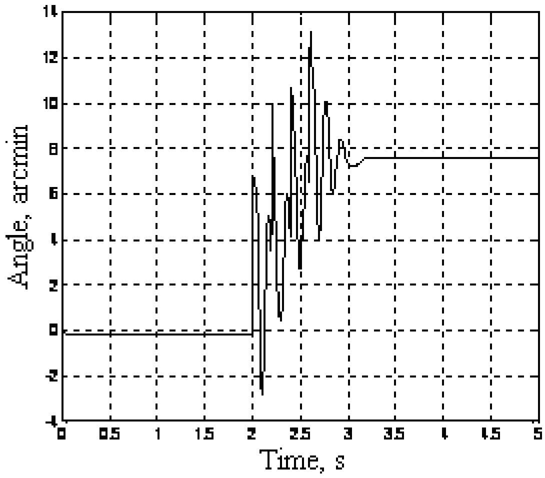


Fig. 3. Simulation results: dynamic error of stabilization system with GT and CVG (3a, 3b); dynamic error for different bandwidths (3c, 3d); the least dynamic error (3e); the smooth signal (3f)



a



b

Fig. 4. Simulation results: reaction on impulse signals with nulling (a) and without it (b)

Sinusoidal and impulse signals have been used as tested ones during simulation. For simulation of the stabilization system with developed CVG the values of adjustable coefficients given in Table 3 have been used [13]

Table 3

Values of adjustable coefficients

Variant	k_1	k_2	k_3
1	0,75	0,07	0,08
2	0,624	0,058	0,0665
3	0,32	0,044	0,064
4	0,75	0,055	0,08
5	0,8	0,05	0,013
6	0,8	0,055	0,013

Choice of the adjustable coefficients in the control contours was carried out on the basis of minimization of H_2-norm of transfer function of the closed loop stabilization system

$$H_2 = \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty} \mathrm{tr}\left[W(j\omega)^* W(j\omega)\right] d\omega}$$

for different initial conditions. Here $W(j\omega)$ is the transfer function of the closed loop stabilization system; * is the symbol of the complex-conjugate matrix. The chosen criterion provides the high accuracy of control processes.

Comparative simulation for different variants of adjustable coefficients represented in Table 3 was carried out using two types of rate gyroscopes such as electromechanical GT-46 and CVG with the above mentioned technical improvements. Results of simulation for the first variant of adjustable coefficients and bandwidth 100 Hz are shown in Figs 3a, 3b.

It is known that increase of gain k_1 influences positively on the stabilization system rigidity. This characteristic is of great importance for systems providing stabilization of devices functioned on the ground vehicles working in difficult conditions of real operation, which are accompanied by external disturbances including shocks [15].

The biggest value of gain k_1 takes place for the first variant of the adjustable coefficients. In contrast to stabilization systems with GT-46, usage of CVG allows increasing of gain, which does not accompanied by oscillativity increase. So, usage of CVG allows increasing of gain and respectively system rigidity. Simulation results have been shown that permissible dynamic error is keeping in conditions of the further gain increase including values $k_1 = 0{,}8$ and $k_1 = 0{,}85$. Increase of k_1 to value 0,9 leads to some increase of the stabilization system dynamic error oscillativity.

Nature of dynamic error amplitude change coincides with gain decrease both for GT-46 and for CVG. This gives the possibility to suppose that the high frequency oscillations shown in Fig. 3a are caused by the sufficiently high gain $k_1 = 0{,}75$. With decrease of gain k_1 to 0,32 the amplitude of the dynamic error and its representation become identical. But in this case the dynamic error amplitude exceeds the permissible value in two times. Such situation was studied for the third variant of adjustable coefficients.

Results of research of changed bandwidth are represented in Figures 3c, 3d. The dynamic error for bandwidths 100 Hz, 200 Hz are represented here. Simulation was considered for the fourth variant of adjustable coefficients. As follows from these results, the dynamic error process is smoother for the bandwidth 200 Hz. And the stabilization accuracy is sufficient in both cases.

The minimum dynamic error for the stabilization system with CVG was obtained for the fifth variant of the adjustable coefficient. It should be noted that the transient has significant oscillations in this case.

The smoothest transient dynamic error takes place for the decreased gain $k_1 = 0{,}32$ and the third variant of adjustable coefficient. But the amplitude of the dynamic error in this case exceeds the permissible value in two times.

The reaction of the stabilization system with CVG on impulse signals is given in Figs 4a, 4b. These graphs were obtained for the fifth variant of adjustable coefficients.

7. Conclusions

Analysis of modern inertial technologies and the grounded choice of inertial technology for rate gyroscopes used in the stabilization systems operated on the ground vehicle were carried out. The advantages of the CVG were discussed.

The technical decisions directed to improvement of CVG were developed. Introducing of the phase detector makes easier information processing and increases reliability of the sensor. Technical means of bias compensation were developed. This provides increase of stabilization system accuracy.

The expressions, which prove efficiency of the proposed technical decisions, are represented. The relation for bias determination was derived.

Simulation of the stabilization system with the improved CVG was carried out. Analysis of represented graphs is represented.

The obtained results can be useful for stabilization of information and measuring devices operated on vehicles of the wide class.

References

[1] Masten M.K., Sebesta H.R. (1987) Line of sight stabilization/tracking systems: an overview. *Proc. IEEE Int. Conf. "American Control"*. Minneapolis, pp. 1477 – 1482.

[2] Hilkert J.M. (2008) Inertially stabilized platform technology. *IEEE Control Systems Magazine*, vol. 26, no. 1, pp. 26–46. doi: 0.1109/MCS.2007.910256

[3] Masten M.K. (2008) Inertially stabilized platforms for optical imaging systems. *IEEE Control Systems Magazine*, vol. 26, no. 1, pp. 47–64. doi: 10.1109/MCS.2007.910201

[4] Nasiri S. A Critical Review of MEMS Gyroscopes Technology and Commercialization Status. Available at http://www.invensense.com /shared/pdf/MEMSGyroComp.pdf

[5] Chikovani V. V. (2014) Trends of Ukrainian all digital Coriolis vibratory gyroscopes development. *Proc. IEEE 3rd Int. Conf. "Methods and systems of Navigation and Motion Control"*. Kyiv, pp. 25–28. doi: 10.1109/msnmc.2014.6979720

[6] Chikovani V.V., Sushchenko O. A. (2014) Differential mode of operation for the Coriolis vibratory gyroscope with ring-like resonator. *Proc. IEEE 34th Int. Conf. "Electronics and Nanotechnology"*. Kyiv, pp. 336–339. doi: 10.1109/apuavd.2015.7346568

[7] Chikovani V.V., Sushchenko O.A., Tsiruk H.V. (2016) Redundant information processing techniques comparison for differential vibratory gyroscope. *Eastern European journal of enterprise technologies*, no. 4, pp. 45–52. doi: 10.15587/1729-4061.2016.75206

[8] Bayard D.S., Ploen S.R. High accuracy inertial sensors from inexpensive components. U.S. Patent 6882964, Int. Cl. A61N 1/36 Apl. 2005.

[9] Stanley F. Wyse, Robert E. Stewart. Vibratory gyroscope bias error cancellation using mode reversal. US Patent7886598, Int. C1. G01P 9/04. Apl. 2006.

[10] Gladiator Technologies. Available at http://www.gladiator technologies.com/.../MEMS-Sensors.html.

[11] Chikovani V.V., Sushchenko O.A. (2013) Balochnyy vibratsiynyy hiroskop z kompensatsiyeyu zmishchennya nulya [Beam vibratory gyroscope with bias compensation]. Patent 85766. Ukrayina, MPK G01S. 19/56, no 201308113, zayavl. 26.06.2013, opubl. 25.11.2013, byul. no. 22. (in Ukrainian)

[12] Chikovani V.V., Sushchenko O.A. (2013) Balochnyy vibratsiynyy hiroskop dlya system stabilizatsiyi [Beam vibratory gyroscope for stabilization systems]. Patent 85316. Ukrayina, MPK G01S. 19/00, no. 201308114, zayavl. 26.06.2013, opubl. 11.11.2013, byul. no. 21. (in Ukrainian)

[13] Sushchenko O. A. (2009) Algorithm for ground vehicle stabilizer optimal synthesis.

Proceedings of the National Aviation University, no. 4, pp. 23–28. doi: 10.18372/2306-1472.41.1790

[14] Sushchenko O.A., Korostelev O.P. (2015) Mathematical modelling of inertially stabilized platforms applied at ground vehicles. *Electronics and Control Systems*, no. 4, pp. 100–108.

[15] Sushchenko O.A., Malyarov S.P., Yankelevich G.E., Saifetdinov R.A. (2010) Osoblyvosti modelyuvannya stabilizatora nazemnoho rukhomoho ob'yekta z tsyfrovym blokom keruvannya [Simulation features of ground vehicle stabilizer with digital control unit]. *Proceedings of the National Aviation University*, no. 4, pp. 23–31. (In Ukrainian) doi: 10.18372/2306-1472.45.1873

Received 15 September 2016

О.А. Сущенко

Інерціальні технології в системах стабілізації обладнання наземних рухомих об'єктів

Національний авіаційний університет, пр. Космонавта Комарова, 1, Київ, Україна, 03058
E-mail: sushoa@ukr.net

Мета: Вібраційна інерціальна технологія є останньою з сучасних інерціальних технологій. Вона являє собою перспективний підхід до проектування інерціальних датчиків, який може бути використано для систем стабілізації та стеження, що експлуатуються на рухомих об'єктах широкого класу. Метою дослідження є розгляд переваг цієї технології у порівнянні з лазерною та волоконно-оптичною. Функціонування інерцального датчика на наземних рухомих об'єктах потребує деякого вдосконалення коріолісова вібраційного гіроскопа з метою спрощення обробки інформації, підвищення надійності та компенсації зміщення нуля. **Методи дослідження:** Вдосконалення коріолісова вібраційного гіроскопа полягає у введенні фазового детектора та додаткового блока збудження. Можливість використання вдосконаленого коріолісова вібраційного гіроскопа в системі стабілізації, що експлуатується на наземних рухомих об'єктах, показано на підставі аналізу вихідного сигналу гіроскопа. Ефективність використання коріолісова вібраційного гіроскопа в системах стабілізації підтверджується за допомогою методу імітаційного моделювання. **Результати:** Розроблено та проаналізовано схему коріолісова вібраційного гіроскопа, що містить фазовий детектор та додатковий блок збудження. Визначено спосіб компенсації зміщення нуля. Виконано моделювання системи стабілізації з вдосконаленим коріолісовим вібраційним гіроскопом. Отримано вирази для вихідних сигналів вдосконаленого коріолісова вібраційного гіроскопа. Виконано оцінку похибки вихідного сигналу та підтверджено можливість використання модифікованого коріолісова вібраційного гіроскопа в системах стабілізації. Представлено результати моделювання системи стабілізації та виконано їх аналіз. **Висновки:** Отримані результати підтверджують ефективність запропонованих рішень та можуть бути корисними для стабілізації платформ з приладовим обладнанням, що експлуатуються на рухомих об'єктах широкого класу.

Ключові слова: компенсація зміщення нуля; коріолісов вібраційний гіроскоп; наземні рухомі об'єкти; система стабілізації; фазовий детектор.

О.А. Сущенко.

Инерциальные технологии в системах стабилизации оборудования наземных подвижных объектов

Национальный авиационный университет, пр. Космонавта Комарова, 1, Киев, Украина, 03058
E-mail: sushoa@ukr.net

Цель: Вибрационная инерциальная технология является последней из современных инерциальных технологий. Она представляет собой перспективный подход к проектированию инерциальных датчиков, который может быть использован для систем стабилизации слежения, эксплуатируемых на подвижных объектах широкого класса. Целью исследования является рассмотрение преимуществ этой технологии в сравнении с лазерной и волоконно-оптической. Функционирование инерциального датчика на наземных подвижных объектах требует некоторого улучшения кориолисова вибрационного гироскопа с целью упрощения обработки информации, повышения надежности и компенсации смещения нуля. **Методы исследования:** Усовершенствование кориолисова вибрационного гироскопа включает введение фазового детектора и дополнительного блока возбуждения. Возможность использования усовершенствованного кориолисова вибрационного гироскопа в системах стабилизации, которые эксплуатируются на наземных подвижных объектах, показана на основании анализа выходного сигнала гироскопа. Эффективность использования кориолисова вибрационного гироскопа в системах стабилизации подтверждается при помощи метода имитационного моделирования. **Результаты:** Разработана и проанализирована структурная схема кориолисова вибрационного гироскопа, которая включает фазовый детектор и дополнительный блок возбуждения. Определен способ компенсации смещения нуля. Выполнено моделирование системы стабилизации с усовершенствованным кориолисовым вибрационным гироскопом. Получены выражения для выходных сигналов усовершенствованного кориолисова вибрационного гироскопа. Выполнена оценка погрешности выходного сигнала и подтверждена возможность использования модифицированного кориолисова вибрационного гироскопа в системах стабилизации. Представлены результаты моделирования системы стабилизации и выполнен их анализ. **Выводы:** Полученные результаты подтверждают эффективность предложенных решений и могут быть полезными для стабилизации платформ с приборным оборудованием, которые эксплуатируются на подвижных объектах широкого класса.

Ключевые слова: компенсация смещения нуля; кориолисов вибрационный гироскоп; наземные подвижные объекты; система стабилизации; фазовый детектор.

Sushchenko Olha (1956). D. Sci., Associate Professor.
Aircraft Control Systems Department of the National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine (1980).
Research area: systems for stabilization of information and measuring devices.
Publications: 120.
E-mail: sushoa@ukr.net