Checking the Required Accuracy of Measuring the State of Elastic Aerospace Vehicle Structure

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***Abstract* — The problem on providing the most accurate measuring information of an elastic aerospace vehicle (AV) state in real time is discussed. Such elastic AV can be large interplanetary spacecraft, a WIG-craft, or an airplane. For this purpose, it is proposed to place a sufficiently large number of inertial measuring modules along the AV body and perform verification and correction of their parameters during the flight. Such measuring modules should provide the necessary accuracy for a long time interplanetary flights. Micromechanical gyroscopes are used as the main measures. The results of digital modeling confirm the effectiveness of the proposed algorithms for verification of such important parameters of micro gyroscopes as the difference in the natural frequencies of primary and secondary oscillations and their Q-factor.**

Keywords — micromechanical gyroscope, real time estimation, elastic aerospace vehicle, distributed measuring system

I. Introduction

Increasing requirements for the maneuverability of aircraft with a minimum weight of the structure and high speed of flight leads to the manifestation of the elastic properties of the hull of aircraft. Elasticity is especially significant when controlling missiles, airplanes, and space stations. The presence of elasticity determines the possibility of oscillations in the control system at various resonant frequencies. There were cases when the elasticity of the plant was the cause of the instability of the control system, led to the development of oscillations and, ultimately, to the destruction of the structure. This fact determines the great interest in the design of systems for the active suppression of elastic oscillations [1 - 4].

The creation of effective controllers is hampered by the difficulty of obtaining reliable information about the elastic properties of the object, a significant dependence of the natural frequencies on the changing mass, speed and velocity head. The last two parameters are largely dependent on the flight path, which is often not known in advance. Actual deformations in the process of elastic vibrations of elastic aerospace vehicle structures depend on distributed dynamic loads on the surface of the object. These distributed aerodynamic loads are largely random and can be very different from theoretical models. The use of a distributed measuring system will allow for each moment in time to determine real deformations and form control actions to suppress these deformations.

Rocket designers strive to create the most lightweight designs. This leads to the fact that in flight the rocket is deformed, the elastic properties of the hull are manifested. Elastic longitudinal and transverse vibrations of complex shape arise, the frequencies of which vary during the flight. Elastic vibrations are usually described by partial differential equations or ordinary high-dimensional differential equations.

Mathematical models of large elastic aerospace structures are calculated based on ground-based experiments with individual fragments of structures. Another approach is based on the use of special programs, such as ANSYS or COMSOL, requiring accurate input of data on the design features of the AV, the elastic properties of individual elements and how to connect them. In the articles [1–3], to obtain a model of a large interplanetary spacecraft, an original version is used, based on a combination of the above two approaches. In any case, in real flight conditions, a high degree of uncertainty remains in the mathematical model of the elastic rockets.

Another feature of modern AV is the concentration of measuring means of orientation in one section of the vehicle. In this case, information on the deformation form of the elastic rocket is made on the basis of the calculated model. In [3–4], it is proposed to use a system of inertial meters distributed over the entire body to measure real deformations of an elastic object during the flight. The problem of optimal placement of meters for a given number of them is solved. Corresponding verification and refinement algorithms of the current form of bends during the flight are proposed.

Preliminary studies have shown that this approach can significantly improve the accuracy of estimating the real state of the elastic structure during the flight with a sufficient number of inertial meters. From the point of view of minimizing mass and energy consumption, it is proposed to use inertial modules made on the basis of micromechanics. In this case, the big problem is to ensure sufficient measurement accuracy and the band of the measured frequencies.

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II. Mathematical Models

Fig. 1 shows the coordinate axes used for micromechanical gyroscope (MMG). For its sensing element with autoexcitation, equations of the motion are presented in the following form [3]

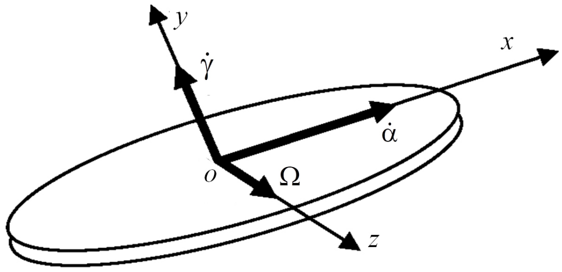

Fig. 1 Sensing element of micromechanical gyroscope

$$\ddot\gamma + 2\xi_\gamma \nu\dot\gamma + \nu^2\gamma = m_0 \cdot sign(\dot\gamma(t)), \tag{1}$$

$$\ddot\alpha + 2\xi\omega\dot\alpha + \omega^2\alpha = \chi\cdot\dot\gamma\cdot\Omega, \tag{2}$$

where γ is the angle of rotation of the sensing element; ν is its eigen-frequency relatively axis Oy; ω is the eigen-frequency of the sensing element relatively the Ox axis; ξ_γ is dimensionless factor of oscillation damping relatively the axis Oy; ξ is dimensionless factor of oscillation damping relatively the axis of measurement Ox; $\chi = I_y / I_x$ is the ratio of the moments of inertia of the sensing element; Ω is the measured angular rate. Since parameter $\xi_\gamma << 1$, then the solution of (1) can be written with high accuracy as

$$\dot\gamma(\mathrm{t}) = \dot\gamma_\mathrm{m}\ \sin(\nu\mathrm{t}), \tag{3}$$

where $\dot\gamma_\mathrm{m}$ is a constant magnitude of primary oscillations relatively oy axis. The initial phase of these primary oscillations can be assumed to be zero. In this case the solution of (2) can be written as folllows

$$\alpha(t) = A^{\text{in-phase}}(t)\sin\nu t + A^{\text{quadr}}(t)\cos\nu t. \tag{4}$$

The first term in the formula is an in-phase component, and the second term is a quadrature component.

The amplitudes of the in-phase and quadrature components can be obtained from the signal $\alpha(t)$ using well-known schemes of amplitude or phase detectors. In the future, these signals will be used as a measured signals to build the appropriate filters.

For functions $A^{\text{in-phase}}(t)$ and $A^{\text{quadr}}(t)$ it is possible to calculate the following inverse Laplace transforms [3, 6]

$$W^{\text{ in-phase}}(s) = \frac{k_s(T_s s + 1)}{T_0^2 s^2 + 2\xi_0 T_0 s + 1}, \tag{5}$$

$$W^{\,quadr}(s) = \frac{k_q}{(T_0^2 s^2 + 2\xi_0 T_0 s + 1)}, \tag{6}$$

where

$$T_s = \frac{1}{\xi\omega};\ T_0 = \frac{1}{\xi\omega}\cdot\frac{1}{\sqrt{1+\lambda^2}};\ k_s = \frac{\chi\gamma_m}{4}\frac{1}{\xi\omega}\cdot\frac{1}{\sqrt{1+\lambda^2}};$$

$$\lambda = \frac{\Delta}{\xi\omega};\quad \xi_0 = \frac{1}{\sqrt{1+\lambda^2}};\quad \Delta = \nu - \omega;\ k_q = \lambda k_s,$$

and parameter $\Delta = \nu - \omega$ is off-tuning between primary and secondary eigen-frequencies.

The functions $A^{\text{in-phase}}(t)$ and $A^{\text{quadr}}(t)$ are envelopes of two components of the secondary oscillations.

Note that the frequency of the primary oscillations is set by the quartz oscillator and is fairly accurately known. The frequency of secondary vibrations may vary during the long-term operation of the device may vary. Together with this frequency, the magnitude of the frequency detuning also changes $\Delta = \nu - \omega$.

In reference [6] it is shown that the parameter Δ specifies the bandwidth of the gyroscope and the slope of the output signal. For this reason, variations of this parameter in the operation of the device lead to errors of measurement of angular rate by the gyroscope. One of the main tasks of this article is to develop an algorithm for estimating variations of Δ in real time.

III. First Level Of Estimation Algorithm

Fig. 2 shows a fragment of Simulink program that explains the calculation of in-phase and quadrature components of the signal $\alpha(t)$.

In accordance with this scheme, there are two alternative methods for calculating in-phase and quadrature components. Modelling showed that the use of Peak detectors and Amplitude detectors gives equivalent results, but is accompanied by a high level of noise. This means that the use of in-phase and quadrature components requires effective filtering.

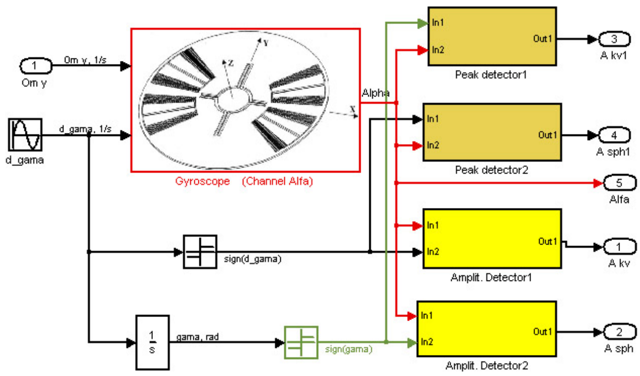

Fig. 2 Fragment of Simulink software that explains the calculation of in-phase and quadrature components

In accordance with (5) and (6) the following formula can be written for the amplitude envelopes of in-phase and quadrature component the following formula:

$$\frac{W^{quadr}}{W^{\text{in-phase}}} = \frac{\alpha_q(s)}{\alpha_s(s)} = \frac{k}{s+b}, \tag{7}$$

where $b = \xi\omega$; $\quad k = \dfrac{k_q}{k_s} = \lambda = \dfrac{\Delta}{\xi\omega}$

This goal is achieved using the algorithm proposed below. Previously, the output signal of the gyroscope $\alpha(t)$ is divided into two components $\alpha_s(t)$ and $\alpha_q(t)$. The measured values of the in-phase $\alpha_{sm}(t)$ and quadrature components $\alpha_{qm}(t)$ contains measurement errors $\delta\alpha_s(t)$ and $\delta\alpha_q(t)$.

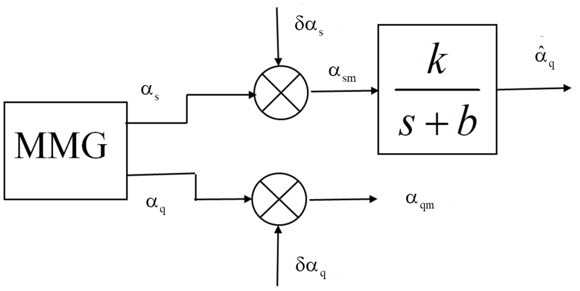

Fig. 2 Diagram that explains the calculation of the magnitudes of in-phase α_s and quadrature α_q components of output signal of gyroscope.

In the process, the internal parameters of the device are slowly changing. Along with these parameters, important parameters such as the transmission coefficient of the device and bandwidth are changed. Typically, during the calibration of the instrument, certain transmission coefficients are set between the measured angular velocity and the output electrical signal. Identification of these parameters during the operation of the device can significantly increase its accuracy.

According to the (7) it is possible to write

$$\dot{\alpha}_q = -b\alpha_q + \Delta\alpha_s + \Delta\delta\alpha_s \quad . \tag{8}$$

As a result, we obtain a system of equations in vector form:

$$\dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x},t) + \mathbf{B}\cdot w(t), \tag{9}$$

where

$$\mathbf{x}(t) = \begin{bmatrix} \alpha_q \\ \Delta \\ b \end{bmatrix}; \quad \mathbf{f}(x,t) = \begin{bmatrix} -b\alpha_q + k\alpha_s(t) \\ 0 \\ 0 \end{bmatrix}; \quad \mathbf{B} = \begin{bmatrix} \Delta \\ 0 \\ 0 \end{bmatrix};$$

$$w(t) = [\delta\alpha_s(t)].$$

Quadrature component output signal will be used as a measure. In this case, we write

$$y = \mathbf{H}x + \delta\alpha_q \ , \tag{10}$$

where $\mathbf{H} = [1 \quad 0 \quad 0]$.

Assume that the measurement error of output signal of MMG are broadband noise that during synthesis estimation algorithm may be approximated by white noise with the intensities of Q and R, respectively.

The equation of generalized nonlinear Kalman filter for object described by (3) and (4) has the following form

$$\dot{\hat{\mathbf{x}}}(t) = \mathbf{f}(\hat{\mathbf{x}}(t),t) + \mathbf{K}(t)\cdot(y(t) - \mathbf{H}\hat{\mathbf{x}}(t)) \tag{11}$$

or in expanded form:

$$\begin{cases} \dot{\hat{a}}_k = -\hat{b}\hat{a}_k + \hat{a}a_c + K_1(y - \hat{a}_k); \\ \dot{\hat{b}} = K_2(y - \hat{a}_k); \\ \dot{\hat{a}}_k = K_3(y - \hat{a}_k) \end{cases}$$

with initial conditions are a priori data

$$\dot{\hat{a}}_k(0) = m_{a_k}; \quad \dot{\hat{b}}(0) = m_b; \quad \dot{\hat{a}}(0) = m_a .$$

Riccati equation for the filter in this case has the following form:

$$\dot{\mathbf{P}} = \mathbf{f}_x(\hat{\mathbf{x}},t)\mathbf{P} + \mathbf{P}\mathbf{f}_x^T(\hat{\mathbf{x}},t) - \mathbf{P}\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}\mathbf{P} + \mathbf{G}\mathbf{Q}\mathbf{G}^T, \tag{12}$$

where P is a covariance matrix of the state vector estimation. The equation for calculating the coefficients of the matrix $K(t)$ has the following form

$$\mathbf{K}(t) = \mathbf{P}(t)\mathbf{H}^T\mathbf{R}^{-1}. \tag{13}$$

As a result of the use of the proposed algorithm filtering obtained amplitude evaluation of a quadrature component α_q, the parameters Δ and b. Because $\hat{\Delta}$ and $b = \xi\omega$ for certain frequency of the primary oscillation the damping factor is calculated by the following formula:

$$\hat{\xi} = \frac{\hat{b}}{\omega}. \tag{14}$$

IV. Analysis Of The Effectiveness Of Estimation Algorithm

The effectiveness of the proposed algorithm is assessed using simulation. To simulate the real gyroscope measurements model the Simulink was used.

The effectiveness of the proposed algorithm is assessed using. The simulation results of the estimation $\hat{\Delta}(t)$ process off-tuning primary and secondary own frequencies at different constant values Δ in the range of 1 to 100 Hz are shown in Fig. 3. It is shown that the proposed algorithm can accurately estimate values Δ in a wide range of change.

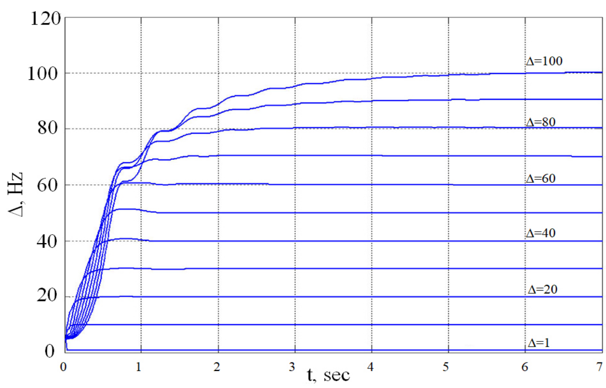

Fig. 3. Process of estimation off-tuning for different constant values Δ

The simulation results of the estimation for different constant values ξ in the range of 10^{-4} to $3\cdot10^{-3}$ are shown in Fig. 4. Calculations show that at increase ξ and Δ the time of estimation of these parameters is increased too.

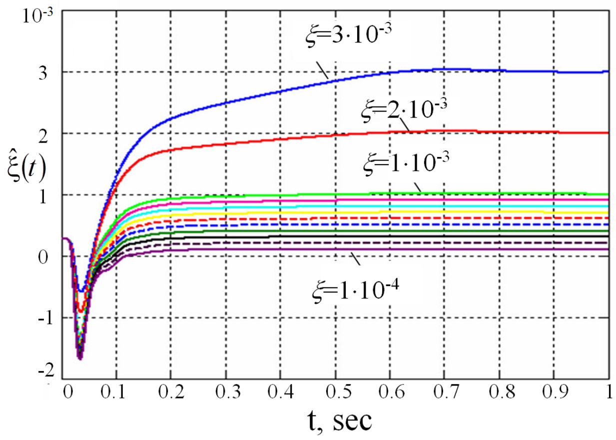

Fig. 4. Process of estimation ξ for different real values
1. $\xi=3\cdot10^{-3}$; 2. $\xi=2\cdot10^{-3}$; 3. $\xi=1\cdot10^{-3}$; 4. $\xi=3\cdot10^{-4}$

V. Second Level of Estimation Algorithm

Despite the variety of MMG circuitry, the simplified mathematical description of their dynamics is essentially the same as in [3, 6]. As a first approximation the movement of the sensitive element in RR-microgyro given the angular speed of the basis can be described by the following equation

$$\ddot\alpha + 2\xi\omega\dot\alpha + \omega^2\alpha = 2\dot\gamma\Omega + kU(t) + g_w w(t) \qquad (15)$$

where $\alpha(t)$ is the MMG angle of rotation relative to the sensitive axis, ω is a the secondary oscillations resonant frequency, $\dot\gamma(t)$ is the instantaneous value of the angular rate of MMG sensing mass relative to the axis of excitation of oscillations, γ_0 is the established amplitude of primary oscillations; $\Omega(t)$ is the angular rate of sensor frame or measured angular rate, $U(t)$ is the control signal operating on the gyro, and w(t) represents a broad-band stochastic external disturbances.

The elementary model, defining maneuverability of the AV on which the microgyroscope is installed, takes the form

$$\dot\Omega(t) = -\frac{1}{T_\Omega}\Omega(t) + \sqrt{\frac{2}{T_\Omega}}\sigma_\Omega w_\Omega(t), \qquad (16)$$

where T_Ω is the time constant of the AV; w_Ω is a random process of white noise type with unit intensity; σ_Ω is a root-mean-square error of angular rate of the AV.

This equation can be used for description of a wide class of AV. The same approach as presented below can be used for more complex linear equations.

Equations (15) and (16) in the state space are recorded as follows:

$$\begin{bmatrix}\dot\alpha(t)\\ \dot\omega_\alpha(t)\\ \dot\Omega(t)\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ -\omega^2 & -2\xi\omega & 2\dot\gamma(t)\\ 0 & 0 & -\frac{1}{T_\Omega}\end{bmatrix}\cdot\begin{bmatrix}\alpha(t)\\ \omega_\alpha(t)\\ \Omega(t)\end{bmatrix} + \begin{bmatrix}0 & 0\\ g_w & 0\\ 0 & \sqrt{\frac{2}{T_\Omega}}\sigma_\Omega\end{bmatrix}\cdot\begin{bmatrix}w(t)\\ w_\Omega(t)\end{bmatrix}. \qquad (17)$$

The equation of measurements of the angle is

$$y(t) = \alpha_m(t) = \alpha(t) + v(t), \qquad (18)$$

where $v(t)$ is error of angle $\alpha(t)$ measurement.

Generally, non-stationary differential equations (17) and (18) in the following vector form can be recorded

$$\dot{\mathbf{x}}(t) = \mathbf{A}(t)\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{K}(t)(y(t) - \hat\alpha(t))\,; \qquad (19)$$

$$y(t) = \mathbf{H}\mathbf{x} + v(t)\,;\ \mathbf{H} = \begin{bmatrix}1 & 0 & 0\end{bmatrix}. \qquad (20)$$

For the observability of the state vector $\mathbf{x}(t)$ it is necessary that the matrix *[H HA HA^2]*^{T} would have a rank equal to 3. For this case the condition of observability is

$$\operatorname{rank}\begin{bmatrix}1 & 0 & -\omega^2\\ 0 & 1 & -2\xi\omega\\ 0 & 0 & 2\dot\gamma(t)\end{bmatrix} = 3.$$

This condition of observability holds with the exception of the time instants *t* for which $\dot\gamma(t) = 0$.

The equation of a non-stationary Kalman filter (KF), which corresponds to (19) and (20) can be written in the following form:

$$\begin{bmatrix}\dot{\hat\alpha}(t)\\ \dot{\hat\omega}_\alpha(t)\\ \dot{\hat\Omega}(t)\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ -\omega^2 & -2\xi\omega & 2\dot\gamma(t)\\ 0 & 0 & -\frac{1}{T_\Omega}\end{bmatrix}\begin{bmatrix}\hat\alpha(t)\\ \hat\omega_\alpha(t)\\ \hat\Omega(t)\end{bmatrix} + \begin{bmatrix}k_1(t)\\ k_2(t)\\ k_3(t)\end{bmatrix}(y(t) - \hat\alpha(t)),$$

or in vector form

$$\dot{\hat{\mathbf{x}}}(t) = \mathbf{A}(t)\hat{\mathbf{x}}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{K}(t)(y(t) - \hat\alpha(t)) \qquad (21)$$

where

$$\mathbf{K}(t) = \mathbf{P}(t)\mathbf{H}^T\mathbf{R}^{-1} \qquad (22)$$

$$\dot{\mathbf{P}} = \mathbf{A}(t)\mathbf{P} + \mathbf{P}\mathbf{A}^T(t) + \mathbf{B}\mathbf{Q}\mathbf{B}^T - \mathbf{P}\mathbf{C}^T\mathbf{R}^{-1}\mathbf{C}\mathbf{P}; \qquad (23)$$

$$\mathbf{P}(0)=\mathbf{P}_0$$

where $\mathbf{Q}$ is the intensity of generating vector noise $\mathbf{w}(t)$; $\mathbf{R}$ is the intensity of noise of measurement $\mathbf{v}(t)$; $\mathbf{P}_0$ is the initial conditions for the (23).

VI. Simulation Results

Equations (17 – 23) for simulation and investigation of properties of MMG with KF are used. In Fig. 5 the functions of third components of matrix $K(t)$, is given. All these components are functions of time. The frequency of oscillations corresponds to ν and 2ν, where ν is the frequency of primary oscillations of the sensing mass. For the test example this frequency is ν =3000 Hz.

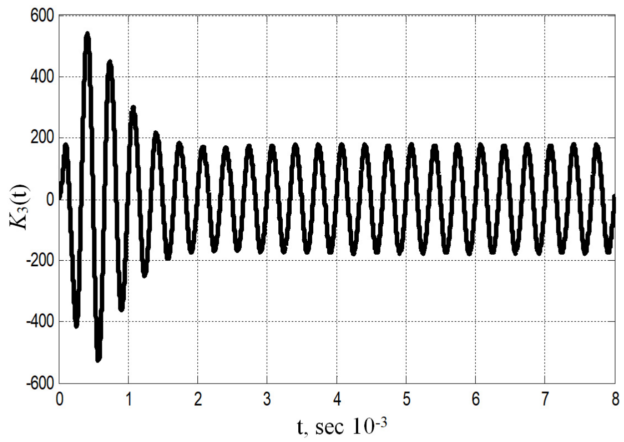

Fig.5 The dependence of the third matrix coefficient **K**(t) on time

The process of estimating the measured angular velocity with its step change by 10 deg/sec is shown in Fig. 6.

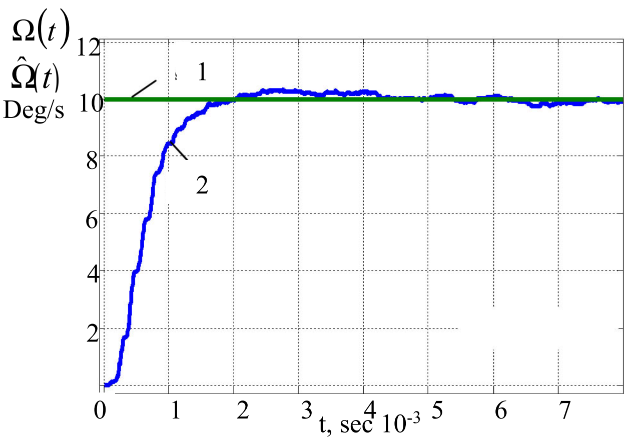

Fig.6 Angular velocity of the AV is $\Omega(t)$ and the estimate of this velocity is $\hat{\Omega}(t)$. 1.- $\Omega(t)$; 2.- $\hat{\Omega}(t)$

For the realization of the considered filtration algorithm in a numerical controller, it is necessary to use the step of integration smaller than 1/ (20·2· ν) or to use special methods of simplification. It is not possible to use the constant average values of theses coefficients because the components of matrixes **P**(t) and **K**(t) oscillate about zero with high frequency. For this reason it is convenient to generate these functions on the bases of measured primary oscillations of sensing mass. In Fig. 6 the time response of estimation of the mobile craft velocity =10 deg/sec. Initial value = 0.

The simulation shows the effectiveness of the considered algorithm for the estimate of output oscillations and the angular velocity of the mobile craft $\Omega(t)$.

These equations compose a non-stationary system of ordinary differential equations with sinusoidal high frequency parameter $\dot{\gamma}(t)$. This is the instantaneous value of the primary oscillations of the sensing mass, which are measured in the conventional MMG. The function synchronizes the components of the matrix **P**(t) according the (23). Components of the matrix **P**(t) modulate the oscillations of the components of the matrix **K**(t) according the Equation (22) which can be rewritten in simplify form as follows:

$$\mathbf{K}(t)=[p_{11}(t)/r \quad p_{12}(t)/r \quad p_{13}(t)/r]$$

where coefficients $k_1(t)$, $k_2(t)$, $k_3(t)$ will be synchronized with primary oscillations. This is a very significant fact because the frequency of primary oscillations can be used for generation of the components of the matrix **K**(t) without complex calculations of equations (22) and (23).

VII. The General Algorithm for the Estimation and Filtering of Signals in MGG

The common structure of algorithm of estimation is shown in Fig. 7. In this figure denoted: $\Omega(t)$ and $\hat{\Omega}(t)$ are measured angular rate and its estimation; Synch. Det. is synchronous detector; FDU is frequency determination unit (frequency meter) for measuring of the frequency of oscillation $\gamma_m(t)$. RF is reference frequency from the quartz oscillator.

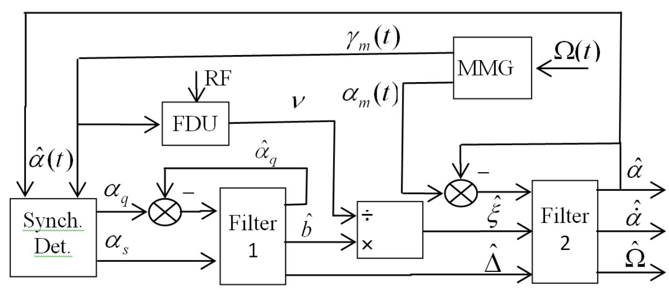

Fig.7 The common algorithm for the estimation and filtering of signals in MGG

As the unit, MMG the most detailed model is used. The program uses the measured values of the angles of rotation of the sensor relative to the axes 0x and 0y (see Fig. 1). Usually these small angles measured electrostatic sensors contain high noise level and require filtering. Synchronous detector selects an in-phase and quadrature components of $\alpha(t)$. FDU accurately determine the actual value of the frequency. Filtering algorithm in the unit Filter1 based on

(13), (15) and (16). A variable ξ is defined according to (14).

The algorithm of the unit Filter 2 on the (21), (22) and (23) is based.

CONCLUSION

The problem of increasing the accuracy of measuring instruments for elastic vibrations AV in the real time was stated and solved. These MMG should be placed along the entire AV. The optimal placement of such MMG depends on the amount and structure AV.

Methods for calculating the optimal placement and information processing algorithms are considered by the authors in previous works. An algorithm for identifying parameters and a micromechanical gyroscope is proposed, which can significantly increase its accuracy under long-term operation in difficult conditions.

The algorithm is designed to be implemented in the built-in MMG controller. It is shown that all identifiable components of the state vector are observed for any maneuvers of a moving object.

The analysis of the algorithm and modeling showed fundamental efficiency with significant changes in internal parameters. It is shown that the time of parameter estimation depends on the actual frequency of detuning of primary and secondary oscillations and the relative damping value.

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