MATHEMATICAL MODELING OF PROCESSES AND SYSTEMS

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COMPENSATION OF QUADRATURED ERROR IN THE AUTO-OSCILLATION MICROMECHANICAL GYROSCOPE

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***Abstract**—In this paper, attention was paid to the analysis of the micromechanical sensor unit of the inertial navigation system as the main component of an unmanned aerial vehicle, as well as to improve the technical characteristics. This type of sensor is characterized by large instrumental errors and low sensitivity. In order to increase the sensitivity of a micromechanical gyroscope, the article proposes using resonant oscillation modes, which "enliven" its inertial mass. And in order to reduce the quadrature error of the gyroscope, which is one of the main obstacles to achieving its accuracy, it was proposed to reduce the level of these interferences not only using the synchronous detector, but also in front of it. A scheme is proposed that provides compensation for quadrature interference not by the mechanical moment generation contour, but by the output voltage channel. Since such a scheme does not affect the mechanical quadrature oscillations of the inertial mass, this effect can be interpreted as a self-oscillation mode, which increases the sensitivity of the secondary contour of the micromechanical gyroscope.*

Index Terms—Microelectromechanical sensors; micromechanical gyroscope; self-oscillation mode; sensor sensitivity; sensitive element; secondary circuit; quadratured error; synchronous detector; feedback.

I. INTRODUCTION

The article discusses one of the most pressing problems of information support for navigation systems – improving the accuracy of information sensors. In this paper, attention was paid to the development of a strapdown inertial navigation system (SINS) sensor unit as the main component of an unmanned aerial vehicle (UAV), as well as the study of their methodical and instrumental errors.

Current miniature SINS of UAV are builds on the basis of microelectromechanical (MEMS) sensors, in particular, on MEMS accelerometers and micromechanical gyroscopes (MMG). In this case, the main contribution to the error of the SINS provides MMG – angular velocity sensor. Therefore, this paper focuses on this sensor. When creating miniature SINS there are fundamental difficulties, the main of which is: the development of information sensors with a wide range of measurements and acceptable accuracy in the conditions of their rigid mounting on board the UAV.

II. PROBLEM STATEMENT

Micromechanical gyroscopes miniature SINS are microelectromechanical systems in which the energy of the forced (primary) oscillations of the inertia mass (IM) on an elastic suspension (resonator) under the influence of a portable angular velocity is converted into secondary vibration energy, which contains information about the measured angular velocity. This transformation is due to the effect on the resonator of the forces (or moments) of the Coriolis inertia when the resonator is rotated with a bulk angular velocity, the vector of which is perpendicular to the vector of the instantaneous velocity of the inertial mass of the resonator. Since MMG of miniature SINS of UAV must have a wide range of measurements, high sensitivity and accuracy, the task of improving existing MMGs is crucial for creating more accurate compared with existing SINS analogs.

To achieve high sensitivity MMG designers try to reduce the elastic of the suspension of moving parts of the device, but this, as a rule, reduces the range of measurements and reduces the accuracy of MMG. Therefore, in order to solve this problem, it is proposed to use resonant oscillation modes that "energize" the IM, with further amplitude modulation of the measuring signal.

Among the main sources influencing the accuracy of MMG mark out:

- changes in the geometric dimensions of the elastic elements;
- unbalances;

– unequal stiffness of the elastic suspension;

– distortions of the axis of the suspension;

– divergences of the crystallographic directions with the axes of the device, etc.

In particular, due to the non-perpendicularity of the axes of the frame's rotation, there is oscillation around the output shaft even in the absence of the MMG rotation. These oscillations lead to the onset in the output signal of the vibratory MMG quadrature component (QC) – quadrature interference. The name "quadrature" is due to the fact that the phase of this component differs from the phase of the useful signal by π/2. The QC level may exceed the errors of other sensors by several orders of magnitude, therefore, the problem of a radical reduction in quadrature interference in the MMG is very relevant, since the requirements on the accuracy of the MMG constantly increase.

Therefore, the problem statement can be formulated as follows: to reduce the QC, which is one of the main barriers to achieving the high accuracy of vibratory MMG, while increasing their sensitivity.

III. PROBLEM SOLUTION

To achieve high sensitivity of MMG, it is proposed to use self-oscillatory modes of operation of MMG in the below resonance region.

One of variants of conversion devices into the regime of self-oscillations is the use of compensating mode of operation of electromechanical devices. Compensation mode results in the expansion of the measurement range and increase the accuracy of the device. And if the compensation mode is combined with self-oscillating, then, as a result, you can get an additional increase in the sensitivity of MMG. In addition, the self-oscillation mode allows you to switch from amplitude modulation (AM) of the output signal to frequency modulation (FM), which, in turn, leads to an extension of the measurement range and increased accuracy.

Thus, in order to improve the accuracy characteristics of the MMG, it is necessary to combine the compensation and self-oscillation modes of the instrument with a simultaneous transition from the AM to the FM signal, which forms the primary measuring information.

A generalized structural chart of self-oscillating MMG is presented in Fig. 1.

The Position sensor 1 detects the position of the sensitive element (SE) relative to the axis of excitation. The signal from Position sensor 1 is fed to the comparator, the output voltage of which controls the Key. The force sensor (FS) causes the SE to oscillate in accordance with the signal received on the FS from Key.

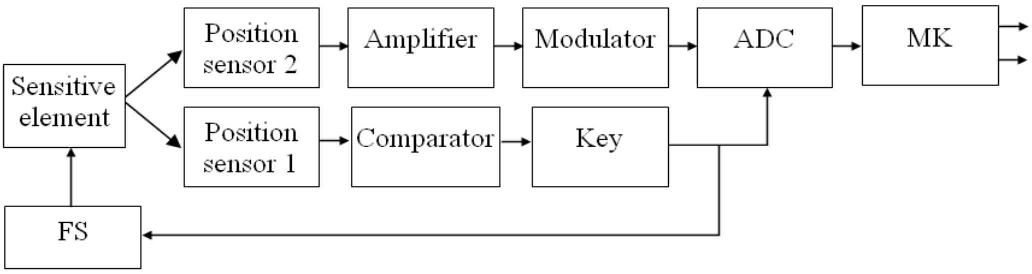

Fig. 1. Structure chart of self -oscillation MMG

In the presence of an angular velocity along the sensitivity axis of MMG the SE oscillates in antiphase relative to the initial axis due to the influence of the Coriolis force. The Position sensor 2 detects these vibrations. The signals at the Position sensor 2 output are amplified by the amplifier and fed to the Modulator, respectively, and then through the analog-digital converter (ADC) to the microcontroller (MK). The signal at the output of the MC carries information about the measured angular velocity of the MMG.

The creation of self-oscillation mode is carried out by introduction into the feedback circuit of the devise a non-dynamic element FS with a known static characteristic. In this case, the SE of the MMG is converted into an oscillatory system, to which the input and compensating action is applied. The input action is formed as a result of MMG interaction with the measured physical quantity, and the compensating effect is generated by the FS. The insertion of a nonlinear link into the device circuit results in the formation of a bipolar electric signal in the feedback circuit, under the action of which the SE performs a harmonic motion.

Since in this case MMG becomes a compensation measurement sensor, its accuracy depends mainly on the characteristics of the nonlinear link FS in the feedback circuit.

The research of the proposed scheme for constructing MMG was carried out by mathematical modeling using a mathematical model of the movement of SE of MMG along the x and y axes in the form:

$$m\ddot{x} + \mu_x \dot{x} + [c_x - m(\omega_z^2 + \omega_y^2)]x - 2m\omega_z \dot{y} - m\dot{\omega}_z \dot{y} + m\omega_x \omega_y y = -m\dot{V}_x + m(V_y \omega_z - V_z \omega_y) + F,$$

$$m\ddot{y} + \mu_y \dot{y} + [c_y - m(\omega_z^2 + \omega_x^2)]y - 2m\omega_z \dot{x} - m\dot{\omega}_z \dot{x} + m\omega_x \omega_y x = -m\dot{V}_y + m(V_z \omega_x - V_x \omega_z),$$

where μ_x, μ_y are coefficients of viscous force, which determine the oscillation energy dissipation of SE along x and y direction; c_x, c_y are coefficients of elastic forces; m is the mass of SE; F is the peak value of the force, produced FS; V_x, V_y are linear velocities of SE in the system of moving axes; x, y are inline offsets of SE from balance position. Sensitivity of SE is simulation by "Dead Zone" link, and FS nonlinear link is simulation by relay characteristic.

The simulation confirmed the high sensitivity of the device. The MMG fixed a change in angular velocity even at 0.01 °/s (Fig. 2).

However, the proposed approach to the construction of MMG does not solve the problem of compensating quadrature interference.

At the initial stage of the development of MMG, the task of selecting the useful signal and suppressing the QC was carried out with the help of one element – the synchronous detector (SD).

However, the SD makes its own mistakes, which can be attributed to the noise and zero biases that arise due to the phase shift $\Delta\varphi$ between the input and reference voltages. Therefore, it is advisable to reduce the level of quadrature interference by several orders of magnitude until the voltage is fed from the SE sensor to the output signal box. That is, a signal proportional to quadrature interference must be compensated directly at the output of the SE sensor.

The structure chart of secondary circuit with suppression circuit of the moment of quadrature interference M_{QC}, by creating the compensating moment of the M_{comp}, is represented in Fig. 3.

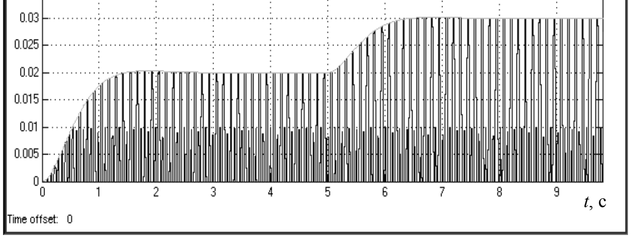

Fig. 2. Simulation results of auto-oscillation MMG

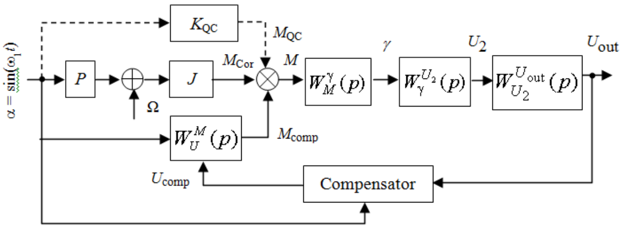

Fig. 3. Structure chart of secondary circuit with QC suppression circuit

The use of this approach is possible only for gyroscopes with a large difference in their own resonance frequencies of the suspension. In this case, the signal at the output of the SE sensor, proportional to the quadrature interference, coincides with the phase with the signal of the primary oscillations. This operation is simple, however, given that the value of QC varies from sample to sample, it is expedient that the selection operation of the compensating moment be performed automatically.

But in the work the scheme was proposed that provides the automatic selection of the coefficient μ and compensation of quadrature interference not in the contour of moments generation, but in the output voltage channel (Fig. 4).

Two signals from sensors of the SE: U_1 and U_2 are received at the input of the device, which are proportional to the primary and secondary SE oscillations, respectively. Enhanced in K times, the input voltage U_2 enters on the first multiplier, where the quadrature component μ is demodulated. The signal μ represents the sum of the constant voltage proportional to the quadrature noise amplitude and the two high-frequency harmonic signals at the double frequency of the primary oscillations. With the help of the PI controller, a constant component is allocated, which is used on the second multiplier as a modulating signal, giving the required amplitude of the reference voltage U_1. In this case, the multiplier is considered as a device with an amplification factor, controlled voltage, or as an amplitude modulator.

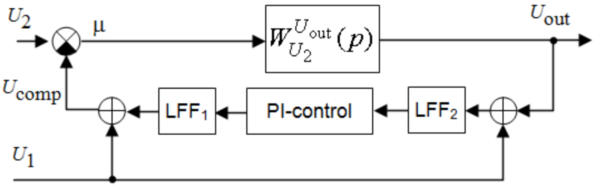

Fig. 4. Flow chart QC compensating device

In order to reduce the effect of high frequency noise in the circuit, low frequency filters LFF$_1$, LFF$_2$ of the first order are used (from the total output sensor's signal extract harmonic having a frequency of primary oscillations which excitations in the SE). As a result, the voltage is formed of the same amplitude and frequency as the signal of quadrature interference. The signal U_{comp} is subtracted from U_2, thereby to compensate the quadrature interference.

Thus, a compensatory signal is generated at the output of the quadrature jamming device. Such a scheme is much more precise than the programmatic suppression of the quadrature interference signal, which is commonly used in existing MMG.

In the implementation of the proposed compensation scheme for quadrature interference, MMG in the secondary circuit under the influence of an uncompensated moment of quadrature interference does not fluctuate even in the absence of a measurable angular velocity Ω.

The expression describing the change in the amplitude of quadrature oscillations has the form:

$$\gamma_{\text{quad}} = \left| W_M^{\gamma}(p) \right|_{p=j\omega_1} K_{\text{QC}} \alpha,$$

where $W_M^{\gamma}(p) = \left(T^2 p^2 + 2\xi T p + 1 \right)^{-1}$ is the transfer function of the circuit of secondary oscillations; ω_1 is the frequency of primary oscillations.

It follows from this expression that the amplitude of the oscillations depends (see Fig. 3) on the mechanical gain $K_{\text{M}} = \left| W_M^{\gamma}(p) \right|_{p=j\omega_1}$, on the amplitude of the primary co-oscillations $\alpha = \sin(\omega_1 t)$ and on the coefficients of cross-stiffness K_{QC}.

This effect can be interpreted as the previously considered self-oscillation mode of the MMG. But here, in order to increase the sensitivity of the secondary circuit, quadratured oscillations of SE, which arise under the influence of an uncompensated moment of QC, and have a frequency of excitations in the primary oscillations of the EC, are used.

Naturally, such a scheme for increasing the sensitivity of MMG is much simpler than the scheme of artificial switching the device into a mode of self-oscillation using a compensatory mode of operation. But since the level of quadrature noise MMG varies from sample to sample, in case of increased requirements to the characteristics of such a self-oscillating circuit, its additional adjustment is necessary.

In this case, it is necessary that a time-varying signal, coinciding in frequency and amplitude with the signal of a quadrature interference, should arrive at the sensors of the moment channel of secondary oscillations.

Testing the performance and stability of the circuit with QC suppression under various conditions was carried out in the software package MatLab. The results of research show that the proposed method is invariant to frequency mismatch. Regardless of the frequency difference between the primary and secondary circuits, the steady-state value of the compensating signal does not change. The method ensures the stable operation of the circuit regardless of the phase delay of the signals introduced by the means of measurement and compensation of the quadrature interference of any level.

An analysis of the stability of the developed system shows that the feedback does not affect the useful signal, orthogonal quadrature interference.

In order to study the dynamic characteristics of the developed system, a mathematical model of the MMG secondary circuit was developed, taking into account quadrature interference.

$$J_x \ddot{\gamma} + d_x \dot{\gamma} + \left[k_x + k_{\text{QC}} M_{\text{QC}} - k_{\text{comp}} M_{\text{comp}}) \right] \gamma = 2 J_x \Omega \dot{\alpha},$$
$$M_{\text{QC}} = k_{zx} \alpha, \; M_{\text{comp}} = f\left[\alpha \right], \; \alpha = \sin(\omega_1 t).$$

Here α, γ are primary and secondary oscillations of the SE; Ω is the measured angular velocity; k_{zx} is the coefficient of cross stiffness; ω_1 is the frequency of primary oscillations; J_x is the moment of inertia; f is the function describing the operation of the QC compensator.

The QC compensating device simulation and analysis of a useful component extraction was carried out using the program of visual simulation *Simulink*.

The transition function plot shows (Fig. 5) that in the initial period of time, the output amplifiers are in saturation mode, preventing the allocation of a useful component.

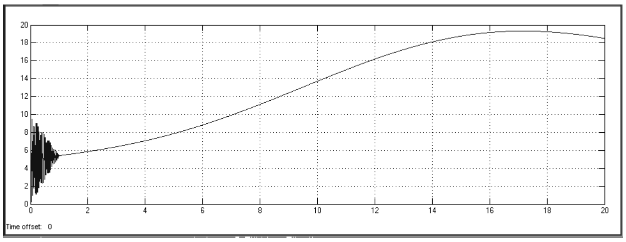

Fig. 5. Research results of the QC compensating device simulation

Upon completion of the transition process of compensating the quadrature error it's form an amplitude-bottom-modulated signal, the envelope of which contains information about the measured angular velocity of the base. The observed phase shift is introduced using the LFF circuit.

IV. CONCLUSIONS

Analysis have shown the capacity for work and effectiveness of the proposed method for suppressing quadrature interference. Its implementation in the MMG will reduce the offset of the output voltage of the sensor, increase the slope of output characteristics of the MMG, as well as reduce the threshold of sensitivity.

Micromechanical gyroscopes, operating in self-oscillation mode with the compensation system of the quadrature interference in the electronic part of the control channel SE, is able to significantly improve the dynamic and accurate characteristics of the block of inertial sensors for the navigation systems of unmanned aerial vehicles.

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М. К. Філяшкін, О. І. Черняй. Компенсація квадратурної похибки в автоколивальному мікромеханічному гіроскопі

У статті проаналізовано мікромеханічний сенсорний блок безплатформної інерціальної навігаційної системи, як основного компонента безпілотного літального апарата, а також розглянуто питання покращення технічних характеристик мікромеханічних гіроскопів. Такий тип датчиків характеризується значними інструментальними похибками та низькою чутливістю. Для підвищення чутливості мікромеханічного гіроскопа в статті запропоновано використовувати режими резонансних коливань, які «оживляють» його інерційну масу. А для зменшення квадратурної похибки гіроскопа, яка є одною з основних перешкод на шляху підвищення його точності, запропоновано знизити рівень цих похибок не тільки за допомогою синхронного детектора, а й на його вході. Розроблено схему, яка забезпечує компенсацію квадратурних похибок не за контуром генерації механічного моменту, а за каналом вихідної напруги. Оскільки така схема не впливає на механічні квадратурні коливання інерційної маси, цей ефект можна інтерпретувати як режим автоколивань, який підвищує чутливість вторинного контуру мікромеханічного гіроскопа.

Ключові слова: мікроелектромеханічні датчики; мікромеханічний гіроскоп; режим автоколивань; чутливість датчика; чутливий елемент; вторинний контур; квадратурна похибка; синхронний детектор; зворотний зв'язок.

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Н. К. Филяшкин, О. И. Черняй. Компенсация квадратурной погрешности в автоколебательном микромеханическом гироскопе

В статье проанализирован микромеханический сенсорный блок безплатформенной инерциальной навигационной системы, как основной компонент беспилотного летательного аппарата, а также рассмотрены вопросы улучшения технических характеристик микромеханических гироскопов. Такой тип датчиков характеризуется большими инструментальными погрешностями и низкой чувствительностью. Для повышения чувствительности микромеханического гироскопа в статье предложено использовать режимы резонансных колебаний, которые «оживляют» его инерционную массу. А для уменьшения квадратурных помех гироскопа, являющимся одним из основных препятствий на пути повышения его точности, предложено снизить уровень этих помех не только с помощью синхронного детектора, но и на его входе. Предложена схема, которая обеспечивает компенсацию квадратурных помех не по контуру генерации механического момента, а по каналу выходного напряжения. Поскольку такая схема не влияет на механические квадратурные колебания инерционной массы, этот эффект можно интерпретировать как режим автоколебаний, который повышает чувствительность вторичного контура микромеханического гироскопа.

Ключевые слова: микроэлектромеханические датчики; микромеханический гироскоп; режим автоколебаний; чувствительность датчика; чувствительный элемент; вторичный контур; квадратурная ошибка; синхронный детектор; обратная связь.

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