DYNAMIC BEHAVIOR OF MICROMECHANICAL ANGULAR RATE TWO-COMPONENT SENSOR

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Abstract: a mathematical model was designed; dynamic behavior of angular rate sensor was detected. The influence of cross rates on primary and informational sensor channels' properties was stated.

Keywords: micromechanical gyroscope, vibrodrive, natural frequencies, informational oscillations.

1. INTRODUCTION

The development of microelectronics has promoted a new class of sensors which are called microelectromechanical systems (MEMS). Micromechanical gyroscopes (MMG) are the most complex MEMS devices which correspond to angular rate sensors applied for objects of different purposes.

The advantages of MMG are their ultra low mass (fractional weights) and dimension (units and fractional lengths), low cost and power. Mechanical part of sensors is fully integrated in electronic devices, that allows providing assembly operation on one microchip with volume of some cubic centimeters and consumption of fractional powers [1].

The advantages of MMG facilitate widening of fields of their application, namely: motor industry; navigation equipment and military; consumer electronics and video equipment (portable systems including smartphones, telephones, video cameras); robotic technology and intelligent systems.

This paper presents the author's realization of two-component micromechanical gyroscope for a wide range of objects. A mathematical model of the MMG is developed and the dynamic characteristics of its are investigated.

2. SCHEME AND OPERATION MMG

MMG consists of a sensor (S) which represents a mechanical structure shown in Figure 1. This diagram is a two-component sensor of angular rate [2] which contains inertial mass 2 mounted on elastic members 1 in the inner frame 5.

The inner frame is mounted on elastic members 4 in the outer frame 8 which is mounted on elastic members 7 in package 11. MMG measures angular rates of an object about axes X and Y. For this, electrostatic vibrodrive 9 excites periodical oscillations of the outer frame along axis Z together with the inner frame and inertia block at a rate of $\dot{z} = \dot{z}_m \cos qt$.

The electrostatic displacement transducer 10 measures the amplitude of primary oscillations.

In base rotating about axis X at a rate of Ω_x, Coriolis force appears which causes oscillations of inertia block 2 along axis Y (secondary informational oscillations). Oscillation amplitude detected by capacitive displacement sensor 3 is proportional to angular rate Ω_x of the object's rotation.
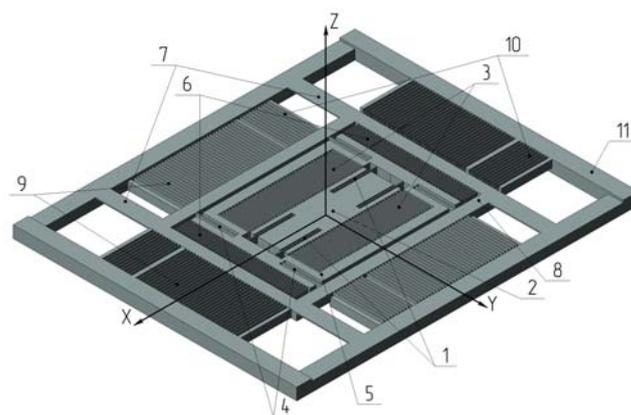

Figure 1. Kinematic diagram of micromechanical angular rate sensor.

In base rotating about axis Y at a rate of Ω_y, Coriolis force appears which causes oscillations of inner frame 5 together with inertia block 2 along axis X (secondary informational oscillations).

Oscillation amplitude detected by capacitive displacement sensor 6 is proportional to angular rate Ω_y of the object's rotation. Thus, measuring axes of gyroscope are axes X and Y, oscillation amplitudes of which are the measure of rates Ω_x and Ω_y.

By its operating principle MMG refers to vibration testers, therefore, to achieve the required properties it is necessary to apply special devices which will provide control for primary and output informational oscillations of a sensor.

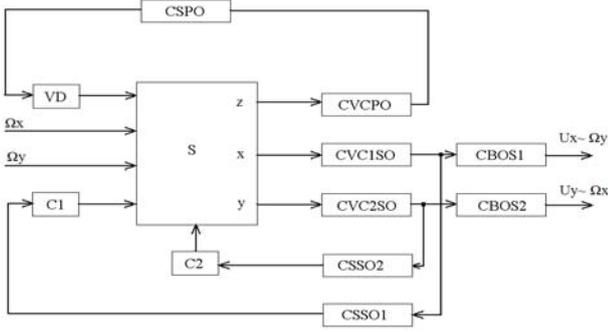Reciprocal coupling between all elements of MMG is presented in Figure 2.

Figure 2. MMG chain diagram.

A vibrodrive (VD) excites sinusoidal vibrations of a sensor. To control primary oscillations a Capacitance / Voltage Converter (CVCPO) is used that measures the primary oscillation amplitude and transmits the signal to the control system of primary oscillations (CSPO).

In presence of rates Ω_x, Ω_y, informational movements of sensor elements are converted by converters of secondary oscillations CVC1SO and CVC2SO into voltages which are supplied into output signal CONVERSION BLOCKS (CBOS1 and CBOS2) of the both measuring channels. These blocks carry out amplification, filtering, and correction of signals entering from converters CVC1SO and CVC2SO so as to highlight the useful components proportional to rates under measurement.

Signals from converters CVC1SO and CVC2SO also enter the control systems of secondary oscillations (CSSO1 and CSSO2) of the both informational channels. CORRECTORS (C1 and C2) and control systems of secondary oscillations control sensor S by axes of secondary oscillations. Using these devices, the required compensation and the mode of gyroscope operation can be performed (forward transform or compensating mode).

MMG characteristics are defined by the properties of and interaction between all its units (mechanical and electric) [3].

3. MATHEMATICAL MODEL OF SENSOR

MMG sensor equations are [4]:

$$m_1\ddot{y} + \mu_y\dot{y} + y\left[k_y - m_1(\Omega_z^2 + \Omega_x^2)\right] =$$
$$2m_1\dot{z}\Omega_x - 2m_1\dot{x}\Omega_z - m_1 x\Omega_x\Omega_y - m_1 z\Omega_y\Omega_z, \quad (1)$$

$$(m_1 + m_2)\ddot{x} + \mu_x\dot{x} + x\left[k_x - (m_1 + m_2)(\Omega_z^2 + \Omega_y^2)\right] =$$
$$= -2(m_1 + m_2)\dot{z}\Omega_y + 2(m_1 + m_2)\dot{y}\Omega_z + \quad (2)$$
$$+ 2(m_1 + m_2)z\Omega_x\Omega_z - m_1 y\Omega_x\Omega_y,$$

$$(m_1 + m_2 + m_3)\ddot{z} + \mu_z\dot{z} + z\left[k_z - (m_1 + m_2 + m_3)(\Omega_x^2 + \Omega_y^2)\right] =$$
$$= F_m\sin qt - 2m_1\dot{y}\Omega_x + 2(m_1 + m_2)\dot{x}\Omega_y - \quad (3$$
$$- m_1 y\Omega_y\Omega_z - (m_1 + m_2)x\Omega_x\Omega_z.$$

where $F_m\sin qt$ is a force created by a vibrodrive; μ_x, μ_y, μ_z, k_x, k_y, k_z are coefficients of viscous friction force and

suspension fixity of gyroscope elements by the corresponding axes; Ω_x, Ω_y, Ω_z are angular rotation rates; m_1, m_2, m_3 are masses of inertia body, inner and outer frames, correspondingly.

4. DYNAMIC PROPERTIES OF SENSOR

Equations (1) and (2) define the informational movement of gyroscope; equation (3) describes primary oscillations which occur in accordance with harmonic law $z = z_m\sin qt$ and are excited by a vibrodrive due to application of force $F_m\sin qt$ to the outer frame.

Figure 3 presents the amplitude-frequency characteristic of a gyroscope along axis Z of the primary oscillations at $\Omega_x = \Omega_y = \Omega_z = 0$.
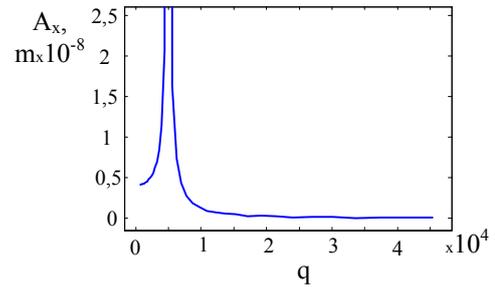

Figure 3. Amplitude-frequency characteristic of a gyroscope along axis Z

The output signal of the gyroscope increases in increasing the amplitude of primary oscillations rate which achieves its maximum at resonance. Therefore, the primary circuit should be in resonance tuning that is provided by the control and stabilizing system of primary oscillations.

Force $F_m\sin qt$ is useful one, while all rest summands in equation (3) are disturbances and distort primary oscillations of a gyroscope. Figures 4 and 5 illustrate the dependences of amplitude A_z of primary oscillations in presence of rates Ω_x, Ω_y, Ω_z, which are disturbances for the primary circuit.

The figures represent that the presence of angular rates of the object rotation changes the natural frequency of primary oscillations and, therefore, the transmission coefficient of MMG.

Change of frequency makes it necessary to use the stabilizing system of amplitude and frequency of primary oscillations.
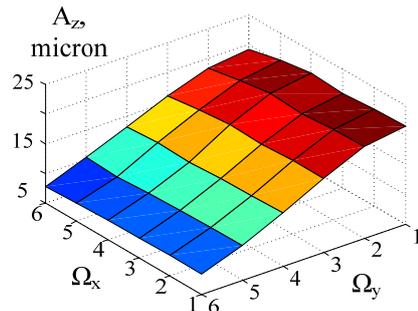

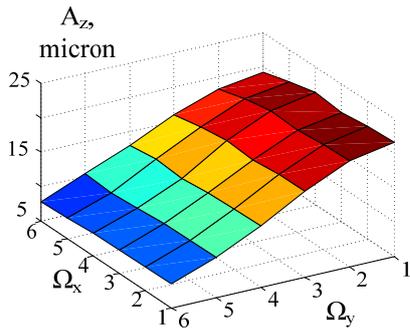Figure 4. Amplitude of primary oscillations at $\Omega_z = 0$ rad/s

Figure 5. Amplitude of primary oscillations at $\Omega_z = 10$ rad/s

Coriolis forces $2m_1 z_m q \Omega_x \cos qt$, $2m_{\text{B}} z_m q \Omega_y \cos qt$ in equations (1) and (2) are useful and cause secondary oscillations of gyroscope elements along axes X and Y depending on rates Ω_x, Ω_y under measurement. All other summands in the equations are the disturbances because of cross-connections and cause errors of gyroscope.

In Figures 6 and 7 the amplitudes of informational oscillations by axis X are shown in its resonance tuning. It is seen that 'cross' rates Ω_x and Ω_z change the transmission coefficient of gyroscope along axis X, and at that this change increases with the increase of 'cross' rates.
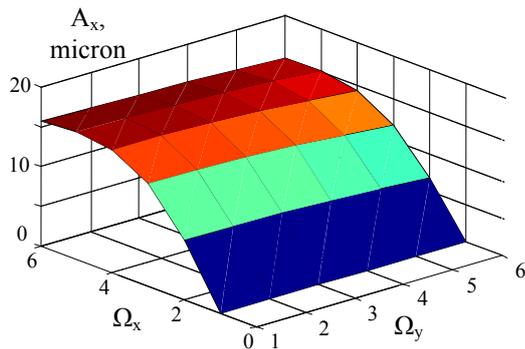

Figure 6. Amplitude of gyroscope oscillations along axis X at resonance tuning and $\Omega_z = 0$ rad/s
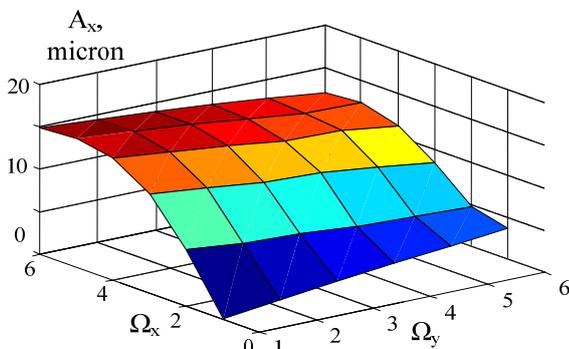

Figure 7. Amplitude of gyroscope oscillations along axis X at resonance tuning and $\Omega_z = 8$ rad/s

As it is seen from these diagrams, the amplitude of informational oscillations along axis X depends not only on the measured angular rate Ω_y, but also angular rates Ω_x, Ω_z along cross axes. Similarly, the cross rates influence the informational oscillations of gyroscope along axis Y.

In summary, data suggest that the considered sensor represents as three interconnected oscillators and it is necessary to maintain the resonant tuning of the primary and secondary channels for stable operation of the sensor.

Besides, at gyroscope operation in the mode of resonance tuning 'cross' rates of the object cause errors in measuring useful rates Ω_x, Ω_y.

At gyroscope operation in the mode of frequency separation of primary and secondary oscillations 'cross' rates influence insignificantly its accuracy, and errors are insignificant.

Thus, the proposed scheme of the two-component angular rate sensor is efficient. It is possible to make this sensor applied for objects of different purposes.

5. REFERENCES

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