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Digital Excitation Channel for Ring Micromechanical Gyroscope

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Abstract. This research is devoted to the design of a digital excitation channel for a ring micromechanical gyroscope. The main methods of excitation of oscillations in angular rate vibration sensors were considered. The possibility of using a self-oscillating mode of operation for a ring resonator has been demonstrated. A mathematical model of operation of such system was created for this purpose. Besides a prototype electronics was built. It has experimentally confirmed the operability of the digital oscillation excitation channel and the possibility of stable maintenance of the oscillation velocity amplitude.

Keywords: micromechanical gyroscope, self-oscillations, digital control system, microcontroller, ring resonator.

Introduction

All micromechanical angular rate sensors are vibration. This means that the principle of their operation is based on mechanical vibrations. There are several main ways to excite oscillations in micromechanical gyroscopes. Each of them has its own characteristics, advantages and disadvantages. The most promising is the autoexcitation method. In this case, the maintenance of the resonant frequency of oscillations is provided by mechanical parameters (coefficient of elasticity and damping) of the oscillatory system, consisting of a sensing element, displacement and force sensors and a positive feedback loop.

There is currently a trend towards using more digital components in control electronics for micromechanical gyroscopes. This is due to the possibility of increasing the accuracy and stability of the parameters of the angular rate sensors, flexible adjustment of such components, as well as reducing the overall dimensions. Researches in this direction are relevant.

The purpose of this work is to create an oscillation excitation circuit for a ring micromechanical gyroscope using digital technologies.

1. Existing methods for excitation of oscillations in micromechanical gyroscopes

Two main methods are of excitation of oscillations are used in oscillatory vibrating gyroscopes: by supplying an alternating voltage from an external generator to a force sensor and an auto-excitation method using position and force sensors.

When AC voltage is applied to the force sensor, it is necessary to stably maintain the oscillation frequency at the resonant frequency to increase the sensitivity of the device. So that a frequency feedback is required. In this regard, circuits with external generators and phase-locked loop frequency control are used [4, 8, 12].

Besides, an automatic gain control loop is used to maintain a constant amplitude of the vibration velocity. The difference between the set and measured amplitudes is fed to the input of the control link loop, and the corresponding voltage change on the force sensors is formed at the output.

This approach to maintaining the resonant frequency is complex and has low stability but provides a large space for tuning the device [4]. This feature is due to the use of a voltage controlled oscillator (VCO) or a code controlled oscillator. The phase noise of the VCO affects the instability of the target frequency.

The auto-excitation method consists in creating self-oscillations at the resonance frequency along the excitation axis of the gyroscope's sensitive element. A necessary condition for the occurrence oscillations is the instability of the system. It means that it is essential to make feedback so that either the damping coefficient of the system is less than zero or the elastic coefficient. That's why a positive feedback loop is created either in velocity or in position. The auto-excitation method is more stable because the oscillations always occur at the resonant frequency due to the design of the feedback loop.

Electrostatic force sensors and capacitive position sensors are used in most of the manufactured micromechanical gyroscopes. The signal generated by the position transmitters is proportional to the displacement of the sensitive mass. A positive position feedback is implemented in such devices to create self-oscillations. In addition, this type of feedback is used in a gyroscope if the position sensors have a photoelectric principle of operation [1, 5, 10].

It is necessary to use a differentiation link to maintain a constant signal in terms of the velocity of movement of the sensitive element when creating a self-oscillating circuit with positive velocity feedback in micromechanical gyroscopes with capacitive position sensors [3, 6, 7, 11, 13, 14, 15]. The application of differentiating links leads to a noise increasement in the circuit and, as a consequence, to a lower stability of its operation.

In connection with the widespread use of digital electronics, control circuits for micromechanical gyros based on it began to appear. In [12], the author considers the creation of a digital electronic subsystem for a ring micromechanical angular rate sensor. The constructed circuit repeats the operation of analog electronics, presented in [4, 8]. The excitation of oscillations is implemented using a code-driven generator. The feedback loops for the oscillation excitation channel and for the measurement channel are implemented using a field-programmable gate array (FPGA). However, the application of digital elements makes it possible to calibrate the gyroscope and provide the user with a signal, which dependence on external influences is reduced.

In [5, 10], the microcontroller is involved only in signal processing when an angular rate occurs.

The use of digital control devices in the construction of the oscillation excitation circuit is an urgent task, since this will make the operation of the micromechanical gyroscope more stable. Moreover, the implementation of regulating links inside the microcontroller or FPGA solves the problem of rebuilding the entire circuit when changing its parameters.

2. Operation mode of the excitation channel for the ring micromechanical gyroscope

The problem of creating velocity feedback arises in most oscillatory vibration gyroscopes, since capacitive position sensors are used in them. The use of differentiating links leads to a noise increasement in the excitation circuit, which has a negative effect on the stability of its operation. Thus, a scheme for creating self-oscillations with positive position feedback is more preferable in micromechanical gyroscopes with capacitive position sensors.

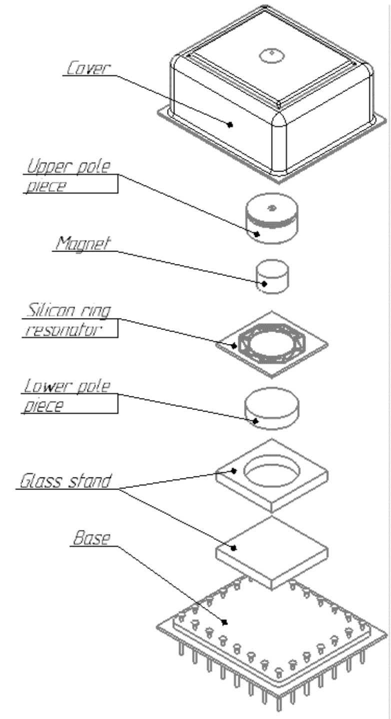

Figure 1. Ring micromechanical gyroscope sensing element design.

Figure 1 shows the design of the ring micromechanical gyroscope. The silicon ring resonator is a distinctive feature of such devices. Conductive metal tracks, which are located on the surface of the ring, divide it into eight segments. The resonator is located in the gap between the upper and lower pole pieces of the magnetic system. The conductors on the ring, in conjunction with the magnetic system, act as force and velocity sensor. Thus, force sensors have a magnetoelectric principle of operation and velocity sensors – electromagnetic.

Oscillations are excited by supplying alternating current to the force sensor. Figure 2 shows a simplified model of ring vibrations under the assumption that the ring mass is concentrated at eight points.

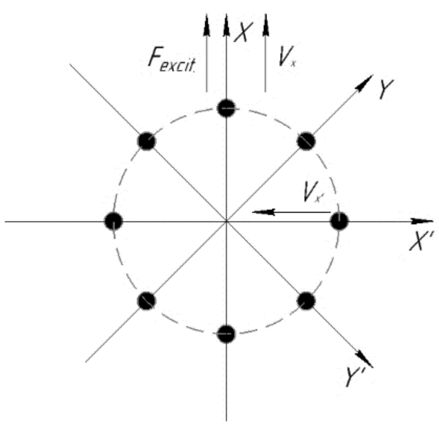

Figure 2. Simplified model of ring resonator oscillations.

The equations of motion along the axis of excitation of oscillations (in Figure 2, the X axis) for a point of the ring are:

$$m\ddot{x} + d_e\dot{x} + k_e x = F_a(t) = BLi \cdot \sin(\omega t), \quad (1)$$

where m – the mass of a point on the ring, d_e – the damping coefficient along the excitation axis, k_e – the elasticity coefficient along the excitation axis, $F_a(t)$ – the Ampere force applied from the force sensor to the point of the ring.

In the steady state, the vibration velocity of the ring point is calculated by the formula:

$$\dot{x}_s = \frac{BLi}{m2\xi_e\omega_e} \cdot \sin(\omega t), \quad (2)$$

where $\xi_e = \frac{d_e}{2\sqrt{k_e m}}$ – damping factor, $\omega_e = \sqrt{\frac{k_e}{m}}$ – natural vibration frequency. Thus, the oscillation velocity of this point is in the same phase as the applied current. At the same time the velocity of the ring point located at an angle of $\frac{\pi}{2}$ on the *X'* axis:

$$\dot{x}'_s = -\frac{BLi}{m2\xi_e\omega_e} \cdot \sin(\omega t) \quad (3)$$

So, the velocity of the ring point along the *X'* axis differs in phase from the current applied along the excitation axis by π.

Therefore, according to the principle of operation of the velocity sensor (the law of electromagnetic induction), the signal from this sensor is also in phase with the applied alternating current and this signal carries information about the velocity of the ring point:

$$\varepsilon_x^i = \frac{(BL)^2 i}{m2\xi_e\omega_e} \cdot \sin(\omega t) \quad (4)$$

From equation (4), it can be concluded that it is possible to build a self-oscillating circuit when the output of the velocity sensor is closed with the input of the force sensor and an appropriate gain in the feedback is choosed.

The microcontroller is responsible for the selection of the required gain in the feedback loop and for maintaining the given amplitude of the resonator oscillation velocity.

3. Digital excitation circuit for ring micromechanical gyroscope

A feature of the developed digital oscillation excitation circuit is the use of analog-to-digital and digital-to-analog converters included in the microcontroller.

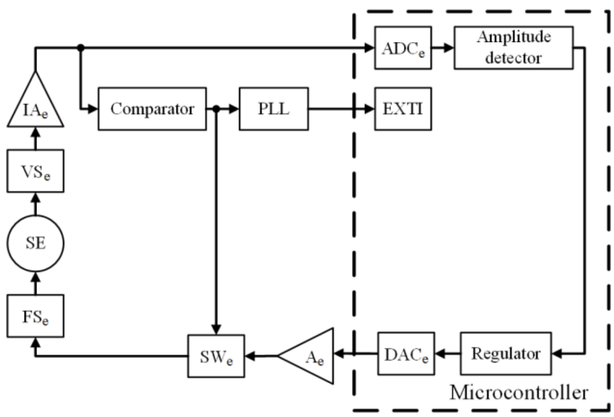

Figure 3. Functional diagram of a digital circuit for excitation of oscillations in a ring micromechanical gyroscope.

Figure 3 denotes:

- SE – ring sensing element;
- VS – velocity sensor;
- IA – instrumental amplifier;
- PLL – phase-locked loop;
- ADC – analog-to-digital converter;
- EXTI – microcontroller pin for external interrupt;
- DAC – digital-to-analog converter;
- A – amplifier;
- SW – current direction switch;
- FS – force sensor.

The signal at the output of the comparator corresponds to a low logic level, voltage is supplied to the DAC_e in the microcontroller, sufficient to remove the ring SE from the rest state at the moment of starting the electronics. A_e plays the role of a voltage follower, since the FS_e is magnetoelectric and requires a current to flow. SE begins to stretch due to the action of the Ampere force. The SE velocity is detected by VS_e. The signal from the VS_e is amplified and shifted by U_{ref} (corresponds to half of the microcontroller supply voltage) by an instrumental amplifier (IA_e). The voltage from the IA_e goes to the comparator and to the ADC_e.

The output of the comparator becomes a high logic level when the signal of the oscillation velocity from the output of the IA_e exceeds U_{ref}. This signal is applied to the current direction switch (SW_e), and the current begins to flow in the opposite direction, which leads to the compression of the SE along the excitation axis.

In addition, the frequency of the signal from the comparator is multiplied by 64 using PLL and applied to EXTI to clock the ADC_e. The values obtained after analog-to-digital conversion are fed into the block for calculating the amplitude of the vibration velocity (amplitude detector). The regulator unit generates a value depending on the required amplitude of the SE oscillation velocity. Then the generated value is fed to the DAC_e.

4. Electronics modeling and mock-up

It is necessary to simulate operation of a micromechanical angular rate sensor in order to develop digital control loops for its oscillations. A ring micromechanical gyroscope is analogous to a solid-state wave gyroscope by its principle of operation. A detailed mathematical description of the solid-state wave gyroscope operation is presented in [16, 17]. The equations of motion adapted for a ring micromechanical gyroscope are presented in [9, 12, 18]. The mathematical description of the radial displacement of the ring resonator element during oscillations in the second mode [12, 18]:

$$\omega(\varphi,t) = p(t)\cdot\cos(2\varphi) + q(t)\cdot\sin(2\varphi), \tag{5}$$

In this case, the equations of motion of the ring micromechanical gyroscope and the primary electrical signals [12, 18]:

$$\begin{cases} \ddot{p}(t) + \frac{36}{5}k^2\xi\dot{p}(t) + \frac{36}{5}k^2 p(t) - \frac{8}{5}\Omega\dot{q}(t) = \frac{1}{5}Hi_1(t), \\ \ddot{q}(t) + \frac{36}{5}k^2\xi\dot{q}(t) + \frac{36}{5}k^2 q(t) + \frac{8}{5}\Omega\dot{p}(t) = \frac{1}{5}Hi_2(t), \\ E_1 = 2B\left(-\frac{\sqrt{2}}{2}R + \frac{\pi+2}{8}p(t)\right)\dot{p}(t) + 2B\frac{\pi+2}{8}\dot{q}(t)q(t), \\ E_2 = 2B\left(-\frac{\sqrt{2}}{2}R + \frac{\pi+2}{8}q(t)\right)\dot{q}(t) + 2B\frac{\pi+2}{8}\dot{p}(t)p(t), \end{cases} \tag{6}$$

where $k = \sqrt{\frac{EJ}{\rho S R^4}}$, $\xi = \frac{1}{\omega_0 Q}$, $H = \frac{4B\sqrt{2}}{\pi \rho S}$, Ω – projection of the angular rate of the base on the axis of sensitivity of the gyroscope, B – magnetic field induction in the area of the ring resonator, E_1, E_2 – electromotive force in the circuit of primary and secondary oscillations, i_1, i_2 – current in the circuit of primary and secondary oscillations, R – ring resonator radius, S – ring cross-sectional area, J – moment of inertia of the cross section of the ring, ρ – resonator material density, E - Young's modulus for resonator material, Q – resonator Q-factor.

A mathematical model of a ring resonator with a digital oscillation excitation channel was implemented in Matlab Simulink according to the equations of motion (6). Characterestics of a silicon ring resonator are in [2].

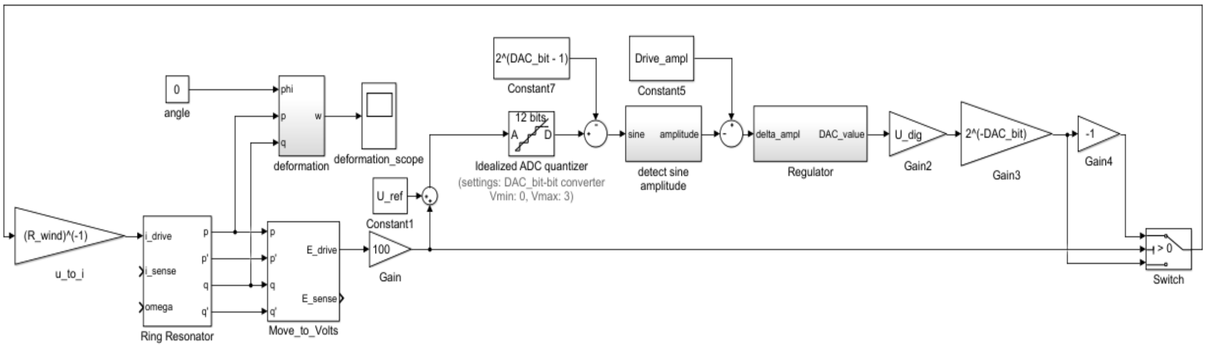

Figure 4. Model of a ring micromechanical gyroscope with a digital oscillation excitation channel.

For the model shown in Figure 4, it is required to set the parameters of the ring resonator and the control loop for the amplitude of the vibration of the vibration velocity. The model reflects the behavior of the resonator with the known geometric parameters, corresponding to the real design, upon excitation of oscillations.

A model of digital electronics (Figure 5) was developed and manufactured in order to investigate the possibilities of the digital channel for excitation of oscillations.

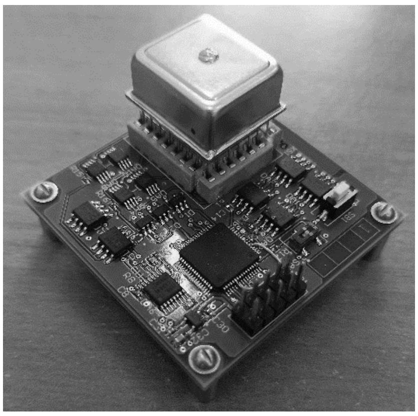

Figure 5. Digital electronics layout for a ring micromechanical gyroscope.

The model uses the sensor of the ring micromechanical gyroscope produced by JSC «Inertial technologies of «Technocomplex», Ramenskoye. The sensing element is mounted on an electronics board that contains the functional units described above.

STM32F103RCT6 manufactured by STMicroelectronics was chosen as a microcontroller. This microcontroller contains three 12-bit A/D and two 12-bit D/A converters. The reference voltage for the

ADC and DAC corresponds to the supply voltage – 3V. A phase-locked loop was created to clock the ADC, which multiplies the reference frequency (the resonant frequency of the ring resonator oscillations) by 64. This is necessary to maintain a constant number of points processed by the microcontroller during the oscillation period.

The microcontroller implements a control algorithm that maintains a constant specified amplitude of the oscillation velocity. Besides, it implements a protocol for interacting with external devices using UART and SPI interfaces. This allows to change parameters of the oscillation excitation circuit during its operation.

5. Research result

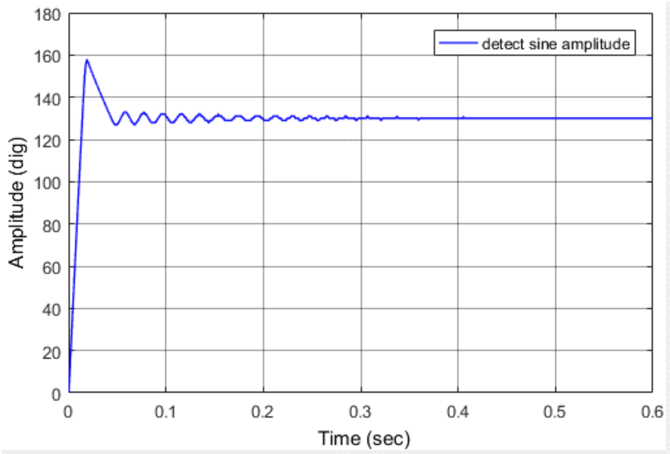

Figure 6. Transient excitation process.

Figure 6 shows a graph of the transient process when oscillations are created after power-on for the oscillating circuit model in the Matlab Simulink. Transient time does not exceed 0.3 s. The overshoot amount is 20 %.

The measured amplitude of the oscillation velocity was recorded after the instrumental amplifier at a data update rate of 100 Hz in normal climatic conditions (t ≈ 25°C) for an hour for different values of the given amplitude in order to experimentally determine the stability of the digital oscillation excitation circuit. The test results are summarized in the table 1.

Table 1. Dependence of the error in maintaining the amplitude of the oscillation speed on a given value.

Specified vibration velocity amplitude (mV)	Error mean value (mV)	Standard deviation (mV)
95	-0.0003527	1.447
110	0.00335	1.625
145	-0.00843	2.129
183	-0.00015019	2.618
220	0.00276	3.194

It can be concluded that the noise in the channel increases with an increase in the specified amplitude of the vibration velocity according to the data presented in Table 1. This behavior is due to the peculiarities of the work of the components that make up the circuit. The smallest possible amplitude of the oscillation velocity should be chosen from the point of view of minimizing the noise component and increasing the stability of the circuit. It should be borne in mind that the sensitivity of the gyroscope also depends on the amplitude of the vibration velocity.

Conclusion

Positive velocity feedback in the excitation loop is more preferable for a ring micromechanical gyroscope with electromagnetic velocity sensors and magnetoelectric force sensors. The oscillations of the resonator differ in phase from the excitation signal by -π/2, but the signal from the velocity sensor is ahead of the oscillation by π/2 at resonance. This condition leads to the fact that the phase shift in the circuit is equal to zero, and the signal from the velocity sensor can be used to excite oscillations. Moreover, the described features of the operation of the ring micromechanical gyroscope make it possible to abandon the use of differentiating links.

The proposed scheme of the digital excitation channel allows:

- to simplify the composition of electronics;
- to reduce the error of the gyroscope, since the accuracy of maintaining the resonant frequency is due to the parameters of the sensitive element and the feedback loop;
- to make the adjustment of the feedback loop by the amplitude of the oscillation velocity more accessible during debugging stage, since the transfer function of the regulator is implemented inside the microcontroller.

In addition, in the course of the research a mathematical model was created in Matlab Simulink and a prototype was made, which confirmed the performance of the proposed circuit.

Further steps based on the result of the research were identified to improve the digital circuit for exciting oscillations of the ring micromechanical gyroscope: noise reduction by changing the input stage of amplifiers and finding a suitable transfer function of the regulator.

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