Microoptoelectromechanical ring angular velocity transducer based on the optical tunnel effect for control system of mobile objects

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Abstract. In this article, the influence of the ring resonator parameters on the characteristics of the angular velocity transducer based on the optical tunneling effect (OTE) is investigated and model is introduced. The sensitivity of the module based on the optical tunneling effect is calculated to provide a quasi-linear range. The analysis of influence of linear acceleration on the ring angular velocity transducer based on the OTE is described. The compensation of the linear acceleration effect by using the differential processing method and switching, which provide the measurement of angular velocities with high accuracy for the entire measurement range, is described.

1. Introduction
Angular velocity transducers are one of the main elements for moving object control systems. The direction for development of angular velocity transducers based on microelectromechanical (MEM) technologies is promising in instrument engineering, ensuring a reduction in mass and dimensional parameters [1–3]. However, their accuracy characteristics deteriorate due to the use of the capacitive sensing method for measuring primary signals. To reduce measurement errors, optical sensing methods are used to receive primary information, which allows for isolation and eliminating the mutual influence of the excitation circuits and the measurement of the primary signals [4]. To get the information about submicron oscillations of ring resonator of microoptoelectromechanical angular velocity transducers, the method based on the optical tunnel effect can be effectively used.

The primary reasons of the modeling for the characteristics of a ring microoptoelectromechanical angular velocity transducer based on OTE are the range of measured angular velocity, sensitivity, primary and additional errors, and dimensions.

2. The influence of the ring resonator parameters on the characteristics of the angular velocity transducer
The main element of the transducer is the sensing element (SE). In the particular case the angular velocity sensor is ring resonator (RR), which oscillates in the direction corresponding to the primary oscillatory mode (primary mode) [5,6]. When the ring resonator is vibrating, by stretching in opposite directions and contracting, it constantly changes its ellipticity, maintaining the position of the main axes. When angular velocity is applied, the ring resonator is deformed by Coriolis forces, which cause an additional radial displacement \( d \) along the axes 45° (Figure 1). The amplitudes of the additional radial
displacement can be determined by the formula: \( \Delta d(\Omega Z) = \frac{(2 \cdot n \cdot \Omega Z \cdot A)}{(n^2+1) \cdot \gamma \cdot f_1} \) [7].

![Figure 1. Microoptoelectromechanical ring angular velocity transducer based on the optical tunneling effect](image)

For the modeling of additional radial displacement, the design parameters of the ring resonator were determined to ensure the measurement range with the initial gap \( d_0 \) of the transducer corresponding to the center of the quasi-linear region of the transfer function when using the OTE module interacting with the ring resonator. The calculated initial gap \( d_0 \) between the base of the prism of the module based on OTE and the surface of the ring resonator is less than the wavelength of optical radiation source and depends on the wavelength of optical radiation source. The range of displacements of the additional radial motion of the ring resonator is about hundreds of nanometers. It should be taken into account that value of additional radial movement is possible by an amount of no more than 30% of the value of the ring thickness. The diameter of the ring resonator is determined by the required range of angular velocity measurement.

3. Selection of a quasi-linear range of the angular velocity transducer

Under the influence of the angular velocity there is a periodic change in the gap between the areas of the ring resonator and the prisms of the modules based on the optical tunneling effect (MOTE). The transfer function of the transducer of each channel is determined by taking into account the reflectivity of the module based on the OTE which depends on the radiation source power and gap. The size of the operating gap between the prism of \( i^{th} \) module and the ring resonator is defined as: \( d_{md}(\Omega) = d_0 - \Delta d_i(\Omega) \).

In the transducer, the optical radiation source power at the photo detector \( P_{PD_i} \) in the contact optical region of the modulated boundary of prism depends on the gap changing \( \Delta d_i \) under the action of the measured angular velocity. It is assumed that at each time the gap is constant along the contact optical region, and the output optical power \( P_{PD_i} \) can be determined by an approximate model in which the calculation of the gap \( \Delta d_i \) is carried out by the central beam of the radiation source as a point of contact at the modulated boundary of the prism. The sensitivity \( S \) of the transducer is not constant in the calculated measurement range and varies with the parameters (Figure. 2a). In this time, by changing the sensitivity \( S(d) = \Delta R_{PD}(d(\Omega))/\Delta d_i(\Omega) \), the area at which the sensitivity decreases by no more than \( n \) times from the maximum value, is determined and that will define the range of measured angular velocity \( \pm \Omega_{\text{max}} \).
Figure 2. Relationship of the reflectivity $R$ and the sensitivity of MOTE for the gap $d$ between the prism and RR (a) and the primary error of MOTE by the applied angular velocity (b) (the refractive index of the prism $n_1 = 1.544$; wavelength of radiation $\lambda = 1.4 \mu m$; the separation medium $n_2 = 1$, angle of incidence $\theta = 42^\circ$)

In the absence of the measured angular velocity, the position of the RR will correspond to the middle of the changing region in the relative gap. The primary error of the module based on OTE, using as an operating area of ratio $R_d = f(d/\Omega)$, (Figure. 2b), is equal to:

$$
\delta = \frac{2 \cdot R_{d0} (d_0 / \Omega) - R_{d\text{max}} (d_{\text{max}} / \Omega) - R_{d\text{min}} (d_{\text{min}} / \Omega)}{R_{d\text{max}} (d_{\text{max}} / \Omega) - R_{d\text{min}} (d_{\text{min}} / \Omega)} \cdot 100\%.
$$

(1)

The maximum primary error is observed at the deformation of the ring resonator, corresponding to the maximum value of the angular velocity. With a decrease in the angle of incidence $\theta$ of radiation source and an increase in the wavelength $\lambda$, there is some expansion of the gap range, in which the value of the maximum sensitivity also decreases. The range of the gap variation ($2\Delta d = d_{\text{max}} - d_{\text{min}}$), which allows to obtain a quasi-linear transformation function, is determined.

4. The analysis of influence of linear acceleration effect

In the angular velocity transducer, the ring resonator with electrostatic excitation can be supported eight semicircular supported beams [8, 9]. Under the action of linear acceleration, the position of the ring resonator changes due to the deflection of the supports. Under the influence of acceleration, the ring resonator (RR) is shifted without changing its shape, which leads to an additional asymmetric change in the reflectivity of the faced MOTE. Deformations of supported beams can vary effectively in their geometry and composition [12-14].

In the case of linear acceleration, the size of gap between the ring resonator and the prism is determined by the following ratio [7]:

$$
d_i (\Omega, a) = d_0 \pm \Delta w_x (\Omega_x) \pm \Delta w_a (a).
$$

(2)

In the transducer, the optical radiation passes through the MOTE, interacting with the ring resonator, and reaches the photo detector. The power of the optical radiation $P_{PD}(\Omega, a) = |R[d_i(\Omega, a)]|P_0$ on the photo detector depends on the linear acceleration and the measured angular velocity, which affect the reflectivity and gaps of the MOTE. The reflectivity is related to the size of gap $d_i(\Omega, a)$. As the gap $d_i(\Omega, a)$ decreases, the output signal of the photo detector decreases.
By using the current-voltage converter based on the operational amplifier with resistance in the feedback circuit $R_{FB}$ taking into account the current of the photo detector, the output voltage of the sensing units is described as:

$$U_{1,i_0}(\Omega_Z, a_{X'}) = R_{FB} \cdot S_{PD} \cdot P_{OS} \cdot k \cdot R \left[ d_0 \pm w_{wa}(a_{X'}) \pm w_{wa}(\Omega_Z) \right], \quad (3)$$

where $S_{PD}$ – the sensitivity of the photo detector; $P_{OS}$ – power of the optical radiation source; $R_{FB}$ – resistance in the feedback circuit of the operational amplifier of the current–voltage converter; $k$ – coefficient of optical loss; $R[d_0 \pm \Delta w_{wa}(a_{X'}) + \Delta w_{wa}(\Omega_Z)]$ – the reflectivity of the boundary medium.

The transfer function of the amplitude of the output voltage of the angular velocity transducer based on the OTE is determined by the signals of four quasi-linear channels and can be represented in the form:

$$U_{OUTm}(\Omega_Z, a_{X'}) = \frac{[U_{1,m_1}(\Omega_Z, a_{X'}) + U_{1,m_2}(\Omega_Z, a_{X'})] - [U_{1,m_3}(\Omega_Z, a_{X'}) + U_{1,m_4}(\Omega_Z, a_{X'})]}{2}, \quad (4)$$

where $U_{1,m_1}(\Omega_Z, a_{X'})$ – the amplitude of the output voltage for the $i^{th}$ sensing unit, depending on the angular velocity and linear acceleration.

The ring resonator is located in the elastic suspension and all disturbing factors influence the spatial position of the ring resonator. Therefore, under the influence of linear acceleration, the position of the center of the ring resonator is changed. This leads to the spatial displacement of the optical interaction regions on the ring resonator relative to the sensing prisms.

When linear acceleration is applied, the amplitude of the output voltage of the angular velocity transducer is calculated for width of supported semicircular bar $h$=105 µm, thickness of supported semicircular bar $t$=100 µm, $\lambda$=1400 nm, $\theta$=42°, $d_0$=300 nm and $P_{OS}$=2 mW. The results show that the error from the effect of acceleration along the $OX'$ and $OY'$ axes is about 10% at $a$=10g.

5. Compensation of linear acceleration effect

The microoptoelectromechanical ring angular velocity transducer uses an optical sensing method, using four pairs of MOTE sensing modules with a variable gap between the prism and the ring resonator. When channels for sensing angular velocities are combined, the considered ring transducer operates in a joint mode of modulation of four optical signals, which can provide consideration of the effect of linear acceleration and obtain a quasi-linear transfer function. The block diagram of compensation of influence of linear acceleration on a ring resonator of the angular velocities transducer based on the OTE by using the method of differential processing and switching is shown in Figure 3. Under the action of the measured linear acceleration ($a_{X'}$) sensitivity changes occur on MOTE1, MOTE2, MOTE3 and MOTE4, reducing the amplitudes of the output voltages $U_{1,1}$, $U_{1,2}$, $U_{1,3}$ and $U_{1,4}$. The reduction of the output voltage amplitudes is compensated by the method of differential processing and control of the expression selection to determine the compensated signal by means of a switch module. The value of the output voltage of the switch module depends on the linear acceleration determined by the output signals of the channels $U_{1,1}$ and $U_{1,3}$ (for axis $OX'$) and channels $U_{1,2}$ and $U_{1,4}$ (for axis $OY'$).
Figure 3. Block diagram of compensation for influence of linear acceleration on a ring resonator of the angular velocity transducer based on OTE

In the absence of linear acceleration, the general transfer function (the ratio of the output voltage amplitude to the angular velocity \( U_{\text{OUTm}} = f(\Omega_z) \)) for ring transducer based on the OTE is represented as:

\[
U_{\text{OUTm}}(\Omega_z) = K_{\Omega} \cdot \Omega_z,
\]

where \( K_{\Omega} \)– coefficient of transfer function of the angular velocity transducer based on the OTE.

When linear acceleration is applied, the expression for the amplitude of the output voltage is defined as:

\[
U_{\text{OUTm}}(\Omega_z, a_{x'}) = K_a \cdot a_{x'} + K_{\Omega_a} \cdot \Omega_z,
\]

where \( K_a, K_{\Omega_a} \) – coefficients of transfer function of linear acceleration and angular velocity.

The acting linear acceleration generates, for example, for the axis \( OX' \), the output voltage \( U(a_{x'}) \), which is determined by the signals of the two channels (\( U_{1:U1}(\Omega_z, a_{x'}) - U_{1:U3}(\Omega_z, a_{y}) \)) and can be represented in the form:

\[
U(a_{x'}) = \frac{[U_{1:U1}(\Omega_z, a_{x'}) - U_{1:U3}(\Omega_z, a_{x'})]}{2}.
\]

The expression for the output voltage \( U(a_{x'}) \), which depends on linear acceleration, is described as:

\[
U(a_{x'}) = K_1 \cdot a_{x'} + K_2 \cdot \Omega_z,
\]

where \( K_1, K_2 \) – coefficients of formation channel for the linear acceleration signal.

Under the influence of linear acceleration, the compensated values of the output voltages by the method of differential processing of the switch module are determined as:

\[
U_{\text{OUT, CORR}}(\Omega_z, a_{x'}) = (K_a \cdot a_{x'} + K_{\Omega} \cdot \Omega_z) + U_m[U(a_{x'})].
\]

The output voltage of the switch module, depending on the linear acceleration, is described as:

\[
U_m[U(a_{x'})] = U_{\text{OUT}}(\Omega_z) - [K_{\Omega} \cdot \Omega_z + K_a \cdot a_{x'}].
\]

Taking into account the equations (5, 6 and 8), the output voltage of the switch module, depending on the output voltage of the measured linear acceleration \( U(a_{x'}) \), is written as:
\[ U_m[U(a_{X'})] = U_{\text{OUT}}(\Omega_z) - \left[ K_{\Omega} \cdot \Omega_z + K_u \cdot \left( \frac{U(a_{X'}) - K_u \cdot \Omega_z}{K_1} \right) \right]. \] (11)

For the formation of the compensated values of the output signal of angular velocity transducer, the output voltage of switch module \( U_m[U(a_{X'})] \) is defined by different expressions for the ranges of angular velocities. The number of measurement ranges depends on the required transformation accuracy. Thus, to provide additional error due to the influence of acceleration up to 10g along the axis \( OX' \) no more than 0.8%, it is necessary to provide ten ranges, in each of which the output voltage of the switch module \( U_m[U(a_{X'})] \) is determined by its expression.

6. Conclusion
In this article the influence of the parameters of the ring resonator on the characteristics of the angular velocity transducer is proposed. The choice of quasi-linear region of the MOTE and analysis for the linear acceleration effect on the ring angular velocity transducer based on the optical tunneling effect are described.

A compensation method for the sensitivity change of the module based on the optical tunneling effect (MOTE) transfer function due to the displacement of the ring resonator from the linear acceleration by using differential processing and control of the correction signal formation by means of a switch is proposed. The number of switch ranges depends on the required accuracy of the angular velocity transducer and the maximum linear acceleration.

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