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Investigation of the Characteristics of the Three-axis Ring Typed Angular Velocity Transducer Based on Optical Tunneling Effect

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Abstract

The structure of a three-axis ring type angular velocity transducer based on the optical tunnel effect (OTE) is proposed. In this article considered the primary motion, which is excited by the electrostatic means and on the secondary displacements which provide the applied angular velocity information.

Keywords: three-axis transducer, angular velocity, optical tunneling effect, ring resonator.

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1. Introduction

The ring resonator is the primary sensing element of the micro-electromechanical three axis ring typed angular velocity transducers based on the optical tunneling effect (OTE). When angular velocity is applied, Coriolis forces induce displacements of in plane and out of plane inertia forces around the ring resonator. When the ring resonator is deformed, secondary modes can be distinguished in Ref. [1]. The magnitudes of the measured angular velocity (Ω) are shown at points (45 °, 135 °, 225 ° and 315 ° for Ω_z; 0°,60°,120°,180°,240° and 300° for Ω_x; 30°,90°,150°,210°,270° and 330° for Ω_y). For receiving information of applied angular velocities four pairs of optical modules based on optical tunneling effect are used. These four pairs of optical modules based on optical tunneling effect are located at points (45 °, 135 °, 225 ° and 315 ° for applied angular velocity Ω_z at Z axis; 0° and 180° for applied angular velocity Ω_x at X axis; 90° and 270° for applied angular velocity Ω_y at Y axis) in Ref.[2]. Block diagram of the three-axis ring typed angular velocity transducer is shown in Fig. 1. The structural diagram of three-axis angular velocity transducer includes: optical source (OS), a module based on optical tunneling effect (MOTE), photo detector (P) and processing unit.

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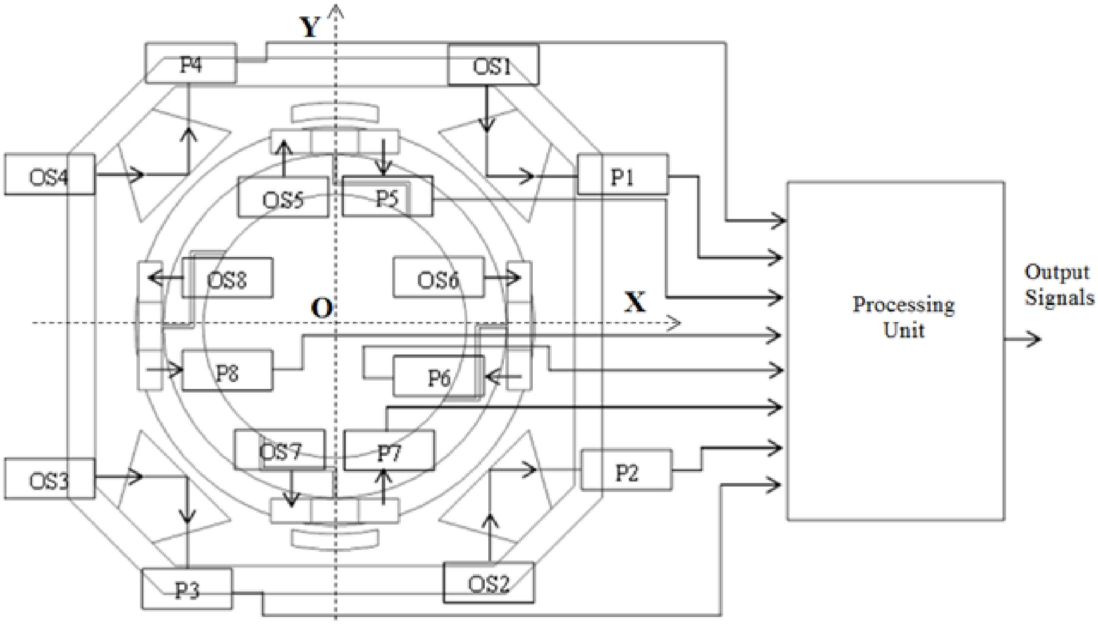

Figure 1: Structural block diagram of three-axis ring typed angular velocity transducer based on optical tunneling effect.

2. Material and Theoretical Bases of Investigation

In the primary mode with constant amplitude of vibration, the ring resonator deforms elliptically along the axes OX and OY. This state is called the primary mode. The primary mode can be excited by the method of position excitation. To provide excitations of the ring resonator, a positional excitation is applied, which is realized by means of a pair of electrodes. The internal surface of the ring resonator and the electrodes are covered with a thin electro-conductive layer, so the ring resonator and the electrode are the plates of a cylindrical capacitor. A couple of opposite electrodes are supplied with an alternating electric voltage with a certain frequency, which is less than the natural frequency by a factor of 2 in Ref. [3]. In this three-axis angular velocity transducer for the primary excitation electrostatic methods is used. In this excitation system consists of movable part (ring resonator) and fixed electrode plates. This model leads to variable capacitors. Any plates of the charged capacitor are attracted, so attractive forces appear between electrodes and ring resonator. The attractive force between electrode and ring resonator is determined by the expression:

$$F = \frac{\xi_0 \cdot \xi_r \cdot A \cdot V^2}{2 \cdot d_C^2},$$

where ξ_0 – permittivity of free space; ξ_r – dielectric constant; A – area of electrode: V – voltage applied between two plates; d_C – initial distance between ring resonator and electrode.

When electrodes are attracting ring resonator, ring resonator deforms. Ring resonator deflection by applying attractive force between electrodes and ring resonator is described as:

$$\Delta d_{Ring} = \frac{0,0186 \cdot F \cdot D^2}{E \cdot I},$$

where *E* – Young's Modulus of ring resonator; *I* – Moment of inertia ($I = t.h^3/12$: *t* – thickness of ring resonator, *h* – height of ring resonator); *D* – diameter of ring resonator; *F* – attractive force between ring resonator and electrode.

The attractive force for primary mode with constant vibration is calculated with the following parameters: diameter of ring resonator – 5mm, thickness of ring resonator – 300 μm, height of ring resonator – 100 μm. To be maintaining the amplitude of primary mode excitation at 50μm the attractive force between ring resonator and electrode must be nearly 4 x 10^{-3} N. Under the action of angular velocity deform the ring resonator, causing additional secondary displacement. Knowing the amplitude of the secondary displacement, we can determine the direction and magnitude of the angular velocity. The secondary radial displacement of the ring resonator depends on the angular velocity of rotation Ω, the amplitude of primary displacement with the constant vibrations A, the vibration frequency, and the damping γ. The amplitudes of secondary displacements "in-plane-mode" and "out-of-plane-mode" can be expressed as in Ref. [1, 4]:

$$\Delta d_Z(\Omega_Z) = \frac{2 \cdot \pi \cdot A \cdot D^2}{\gamma \cdot t} \cdot \sqrt{\frac{\rho}{15 \cdot E}} \cdot \Omega_Z,$$

$$\Delta d_X(\Omega_X) = \frac{1,5 \cdot A}{\left(1 + 6,75 \cdot h^2 \cdot \xi^2\right) \cdot \gamma \cdot f_2} \cdot \Omega_X,$$

$$\Delta d_Y(\Omega_Y) = \frac{1,5 \cdot A}{\left(1 + 6,75 \cdot h^2 \cdot \xi^2\right) \cdot \gamma \cdot f_2} \cdot \Omega_X,$$

where *A* – primary displacement with constant vibration; γ – damping; Ω **–** applied angular velocity; ρ, h, t – density for ring resonator, thickness of ring resonator и height of ring resonator; *D* – diameter of ring resonator; *E* – Young's Modulus;

$$\xi = \frac{2 \cdot \left[E \cdot \left(t^2 + h^2\right) + 12 \cdot G \cdot t \cdot h\right]}{D \cdot \left[E \cdot \left(t^2 + h^2\right) + 108 \cdot G \cdot t \cdot h\right]} \quad ;$$

f_2 –natural frequency out-of-plane-mode

$$\left(f_2 = \frac{2 \cdot n \cdot h \cdot \left(n^2 - 1\right)}{\pi \cdot D^2} \cdot \sqrt{\frac{E}{\rho \left(12 \cdot n^2 + 6.67 \cdot \left(1 + \frac{h^2}{t^2}\right) \cdot (1 + \nu)\right)}}, \right)$$

In this calculation determine the secondary displacements by using the following the structural parameters of the ring resonator: primary displacement A = 20 μm Young's modulus E = 1,65 · 10^{11} Pa, material density ρ = 2330 kg / m^3, diameter of ring resonator – 5mm, thickness of ring resonator – 300 μm, height of ring resonator – 100 μm. Under the action of a constant angular velocity Ω_X, Ω_Y, Ω_Z = 360 °/s, the variations of the magnitudes of the secondary displacements at a constant frequency (*f2* = 47 kHz) are shown in Fig. 2.

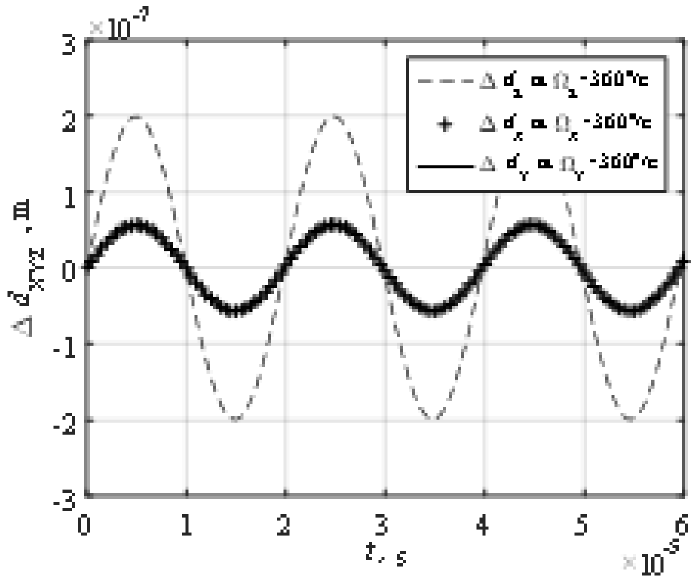

Figure 2: The amplitude of the secondary displacement at a constant frequency.

In this three-axis angular ring typed angular velocity transducer based on the optical tunneling effect, the gap, which express the applied angular velocity, between the prism (optical sensing element) and the ring resonator depends on the initial gap, the structure of transducer and the amplitude of the secondary displacement of the measured angular velocity. The gaps, which express the applied angular velocity, can be determined by the formulas:

$$d_Z(\Omega) = d_{0\_Z} - \Delta d_Z\left(\Omega_Z\right).$$

$$d_X(\Omega) = d_{0\_X} - \Delta d_X\left(\Omega_X\right).$$

$$d_Y(\Omega) = d_{0\_Y} - \Delta d_Y\left(\Omega_Y\right).$$

The three-axis angular velocity transducer constructed with structure which consists of optical module of total internal reflection and ring resonator. The variation output power of each optical sensing module is estimated by the reflectivity of the modulated media boundary. The reflectance $R_i = f[d_i(t,\Omega)]$ varies in time with the amplitude depending on the angular velocity with the variation of the gap d_i (t, Ω) and is defined as:

$$R_i\left[d_i(t,\Omega)\right] = 0,5\cdot\frac{\exp(-\frac{4\pi}{\lambda}d_i(t,\Omega)\sqrt{n_1^2\sin^2\theta-n_2^2}) + \exp(\frac{4\pi}{\lambda}d_i(t,\Omega)\sqrt{n_1^2\sin^2\theta-n_2^2}) + 2\cos(\varphi_{12\perp}-\varphi_{23\perp})}{\exp(-\frac{4\pi}{\lambda}d_i(t,\Omega)\sqrt{n_1^2\sin^2\theta-n_2^2}) + \exp(\frac{4\pi}{\lambda}d_i(t,\Omega)\sqrt{n_1^2\sin^2\theta-n_2^2}) + 2\cos(\varphi_{12\perp}+\varphi_{23\perp})}$$
$$+0,5\cdot\frac{\exp(-\frac{4\pi}{\lambda}d_i(t,\Omega)\sqrt{n_1^2\sin^2\theta-n_2^2}) + \exp(\frac{4\pi}{\lambda}d_i(t,\Omega)\sqrt{n_1^2\sin^2\theta-n_2^2}) + 2\cos(\varphi_{12\parallel}-\varphi_{23\parallel})}{\exp(-\frac{4\pi}{\lambda}d_i(t,\Omega)\sqrt{n_1^2\sin^2\theta-n_2^2}) + \exp(\frac{4\pi}{\lambda}d_i(t,\Omega)\sqrt{n_1^2\sin^2\theta-n_2^2}) + 2\cos(\varphi_{12\parallel}+\varphi_{23\parallel})},$$

where $\varphi_{12\perp}$, $\varphi_{23\perp}, \varphi_{12\parallel}, \varphi_{23\parallel}$ - phase of the wave upon reflection from the media in Ref. [5].

In this three axis angular velocity transducer, the optical power of the photo detector is determined taking into account the reflectivity in the contact optical region of the modulated boundary of the prism, which depends on the variation of the gap under the action of the measured angular velocity. The output optical power, which reached the photodiode through the prism, of the optical sensing module is expressed by the equation:

$$P_{PD-i}\{R_i[d_i(\Omega)]\} = P_{OS}\cdot R_i[d_i(\Omega),\theta,\lambda]\cdot K_{lost},$$

where P_{OS} – power of optical source; λ – wavelength of optical source; θ – angle of incidence, R [d (Ω),θ, λ] – reflectivity of structure.

The function between applied angular velocity and output voltage of sensing unit of the ring typed transducer is determined by the dependence of the output voltage $V_{out} = f(P_{PDi}\{R_i[d_i(t,\ \Omega)]\})$ on the angular velocity. The output voltage when using a "current-voltage" converter based on an operational amplifier with feedback resistor, R, taking into account the current of the photo detector, will be determined as:

$$V_{out} = R_F\cdot(S_{PD}\cdot P_{PDi}\{R_i[d_i(t,\ \Omega)]\} + I_d).$$

Figure 3 shows the relationship between the output voltage and applied angular velocity for one channel of optical sensing module based on optical tunneling effect.

3. Conclusion

In this article functional block diagram of the three-axis ring typed angular velocity transducer based on the optical tunneling effect is described. The primary mode vibration and the secondary displacements which provide the applied angular velocity are presented. The influence of incidence angle of optical source, optical power of photo detector and the output voltages of the optical sensing module of transducer are investigated.

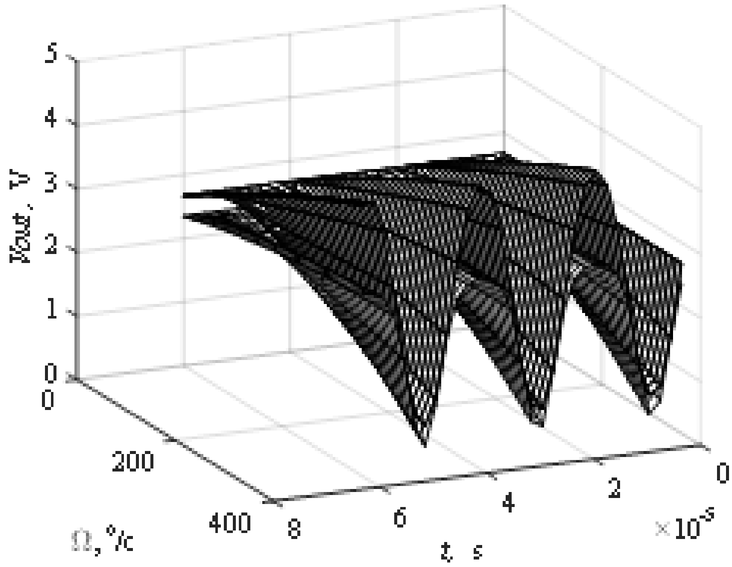

Figure 3: Amplitudes of the output voltages of the three-axis ring typed angular velocity transducer based on optical tunneling effect.

Acknowledgments

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