A Digitized Decoupled Dual-axis Micro Dynamically Tuned Gyroscope with Three Equilibrium Rings

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Abstract – A new digitized decoupled dual-axis micro dynamically tuned gyroscope with three equilibrium rings (TMDTG) is proposed which can eliminate the constant torque disturbance (CTD) caused by the double rotation frequency of a driving shaft with a micro dynamically tuned gyroscope with one equilibrium ring (MDTG). A mechanical and kinematic model of the TMDTG is theoretically analyzed and the structure parameters are optimized in ANSYS to demonstrate reliability. By adjusting the thickness of each equilibrium ring, the CTD can be eliminated. The digitized model of the TMDTG system is then simulated and examined using MATLAB. Finally, a digitized prototype based on FPGA is created. The gyroscope can be dynamically tuned by adjusting feedback voltage. Experimental results show the TMDTG has good performance with a scale factor of 283 LSB/°/s in X-axis and 220 LSB/°/s in Y-axis, respectively. The scale factor non-linearity is 0.09% in X-axis and 0.13% in Y-axis. Results from analytical models, simulations, and experiments demonstrate the feasibility of the proposed TMDTG.

Keywords: Micro dynamically tuned gyroscope, Three equilibrium rings, Digitized, Decoupled

1. Introduction

Gyroscopes have attracted significant attention during the past few years for applications in many areas, including micro-inertial navigation systems, automobile security systems, and control stabilization [1]. To date, the application of traditional micro gyroscopes has been limited due to physical restrictions such as large volume, heavy weight, high cost, etc. Compared with other gyroscopes, micro electrical mechanical system (MEMS) gyroscopes have been investigated for applications requiring low-cost and compact size. Most MEMS gyroscopes are built using the Coriolis coupling principle [2-3]. Using the Coriolis-effect, MEMS gyroscopes can measure the external input angular rate and variation in orientation. Through the development of silicon processing technologies, the production cost and power consumption of MEMS gyroscopes have been reduced greatly. However, developing MEMS gyroscopes that are small enough to fit design specifications has been difficult. Moreover, MEMS gyroscopes also have very low mass, poor accuracy, and can be shaped only once. These limitations affect performance and restrict future MEMS gyroscope developments [4-6]. Research on the micro electro mechanical hybrid gyroscope (MHG) with a single equilibrium ring was

first proposed by Jenkins in 2003 [7]. Ten years later, a novel micro dynamically tuned gyroscope (MDTG) with adjustable static capacitance was proposed [8]. However, because of the single equilibrium ring, the MDTG has a constant torque disturbance (CTD) caused by the double rotation frequency of the driving shaft which cannot be eliminated completely [9]. In order to eliminate the CTD and improve accuracy, lower cost, lower power consumption, and reduce size and weight, a digitized decoupled dual-axis novel micro dynamically tuned gyroscope with three equilibrium rings (TMDTG), based on previous MDTG and MEMS gyroscopes, has been developed.

At present, the closed loop detection circuits of micro gyroscopes depend on pure analog circuits and interface circuits for common mode signal detection [10-13]. Pure analog closed-loop circuits lack flexibility and compatibility, and have error characteristics that are easily influenced by external disturbances such as temperature variation, vibration interference and so on. Thus, the closed-loop detection circuit of a micro gyroscope needs improvement. The digitized circuit can eliminate external disturbances and advanced algorithms can be updated by programming. In [14-15], digitized circuit systems were presented which were built in DSP (Digital Signal Processor). In comparison, a system was built using FPGA (Field Programmable Gate Array) which improved upon the parallel speed and power consumption of DSP [16-18]. Hence, the digitized closed-loop circuit based on FPGA is now the most common. In addition, FPGA can make adjustment for variable temperature and vibration environments [19-20].

This paper is organized as follows: In section 2, the

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structure of TMDTG is proposed and the condition of eliminating the constant torque disturbance (CTD) is derived. Analysis and simulation of the stiffness is modeled by ANSYS, proving design feasibility. In section 3 and section 4, the digitized dual-axis closed-loop detection circuit is illustrated and simulated respectively. The measurement results are compared with the previous simulation in section 5. This paper concludes in section 6.

2. Structure Design

The 3D structure of the TMDTG is illustrated in Fig. 1. The novel TMDTG consists of three equilibrium rings, a rotor wafer, an inner ring, inner beams and outer beams. From top to bottom, the equilibrium rings are called equilibrium ring I, equilibrium ring II and equilibrium ring III, respectively. In an ideal situation, each equilibrium ring has the same inner and outer diameter. The torsional beams have the same length, width, and thickness. The inner ring is rigidly attached to the micro motor drive shaft.

The inner ring, equilibrium rings, and rotor wafer are connected by torsional beams, while the inner ring and the equilibrium rings are connected by inner beams. The equilibrium rings and the rotor wafer are connected by outer beams. The outer beams and the inner beams are perpendicular to each other. Furthermore, inner beams I

Fig. 1. The 3D structure of TMDTG

Fig. 2. The selected coordinates of TMDTG system

and III are parallel to each other and perpendicular to inner beam II. Similarly, outer beams I and III are parallel to each other and perpendicular to outer beam II.

To facilitate description, the selected coordinate system is defined in Fig. 2. Due to the effects of torsional and bending stiffness of the inner/outer beams, the rotor wafer and equilibrium rings can only rotate along the inner beams or the outer beams, respectively. The selected coordinates are described as follows:

- 1) OXYZ is the inertia coordinate;
- 2) $OX_1Y_1Z_1$ is the object coordinate of the TMDTG;
- 3) $OX_2Y_2Z_2$ is the driving shaft coordinate;
- 4) $OX_3Y_3Z_3$, $OX_4Y_4Z_4$, $OX_5Y_5Z_5$ are the coordinates of equilibrium ring I, II, III, respectively. The outer beams are defined as the X-axis, while the inner beams are defined as the Y-axis;
- 5) $OX_6Y_6Z_6$ is the rotor wafer coordinate;
- 6) $\dot{\phi}_x, \dot{\phi}_y, \dot{\phi}_z$ are the object angular rate relative to inertia space around the object coordinate axis: X, Y, and Z, respectively;
- 7) θ is the angle of the driving shaft coordinate $OX_2Y_2Z_2$ around axis Z_2 relative to the object coordinate $OX_1Y_1Z_1$;
- 8) Ω is the angular rate of the driving shaft coordinate $OX_2Y_2Z_2$ around axis Z_2 relative to the object coordinate $OX_1Y_1Z_1$;
- 9) γ is the angle of the equilibrium rings coordinates around axis X_3 (X_4, X_5) relative to the driving shaft coordinate $OX_2Y_2Z_2$;
- 10) φ is the angle of the rotor wafer coordinate $OX_6Y_6Z_6$ around axis Y_3 (Y_4, Y_5) relative to the equilibrium rings coordinates;
- 11) β is the angle of the spin axis of the gyroscope rotor wafer around the positive X_1 -axis relative to the driving shaft;
- 12) α is the angle of the spin axis of the gyroscope rotor wafer around the positive Y_1 -axis relative to the driving shaft.

According to the relationship among the coordinates in Fig. 2, the change regulation of $\gamma, \varphi, \alpha, \beta$ can be expressed as Eq. (1):

$$\begin{aligned}\gamma &= \alpha \sin \theta + \beta \cos \theta \\ \varphi &= \alpha \cos \theta - \beta \sin \theta\end{aligned}\quad (1)$$

2.1 Eliminating the constant torque disturbance (CTD)

When the driving shaft rotates at the angular velocity of Ω , assuming the N_{th} equilibrium ring rotates at the angular velocity of Ω_n , the angular velocity of each axis in the equilibrium ring projection coordinates are $\Omega_{xn}, \Omega_{yn}, \Omega_{zn}$, respectively.

$$\begin{cases} \dot{\Omega}_{xn} = \dot{\gamma} \\ \Omega_{yn} = \Omega \sin \gamma \\ \Omega_{zn} = \Omega \cos \gamma \end{cases} \quad (2)$$

Assuming γ is very small, Eq. (3) can be derived:

$$\begin{cases} \dot{\Omega}_{xn} = \dot{\beta} \cos \theta + \dot{\alpha} \sin \theta \\ \Omega_{yn} = \Omega(\beta \cos \theta + \alpha \sin \theta) \\ \Omega_{zn} = \Omega \end{cases} \quad (3)$$

The torque of the outer torsional beams of the N_{th} equilibrium ring applied on the OX_n -axis of the rotor wafer can be derived as Eq. (4):

$$M_{xn} = K_{xn} \gamma = K_{xn} (\beta \cos \theta + \alpha \sin \theta) \quad (4)$$

The torque of the outer torsional beams of the N_{th} equilibrium ring applied on the OY_n -axis of the rotor wafer can be derived from the torque balance equation:

$$\begin{aligned} M_{yn} = & -(I_{yn} - I_{zn} + I_{xn}) \Omega (\dot{\beta} \cos \theta + \dot{\alpha} \sin \theta) \\ & + K_{yn} (-\beta \sin \theta + \alpha \cos \theta) \end{aligned} \quad (5)$$

where K_{xn} is the combination of torsional elasticity coefficients of the outer torsional beams, K_{yn} is the combination of torsional elasticity coefficients of the inner torsional beams, I_{xn} , I_{yn} are the equatorial inertia moments of the N_{th} equilibrium ring, and I_{zn} is the polar moment of inertia the N_{th} equilibrium ring.

The instantaneous angle of the driving shaft around the OX_2 -axis relative to the inertia coordinate is given by ϕ . Given this input angular rate, the angles of the spin axis of the gyroscope rotor wafer around the positive X_2 -axis and Y_2 -axis relative to the driving shaft β , α can be written as Eq. (6):

$$\begin{cases} \beta = \phi \cos \Omega t \\ \alpha = -\phi \sin \Omega t \end{cases} \quad (6)$$

Take the derivative of Eq. (6) gives Eq. (7) :

$$\begin{cases} \dot{\beta} = -\phi \Omega \sin \Omega t \\ \dot{\alpha} = -\phi \Omega \cos \Omega t \end{cases} \quad (7)$$

Substituting Eqs. (6) and (7) into Eqs. (4) and (5) gives:

$$\begin{cases} M_{xn} = K_{xn} \phi \cos(\Omega t + \theta) \\ M_{yn} = [(I_{xn} + I_{yn} - I_{zn}) \Omega^2 - K_{yn}] \phi \sin(\Omega t + \theta) \end{cases} \quad (8)$$

Eq. (8) is the torque of the outer torsional beams applied to the rotor wafer, which is relative to the N_{th} equilibrium ring. Converting Eq. (8) into the rotor wafer coordinate, it can be written :

$$\begin{cases} M_{xn6} = M_{xn} \cos \theta - M_{yn} \sin \theta \\ M_{yn6} = M_{xn} \sin \theta + M_{yn} \cos \theta \end{cases} \quad (9)$$

where M_{xn6} and M_{yn6} are the torque components of the N_{th} equilibrium ring applied on the rotor wafer along the OX_6 -axis and OY_6 -axis, respectively.

Since the torque of each equilibrium ring is applied on the rotor wafer, the sum of the torques applied to the rotor wafer is:

$$\begin{cases} M_{x6} = \sum_{n=1}^3 (M_{xn} \cos \theta - M_{yn} \sin \theta) \\ M_{y6} = \sum_{n=1}^3 (M_{xn} \sin \theta + M_{yn} \cos \theta) \end{cases} \quad (10)$$

The torques in Eq. (10) projected onto the OX_1 -axis and OY_1 -axis are:

$$\begin{cases} M_{x1} = \sum_{n=1}^3 \frac{1}{2} \left[(K_{xn} + K_{yn} - K_{en}) \phi \right. \\ \quad \left. + (K_{xn} - K_{yn} + K_{en}) \phi \cos 2(\Omega t + \theta) \right] \\ M_{y1} = \sum_{n=1}^3 \frac{1}{2} (K_{xn} - K_{yn} + K_{en}) \phi \sin 2(\Omega t + \theta) \end{cases} \quad (11)$$

where $\sum_{n=1}^3 \frac{1}{2} (K_{xn} + K_{yn}) \phi$ is the positive elastic torque generated by the twisting motion of torsional beams applied on the rotor wafer, whereas $\sum_{n=1}^3 \frac{1}{2} K_{en} \phi =$

$\sum_{n=1}^3 \frac{1}{2} (I_{xn} + I_{yn} - I_{zn}) \Omega^2 \phi$ is the inverse elastic torque generated by pendulum motion of the equilibrium rings. The sum of the positive elastic torque and the inverse elastic torque is constant. This is particularly significant when the constant torque is zero and a dynamically tuned state is achieved. In addition, $\sum_{n=1}^3 \frac{1}{2} (K_{xn} - K_{yn} + K_{en}) \phi \cos 2(\Omega t + \theta)$ is the second harmonic torque.

When the DTG has only one equilibrium ring, to make the constant torque and the second harmonic to be zero, Eq. (12) must be satisfied:

$$\begin{cases} K_{xn} + K_{yn} - K_{en} = 0 \\ K_{xn} - K_{yn} + K_{en} = 0 \end{cases} \quad (12)$$

For a general case, set $K_{xn} = K_{yn}$ and $\Omega^2 > 0$. In order to satisfy the dynamically tuned condition, $I_{x1} + I_{y1} - I_{z1} > 0$

must be satisfied. In order to eliminate the second harmonic torque, $I_{x1} + I_{y1} - I_{z1} = 0$ must be satisfied. Thus, dynamic tuning cannot be maintained while eliminating the second harmonic torque with a single equilibrium ring.

Adding equilibrium rings increases the complexity of the MDTG. When the MDTG has three equilibriums, it can be shown: $\theta_1 = 0$, $\theta_2 = \frac{\pi}{2}$, $\theta_3 = 0$. The dynamically tuned condition is:

$$K_{x3} + K_{y3} - K_{e3} + K_{x4} + K_{y4} - K_{e4} + K_{x5} + K_{y5} - K_{e5} = 0$$

$$\Rightarrow K_{x3} + K_{y3} + K_{x4} + K_{y4} + K_{x5} + K_{y5} = K_{e3} + K_{e4} + K_{e5} \quad (13)$$

The condition for eliminating the second harmonic torque is:

$$K_{x3} - K_{y3} + K_{e3} - K_{x4} + K_{y4} - K_{e4} + K_{x5} - K_{y5} + K_{e5} = 0$$

$$\Rightarrow K_{x3} - K_{y3} + K_{x5} - K_{y5} + K_{y4} - K_{x4} = K_{e4} - K_{e3} - K_{e5} \quad (14)$$

From Eqs. (13) and (14), it is obvious that the TMDTG can simultaneously achieve the dynamically tuned state and eliminate the second harmonic torque.

The moments of inertia may be defined as follows:

$$I_{x3} = I_{y3} = \frac{1}{4}(R^2 + r^2 + \frac{h_1^2}{3})m_1 \quad (15)$$

$$I_{x4} = I_{y4} = \frac{1}{4}(R^2 + r^2 + \frac{h_2^2}{3})m_2 \quad (16)$$

$$I_{x5} = I_{y5} = \frac{1}{4}(R^2 + r^2 + \frac{h_3^2}{3})m_3 \quad (17)$$

$$I_{z3} = I_{z4} = I_{z5} = I_z = \frac{1}{2}(R^2 + r^2)m_i \quad (18)$$

$$m_i = \pi(R^2 - r^2)h_i\rho, i = 1, 2, 3 \quad (19)$$

where R is the outer diameter of the equilibrium rings, r is the inner diameter of the equilibrium rings, h_1, h_2, h_3 are the thicknesses of the equilibrium ring I, II, III, respectively; m_1, m_2, m_3 are the masses of the equilibrium rings I, II, III; m_i denotes m_1, m_2, m_3 when i is 1, 2, 3 respectively; ρ is the density of the silicon; h_i denotes h_1, h_2, h_3 when i is 1, 2 and 3, respectively.

Substituting Eqs. (15), (16), (17), (18) and (19) into Eq. (14), the condition of eliminating the CTD can be simplified to Eq. (20):

$$h_1^3 + h_3^3 = h_2^3 \quad (20)$$

This becomes the design criteria for the proposed MDTG. The dynamically tuned condition can be simplified to Eq. (21):

$$h_1^3 + h_2^3 + h_3^3 = (36K_{x1}) / (\pi(R^2 - r^2)\rho) \quad (21)$$

Fig. 3. The solutions to Eq. (20) and (21)

where K_{x1} is the torsional coefficient of the torsional beams,

$$K_{x1} = \frac{J_z \Omega^2}{2Q}, J_z \text{ is the polar moment of inertia of the rotor}$$

wafer, $Q = \frac{J_z}{2I_{x(y)} - I_z}$ is the quality factor (which is

different from the quality factor of a resonant gyroscope). The CTD can be eliminated effectively as long as Eq. (20) is satisfied. Using MATLAB, Eqs. (20) and (21) are shown in Fig. 3. The pink plane displays solutions to Eq. (20), while the orange plane gives the solutions to Eq. (21). The intersection of the two planes gives common solutions to Eqs. (20) and (21), which means the dynamically tuned state and the elimination of the CTD can be simultaneously achieved. Limitations in manufacturing technology and the symmetry of the TMDTG present a tradeoff between structure parameters. Detailed structure parameters are listed in Table 1.

2.2 Reliability analysis of the torsional beams stiffness

Considering the three equilibrium rings structure, the small angle torsional stiffness of the torsional beams should be much smaller compared with the bending stiffness. According to the theoretical mechanics of materials, the tensile and compressive stiffness of the torsional beams can be expressed as Eq. (22):

$$K_t = \frac{EA}{l} \quad (22)$$

where E is the silicon modulus of elasticity, A is the sectional area of the torsional beams, and l is the length of the torsional beams.

The shear stiffness of the torsional beams can be expressed as:

$$K_s = \frac{GA}{f_s} = \frac{GA}{\frac{A}{P^2} \int \frac{q^2}{b^2} dA} \quad (23)$$

where G is the shear modulus of the torsional beams, f_s is the shear coefficient, $P = \frac{hb^3}{12}$ is the sectional moment of inertia, q is the sectional static moment, b is the width of the torsional beams, h is the thickness of the torsional beams. The bending stiffness of the torsional beams can be expressed as:

$$K_b = \frac{EP}{l} \quad (24)$$

When the axial load is applied on the torsional beams, the total axial stiffness can be written as Eq. (25), where K_{t2i} is the tensile and compressive stiffness of the inner beams of equilibrium ring II, and K_{s1o} and K_{b1o} are the shear stiffness and the bending stiffness of the outer beams of equilibrium ring I, respectively. K_{s3o} and K_{b3o} are the shear stiffness and the bending stiffness of the outer beams of equilibrium ring III, respectively.

$$K_a = \left[\frac{1}{2K_{t2i}} + \frac{1}{2K_{t2i}} \right]^{-1} + \left[\frac{K_{s1o} + K_{b1o}}{2K_{s1o}K_{b1o}} + \frac{K_{s1o} + K_{b1o}}{2K_{s1o}K_{b1o}} \right]^{-1} + \left[\frac{K_{s3o} + K_{b3o}}{2K_{s3o}K_{b3o}} + \frac{K_{s3o} + K_{b3o}}{2K_{s3o}K_{b3o}} \right]^{-1} \quad (25)$$

$$= K_{t2i} + \frac{K_{s1o}K_{b1o}}{K_{s1o} + K_{b1o}} + \frac{K_{s3o}K_{b3o}}{K_{s3o} + K_{b3o}}$$

When a radial load is applied on the inner beams and outer beams, the total radial stiffness can be written as Eq. (26), where K_{t1o} is the tensile and compressive stiffness of the outer beams of equilibrium ring I. K_{s2i} and K_{b2i} are the shear stiffness and the bending stiffness of the inner beams of equilibrium II. K_{s2o} and K_{b2o} are the shear stiffness and the bending stiffness of the outer beams of equilibrium II. K_{t3o} is the tensile and compressive stiffness of the outer

beams of equilibrium III.

$$K_r = \left[\frac{K_{s2i} + K_{b2i}}{2K_{s2i}K_{b2i}} + \frac{K_{s2o} + K_{b2o}}{2K_{s2o}K_{b2o}} \right]^{-1} + \left[\frac{1}{2K_{t1o}} + \frac{K_{s1o} + K_{b1o}}{2K_{s1o}K_{b1o}} \right]^{-1} + \left[\frac{1}{2K_{t3o}} + \frac{K_{s3o} + K_{b3o}}{2K_{s3o}K_{b3o}} \right]^{-1}$$

$$= \frac{2K_{s2i}K_{b2i}K_{s2o}K_{b2o}}{K_{s2i}K_{s2o}K_{b2o} + K_{b2i}K_{s2o}K_{b2o} + K_{s2i}K_{s2o}K_{b2i} + K_{s2i}K_{b2i}K_{b2o}} + \frac{2K_{t1o}K_{s1o}K_{b1o}}{K_{s1o}K_{b1o} + K_{t1o}K_{s1o} + K_{t1o}K_{b1o}} + \frac{2K_{t3o}K_{s3o}K_{b3o}}{K_{s3o}K_{b3o} + K_{t3o}K_{s3o} + K_{t3o}K_{b3o}} \quad (26)$$

After substituting the structure parameters in Table 1 into Eqs. (22), (23), (24), (25), and (26), the calculated stiffness values are summarized in Table 2. All of the outer beams and inner beams have the same structure, thus their tensile and compressive stiffness (K_t), shear stiffness (K_s) and bending stiffness (K_b) are the same. The tensile and compressive stiffness (K_t), the shear stiffness (K_s), and the bending stiffness (K_b) of the torsional beams are 832 N/m, 18.368 N/m, and 4.373×10^{-4} N/m, respectively, as shown in Table 2. The total axial stiffness (K_a) and the total radial stiffness (K_r) are 832 N/m and 1.09×10^{-3} N/m, respectively. Comparison of these numbers demonstrates that the torsional beams can provide enough stiffness for driving the rotor wafer and the equilibrium rings.

The torsional beams of TMDTG and MDTG have the same structure, thus the torsional stiffness (K_x) is identical between TMDTG and MDTG. Because the torsional stiffness (K_x) is much smaller than the total axial stiffness (K_a) and the total radial stiffness (K_r), it may be ignored.

Fig. 4 shows the spring structure design of the TMDTG. When an axial load is applied on the torsional beams, the beams connected with equilibrium ring II are affected by

Table 1. The parameters of TMDTG

Parameter		Value
Rotor wafer	Inner diameter	6mm
	Outer diameter	10mm
	Thickness	500μm
Inner ring	Inner diameter	1.5mm
	Outer diameter	2.5mm
	Thickness	500μm
Torsional beams	Length(l)	1mm
	Width(b)	80μm
	Thickness(h)	80μm
Equilibrium rings	Inner diameter(r)	3.5mm
	Outer diameter(R)	5mm
The thickness of the equilibrium rings	I(h ₁)	126μm
	II(h ₂)	158μm
	III(h ₃)	126μm
Distance between the equilibrium rings and the surface of the rotor wafer	I and II	30μm
	II and III	30μm
	I and the upper surface of the rotor	15μm
	III and the bottom surface of the rotor	15μm

Table 2. The calculated stiffness values of the torsional beams

K_t (N/m)	K_s (N/m)	K_b (N/m)
832	18.368	4.373×10^{-4}
K_a (N/m)	K_r (N/m)	
832	1.09×10^{-3}

Fig. 4. The spring structure design of TMDTG

tension (pressure) and the beams connected with equilibrium rings I and III are affected by shearing and bending. Also, when a radial load is applied on the torsional beams, the beams of equilibrium ring II are affected by shearing and bending, the inner beams of equilibrium rings I and III are affected by tension (pressure) and the outer beams of equilibrium rings I and III are affected by shearing and bending. The optimal spring structure design shown in Fig. 4 allows the structure to reach a dynamically tuned state.

2.3 The kinetic model of TMDTG

When the moving coordinate connects with the rigid body and coincides with the inertia principal axis, the Euler kinetic equation of the rigid body rotating around a fixed point can be written as Eqs. (27), (28) and (29).

$$J_x \frac{d\omega_x}{dt} + (J_z - J_y) \omega_y \omega_z = M_x \quad (27)$$

$$J_y \frac{d\omega_y}{dt} + (J_z - J_x) \omega_x \omega_z = M_y \quad (28)$$

$$J_z \frac{d\omega_z}{dt} + (J_y - J_x) \omega_x \omega_y = M_z \quad (29)$$

where J_x, J_y, J_z are the moments of inertia of the rigid body around the x, y, or z axis, respectively. $\omega_x, \omega_y, \omega_z$ are the rigid body rotation angular rate projections on the moving coordinate axis x, y and z, respectively. M_x, M_y, M_z are the external torque projections on the moving coordinate axis x, y, and z applied on the rigid body, respectively.

$$\omega_{x6} = \dot{\gamma} - (\Omega + \dot{\phi}_z) \phi + \dot{\phi}_x \cos \theta + \dot{\phi}_y \sin \theta \quad (30)$$

$$- \dot{\phi}_x \gamma \phi \sin \theta + \dot{\phi}_y \gamma \phi \cos \theta$$

$$\omega_{y6} = \dot{\phi} + \left(\Omega + \dot{\phi}_z \right) \gamma - \dot{\phi}_x \sin \theta + \dot{\phi}_y \cos \theta \quad (31)$$

$$\omega_{z6} = \left(\Omega + \dot{\phi}_z \right) + \dot{\gamma} \phi + \dot{\phi}_x \phi \cos \theta \quad (32)$$

$$+ \dot{\phi}_y \phi \sin \theta + \dot{\phi}_x \gamma \sin \theta - \dot{\phi}_y \gamma \cos \theta$$

$$\begin{aligned} & \underbrace{\left(J_e + \frac{3I_1}{2} \right)}_{J_1} \ddot{\alpha} - \underbrace{(J_z + 3I_1)}_H \Omega \dot{\beta} + \underbrace{\left[3K_p - (3I_1 - \frac{3I_z}{2}) \Omega^2 \right]}_{\Delta K} \alpha - \underbrace{(3K_c + 3K_d)}_D \Omega \beta = 3M_y - \underbrace{\left(J_e + \frac{3I_1}{2} \right)}_{J_1} \ddot{\phi}_y + \underbrace{\left(J_z + \frac{3I_z}{2} \right)}_{H^*} \Omega \dot{\phi}_x \\ & \underbrace{\left(J_e + \frac{3I_1}{2} \right)}_{J_1} \ddot{\beta} + \underbrace{(J_z + 3I_1)}_H \Omega \dot{\alpha} + \underbrace{\left[3K_p - (3I_1 - \frac{3I_z}{2}) \Omega^2 \right]}_{\Delta K} \beta + \underbrace{(3K_c + 3K_d)}_D \Omega \alpha = 3M_x - \underbrace{\left(J_e + \frac{3I_1}{2} \right)}_{J_1} \ddot{\phi}_x - \underbrace{\left(J_z + \frac{3I_z}{2} \right)}_{H^*} \Omega \dot{\phi}_y \end{aligned} \quad (37)$$

According to the relative motion relationship among coordinates, the absolute angular rate of the rotor wafer can be written using Eqs. (30), (31) and (32). By analyzing the torque applied on the rotor wafer, it can be shown that the external torque around the X-axis and Y-axis applied to the

rotor wafer of the MDTG with a single equilibrium ring can be written as Eqs. (33) and (34):

$$M_{x6} = -K_p \gamma - K_c \dot{\gamma} - I \ddot{\gamma} - (I_z - I) \Omega^2 \gamma + (M_x - K_d \Omega \gamma) \cos \theta + (M_y + K_d \Omega \beta) \sin \theta \quad (33)$$

$$M_{y6} = -K_p \phi - K_c \dot{\phi} + (M_y + K_d \Omega \beta) \cos \theta - (M_x - K_d \Omega \alpha) \sin \theta \quad (34)$$

where K_p is the positive stiffness coefficient of the torsional beams, K_c is damping coefficient of the torsional beams, I is the moment of inertia of each equilibrium ring around the x and y axis where $I \approx I_{x3} \approx I_{x4} \approx I_{x5}$, M_x and M_y are the disturbance torques applied on the rotor wafer, and K_d is the damping coefficient of the rotor wafer around its spin axis. Since the TMDTG has three equilibrium rings and $J_x = J_y = J_e$, the kinetic Eq. (29) can be ignored. Substituting Eqs. (30), (31), (32), (33) and (34) into (27) and (28), the Euler kinetic equation can be written as Eqs. (35) and (36).

$$J_e \frac{d\omega_{x6}}{dt} + (J_z - J_e) \omega_{y6} \omega_{z6} = 3M_{x6} \quad (35)$$

$$J_e \frac{d\omega_{y6}}{dt} + (J_e - J_z) \omega_{x6} \omega_{z6} = 3M_{y6} \quad (36)$$

Eqs. (35) and (36) show that the external torque around the X_6 -axis and Y_6 -axis applied on the rotor wafer is three times greater than that for a single ring, indicating that the structure is more stable compared with the MDTG. By ignoring the second harmonic torque and the third order microscale item, and considering $\Omega \beta \gg \dot{\alpha}$, $\Omega \alpha \gg \dot{\beta}$, the kinetic equations of TMDTG may be expanded into Eq. (37), where $I_1 = I_x = I_y$ is the moment of inertia, ΔK is the residual stiffness coefficient, and D is the composite damping coefficient. J_1 is the moment of inertia and H is the momentum moment, K_{bc} is the angle to capacitance transformation coefficient, K_{cv} is the capacitance to voltage transformation coefficient, and K_{vf} is the voltage to torque transformation coefficient. These coefficients are listed in Table 3.

According to [20], the total disturbance torque applied

on the rotor wafer can be expressed as:

$$M_{x(y)} \approx K_f V_{fx(fy)} + K_{uf} \beta(\alpha) \quad (38)$$

where K_f is the torque coefficient and K_{uf} is the inverse

Table 3. Parameters of the digitized dual-axis closed-loop detection circuit

Parameter	Value(kg·m ² /s)	Parameter	Value(kg·m ² /s)
J_1	3.53×10^{-9}	H	7.40×10^{-6}
K_{bc}	1.63×10^{-9}	K_{cv}	7.36×10^{10}
K_{vf}	-2.39×10^{-7}		

stiffness coefficient. $V_{fx(fy)}$ is the feedback voltage which will be explored in section 3.

By ignoring the damping torque, the second harmonic torque, and considering $J_z \gg I_z$, $J_z \gg I_z$, $H^* \approx H$, the kinetic equations can be simplified as Eqs. (39) and (40).

$$J_1 \ddot{\alpha} - H \dot{\beta} + (\Delta K - 3K_{uf})\alpha = 3M_y - J_1 \ddot{\phi}_y + H \dot{\phi}_x \quad (39)$$

$$J_1 \ddot{\beta} + H \dot{\alpha} + (\Delta K - 3K_{uf})\beta = 3M_x - J_1 \ddot{\phi}_x - H \dot{\phi}_y \quad (40)$$

Because of the existence of processing error, the residual stiffness coefficient ΔK cannot be completely eliminated. Therefore, a high preload voltage is used to achieve a dynamically tuned state.

In the ideal dynamically tuned state, the Laplace transform of the Eqs. (39) and (40) can be expressed as Eq. (41):

$$\begin{bmatrix} \beta(s) \\ \alpha(s) \end{bmatrix} = 3G(s) \begin{bmatrix} M_x(s) \\ M_y(s) \end{bmatrix} - \begin{bmatrix} \phi_x(s) \\ \phi_y(s) \end{bmatrix} \quad (41)$$

where

$$G(s) = \begin{bmatrix} \frac{1/J_1}{s^2 + (H/J_1)^2} & -\frac{H/J_1^2}{s[s^2 + (H/J_1)^2]} \\ \frac{H/J_1^2}{s[s^2 + (H/J_1)^2]} & \frac{1/J_1}{s^2 + (H/J_1)^2} \end{bmatrix} \quad (42)$$

Compared with the dynamically tuned gyroscope with only one equilibrium, the values of the inertia moment J_1 and the momentum moment H are larger, which eliminates drift error caused by the CTD. Simulation results are introduced in section 4.

2.4 The model simulation

In order to verify the basic principle of TMDTG, a simulation was implemented utilizing ANSYS software. Simulation results of some unexpected resonant modes are shown in Fig. 5.

When TMDTG rotates at a high speed, up to more than 10000 r/m (167Hz), the equilibrium rings and the rotor wafer obtain a sufficient and stable moment of inertia. At this rotational rate, the rotor wafer and the equilibrium

Fig. 5. The simulation model utilizing the ANSYS software (a) The mode rotating along X-axis at the frequency of 1.69kHz and (b) the mode rotating along Y-axis at the frequency of 1.73kHz

rings also rotate along the inner beams and the outer beam. In an ideal situation, the TMDTG is dynamically tuned. Theoretically, the inverse stiffness of equilibrium rings can cancel out the positive stiffness of the torsional beams, where the residual stiffness is approximately equal to zero. Fig. 5 (a) displays an undesirable resonant mode where the rotor wafer rotated along the X_3 (X_5) axis at the frequency of 1.69 kHz. Fig. 5 (b) is another undesirable resonant mode where the rotor wafer rotated along the Y_3 (Y_5) axis at the frequency of 1.73 kHz. It is obvious that the rotation frequency (167Hz) is far from the resonant frequency (about 1.7 kHz), indicating that the potential resonant mode will not be excited by the rotational frequency of the rotor.

3. Design of the Digitized Dual-axis Closed-loop Detection Circuit

Fig. 6 shows the schematic diagram of the digitized dual-axis closed-loop detection circuit. When TMDTG rotates at high speed, the external input angular rate can be detected by the upper and lower sensing electrode plates (ESU_x , ESU_y , ESL_x , ESL_y). The capacitive change between the sensing electrode plates (ESU_x , ESU_y , ESL_x , ESL_y) and

rotor wafer is converted into a voltage signal by the diode ring demodulator. After filtering through a low-pass filter (LPF) circuit and A/D sampling, the voltage signal is processed using FPGA. Considering TMDTG is a two-degree of freedom gyroscope system with X-axis and Y-axis loops, there is a strong dual-axis cross coupling effect. This coupling effect may lead to high frequency nutation, degrading performance and limiting the dynamic operating range. Therefore, to improve performance, the decoupling block (D) should be designed to decrease dual-axis interaction. In addition, the TMDTG open-loop system was designed as a type-II system. The lead-lag correction (GJ) was adopted to attain the necessary gain margin and phase margin. Both the decoupling block and correction block were simulated in DSP Builder tools. Through the D/A conversion module and adjustments to the gain control (GC) block, the voltage signal (V_{fx} or V_{fy}) and the preload high voltage (PLHV) were converted into a torque signal by the block (K_{vf}). By feeding back the processed torque signal to the upper and lower torque feedback electrode plates (TFDU_x, TFDU_y, TFDL_x, TFDL_y), the closed-loop decoupling system was successfully implemented.

3.1 Design of decoupling block

Considering the superiority of the digitized dual-axis closed-loop detection circuit over the pure analog circuits, the blocks of decoupling (D) were simulated in DSP Builder/MATLAB tools. Here the DSP Builder is a digital domain simulation tool, thus the transfer function must be discrete and the coefficients must be converted into binary complement code for real hardware operation. Given that the TMDTG is a type-II system, the transfer function can be written as Eq. (43):

$$\mathbf{G}' = \mathbf{GD} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} = \begin{bmatrix} G'_{11} & 0 \\ 0 & G'_{22} \end{bmatrix} \quad (43)$$

where

$$\mathbf{G}' = \begin{bmatrix} G'_{11} & 0 \\ 0 & G'_{22} \end{bmatrix} = \begin{bmatrix} \frac{1}{Hs^2} & 0 \\ 0 & \frac{1}{Hs^2} \end{bmatrix} \quad (44)$$

By bilinear transform and calculation in MATLAB, the Z-domain decoupling matrix D can be written as Eqs. (45), (46) and (47). All coefficients of Eqs. (46) and (47) are listed in Table 4.

$$\mathbf{D}(z) = \begin{bmatrix} G_{11}(z) & G_{12}(z) \\ G_{21}(z) & G_{22}(z) \end{bmatrix}^{-1} \begin{bmatrix} G'_{11} & 0 \\ 0 & G'_{22} \end{bmatrix} \quad (45)$$

$$D_{11}(z) = D_{22}(z) = \frac{a_{11}z^4 + a_{12}z^3 + a_{13}z^2 + a_{14}z + a_{15}}{b_{11}z^4 + b_{12}z^3 + b_{13}z^2 + b_{14}z + b_{15}} \quad (46)$$

Table 4. The coefficients of the Eqs. (46), (47) and (48)

Coefficient	Fixed Point Value	Coefficient	Fixed Point Value
a ₁₁	33059	a ₁₂	6260
a ₁₃	-53598	a ₁₄	6260
a ₁₅	33059	b ₁₁	65536
b ₁₂	11007	b ₁₃	-103716
b ₁₄	11007	b ₁₅	65536
c ₁₁	4865	c ₁₂	15329
c ₁₃	-14702	c ₁₄	-14702
c ₁₅	15329	c ₁₆	4865
d ₁₁	65536	d ₁₂	-54530
d ₁₃	-114722	d ₁₄	114722
d ₁₅	54530	d ₁₆	-65536
e ₁₁	2206597	e ₁₂	-2162688
e ₁₃	57829	e ₁₄	57829
f ₁₁	65536	f ₁₂	-21843
f ₁₃	65536	f ₁₄	50115
K ₁	1101005		

$$D_{12}(z) = -D_{21}(z) = \frac{c_{11}z^5 + c_{12}z^4 + c_{13}z^3 + c_{14}z^2 + c_{15}z + c_{16}}{d_{11}z^5 + d_{12}z^4 + d_{13}z^3 + d_{14}z^2 + d_{15}z + d_{16}} \quad (47)$$

3.2 Design of the correction block

In order to establish the necessary gain margin and phase margin, the lead-lag correction was adopted. By bilinear transform and calculation in MATLAB, the correction block can be transformed as Eq. (48):

$$GJ(z) = K_1 \frac{(e_{11}z + e_{12})(e_{13}z + e_{14})}{(f_{11}z + f_{12})(f_{13}z + f_{14})} \quad (48)$$

where all the coefficients in Eq. (48) are listed in Table 4. The coefficients in Eq. (48) are also converted into binary complement code.

4. Simulation of the Digitized Dual-axis Closed-Loop Detection Circuit

Based on the schematic diagram in Fig. 6, a set of simulations were conducted in realistic conditions to verify the performance of the digitized dual-axis closed-loop system. By default, all parameters of the digitized detection circuit were given nominal values and both external input rates V_x and V_y were set to 0°/s. Vout1 and Vout2 are output signals after the D/A block, where Vout1 corresponds to V_y and Vout2 corresponds to V_x . As shown in Fig. 7, the coupling effect may be totally reduced when V_y is set to $\sin(10\pi t)$ /s and V_x is set to $\sin(100\pi t)$ /s, respectively.

5. Experimental Results

The digitized decoupled dual-axis micro dynamically

Fig. 6. The digitized dual-axis closed-loop detection circuit of TMDTG

Fig. 7. The decoupling results of system simulation in MATLAB (a) V_y is set to $\sin(10\pi t)$ o/s and (b) V_x is set to $\sin(100\pi t)$ o/s

tuned gyroscope with three equilibrium rings (TMDTG) was investigated experimentally to verify both principle and performance. Based on the schematic diagram in Fig. 6, the experimental TMDTG setup was designed and debugged as shown in Fig. 8. Fig. 8 (a) shows an oscilloscope, a multimeter, a motor, two power sources, and the test setup system. In order to verify the feasibility of the digitized dual-axis closed-loop detection circuit, the correction block and decoupling block were included using FPGA. The FPGA circuit board shown in Fig. 8 (b) includes the A/D, D/A, FPGA and various other power conversion chips. Fig. 8 (c) shows the rotor wafer, which is driven by the driving shaft. The motor drives the rotor wafer rotation along the driving shaft.

The oscilloscope and multimeter displayed zero bias output in the absence of an angular rate input. The upper

Fig. 8. The experimental setup of TMDTG: (a) The test setup of TMDTG and (b) The FPGA circuit board and (c) TMDTG structure

Fig. 9. The drift data of TMDTG system. (a) X-axis drift data of TMDTG and (b) Y-axis drift data of TMDTG

power supply drives the motor and the PCB board. The lower power source provides the preloaded high voltages of 40 V and 60 V, respectively, for the digitized dual-axis closed-loop system.

Drift data comes from the measurement system of the

Fig. 10. The fitting lines of the digital signal output versus input angular rates for X-axis and Y-axis

Fig. 11. The experimental results of TMDTG closed-loop system

TMDTG with 3600 s sampling interval as depicted in Fig. 9. The drift mean value is about 0.068V in the X-axis and 0.064V in the Y-axis.. Fig. 10 shows the fitting lines of the digital signal output versus the input angular rates for the X-axis and Y-axis, respectively, within the input range of -400°/s to 400°/s for both dual axis (Note: Fig. 10 was recorded in FPGA).

In Fig. 10, the output signal is converted into the 18 bit binary complement code. The fitting graph shows that the scale factor in the X-axis is 283 LSB/°/s and the scale factor in the Y-axis is 220 LSB/°/s. In addition, the scale factor non-linearity is 0.09% in the X-axis and 0.13% in the Y-axis. (Note: All experiments were performed at room temperature.)

When the external input angular rates V_x and V_y were set to $\sin(100\pi t)$ °/s and $\sin(10\pi t)$ °/s, respectively, the output signals of V_{out1} and V_{out2} are shown in Fig. 11. There were obvious coupling waves in V_{out1} and V_{out2} , which resulted from the cross coupling effect between the X- and Y-axes. Data analysis shows that the decoupling effect is about 1%. Thus, the digitized dual-axis closed-loop circuit can suppress the cross coupling effect.

6. Conclusions

This paper describes a novel TMDTG based on the

previous MDTG. Theoretical analysis has shown that the constant torque disturbance caused by the double rotation frequency of the driving shaft may be eliminated by adjusting the thickness of each equilibrium ring. Simulation results show the TMDTG can significantly reduce drift compared with the MDTG. The TMDTG model was simulated using ANSYS software, which demonstrated modal interference at a frequency around 1.69 kHz in the X-axis and 1.73 kHz in the Y-axis. To validate the capability of the proposed digitizer to decouple the signal from two sense channels, the TMDTG closed-loop system was built using the DSP Builder/MATLAB. Feasibility of the digitized detection circuit was verified by simulation. Finally, experimental results showed that the scale factor is 283 LSB/°/s in the X-axis and 220 LSB/°/s in the Y-axis. Drift was about 0.068V in the X-axis and 0.064 V in the Y-axis. The scale factor non-linearity was 0.09% in the X-axis and 0.13% in the Y-axis. However, due to the strong damping in the atmosphere, performance was inevitably degraded.

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