MSCSG two degree of freedom attitude measurement method

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Abstract. MSCSG (Magnetically Suspended Control & Sensing Gyroscope) is a new type of gyroscope which combines attitude control with attitude measurement. Firstly, the structure characteristics of the magnetic suspension control sensitive gyroscope are analyzed. On this basis, the dynamic model of MSCSG is established and calculated and simplified. Thus, the two degree of freedom attitude measurement method based on MSCSG is improved. Finally, the validity of the measurement method is verified by experiments. The experimental results show that the improved two degree of freedom attitude measurement method is effective and feasible.

1. Introduction

With the development of spacecraft application, the integration of spacecraft attitude measurement and control is an important development trend. MSCSG is an inertial device in the spacecraft attitude control loop. It is a new concept gyro that combines attitude control and attitude measurement functions \cite{1}. MSCSG has the outstanding advantages of low noise, micro-vibration, non-contact and so on. It is an ideal choice to effectively solve the very stable hyperstatic attitude control problem faced by high-resolution reconnaissance technology. The characteristics of MSCSG integration can greatly reduce the volume, weight and power consumption of spacecraft.

In the study of attitude measurement, Zheng Shiqiang \cite{2} combines the moment execution with the attitude measurement through the double frame magnetic levitation control moment gyroscope. However, the gyroscope bandwidth is low, and the high-order approximation accuracy has room for improvement. Liu Bin \cite{3} proposed a design scheme of magnetic levitation gyro flywheel. Although the control and measurement of magnetic levitation gyro flywheel can be carried out simultaneously, but this method has not been verified by experiments. Bristol Aerospace Co., Ltd. of Canada has developed a flexible gyroscopic flywheel device which integrates actuators and sensors\cite{4}. It can provide the control moment of three axes and measure the angular velocity of two axes simultaneously. It can significantly reduce the number of components needed in the attitude control system. The device has been successfully applied to the SCISAT-1 scientific experimental satellite launched by the Canadian Space Agency in 2003. However, the gyroscopic flywheel translational deflection channel is coupled, and the measurement accuracy is limited.

MSCSG, as the first international control sensitive gyroscope, has good linearity and no coupling. However, the research on MSCSG attitude measurement is not thorough enough. In this paper, a dynamic model of MSCSG is established based on its structural characteristics, and on the basis of predecessors, the attitude angle velocity measurement method based on MSCSG is improved. Finally, experimental verification will be carried out in combination with MSCSG material.
2. MScSG working principle and dynamic decoupling control

2.1. Working principle

The rotor system parameters of MScSG are shown in Table 1, where \( N \) denotes coil turns, \( L \) denotes coil span, \( J_z \) denotes rotor rotational inertia about \( z \) axis, \( x_0 \) denotes unilateral magnetic clearance, \( x_b \) denotes unilateral protection clearance, \( I_0 \) denotes control current, and \( l_m \) denotes moment diameter.

| Parameter name (unit) | Parameter values |
|-----------------------|------------------|
| \( N \) (turns)       | 200              |
| \( L \) (°)           | 84               |
| \( J_z \) (kg·m²)     | 0.0287           |
| \( x_0 \) (μm)        | 350              |
| \( x_b \) (μm)        | 200              |
| \( I_0 \) (A)         | 0.5              |
| \( l_m \) (mm)        | 114              |

MScSG is composed of high speed rotor, motor, sensor, and magnetic bearing. Figure 1 shows the schematic diagram of the MScSG gyro room structure. When the rotor rotates at high speed in its equilibrium position, the magnetic field generated by the axial magnetic bearing suspends. When rotation occurs, the rotor will produce a deflection angle along the \( x \) or \( y \) direction, and the high-precision sensor will detect the change of the rotor position and transmit it to the controller. The controller will apply the corresponding control current to the coil in the \( x \) or \( y \) direction, change the magnetic field distribution and generate the restoring force acting on the rotor, so that the rotor can return to the balance position. Finally, the angular velocity of MScSG can be deduced by measuring the control current on the coil [5]. The angular velocity measurement of MScSG is mainly related to radial rotational degree of freedom, so the following analysis will be made by analyzing the rotational degrees of freedom of the radial \( x \) and \( y \) directions of the rotor.

![Figure 1. Schematic diagram of MScSG gyro room structure.](image)

2.2. Dynamic modelling

When the attitude of the high-speed rotor changes, the magnetic bearing control system generates the corresponding electromagnetic force to counteract the gyro moment caused by the attitude change. Ignoring the electromagnetic coupling between radial bearings, the force \( f_m = \begin{pmatrix} f_x \\ f_y \end{pmatrix} \) of each passage in the bearing coordinate system can be expressed by linearizing the force and current in a small range near the stable operating point:
\[ f_m = K_f I \]  
(1)

where \( I = (I_x, I_y) \) is the control current; \( K_f = BL \) is the current stiffness, \( B \) is the intensity of magnetic field, and \( L \) is the total length of the coil perpendicular to the magnetic field. \( f_m \) and \( f_u = \begin{pmatrix} M_x \\ -M_y \end{pmatrix} \) have the following coordinate relations:

\[ f_u = I_m f_m \]  
(2)

where \( I_m \) is the distance from the coil to \( O \), \( M_x \) and \( M_y \) are the synthetic moments of \( x \) and \( y \) axis respectively.

### 2.3. Decoupling control algorithm

When the rotor speed is very high, the gyroscopic effect is very remarkable, so gyro inclines easily. If the control method does not take into account this, it will cause instability of high speed rotor. In addition, the phase lag of the system also reduces the stability of gyro precession. In order to realize the stability of MSCSG rotor system, a PID controller is proposed to solve the above problems, which has cross feedback compensation \[2\]. \( G_{PID} \) for decentralized PID control, \( G_{cr} \) for cross feedback compensation, which is designed as follows:

\[ G_c(s) = G_{PID}(s) + G_{cr}(s) = (k_p + \frac{k_i}{s} + k_d)E_2 + \Omega(-\frac{k_i}{\tau_i s + 1} - \frac{k_d}{\tau_d s + 1})C_r \]  
(3)

where \( k_p \) is proportional gain, \( k_d \) is differential gain, \( k_i \) is integral gain, \( \tau_i \) and \( \tau_d \) are the high and low pass filter coefficients, \( I_2 \) is a unit matrix of 2×2, and \( C_r \) is a cross feedback matrix, the expression is:

\[ C_r = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \]

To achieve wider bandwidth for current proportional feedback control, the model of power amplifier system can adopt first order link, which is shown as:

\[ G_u(s) = \frac{k_w w_u}{s + w_u} E_2 \]  
(4)

where \( k_w \) is gain for power amplifier and \( w_u \) is the cut-off frequency.

In the feedback loop of the sensor signal, it is transmitted to the digital controller by the modulation circuit and the anti-aliasing filter, which is shown as:

\[ K_s(s) = \frac{k_s w_s}{s + w_s} E_2 \]  
(5)

where \( k_s \) is sensor gain and \( w_s \) is the cut-off frequency of anti-aliasing filter.

### 3. Two degree of freedom attitude measurement method

(i) The MSCSG rotor control system is composed of a controller, a signal conditioning circuit, an electromagnet rotor and sensors. In Figure 2, \( O \) is the centroid and the origin. \( \Omega \) is the rotation speed of
the rotor. \( \alpha \) and \( \beta \) are the radial deflection angles of rotors around \( x \) and \( y \) axis.

Figure 2. Schematic diagram of MSCSG rotor structure and control system

According to Newton second law, the dynamic model of MSCSG is as follows [7]:

\[
M_{g_x} = H\dot{\phi}_x + J\ddot{\phi}_x \\
M_{g_y} = -H\dot{\phi}_y + J\ddot{\phi}_y
\]  

(6)

where \( J_x \) is the rotary inertia of the rotor on the \( x \) and \( y \) axis, \( H = J_z \Omega \) is the rotor angular momentum, \( J_z \) is the rotary inertia of the rotor on the \( z \) axis, \( \dot{\phi}_x \), \( \dot{\phi}_y \) are the angular velocities of the rotor around \( x \) and \( y \) axis, \( H\dot{\phi}_x \), \( H\dot{\phi}_y \) are the gyroscopic moment of propulsion for high speed rotor along \( x \) and \( y \) axis and \( J_x\dot{\phi}_x \), \( J_y\dot{\phi}_y \) are the inertial moments of the rotor along the \( x \) and \( y \) axis.

In the formula, the moment is made up of two parts: one is the precession moment of gyroscope caused by attitude angular velocity, the two is the moment of inertia caused by attitude angular acceleration. Since the rotor usually runs at very high rotational speeds and has great angular momentum, the attitude angular acceleration of the spacecraft is very small, the inertial moment term can be neglected as a small quantity.

The Laplace transform of (6) is:

\[
M_g(s) = T_M \varphi(s)
\]  

(7)

where \( M_g = \begin{pmatrix} M_{g_x}(s) \\ M_{g_y}(s) \end{pmatrix} \), \( T_M = \begin{pmatrix} 0 & H \\ -H & 0 \end{pmatrix} \), and \( \varphi(s) = \begin{pmatrix} \varphi_x(s) \\ \varphi_y(s) \end{pmatrix} \), \( \varphi_x(s) \) and \( \varphi_y(s) \) are transformed by \( \dot{\alpha} \) and \( \dot{\beta} \) Laplace transform respectively.

In attitude measurement mode, the estimation of attitude angular velocity can be expressed as:

\[
\dot{\varphi}(s) = T_{\dot{\varphi}}^{-1}M_g
\]  

(8)

According to Newton's second law and gyro technical equation, the rotor dynamic equation in generalized coordinate system is described as follows:

\[
M\ddot{q} + G\dot{q} = f
\]  

(9)
where \( M = \begin{pmatrix} J & 0 \\ 0 & J \end{pmatrix}, G = \begin{pmatrix} 0 & H \\ -H & 0 \end{pmatrix}, f_u = \begin{pmatrix} M_y \\ -M_x \end{pmatrix}, \) and \( q = \begin{pmatrix} \alpha \\ -\beta \end{pmatrix} \). In general, \( M, G, f_u \) and \( q \) are called mass matrix, gyro array, generalized force and rotor position respectively.

The Laplace transform of (9) is:

\[
G_g = (Ms^2 + Gs)^{-1}
\]

Figure 3. Principle block diagram of attitude measurement system

Figure 3 is the block diagram of the attitude measurement system with all the above aspects. With the controller presented in (3), the magnetic bearing controller can compensate for external moment very well, thus can be obtained:

\[
\dot{\phi}(s) = T_w^{-1} \begin{pmatrix} M_{gy} \\ M_{gx} \end{pmatrix}
\]

(11)

In Figure 3 we can get the angular velocity measurement transfer function from \( \varphi(s) \) to \( \dot{\phi}(s) \) as follows:

\[
G(s) = C_{\varphi} \frac{F}{E + F} C_{\varphi}^{-1}
\]

(12)

where \( F = K_c G_w K_l G_b \) and \( C_{\varphi} \) is a constant transformation matrix:

\[
C_{\varphi} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}
\]

Combined (7), (11), and (12) get:

\[
\dot{\phi}(s) = T_w^{-1} K_c G_w I_w BIL
\]

(13)

where \( I = (I_x, I_y) \) is the detected current result. Through the formula (13), we can calculate the two degree of freedom attitude information of MSCSG from the measured current information.

4. Experimental verification

In order to prove the validity and feasibility of the conclusion in practice, The MSCSG prototype was tested on the turntable. The experimental setup is shown in Figure 4, it mainly includes the upper computer of turntable control box and MSCSG, the main body of MSCSG, the turntable body and the oscilloscope used to detect the displacement and current signals of MSCSG. In the experiment, MSCSG keeps 5000r/min rotating speed. The rotating angle of the turntable is 10 degrees, the frequency is 0.1Hz, that is, the rotating speed is 1 degree/s. Using the information provided by the oscilloscope, the attitude information of the rotor X axis and the Y axis can be obtained.
Figure 4. MSCSG experimental devices

Figure 5 shows the current waveform of the X channel and the Y channel. According to the combination of current information (13), the speed is 0.97 degree /s, which is very close to the actual speed. And the sensitive waveform is a good sine wave, which indicates that MSCSG can measure the angular velocity of the sensor sensitively. It is feasible to deduce the speed of spacecraft by controlling the current.

Figure 5. Current waveform of MSCSG radial x channel and Y channel

5. Conclusion
Based on a new concept gyro MSCSG, the attitude sensitivity characteristics of the gyroscope are analyzed and verified. First, based on the study of the physical characteristics of MSCSG, a rotor dynamic model is established. By simplifying the model, designing the controller and analyzing the control block diagram of attitude measurement system, and the two degree of freedom attitude measurement method of MSCSG is improved. Finally, the experimental results show that the current detected in the X and Y channels has good sinusoidal characteristics, which can achieve the purpose of tracking the rotor. The above experimental results prove the effectiveness and manoeuvrability of the MSCSG attitude measurement method proposed in this paper.

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