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Structure Optimization of Magnetic Levitation Motor Rotor

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Abstract. With the development of science and technology, magnetic suspension products are gradually favored by people for the characteristics of no friction and wear, no lubrication and long life. With the increasing consumption of fossil energy, magnetic levitation green energy-saving equipment is gradually studied by researchers. Taking magnetic suspension flywheel (MSMFW) as typical representative, magnetic suspension products in aerospace field have been greatly developed. As the core component of magnetic suspension flywheel, magnetic levitation motor has been widely studied. To obtain the better performance of magnetic levitation motor when it was used in magnetic suspended momentum flywheel, the motor rotor system structure was optimized in this paper. Firstly, the rotor system moment of inertia was calculated and analyzed, and the optimum ratio of polar moment of inertia to equatorial moment of inertia was obtained. Then the basic structure of motor rotor was designed on the basis of the rotor system dynamic analysis. Thirdly, based on the flywheel motor system model, the ANSYS Parametric Design Language (APDL) file was established, and it was applied to optimization software ISIGHT to complete the optimization. In the optimization process, the design variables boundary conditions were given, and the Sequence Quadratic Programming method was used for maintaining the optimization process and the optimization convergence results was obtained. The magnetic flux density as the optimization objective is increased from 0.393 T to 0.53 T through the optimization, which is 34.9% larger than before. It is of great significance for the magnetic levitation motor design, and the engineering application of magnetic levitation motor based on optimization results will be done in the future.

Keywords. Magnetic levitation motor, Optimization design, Moment of inertia, Sequence quadratic programming method

1. Introduction

Momentum flywheel as the main inertial actuators has been used for high accuracy spacecraft attitude control since decades [1-2]. The ball bearing used in momentum flywheel has been considered as one of the main factors which restrict the promotion of control accuracy for the disadvantages of abrasion, friction torque and vibration. Magnetic bearing with the desirable properties of no contact between stator and rotor, low jitter and no need for lubrication, has been widely applied in spacecraft gradually in recent years, and it is used in momentum flywheel, and MSMFW appeared finally.

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MSMFW with high speed, long life, low noise and high control accuracy gradually become dominant attitude control actuator for spacecraft [3-4].

To obtain the desirable performances of high control accuracy, low power consumption, small volume and high momentum output in the MSMFW, much work has been done by researchers. With the limited of costs and technical level, the early MSMFWs are usually suspended by active magnetic bearings combined with passive magnetic bearings. As early as the 1980s, a large amount of research work on MSMFW was carried out [5-7]. In 1986, France launched the first Earth observation satellite 'SPOT1' successfully equipped with a magnetic suspension flywheel as an attitude control device, which opened the prelude to the MSMFW application in space [5]. U. Bichler et al. [6] proposed a 3-DOF actively controlled of MSMFW for attitude control of spacecraft and studied the control method of 1-DOF to 5-DOF active control. K. Yabu-uchi et al. [7] raised a 3-DOF actively controlled of MSMFW with a gimbal-capable hybrid bearing supported by a combination of compact permanent magnet and electromagnetic. The above three types of MSMFW with active magnetic bearings and passive magnetic bearings combined have the advantages of low energy consumption and simple structure, which have been widely used in the aerospace field in the early stage. However, these types of MSMFW have low suspension precision, small stability margin and low control precision, which cannot meet the requirements of high performance attitude control. The 5-DOF actively controlled of MSMFW can solve the shortcomings well. Yasushi Horiuchi et al. [8] suggested a MSMFW which uses eight pairs of electromagnets to control the radial translation and deflection, a pair of electromagnet to achieve the axial translation, and 5-DOF actively controlled is realized finally, but the flywheel system consumes too much power. Hideyuki Sawda et al. [9] developed a MSMFW for high-stability attitude control of satellites, the flywheel is suspended and controlled by cone-shaped electromagnets, which effectively reduces the volume of the flywheel system, but the power consumption is too high and there is coupling in the axial and radial control directions.

In order to overcome the shortcomings of high power consumption, a solution for suspension support using a permanent magnet bias hybrid magnetic bearing appeared. A permanent magnet biased axial hybrid magnetic bearing for MSMFW is designed in [10], the performance parameters of magnetic bearing characteristics are analyzed and calculated, which provides a basis for the design and analysis of the MSMFW system. A new type of permanent magnet biased axial hybrid magnetic bearing structure with auxiliary air gap is designed to separate the bias magnetic flux path from the control magnetic flux path, which reduces the magnetic reluctance of the control magnetic circuit and the power consumption of axial magnetic bearings [11]. The prototype test showed that the device has perfect performance and high operational reliability. The dynamic model of the permanent magnet biased radial hybrid magnetic bearing of MSMFW is established in [12], a closed-loop controller that can be linearly controlled is designed through the analysis and calculation. The paper of [13-14] had done a lot of research work to improve the performance of the flywheel system, but all the focus of these works is on the control schemes and magnetic circuits design of magnetic bearing. The rotor system is the key component of the MSMFW system, its structure, mass, dynamic performance and other factors have the direct impact on the performance of the entire MSMFW system, how to realize the optimal mechanical structure of the MSMFW motor rotor is a problem to be solved. Based on the existing MSMFW system model, this paper used the Sequence Quadratic Programming method to optimize the motor rotor, the optimization results demonstrate that the optimization is effective.

2. MSMFW structure

The spacecraft attitude is controlled by MSMFW, which is worked by changing the rotor system angular momentum to realize the momentum exchange. The MSMFW model studied in this paper is shown in figure 1. It mainly consists of a rotor, a pair of radial hybrid magnetic bearings, a pair of axial hybrid magnetic bearings, one integrated radial/axial displacement sensor, one motor, two touchdown bearings, a shaft, a base and so on. The rotor output momentum torque by changing angular momentum. The radial hybrid magnetic bearing is used for controlling the radial translation of rotor and tilting the rotor, and the axial hybrid magnetic bearings are designed for supporting the rotor and controlling the axial translation. The radial and axial magnetic bearings are permanent magnet biased hybrid magnetic bearings, and the biased permanent magnets are used to reduce the consumption of power when the MSMFW works. The rotor displacements and tilting angles are measured by integrated radial/axial displacement sensor. Two touchdown bearings are used to support the rotor when the magnetic bearings are turned off or in case of failure, and allow the rotor spin down from its full operating to zero. This reasonable mechanical structure ensures that the MSMFW can work stably.

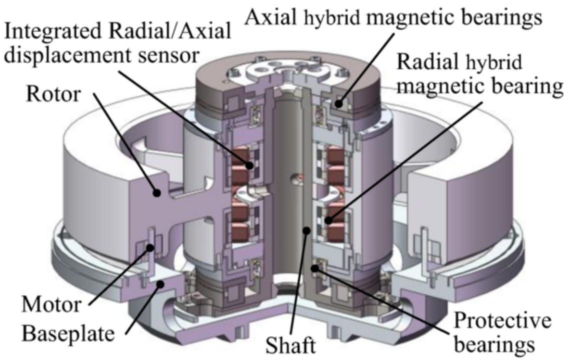

Figure 1. The construction of 15Nms MSMFW.

3. Rotor inertial moment analysis

With the increase of the rotational speed of the MSMFW rotor, precession and nutation modes will have frequency bifurcation under the influence of the strong Gyroscopic Coupling Effect, in which precession frequency is continuously reduced and finally tends to 0, while nutation frequency is constantly rising. This phenomenon brings great difficulty to build the MSMFW control system. Therefore, it is necessary to analysis the precession and nutation mode of the MSMFW rotor.

The gyro rotor is regarded as a rigid rotor, and the rotor centroid is defined as origin, *Z*-axis as the rotation axis, the inertial coordinate system is established. The 2-DOF gyro rotor dynamic equation can be written

$$\begin{cases} J_x\ddot{\alpha} + H\dot{\beta} = M_x \\ J_y\ddot{\beta} - H\dot{\alpha} = M_y \end{cases} \tag{1}$$

The MSMFW angular momentum and moment of inertia can be expressed

$$\begin{cases} H = J_p \Omega \\ J_x = J_y = J_e \end{cases} \tag{2}$$

Assuming the rotor is supported in a resilient manner, the stiffness of abutment is symmetrical and remains the same, it can be concluded that

$$\begin{cases} M_x = -k_\alpha \alpha \\ M_y = -k_\beta \beta \\ k_\alpha = k_\beta = k = \mathrm{C} \end{cases} \tag{3}$$

Combing with equation (2), (3), equation (1) can be written

$$\begin{cases} \ddot{\alpha} + \dfrac{J_P}{J_e} \Omega \dot{\beta} + \dfrac{k}{J_e} \alpha = 0 \\ \ddot{\beta} - \dfrac{J_P}{J_e} \Omega \dot{\alpha} + \dfrac{k}{J_e} \beta = 0 \end{cases} \tag{4}$$

The complex can be used to represent the rotor motions around the *X*-axis and *Y*-axis, and the generalized deflection angle can be described as

$$\varphi = \alpha + \beta \mathrm{i} \tag{5}$$

Equation (4) can be simplified

$$\ddot{\varphi} - \mathrm{i} \frac{J_P}{J_e} \Omega \dot{\varphi} + \frac{k}{J_e} \varphi = 0 \tag{6}$$

It can be seen the motion around the *X*-axis and *Y*-axis is periodic vibration from equation (6). The characteristic equation of equation (6) can be obtained

$$\omega^2 - \frac{J_P}{J_e} \Omega \omega + \frac{k}{J_e} = 0 \tag{7}$$

Combing with equation (7), the solution of equation (6) is given

$$\begin{cases} \omega_1 = \dfrac{1}{2}\left[\dfrac{J_P}{J_e} \Omega + \sqrt{\left(\dfrac{J_P}{J_e} \Omega \right)^2 + 4\left(\dfrac{k}{J_e} \right)^2} \right] \\ \omega_2 = \dfrac{1}{2}\left[\dfrac{J_P}{J_e} \Omega - \sqrt{\left(\dfrac{J_P}{J_e} \Omega \right)^2 + 4\left(\dfrac{k}{J_e} \right)^2} \right] \end{cases} \tag{8}$$

Obviously, the two eddy angular velocities vary as the angular velocity changes of the rotor, and ω_1 and ω_2 are functions of Ω, and J_p/J_e and k/J_e are the parameters which affect the eddy angular velocities. The parameter of k/J_e is kept unchanged, and the influence of the parameter J_p/J_e on ω_1 and ω_2 is studied. Under the undamped condition, the variation of ω_1, ω_2 with J_p/J_e is shown in figure 2.

It can be concluded that, when $J_p/J_e=1$, the rotor nutation frequency curve and the rotation curve will coincide, which causes the system resonance as the rotor speed increasing. When $J_p/J_e > 1$, the formula $\omega_1 > \Omega$ is always established, and the rotor system does not generate the resonance phenomenon at this time. The curve of precession frequency ω_2 will approach zero in the reverse direction as the rotor speed increasing, the precession frequency will not cause the system resonance in this condition. Considering the actual situation of MSMFW engineering and making the same mass flywheels output large torque as much as possible, the ratio of polar moment of inertia to equatorial moment of inertia is limited from 1.4 to 2. It can be written as $1.4 \leq J_p/J_e \leq 2$, which is beneficial to the MSMFW engineering stability control.

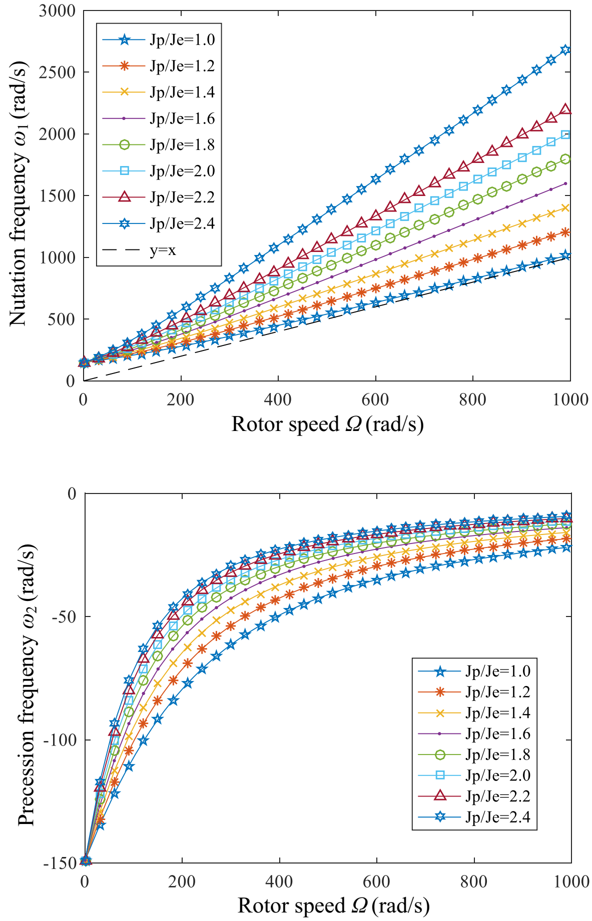

Figure 2. The eddy frequency curve with different ratio of J_p/J_e and Ω

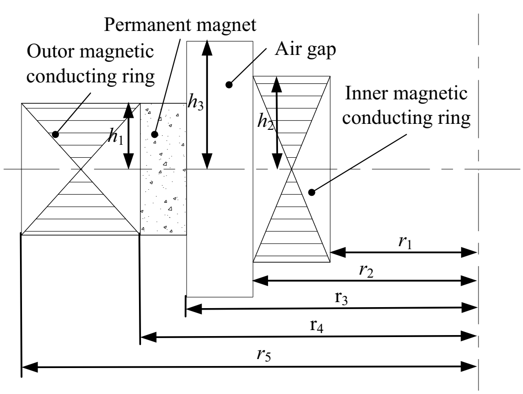

Figure 3. The schematic diagram of motor rotor structure

Based on the analysis above, the basic structure of magnetic levitation motor rotor was designed as shown in figure 3. The air gap size was kept unchanged, and the sizes of magnetic conducting rings and permanent magnet can be optimization.

4. Application of optimization method for MSMFW motor

4.1. Optimization model

Based on the above analysis of the MSMFW system, this paper used the software ANSYS to optimize the motor structural parameters of MSMFW which angular momentum is 15 Nms. The air gap of motor had been determined because of the practical engineering design requirements, only the magnetic conducting rings and permanent magnet of the MSMFW motor system can be optimized.

The design variables are expressed as

$$X = \left(r_1, r_4, r_5, h_1, h_2\right)$$

The objective function is established as

$$f_{max} = \max\left[\mathrm{F}\left(X\right)\right] \tag{9}$$

Where

$$\mathrm{F}\left(X\right) = \mathrm{F}\left(r_1, r_4, r_5, h_1, h_2\right)$$

In practical engineering applications, it is necessary to ensure that the motor topology model does not change, and the design variables need to be limited to a certain range. According to the actual engineering experience, the design variables' constraints are designed as

$$\begin{cases} 85\text{mm} \le r_1 \le 90\text{mm} \\ 100\text{mm} \le r_4 \le 105\text{mm} \\ 102\text{mm} \le r_5 \le 110\text{mm} \\ 4.4\text{mm} \le h_1 \le 6.5\text{mm} \\ 6\text{mm} \le h_2 \le 8\text{mm} \end{cases}$$

Based on the above model and boundary conditions, an optimization block diagram was built, and the APDL command file was established. Then the MSMFW motor rotor was optimized.

4.2. Optimization method and results

The relationship among MSMFW motor rotor structural parameters is nonlinear, which increases the system complexity. So the rotor system multi-disciplinary parameter optimization design should be carried out. Firstly, MSMFW motor rotor model was established. Then static and model analyses were calculated, and the Sequential Quadratic Programming method was applied to maintain the optimization process. The MSMFW motor rotor system optimization flow chart is shown in Figure 3.

According to the optimization calculation, the design variables optimization curves were obtained as shown in Figure 4, and the objective function curve were also plotted in Figure 5. In the first 6 steps, iterative directions of optimization parameters were calculated, and design variables value range were narrowed. Finally, the optimization calculation converges, and the optimal magnetic flux density was obtained through 96 steps iteration. The optimization results are shown in Table 1.

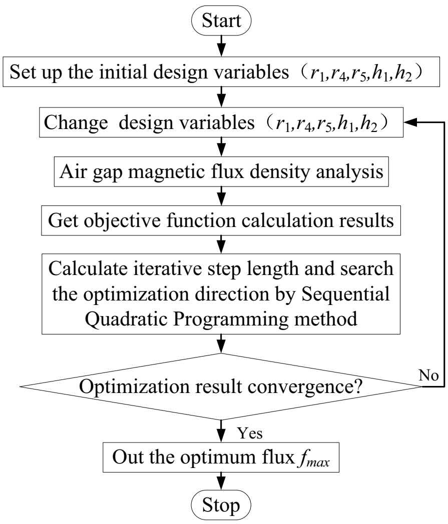

Figure 4. The optimization flow chart.

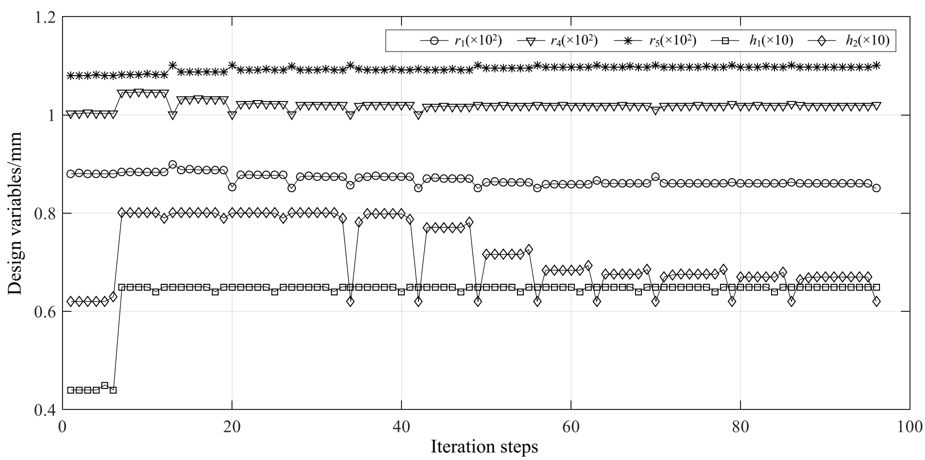

Figure 5. The optimization results of design variables.

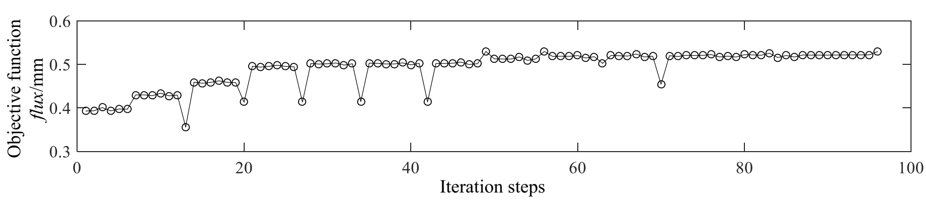

Figure 6. The optimization results of objective function.

Table 1. The results of optimization design

Variables	Before optimization	After optimization
r_1/mm	88	85
r_4/mm	100.3	102
r_5/mm	108	110
h_1/mm	4.4	6.5
h_2/mm	6.2	6.2
f_{max}/T	0.393	0.53

As shown in Table 1, all the boundary conditions can be satisfied after optimization. The magnetic flux density of air gap as optimization objective was increased from 0.393 T to 0.53 T, which is 34.9% larger than before. The optimization results indicate that the optimization method is effective.

5. Conclusion

This paper concerns a magnetic levitation motor rotor system structure optimization. The rotor dynamics was analyzed, and the optimum ratio of polar moment of inertia to equatorial moment of inertia was obtained, and the basic structure of motor rotor was designed. The Sequence Quadratic Programming method was applied in optimization software to maintain the optimization process, and the maximum magnetic flux density was calculated, and the corresponding motor structure was determined. The prototype of magnetic levitation motor based on the optimization is manufacturing, and further work will be studied in the future.

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Appendix I

C	constant
f_{max}	Maximum magnetic flux density (T)
h_1	half the height of permanent magnet (mm)
h_2	half the height of inner magnetic conducting ring (mm)
H	angular momentum (Nms)
i	imaginary unit
J_e	equatorial moment of inertia (kgm^2)
J_p	polar moment of inertia (kgm^2)
J_x, J_y, J_z	moment of inertia around X-axis, Y-axis and Z-axis (kgm^2)
k	generalized stiffness of gyro rotor to generalized coordinate system
k_α, k_β	support stiffness of magnetic bearing around the X-axis and Y-axis
M_x	torque acting on the rotor around the X-axis (Nm)
M_y	torque acting on the rotor around Y-axis (Nm)
r_1	inner radius of inner magnetic conducting ring (mm)
r_4	outer radius of permanent magnet (mm)
r_5	outer radius of outer magnetic conducting ring (mm)
α	rotor deflection angle around the X-axis (rad)
β	rotor deflection angle around the Y-axis (rad)
ω	eddy angular velocity (rad/s)
ω_1, ω_2	nutation and precession frequency (Hz)
Ω	rotor speed (r/min)
φ	rotor generalized deflection angle (rad)