Optimal design and experiment study of the double spherical rotor of the MSCSG

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Abstract
The magnetically suspended control and sense gyroscope (MSCSG) integrates spacecraft attitude measurement and control function; this paper proposes a double spherical rotor (DSR) for MSCSG. The DSR realizes the five degrees of freedom (DOFs) full active control and full channel magnetic path decoupling by the following design: the spherical axial/radial reluctance magnetic bearings are adopted to control the 3DOFs translation of rotor in the range of double spherical envelope, Lorentz force magnetic bearing (LFMB) is used to precisely drive the 2DOFs universal deflection of rotor. The optimization model is established based on the structural mechanical analysis, taking the deviation between rotor centroid and shape center as the optimization objective, choosing the first order resonance frequency, maximum equivalent stress, rigid body displacement, polar moment of inertia and inertia ratio as constraints. Then the DSR is optimized and simulated by the finite element, the MSCSG principle prototype based on DSR is successfully developed, the online dynamic balance experiment and modal test of the DSR are conducted, where the vibration amount of the DSR decreases from 20 μm before the experiment to 0.14 μm after the experiment, which decreases by 99.3%, the first test modal is 2881 Hz which is 5% different from the finite element simulation value of 3034 Hz. The results show that the DSR has the good mechanical properties and magnetic circuit decoupling characteristics.

Keywords
MSCSG, DSR, optimal design, finite element, experiment

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Introduction

MSCSG is a new concept gyroscope, which depends on the magnetic bearing suspension support and integrates spacecraft attitude measurement and control function. Magnetic bearing has the advantages of no friction, low power consumption, and long service life. MSCSG’s performance directly affects the overall performance of the attitude control system, so it has strict requirements for quality, volume, and accuracy. As the core component of the MSCSG, the mechanical structure and magnetic circuit design of the rotor are the key research objects.

In the aspect of mechanical structure, the general research method is to use the multi-disciplinary optimization software ISIGHT integrated finite element software ANSYS to optimize the rotor parameters. In Han et al., Ye et al. and Rafique et al., the optimization of the spoke rotor of the magnetically suspended reaction flywheel is carried out. The gyro disk rotor is optimal designed in Han et al. In Han and Yuan, the optimization of flywheel rotor is studied by combining sequence quadratic programming (NLPQL) and genetic algorithm. In these literatures, the composite structure of magnetic bearings with different degrees of freedom (DOF) is used are usually used. In Liu et al., the first-order resonance frequency of the locked rotor is analyzed under the condition of launching vibration. In Liu et al. and Wang et al., the spherical rotor driven by magnetic resistance and Lorentz force is studied. In Su et al., the stress of high-speed energy storage flywheel is analyzed. The common feature of the above literatures is that the rotor mass is taken as the optimization target, but the actual reduced mass has no substantial impact on the rotor system.

In the field of magnetic circuit design, the traditional research focuses on how to optimize the configuration relationship between permanent magnet and electromagnetic magnetic circuit. The purpose of these research is to reduce the power consumption and the mutual interference force between magnetic circuits, suppress the vibration of high-speed magnetic suspension rotor. A new research hotspot is to use the magnetic bearing clearance support to realize the multi-DOFs momentum exchange and integration of attitude measurement and control by driving the rotor to deflect along the equatorial plane axis in the magnetic clearance, this feature is called the micro-gimbal effect. Fan et al. and Li et al. reviewed the structure principle and development status of magnetically suspended micro-gimbal flywheel (MSMGF). Multiple MSMGF solutions is proposed in Liu et al., Gerlach et al. and Tang et al. However, the rotor of the micro-gimbal effect flywheel is usually a cylinder or cone, rotor deflection capacity is limited, attitude sensitive function is often as a subsidiary function, more importantly, it just stays in the conceptual stage without in-depth study.

Although the above research has promoted the development of the related technology, the key problem of magnetic circuit coupling is not been effectively solved. If we want to develop the high precision MSCSG, this problem is more important. This paper proposes a MSCSG double spherical rotor (DSR). The 2 translational DOFs in the equatorial plane and 1 translational DOF in polar direction are controlled by spherical radial and axial reluctance magnetic bearings. The 2 rotational
DOFs in the equatorial plane are controlled by LFMB. The optimization model is established based on the mechanical analysis and design requirement of DSR. The finite element analysis is simulated by combining ISIGHT and ANSYS software. The MSCSG principle prototype based on the DSR is developed successfully. Through the on-line dynamic balance experiment and modal test, the DSR’s good mechanical properties and magnetic circuit decoupling characteristics is verified.

**MSCSG DSR scheme**

**Scheme design**

MSCSG integrates the functions of 3DOFs momentum exchange and 2DOFs angular rate measurement, has the characteristics of high precision, high bandwidth and high functional density, the comprehensive performance advantages make it a new type of magnetically suspended inertial device with more development potential. MSCSG adopts double spherical suspension and drive technology, consists of gyro house, sensor, spherical radial and axial magnetic bearing, LFMB and motor, as shown in Figure 1. Where, spherical radial and axial magnetic bearings constitute double spherical magnetic pole envelope surfaces (MPES) to realize the rotor 3DOFs translational suspension, LFMB drives the rotor 2DOFs universal deflection, and the motor drives the rotor to rotate at high speed to output the moment of inertia. Theoretically, the spherical radial/axial magnetic bearings share the same center of sphere and coincide with the rotor centroid. The forces of the radial/axial magnetic bearings and LFMB point to the center of the rotor without mutual interference. Therefore, the full active control of the DSR and the full channel decoupling realizes, provides the scheme support for effectively improving the attitude control torque bandwidth and attitude sensitive accuracy of MSCSG.

The DSR is an inner rotor as shown in Figure 2, which is mainly composed of rotor disk, rotor shaft, LFMB rotor, motor rotor and sensor detection plate. Where, the working surface of the sensor detection plate is symmetrical up and down, and the displacement sensors locate on the axial outside as shown in Figure 1, which is used to sense the displacement and deflection angle of the rotor system along the axial direction. The radial spherical surface acts as the detection reference of the rotor radial displacement, and four displacement sensors distribute radially outside as shown in Figure 1.

Compared with the traditional magnetic suspension rotor, the characteristic of DSR is that its rotor disk & shaft act as a functional part as well as a structural part, specifically in the following two aspects.

(1) From the perspective of functional configuration, the rotor disk & shaft are composed of two spheres with the same spherical center located in the polar and equatorial directions of the rotor. The two spheres form the outer envelope of the DSR and constitute the rotor part of the axial/radial reluctance magnetic bearings respectively, the radial sphere also acts as the soft magnetic part of the rotor of the motor and LFMB. Meanwhile, the rotor disk & shaft should not
Figure 1. Contour structure of MSCSG.

Figure 2. Sketch map of DSR system.
only provide most of the rotor inertia, but also bear the LFMB rotor, motor rotor, sensor detection plate and other components as structural parts.

(2) From the perspective of material selection, as a part of the magnetic bearing and motor rotor, the rotor disk & shaft need to provide magnetic circuit medium, so the soft magnetic material with high permeability and high saturation magnetic density should be selected. At present, the commonly used soft magnetic materials mainly include electrical pure iron, iron cobalt vanadium (1J22) and iron nickel (1J50) soft magnetic alloy. Among them, electric pure iron has the advantages of high saturation magnetic density, low coercive force and high permeability, but it is easy to oxidize and rust, as the main body of the DSR, once rusted, the reliability of the rotor cannot be guaranteed. 1J50 has a high saturation magnetic density (1.56T), good rust resistance and processing performance, but the surface of the material is very soft, it is difficult to process the thread, and the spherical surface is easy to scratch. J22 has good magnetic conductivity and the highest saturation magnetic density (2.1T), its soft hardness reaches HRB90, the required precision of the DSR can be achieved by manual grinding. Therefore, 1J22 is selected as the DSR disk & shaft material.

**Working principle**

According to the design requirements, the rotor centroid and center of the two spheres should coincide. Both of LFMB and motor force arm are located in the radial equatorial plane and take the sphere center as the fulcrum, so the force and torque of the rotor are all over the rotor center, avoiding the mutual interference of magnetic bearings, and effectively improving the control accuracy of magnetic bearings.

The spherical axial magnetic bearing is composed of two poles, used to support the rotor axially. By adjusting the coil current and outputting the required electromagnetic force, the active control of rotor axial translation completes. The spherical radial magnetic bearing is composed of four poles, uniformly distributing around the equatorial surface of the spherical rotor. The four poles work in pairs. By adjusting the coil current and outputting the required electromagnetic force, the active control of the rotor radial translation completes. The spherical axial and radial magnetic bearings work together to realize the active control of 3 translational DOFs of the rotor.

LFMB control the radial DOF deflection of the DSR, and realize the output of universal deflection torque. Its structure and principle are shown in Figure 3, which is mainly composed of the inner and outer rotor magnet steel, the inner and outer rotor magnetic guide rings and the stator coil windings.

It can be seen from Figure 3 that the inner and outer rotor magnetic steel, magnetic guide ring and air gap of LFMB constitute the permanent magnetic circuit loop. Four coils are wound to form a pair of work, when the rotor is deflected and the two opposite coils are connected with the differential current, the coil current $i$ cuts the magnetic field line $B$ and produces the Lorentz force, $f = i \times B$. Then a pair
of force couple is produced in $\pm x$ or $\pm y$ direction, and makes the DSR produce angular velocity $\omega$ along radial $x$ or $y$ direction, which can be regarded as precession angular velocity of gyro. The precession formula of gyro is

$$\omega \times H = M$$  

(1)

Where, $H$ is the angular momentum of rotor; $M$ is the deflection moment. According to equation (1), when LFMB controls the radial deflection of the DSR, the control torque is output along $x$ or $y$ direction of the rotor, combining with the axial output torque, thus the MSCSG 3DOFs attitude control function achieves. As shown in Figure 2, LFMB places on the radial outside of the rotor to increase the length of the deflection arm. In the same way, when there is the external disturbance torque of MSCSG, the rotor will also deflect along the radial plane. In this case, LFMB can actively control the rotor to restore the balance state. Through the measurement of LFMB coil current in this process, the external interference torque of the rotor can be calculated, then the attitude parameters of the satellite are obtained, and the MSCSG 2DOFs attitude measurement function achieves.

Based on the above analysis, it can be concluded that for MSCSG DSR, it $z$ direction translation is controlled by the spherical axial magnetic bearing alone. It $x$ and $y$ direction translation are controlled by spherical radial magnetic bearing whose two magnetic forces are perpendicular to each other, and there is no

Figure 3. Principle diagram of Lorentz force magnetic bearing.
magnetic circuit coupling between the two channels. It $x$ and $y$ direction rotation are carried out by LFMB whose two force couples are perpendicular to each other, and there is no magnetic circuit coupling. This is the principle of MSCSG 5DOFs full active control and full channel magnetic circuit decoupling.

**Mechanical analysis of DSR**

**Structural parameters of rotor**

There are two kinds of structural parameters in DSR system. One kind is mutual constraint with the stator system, such as the axial/radial spheres as the rotor part of the axial/radial magnetic bearings, the motor rotor and LFMB rotor, sensor detection plate. These parameters should be considered in the overall design of the stator parameters, which cannot be changed after the scheme is clear. The other is the parameters that affect the mechanical properties and mass distribution of the rotor. Only these parameters can be optimized. Considering the design speed, moment of inertia, geometric dimension and other factors of DSR, the optimized parameters of the rotor structure are finally determined as shown in Figure 4.

**Structural mechanics analysis**

As the key part of MSCSG, the influence of the mechanical properties of the DSR is as follows.

1. The moment of inertia of the rotor determines the moment of inertia of MSCSG at high speed. The rotor deflection torque depends on its polar moment of inertia at design speed.

If the rated angular momentum of MSCSG $H$ is 12 Nms and the design speed is 8000 rpm, the corresponding rated polar moment of inertia $J_z$ is 0.0143 kgm$^2$.

2. The rigid body displacement of the rotor under high-speed rotation directly affects the reliability of the radial magnetic bearing. MSCSG adopts internal rotor structure, especially for spherical radial magnetic bearings, the rotor has a large rotation radius and is more likely to produce deformation when rotating at high speed. Because the air gap between the stator and the rotor is only 0.35 mm, the small rigid body displacement when the rotor rotates at high speed may cause the air gap to change, which increases the difficulty of system control and threatens the safety of the rotor. This requires the structural design to ensure that the maximum rigid body displacement is smaller than the air gap in the working speed range of the rotor.

3. When MSCSG works, if the first resonance frequency of the rotor is lower than the rotation frequency, it will cause the rotor resonance and seriously damage the MSCSG structure. Considering that the design rotation frequency is 133.3 Hz (8000 r/min), the first resonance frequency of the rotor should be at
least greater than this value. This requires the rotor to have good modal performance.

(4) As the magnetic conducting medium of each magnetic bearing and motor rotor, the DSR should have enough safety redundancy in its static performance.

**Optimal design of DSR**

*Optimization model design*

The design requirements of DSR include the design angular momentum, polar moment of inertia, the strength, stiffness, geometry, reliability, mass, especially the deviation between the rotor centroid and shape center should be as close to 0 as possible so as to meet the design of DSR original intention. The optimization design model generally includes optimization variables and feasible region, constraint conditions, optimization algorithm and objective function. Next, the mathematical model of rotor optimization is established.
Optimization variables. As shown in Figure 4, the optimization parameters of rotor structure mainly include $r_1$, $r_2$, $h_1$, $h_2$, $h_3$. Where, $r_1$ is the rotor disk radius of the motor upper end, $r_2$ is the radius of the locating surface of the lower detection plate; $h_1$ is the rotor disk height of the motor radial inner, $h_2$ is the rotor disk height of the motor radial outer, $h_3$ is the rotor disk thickness of the motor bottom. The optimization variables can be expressed as

$$X = (r_1, r_2, h_1, h_2, h_3)$$

Obviously, the optimized variables are all structural parameters of rotor disk. Rotor disk is a functional part as well as a structural part. As a functional part, rotor disk needs to meet the static and dynamic performance of high-speed rotor, which mainly involves $h_1, h_3$, and $r_1$; as a structural part, it needs to meet the location and installation requirements of sensor detection plate, motor rotor and other parts, mainly involving $r_2, h_2$. Therefore, it is necessary to set the boundary value in combination with rotor structure and mechanical performance. According to engineering experience, the boundary value of the optimization variables is

$$\begin{cases}
42\text{mm} \leq r_1 \leq 48\text{mm} \\
31\text{mm} \leq r_2 \leq 38\text{mm} \\
12\text{mm} \leq h_1 \leq 16.5\text{mm} \\
8\text{mm} \leq h_2 \leq 14\text{mm} \\
4\text{mm} \leq h_3 \leq 9\text{mm}
\end{cases}$$

The optimal design of DSR is a constrained non-linear mathematical programming problem. Considering the complex relationship between the first-order resonance frequency, rigid body displacement, maximum equivalent stress and optimization variables, the highly stable NLPQL optimization algorithm is adopted.

Objective function. For the DSR, one of the important factors to realize the decoupling of magnetic circuit and ensure the control accuracy is the coincidence of the centroid and shape center. The deviation between the rotor centroid and shape center is a mathematical problem. As shown in Figure 2, the origin of rectangular coordinate system $O$-xyz is rotor shape center, $z$-axis is the rotor rotation axis. If the rotor is a system of particles with $n$ particles, the mass of the $i$th particle is $m_i$, the mass of rotor is $m = \sum m_i$. In the $O$-xyz, the coordinate of the $i$th particle is $(x_i, y_i, z_i)$, the centroid coordinate is $(x_c, y_c, z_c)$, because the rotor mass distributes symmetrically along the $z$-axis, so we can conclude

$$\begin{cases}
x_c = \sum x_i m_i / m = 0 \\
y_c = \sum y_i m_i / m = 0 \\
z_c = \sum z_i m_i / m = f(X)
\end{cases}$$

Namely, it just needs that the $z$-axis coordinate of the rotor centroid approaches zero, so the objective function can be expressed as

$$z = f(X) = \lim f(r_1, r_2, h_1, h_2, h_3) = 0$$
**Constraint condition.** From the static and dynamic performance point of view, the constraints of rotor are put forward. The static performance requires that the rotor meet the constraints of strength and rigidity, so that the system has a high reliability. Usually the safety factor of the system is greater than 2, this means that the maximum equivalent stress of the rotor $\sigma_{\text{max}} \leq \sigma/2$ at the design speed (8000 rpm), where $\sigma$ is the allowable stress of the rotor material 1J22.

The dynamic requirements are mainly for the rotor modal characteristics. In order to increase the safety redundancy, the first-order resonance frequency of the rotor is required to be greater than twice the rotor rotation frequency, namely $\lambda_1 \geq 270$Hz.

It is known that the moment of inertia of rotor pole is 0.0143 kgm$^2$ at design speed. In order to restrain the gyroscopic effect of high-speed rotor, the rotor should be flat structure, and the ratio of polar moment of inertia $J_z$ to equatorial moment of inertia $J_e$ of rotor should be satisfied

$$1.4 \leq J_z/J_e \leq 2$$

Ideally, the DSR should maintain the regularity of the spherical surface when it works, but the material will inevitably deform when it rotates at high speed. The influence of rotor deformation on spherical radial magnetic bearing is the greatest. If the operation of the radial magnetic bearing is not affected by the rotor deformation, the displacement of the rigid body $d$ compared with the air gap should be small enough. The air gap of the radial magnetic bearing is 0.35 mm, based on the engineering experience $d \leq 0.015$mm.

In conclusion, the constraints of the rotor are

$$\begin{cases}
\sigma_{\text{max}} \leq \sigma/2 \\
\lambda_1 \geq 270$Hz \\
J_z \geq 0.0143$kgm$^2$ \\
1.4 \leq J_z/J_e \leq 2 \\
d \leq 0.015$mm
\end{cases}$$

*Finite element simulation*

The optimization process of the DSR is shown in Figure 5. The static and dynamic finite element model of the rotor is established by using the finite element analysis software ANSYS, and the preliminary analysis results are obtained according to the initial parameter calculation. On this basis, the multidisciplinary design optimization software ISIGHT integrates the above two finite element models, and the optimization analysis of the DSR is conducted according to the optimization model established in section 4.1. A set of optimal design variables are obtained by iterative simulation, which can minimize the deviation between the rotor centroid and shape center.

In order to ensure the accuracy of the finite element calculation, the command flow model of the DSR is established by using the ANSYS parametric design language (APDL). For the finite element analysis, mesh generation is a critical step.
The quality of mesh generation directly affects the accuracy and speed of the solution. In the mesh generation method provided by ANSYS, the swept mesh can automatically form regular hexahedral mesh for complex geometric entities. Compared with the mapping mesh and free mesh, it has greater advantages and flexibility, and can effectively ensure the accuracy of finite element calculation. The swept mesh finite element model of the DSR is shown in Figure 6.

The optimization process of the optimization variables is shown in Figure 7. It can be seen that $h_1$, $h_2$, $h_3$ and $r_1$ change trend are consistent, tending to the lower limit of the optimization interval, then $r_2$ tends to the maximum value of the
Figure 6. Finite element model of rotor.

Figure 7. Optimization curve of design variable.
The common goal of the above change rule of the optimization variables is to promote the deviation between rotor centroid and shape center tend to zero. The optimization process of the constraint variables is shown in Figure 8. It can be seen that the first-order resonance frequency \( f_1 \), polar moment of inertia \( J_z \), inertia ratio \( J_z/J_e \), rigid body displacement of the rotor \( d \) change smoothly, the maximum equivalent stress \( \sigma_{\max} \) jumps slightly. The optimization process of objective variable and rotor quality is shown in Figure 9, where the deviation of centroid converges from \(-0.442\) to \(0.036\) mm, and the absolute deviation is reduced by an order of magnitude. Considering post-processing technology and assembly error, this result meets the actual requirements of the project.

The dynamic and static properties of the optimized rotor are simulated by ANSYS finite element method. The first-order modal shape of the DSR is shown in Figure 10. Where, the first-order resonance frequency of the rotor is 3034 Hz, which is far greater than the 270 Hz specified by the constraint conditions, indicating that the rotor has good modal characteristics.

At the design speed of 8000 rpm, the profile of the maximum stress distribution of the rotor is shown in Figure 11. The maximum equivalent stress obtained from the static analysis is 38.2 MPa, which occurs at the corner of the radial inner side of the mounting surface of the upper detection plate. According to the extreme limit of the alloy soft tensile strength of the 1J22 \( \sigma_s = 490 \) MPa, the safety factor is 12.8, which is far greater than the design threshold and indicates that the rotor has
Figure 9. Optimization curve of objective and constraint.

Figure 10. First model of rotor.
enough strength safety redundancy. At the design speed, the distribution profile of rotor rigid body displacement is shown in Figure 12, where the maximum rigid body displacement is 0.00975 mm and occurs at the lower side of the radial ball. Namely when the MSCSG operates at the design speed, the air gap at the lower side of the radial magnetic bearing is reduced by 0.00975 mm, which is 2.78% of the initial air gap of 0.35 mm, and in line with the engineering practice, it show that the rotor can maintain the stability of the structure at high speed.

The results of optimization variables, objective variables and constraints of rotor structure before and after optimization are compared as shown in Table 1. It can be seen that the rotor mass is reduced by 1.47%.

**Experimental study of DSR**

According to the results of the optimal design, the prototype of DSR and MSCSG is developed, and the spherical mirror machining of DSR is realized by using grid grinding technology. The surface roughness is not less than 0.1 μm, the sphericity is 3/1000 mm, and the dimensional accuracy is ±0.01 mm. By adjusting the thickness of the adjusting ring, the spherical centers of the axial and radial sphere are coincident. Then the dynamic balance and modal test experiments of DSR are conducted.
Due to the restriction of machining level, the deviation between rotor centroid and shape center at high speed cannot meet the requirements of high-precision measurement. Therefore, it is necessary to carry out high-precision online dynamic balance experimental research based on MSCSG rotor to reduce the unbalanced...
interference torque and realize high-speed stable suspension. Figure 13 is the DSR physical drawing; there are 12 screw holes on one side and 24 screw holes on both sides symmetrically for configuration of counterweight screws. The dynamic balance experiment and analysis of the DSR is conducted by using the SCHENCK field balance instrument. The experimental environment is shown in Figure 14. Firstly, the unbalanced weight and position of the rotor are measured by the self-centering field dynamic balance experiment, and then the required counterweight screw is screwed into the counterweight-threaded hole where the unbalanced position is located. The results of dynamic balance experiment are shown in Figure 15. Where, the vibration amount of the DSR decreases from 20 $\mu$m before the experiment to 0.14 $\mu$m after the experiment, which decreases by 99.3%. The coincidence of the rotor centroid and the shape center is basically achieved.

**Rotor modal experiment**

Among the performance indexes of the magnetic suspension rotor, the first order modal is the key index that affects the control performance. In order to verify the
Figure 14. Dynamic balance experiment environment.

Figure 15. Dynamic balance experiment results: (a) before experiment 20 μm and (b) after experiment 0.14 μm.
correctness of the optimization method and DSR performance, the first-order modal test experiment is carried out. In the process of modal test, the DSR is suspended stably, the same frequency current is added to the radial/axial spherical magnetic bearings for frequency sweep test, and the rotor displacement change is monitored by oscilloscope. When the sweep frequency resonates with the first modal, the sensor signal will have obvious ripple. By using the FFT spectrum of displacement signal, the resonance point of the rotor system can be measured, namely the first modal is 2881 Hz, as shown in Figure 16, which is 5% different from the finite element simulation value of 3034 Hz. Both of them show that the DSR has good modal performance, and there is a certain error because of in the finite element simulation the parts are combined into a whole through the body bonding command, while the real rotor is the combination of all parts.

Conclusion

1. One MSCSG DSR is put forward. The detailed design of the spherical rotor is given. The working principle of MSCSG is explained. By using the spherical radial/axial reluctance magnetic bearings and LFMB, the 5DOFs full active control of the DSR and the full channel decoupling between the magnetic circuits of each magnetic bearing are realized.
2. Based on the structural mechanical characteristics and design indexes of the DSR, the optimization model of the rotor is established, and the optimization
variables, objective functions and constraints are given. The finite element simulation shows that the optimized DSR has good modal and static performance. (3) According to the results of the optimization design, the prototype of the MSCSG are developed, and the on-line dynamic balance and modal test experiments of the DSR are carried out. The experimental results verify the feasibility of the structure design and the effectiveness of the finite element simulation.

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