Design of Magnetic Bearing Reaction Wheel for High Precision Attitude Control of Spacecraft *

Han Bangcheng and Fang Jiancheng

The 5th Unit
Beijing University of Aeronautics and Astronautics
Beijing, China, 100083
hanbangcheng@buaa.edu.cn

***Abstract* – In this paper, a kind of 5 degree-of-freedom magnetically suspended reaction flywheel with outer rotor is designed for high-precise stabilization of spacecraft attitude, the rotor velocity is -5000rpm to 5000rpm, its angular momentum is 50Nms. The main structure of this system is given, the rotor is supported by radial active and thrust active magnetic bearings with permanent magnet, a kind of integrated eddy-current sensor for detecting radial and axial displacement of wheel rotor is designed. And the optimization design method of rotor is presented to satisfy the require of strength safety coefficient and first elasticity resonance frequency simultaneously etc. by the software of multidisciplinary design optimization (iSIGHT) and Finite element analysis software (ANSYS).**

***Index Terms* – reaction flywheel, active magnetic bearing with permanent magnet bias, attitude control, optimization design**

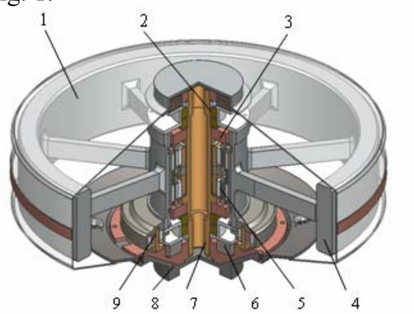
I. Introduction

Most of three-axis-attitude of spacecraft is equipped with momentum or reaction wheels for their attitude control [1]. Conventional ball bearing wheel can't absorb the centrifugal force caused by imbalance of the wheel rotor, so the ball bearing wheel can be one of the most harmful disturbance sources for the spacecraft attitude stability. When the ball bearing reaction wheel's speed crossing zero, step change in the friction moment of wheel seriously influences the accuracy and stability of spacecraft attitude control. In addition, ball bearing lubrication remains the principal life-limiting factor for momentum and reaction wheels [2, 3].

To avoid these problems, wheels supported on magnetic bearings have been the subject of intense development [4-10]. In this paper, a kind of five degrees of freedom (5-DOF) magnetic bearing reaction wheel (MBRW) is designed, for decreasing power consumption of magnetic bearing wheel, active magnetic bearings (AMB) with permanent magnet is applied. The rotor working velocity is -5000r/min to 5000r/min, its angular momentum is 50Nms (5000r/min). The main structure of this system is given, the rotor is supported by radial and thrust magnetic bearings with permanent magnet, a kind of integrated eddy-current sensors for detecting radial and axial displacement is designed. The optimization design method of rotor is presented to satisfy the requirements of strength safety coefficient and first elasticity resonance frequency simultaneously etc. by multidisciplinary design optimization software (iSIGHT) and Finite element analysis software (ANSYS).

II. Mechanical Structure Design of 5-DOF MBRW

For future high precision spacecraft attitude control, a kind of 5-DOF MBRW is designed in this paper. The 5-DOF MBRW is composed of ten electromagnets whose attractive forces have components both in axial and in radial direction. The magnetically suspended rotor is supported by radial and thrust magnetic bearings with permanent magnet bias. Two integrated eddy-current displacement sensors are symmetrically installed so as to measure the rotor displacements in three directions and gimbaling angles around two axes vertical to the wheel rotational axis. The cross section of this 5-DOF MBRW is shown in Fig. 1.



1-vacuum enclosure 2-Auxiliary Bearings 3-eddy current sensors 4-wheel rotor 5-radial magnetic bearing 6-thrust magnetic bearing 7-axis 8-pedestal 9-brushless DC motor

Fig. 1 The cross section of MBRW

The main components and their functions are as follow:

- Wheel rotor: control attitude of spacecraft through exchanging momentum.
- Electric motor: permanent magnet DC brushless motor.
- Radial magnetic bearing: Radial active magnetic bearing with permanent magnet to suspend the wheel rotor in radial direction.

- Thrust magnetic bearing: thrust active magnetic bearing with permanent magnetic to suspend the wheel rotor in axial direction.
- Nocontact displacement sensor: integrated three-dimensional eddy-current sensors for detecting radial and axial displacement.
- Auxiliary bearing: to protect the MSRW system form any suspension failure; double angular contact ball bearings mounted in a face-to-face preloaded configuration or back-to-back preloaded configuration.
- vacuum enclosure: simulating vacuum condition and eliminating windage losses.

TABLE I shows fundamental specification of the 5-DOF MBRW.

TABLE I
Fundamental specification of the 5-DOF MBRW

Item	Note
Thrust magnetic bearing	Active magnetic bearings with permanent magnet bais
Radial magnetic bearing	Active magnetic bearings with permanent magnet bais
Angular momentum	50Nms@5,000r/min
Rotation speed	±5,000 r/min, Max.10,000 r/min
Mass	Total 10 kg, rotor 6.2kg
Size	Φ350mm, 200mm (height)
Moment of inertia	0.0955 kgm^2 (around pin axis)
Motor torque	Max. 0.1Nm
Power consumption	19.2W (steady)
Motor	DC brushless motor

TABLE II shows the parameters of active magnetic bearings with permanent magnet in the 5-DOF MBRW system.

TABLE II
Parameters of active magnetic bearings

	Item & value	
Radial magnetic bearing	Poles	8×2
	Nominal gap (mm)	0.25
	Force/current stiffness (N/A)	110
	Passive stiffness (N/mm)	-477
	Number of winding turns	150
Thrust magnetic bearing	Poles	2
	Nominal gap (mm)	0.3
	Force/current stiffness (N/A)	290
	Passive stiffness (N/mm)	-490
	Number of winding turns	300
Sensor	integrated radial/axial eddy current displacement sensors	2

III. THE OPTIMIZATION DESIGN OF WHEEL ROTOR[11]

Wheel rotor is an important component in MBRW system, which is supported by radial and thrust active magnetic bearings. The angular momentum, mass, statics, and dynamics etc. of rotor will affect directly the magnetic bearings and performances of this system, such as the stability and reliability, so the optimization design of rotor is very important. The optimization design method of rotor is presented to satisfy the requirements of strength safety coefficient and first elasticity resonance frequency simultaneously etc. by the multidisciplinary design optimization software iSIGHT and the finite element (FEM) analysis software ANSYS. The mass of the wheel rotor is the optimize goal, and the rotor statics, first resonance frequency, rotor dynamics and geometry dimension etc. are the constraint condition. The optimization design flow chart of wheel rotor is shown in Fig. 2. First, the models of statics FEM and dynamics FEM are modelled using ANSYS FEM analysis software, and the elementary analysis results are gained through the initial design parameters, then the two simulation models are integrated by the iSIGHT software. The optimization algorithm is chosen for optimizing the wheel rotor. The optimization results of wheel rotor are shown in TABLE III. The parameters of the flywheel rotor satisfy the requirement of design, and its mass is minimized. The method in this paper can increase the design efficiency and quality, has the important applied cost in design of wheel system.

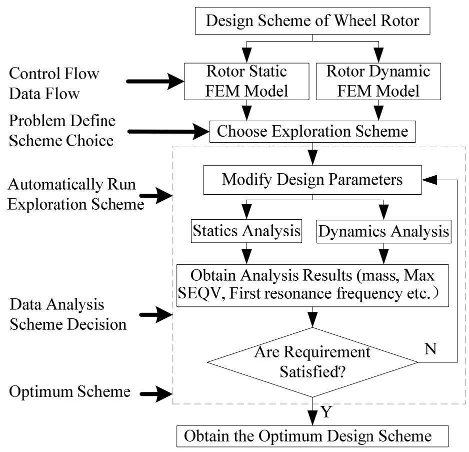


Fig. 2 The optimization disign flow of wheel rotor

TABLE III
Optimization results of wheel rotor

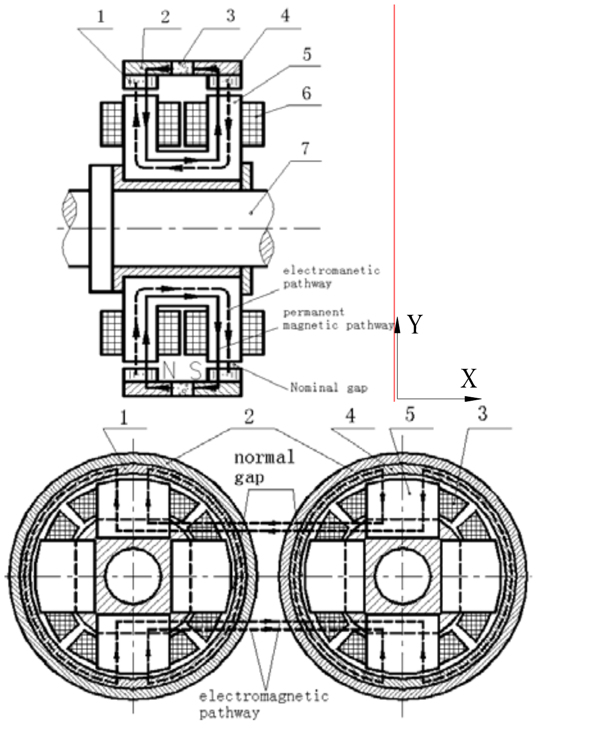
Item	Value
Rim thickness (mm)	65.1
Rim inner diameter (mm)	300
Rim inner diamete (mm)	340
Height of wheel arm (mm)	7.2
Width of wheel arm (mm)	4
Moment of inertia (kgm^2)	0.095
Maximum SEQV（MPa）	205
First resonance frequency (Hz)	829.5
Rotor mass (kg)	4.09

IV. The Active Magnetic Bearing With Permanent Magnet

For decreasing power consumption, size, inductivity and mass of magnetic bearing wheel, active magnetic bearings with permanent magnet to create the bias flux are applied. The radial and thrust magnetic bearings with permanent magnet bias are illustrated as follow.

A. The Radial Active Magnetic Bearing with Permanent Magnet

The radial AMB with permanent magnet is applied in 5-DOF MBRW, its cross section and magnetic pathways are shown in Fig. 3. This kind of radial AMB has a permanent magnetic ring on the rotor and thus allows a very compact design with few parts. This kind of radial bearing separated the electromagnetic pathway from permanent magnet pathway. From the bias flux Φ0 (produced by permanent magnet) point of view this is a homopolar arrangement. The depicted coils (the coils for the y-direction are considered only) are connected in series and have the same winding direction to create the control flux Φc (produced by electromagnetic coils). Φ0 and Φc can be superimposed in the air gap. If the rotor is in the centre position, the control current will set to zero, and resultant force on the rotor is zero. If the current direction is shown as the sketch of Fig. 3, both flux components are in the same direction in the lower airgaps and oppose each other in the upper airgaps, generating a reluctance force on the rotor in negative Y-direction.

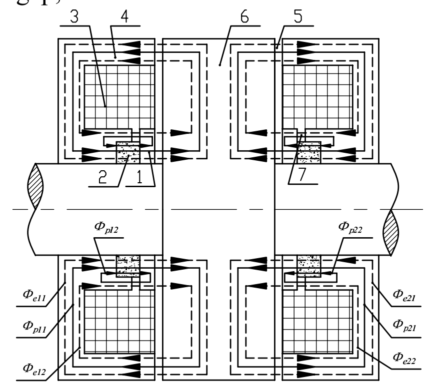


1-left rotor iron core 2-magnetic ring 3-permanent magnet 4-right rotor iron core 5-"U" stator iron core 6-coil 7-axis

Fig. 3 The cross section of radial magnetic bearing and its magnetic circuit

B. The Thrust Magnetic Bearing with Permanent Magnet

The thrust active magnetic bearing with permanent magnet is applied in 5-DOF MBRW also. Its cross section and magnetic circuit are shown in Fig. 4. This kind of thrust magnetic bearing has a permanent magnetic ring on the stator. The electromagnetic circuit of this kind of thrust magnetic bearing is divided into two circuits. One circuit consists of stator iron core, permanent magnet ring, control flux plate, air gap, and the rotor. The other circuit consists of stator iron core, second air gap, control flux plate, air gap, and rotor. The permanent magnet circuit is also divided into two circuits. One circuit consists of permanent magnet ring, control flux plate, air gap, rotor, and stator iron core. And the other circuit consists of permanent magnet ring, control flux plate, second air gap, and stator iron core.



1-control flux plate 2-permanent magnet ring 3-coil 4-stator iron core 5-air gap 6-rotor 7-second air gap

Fig. 4 The cross section view and magnetic circuit of the thrust bearing

The electromagnetic circuit and permanent magnetic circuit of the thrust bearing are shown in Fig.5.

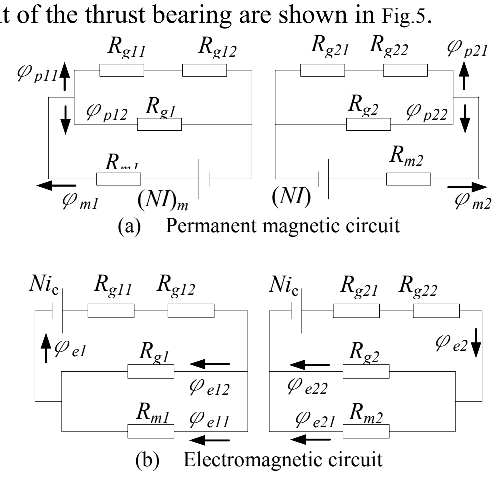


Fig.5 The electromagnetic circuit and permanent magnetic circuit of the thrust bearing

V. The Design Of Integrated Eddy-Current Displacement Sensors

Reliable long-term operation needs a precise control algorithm to achieve a wear-free and nearly frictionless rotation, and the noncontact displacement sensor is the key Smaller size, lighter mass, high reliability, high stability, and high precision are required for displacement sensor of MSRW. Eddy current sensors are widely used for noncontact displacement [12]. Fig.6 illustrates the operation principle of differential position sensing. The sensor is excited by a square-wave carrier. The output of the sensor is a complex voltage vector. If two sensors are applied to measure the displacement, the movement of the target results in a change of the differential output [13].

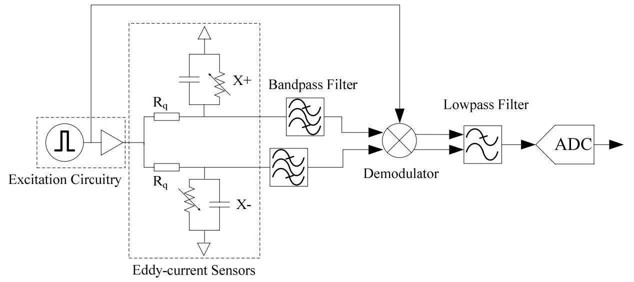


Fig.6 Conventional system architecture for one channel eddy-current displacement sensing device

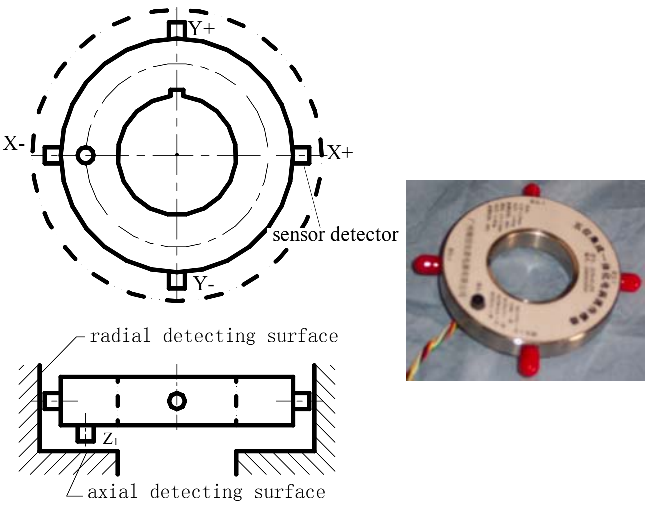


Fig.7 The cross section and photo of integrated radial/axial eddy-current displacement sensors

Position control requires three-dimensional (3-D) rotor displacement information with high resolution for smooth MSRW operation, and five pairs of eddy-current sensors are required for position sensing in 5-DOF MSRW. The power, mass and size budget are tight and the system design is a challenging task. A kind of integrated eddy current sensors for detecting radial direction and axial direction displacement of magnetically suspended rotor is applied in this paper. The cross section and photo of integrated radial/axial eddy-current displacement sensors are shown in Fig.7. The integrated displacement sensors is consist of two-channel differential position sensing in radial direction through two pairs of eddy-current sensors and one-channel displacement sensing in axial direction, which can detect 3-D position of the magnetically suspended rotor, and the power, mass and size can be decreased. All sensor detectors and preamplifier circuits component to realize high precise control for MSRW. are integrated in one system. There are two integrated eddy-current displacement sensors in 5-DOF MSRW.

For the reason of structure of 5-DOF MSRW with outer rotor, the axial sensor can't easy detect center of the magnetically suspended rotor, and can only be located near the centre of rotor as shown in Fig.1. The axial displacement error will be caused for single axial sensor to detect the axial displacement when the rotor is in operation, and the control precision and stability will be affected. For eliminating the detecting error, and improving precision and reliability of MSRW, double axial displacement sensors are adopted. Its principle is carry through mathematical operation for the two displacement signals of the two detectors, and the axial displacement error is eliminated caused by single axial sensor for can't detecting centre displacement of outer rotor, so the precision and reliability of integrated eddy current sensor are improved. The new type of integrated radial/axial eddy-current displacement sensors are shown in Fig.8.

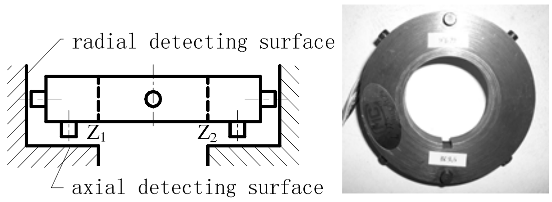


Fig.8 New type of integrated radial/axial eddy-current displacement sensors with double axial sensor

Fig.9 illustrates the reason of the axial displacement sensing error and how to compensate. The distance is R between axial sensor detector and centre of rotor. The axial detecting surface of the magnetically suspended rotor will deflect from the axes of the rotor when the rotor is in operation (real line), the real displacement is L_0 (dashed line), and the deflection angle is θ. For the two axial direction sensors, the sensing displacement (Z_1 and Z_2) is as follow respectively.

$$Z_1=L_0-R*\tan\theta. \quad (1)$$

$$Z_2=L_0+R*\tan\theta. \quad (2)$$

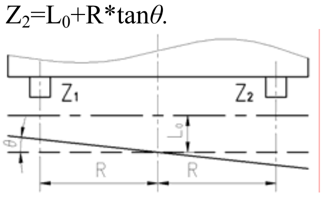


Fig.9 The error analysis and compensation of displacement sensing for axial direction of rotor

The displacement error will be caused for single sensor detector, and the absolute value of the error is $R*\tan\theta$. For eliminating the error caused by single sensor detector, the displacement signals (Z_1 and Z_2) are carried through mathematical operation.

$$((L_0R*\tan\theta)+(L_0+R*\tan\theta))/2=L_0 \quad (3)$$

The algebraic sum of the displacement signals (Z_1 and Z_2) is as the real sensing displacement, so the displacement error is eliminated caused by single detector at axial direction for can't detecting centre displacement of outer rotor, and the control precision and reliability of MSRW are improved by double sensor detectors at axial direction.

VI. THE 5-DOF MBRW SYSTEM

A kind of 5-DOF MBRW system is designed by BUAA. We determined the specification of the MBRW, such as a rotor size and a rotation speed range, based on the AOCS requirement of a kind of civil satellite. Fig. 1 illustrates a cross section, and a perspective view of the 5-DOF MBRW, respectively. TABLE I show major specifications of the MBRW and the parameters of the radial magnetic bearings and the thrust magnetic bearings are summarized in TABLE II in detail. For reducing iron loss, the rotor elements of the radial magnetic bearings consist of soft magnetic iron sheets, and the stator elements are made of laminated iron. The 5-DOF MBRW system is shown in Fig. 10. Aimed at the stability problem of MBRW caused by gyroscopic effect, a proportional cross feedback control algorithm based on decentralized control is adopted in the 5-DOF MBRW system [14, 15]. The wheel rotor is driven by a kind of DC ironless brushless motor. The system can runs stably from 0 r/min to 5,000 r/min. The maximum rotation speed of this flywheel can reach 9400r/min.

Fig. 10 The photo of 5-DOF MBRW system

VII. SUMMARY

The prototype of the 5-DOF MBRW is developed by BUAA for high-precise spacecraft attitude stabilization. For decreasing power consumption, size, inductivity and mass of magnetic bearing wheel, active magnetic bearings with permanent magnet, and a kind of integrated radial/axial eddy-current displacement sensor are developed by BUAA. The optimization design method of rotor is presented to satisfy requirements of strength safety coefficient and first elasticity resonance frequency simultaneously etc. by the multidisciplinary design optimization software (iSIGHT) and Finite element analysis software (ANSYS). The method can increase the design efficiency and quality, has the important applied cost in design of flywheel system.

The disturbance force and torque caused by the MBRW must be analysed and measured, then the high accuracy processing of the rotor and advanced control method should be researched to satisfy the specification required for high-stable attitude control of spacecraft, which are our future goal.

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