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A novel electrodynamic suspension reaction sphere (EDSRS) for satellite attitude control

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Abstract
This paper presents a novel electrodynamic suspension reaction sphere (EDSRS) for satellite attitude control. The EDSRS consists of a magnetically suspended spherical shell-shaped rotor and three pairs of bowl-shaped stators. Suspension force and torque are generated by the interaction between the magnetic field of the stators and the inductive eddy current in the rotor. To analyse the suspension force characteristic of the EDSRS, Finite Element Method（FEM）simulations of the suspension forces of a simplified EDSRS which consists of a single stator and a rotor are done at different currents and different air gaps. To analyse the torque characteristic of the EDSRS, torques of the simplified EDSRS are investigated by FEM simulations at different current amplitudes and frequencies. Finally, prototype test is performed on a prototype EDSRS to validate the suspension force and torque characteristics.

Keywords: Reaction sphere; Electrodynamic suspension; Satellite attitude control; Electromagnetic field simulation

1. Introduction

Satellites in orbit undertake specific tasks of exploration and exploitation the space, where attitude maneuver and stabilization with high precision are required. The attitude control system (ACS) plays an essential role in satellite attitude maneuver and stabilization. The conventional configuration of the ACS is the configuration with reaction wheels. To eliminate the friction drag of mechanical bearings, magnetically suspension is applied to reaction wheels by some researchers as an alternative. Nonetheless, three or more reaction wheels are required for three-axis attitude control in a satellite, which causes the coupling between reaction wheels on different axes. Furthermore, the configuration of the ACS with reaction wheels has disadvantages such as big volume, heavy weight, low payload, and high cost. A reaction sphere has a single spherical rotor which can rotate around any axis, making the satellite attitude controllable in all axes. Therefore, the configuration of the ACS with the reaction sphere can replace three or more reaction wheels and overcome the disadvantages of the conventional configuration to a certain degree, besides it has the advantages of magnetically suspended reaction wheels.

Several configurations of the magnetically suspended reaction sphere have been proposed in literature, but almost no configuration has realized multi-axis rotation function. A magnetically suspended permanent magnet synchronous reaction sphere is proposed by Olivier [1]. However, the manufacture of the rotor is complex and the cost is high, restricting the scope of application and development prospect. A magnetically suspended hysteresis reaction sphere is developed by Lei Zhou [2] and a magnetically suspended inductive reaction sphere is developed by Atsushi Iwakura [3]. For the two types of reaction spheres, the drives of rotation and suspension are separated, making the structure lack of compactness. Besides, the suspension control of the two types of the reaction sphere is complex.

A novel EDSRS which has the potential to achieve small volume, light weight and low cost is presented in this paper. The rotor of the EDSRS can rotate about any axis, and the drives of suspension and rotation are integrated. Structure and principle of the EDSRS are introduced. Simulation research is done on its suspension force characteristics and torque characteristics. Finally, Prototype test is performed on a prototype EDSRS.

2. Structure and principle of the EDSRS

2.1. Structure of the EDSRS

As shown in Figure 1, the EDSRS consists of a magnetically suspended spherical shell-shaped rotor and three pairs of bowl-shaped stators. The air gap is between the rotor and each stator. Three pairs of stators are orthogonally arranged around the rotor. For each pair of stators, the symmetry centre of the two stators is the same with the centre of the rotor. Each stator consists of a bowl-shaped core and a coil array. The inner surface of the core is spherical, which ensures a unified air gap between the stator and the rotor. The core is evenly slotted in the circumferential direction. The coil array is placed in the slots and is divided into three-phases which are respectively represented by red, green, and blue coils. Taking the processing technology into account, the rotor is designed as a combination of two hemispherical shells. Furthermore, the rotor is made of homogeneous conductive material. Thus, the EDSRS have the potential to achieve light weight and low cost.

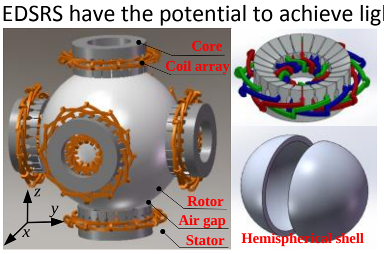
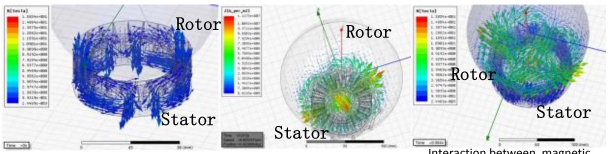


Figure 1. Structure of the EDSRS.

2.2. Principle of the EDSRS

When the current electrical angles between the three-phase coils are 2π/3, the alternating current produces a rotating magnet field around the stator axis in the air gap as illustrated in Figure 2(a). The rotating magnetic field induces eddy current in the rotor as illustrated in Figure 2(b). The interaction between the magnetic field and the inductive eddy current is shown in Figure 2(c). This interaction provides for the rotor a suspension force along the axis of the stator and a torque around the axis of the stator, simultaneously. For each stator, the drives of rotation and suspension are integrated, making the structure compacted, hence the EDSRS can achieve small volume and light weight. If two or more stators are powered by the alternating current and a proper current assignment is utilized, then each stator can provide a suspension force and a torque for the rotor. The resultant suspension force on the rotor controls the stable suspension of the rotor, while the resultant torque drives the rotation of the rotor around any axis.



(a) Magnet field (b) Eddy currents (c) Interaction between magnetic field and eddy current

Figure 2. Principle of the EDSRS.

3. Suspension force characteristic of the EDSRS

Electrodynamic suspension with the bowl-shaped stator in the EDSRS is a type of repulsion suspension, which is beneficial to the stable suspension of the rotor. As shown in Figure 3, at time t1, the currents in Stator A and Stator B are equal. The gap between the rotor and Stator A, denoted as *g1,* is equal to the gap between the rotor and Stator B, denoted as *g2*. Thus, the force between rotor and Stator A, denoted as *F1*, is equal to the force between the rotor and Stator B, denoted as *F2*. At time t2, the rotor centre moves along the positive direction of z axis due to a disturbed force, and *g1* decreases while *g2* increases. As a consequence, *F1* increases while *F2* decreases. The resultant suspension force on the rotor is along the negative direction of z axis, driving the rotor to the initial position at time t3.

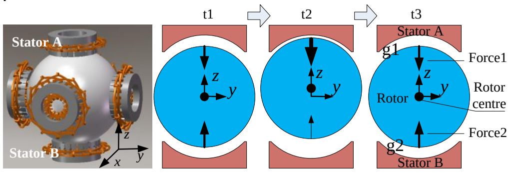


Figure 3. Suspension characteristic of the EDSRS.

To analyse the suspension force characteristic of the EDSRS, Finite Element Method（FEM）simulations of the force between the rotor and stator B are done. As shown in Figure 4, as the position of the rotor centre, denoted as *z*, changes from -1mm to 1mm, the air gap *g2* increases. Figure 3 shows that the suspension force is repulsive force and it decreases as *g2* decreases, which is beneficial to the stable suspension of the rotor.

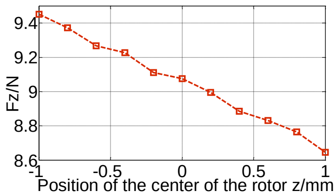
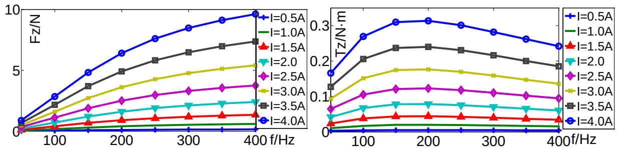


Figure 4. FEM simulations of the force between the rotor and Stator B.

At different current amplitudes and current frequencies, the suspension forces of a simplified EDSRS which consists of a single stator and a rotor are investigated by FEM simulations. In Figure 5(a), *Fz* represents the suspension force, and it increases as current amplitudes *I* and current frequency *f* increase within a certain range. Thus, utilizing a proper current assignment, the resultant suspension force on the rotor could control the stable suspension of the rotor in the EDSRS.

4. Torque characteristic of the EDSRS

At different *I* and *f*, the torques of the simplified EDSRS are investigated by FEM simulations. In Figure 5(b), the torque *Tz* reaches the maximum when the current frequency *f* is about 200HZ. The resultant torque on the rotor could drive the rotation of the rotor around any axis in the EDSRS by a proper current assignment.



(a) Suspension force (b) Torque

Figure 5. Suspension forces and torques of the simplified EDSRS.

5. Prototype test

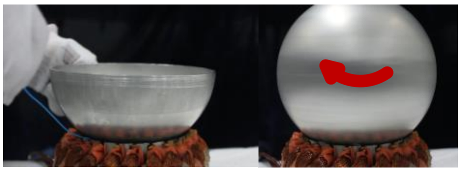


Figure 6. Suspension and rotation experiments.

To validate the suspension force and torque characteristics, suspension and rotation experiments are performed on a prototype EDSRS which consists of a single stator and a rotor. As illustrated in the left of Figure 6, when the current electrical angles between the three-phase coils are 0, the rotor is suspended steadily. A blue wire can easily be moved through the gap between the rotor and the stator, which shows the suspension state. Without closed-loop control, the rotor is still able to move back to the initial equilibrium position quickly when there is an interference force from any direction. As illustrated in the right of Figure 6, the rotor is not suspended. When the current electrical angles between the three-phase coils are 2π/3, the rotor rotates around the axis of the stator as illustrated by the red arrow in different angular velocities under different *I* and *f*.

6. Conclusion

A novel EDSRS which has the potential to achieve small volume, light weight and low cost is presented in this paper. The rotor of the EDSRS can rotate about any axis, making the satellite attitude controllable in all axes, and the drives of rotation and suspension are integrated, providing a compact structure. The suspension force is repulsive force and it is beneficial to the stable suspension of the rotor. Utilizing a proper current assignment, the rotor is able to realize stable suspension and rotation around any axis. The suspension and rotation experiments are done on the prototype EDSRS, and the results verify the suspension force and torque characteristics.

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