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One-axis hysteresis motor driven magnetically suspended reaction sphere

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ABSTRACT

This paper presents the design, modeling, control, and experimental results for a one-axis magnetically suspended reaction sphere (1D-MSRS) driven by a hysteresis motor. The goal of this work is twofold: (a) to conduct a preliminary study for magnetically suspended reaction sphere for three-axis spacecraft attitude control, and (b) study the potential of hysteresis motors for the reaction wheel/sphere drives. The 1D-MSRS uses a hysteresis motor with a spherical rotor made of solid steel. The rotor sphere is magnetically suspended in all translational directions, and is driven about the vertical axis by a bearingless hysteresis motor. We present the modeling and control of the magnetic suspension of the bearingless motor in the 1D-MSRS, and the hysteresis motor dynamics are analyzed by a hysteresis motor equivalent circuit model. The 1D-MSRS system has experimentally demonstrated a starting torque of 8.9 mNm under 0.7 A peak sinusoidal excitation current. With this excitation the sphere can run up to 12,000 rpm synchronously in the presence of air drag. This study demonstrates that the hysteresis motor has strong potential for use in high-speed, low-vibration reaction wheels.

1. Introduction

In the flight control of spacecrafts, rotational maneuvering requires an external torque, which is often provided by reaction wheels. To achieve attitude control in all degrees of freedom (DOFs), a minimum of three reaction wheels are typically needed in the system. By accelerating the appropriate wheels, the system can generate a zero-mean torque about any axis to the spacecraft, and the generated momentum can be stored as well [1]. These wheels can also be used for vibration compensation and for orientation control of solar arrays [2].

As an alternative to reaction wheels, the idea of using a single magnetically suspended reaction sphere (MSRS) for spacecraft attitude control has been investigated by a number of researchers [3–8]. The vision here is that a sphere can be independently accelerated about any axis by a three-dimensional spherical motor, making the attitude of the spacecraft in all axes controllable by a single device. This torque independence can eliminate the gyroscopic coupling as occurs with multiple reaction wheels with fixed rotation axes. In addition, the magnetic suspension eliminates the mechanical friction in the bearings, which relieves the control difficulties due to Coulomb friction when the wheel/sphere speed is crossing zero. The magnetic bearing can also allow the device to operate without lubrication and thus extend the lifetime of the device. Furthermore, by replacing several reaction wheel assemblies with one single device, mass and volume reduction may be achieved.

Although the idea of a MSRS is not new, it remains a challenging problem due to the difficulties of spherical motor design, magnetic suspension, and the combination of the two technologies. One recent MSRS design uses a permanent magnet synchronous motor (PMSM)-based reaction sphere [7,9]. This design uses tiled magnets on the rotor sphere surface, which enables simpler angular position sensing and control. However, the complexity of the rotor structure may make this design difficult to be used in small satellites, and the strength of the bonded rotor may limit its maximum rotational speed.

Other literature relevant to the MSRS design includes studies on spherical motors for robotics applications [10–14]. Various motor drive principles, such as induction motors, permanent magnet motors, reluctance motors, etc., have been explored for the spherical motor design. Among these references, most designs targeting robot wrist applications have a limited motion range. One recent work presents an induction type spherical motor design for mobile robot application [14], which does not have an angle limit and has demonstrated speed and position control capability.

Among many motor principles, the hysteresis motor is receiving increasing attention in the past decade due to its advantages

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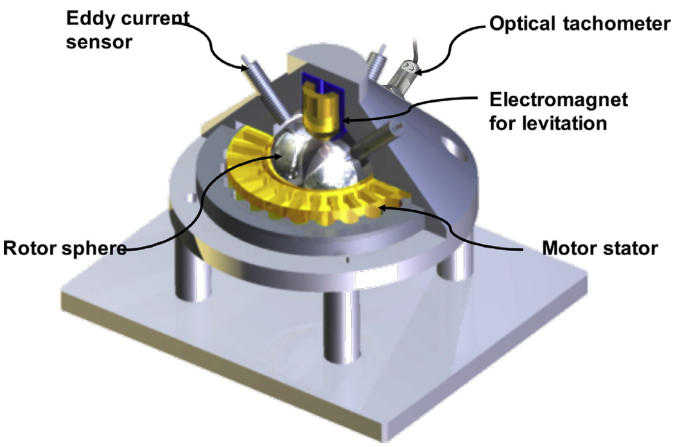

Fig. 1. CAD model for the 1D-MSRS.

of simple structure, vibration-free operation, and self-starting capability. The rotor of a hysteresis motor can be made out of a single piece of hard and strong steel, which allows the rotor to have very small imbalance. This feature also makes the rotor able to sustain large centrifugal force, which makes the hysteresis motor attractive for high-speed applications. These advantages of hysteresis motors provide the motivation for our study of their use in reaction wheel/sphere applications.

As a first step, we focus this study on the design of a magnetically suspended reaction sphere with one-axis hysteresis drive (1D-MSRS). The hysteresis motor in the 1D-MSRS is modeled using an equivalent circuit model developed in [15,16]. A control method to suppress the hunting of the motor is presented and tested. The potential of hysteresis motors for reaction wheel applications is also discussed.

This paper is organized as follows. Section 2 presents an introduction to the 1D-MSRS hardware. Section 3 introduces the design and control for the vertical suspension of the reaction sphere. Section 4 describes the bearingless motor subsystem used for the lateral directional suspension of the sphere. Section 5 introduces the hysteresis motor for the 1D-MSRS. Section 6 discusses the comparison between the 1D-MSRS and a commercial reaction wheel. Conclusion and suggestions for future work are given in Section 7.

2. 1D-MSRS hardware overview

The 1D-MSRS demonstrates a hysteresis motor with a spherical rotor made of solid steel, and the rotor is magnetically suspended in all translational directions. Fig. 1 shows a CAD model of the 1D-MSRS, and the photographs of the device are presented in Fig. 2. The rotor in the 1D-MSRS is a solid sphere of hardened D2 steel. Four eddy current sensors are placed around the rotor to measure the sphere's position in three translational DOFs. These sensors are arranged 45° from the vertical axis, and are separated by 90° in the azimuthal coordinate. The rotor sphere is magnetically levitated in the vertical direction by a reluctance actuator placed at its north pole. A stator is arranged around the sphere's equator line, serving both for levitating the sphere in the horizontal plane and for torque generation about the vertical-axis by means of a bearingless motor configuration. A reflective optical tachometer is used for the sphere's speed detection by sensing a black mark on the sphere.

2.1. Rotor

The rotor of the 1D-MSRS is a 54 mm diameter solid sphere of D2 steel. Although materials with larger hysteresis loops exist, we selected D2 steel for the rotor in the 1D-MSRS for the proof of our design due to its ready availability. D2 steel is a high carbon, high chromium tool steel, which makes it a deep hardening, highly wear resistant and magnetically semi-hard alloy. This allows the D2 steel to be used for the rotor of a hysteresis motor. The rotor material chemical, physical, and magnetic properties are shown in Table 1, and Fig. 3 shows the *B*–*H* curve of D2 steel measured under varying excitation amplitude at a frequency of 20 Hz. The hysteresis data measurement equipment is introduced in detail in [17].

2.2. Stator

The rotary motor and lateral suspension function are implemented with coils on a stator with 24 slots and a length of 10 mm.

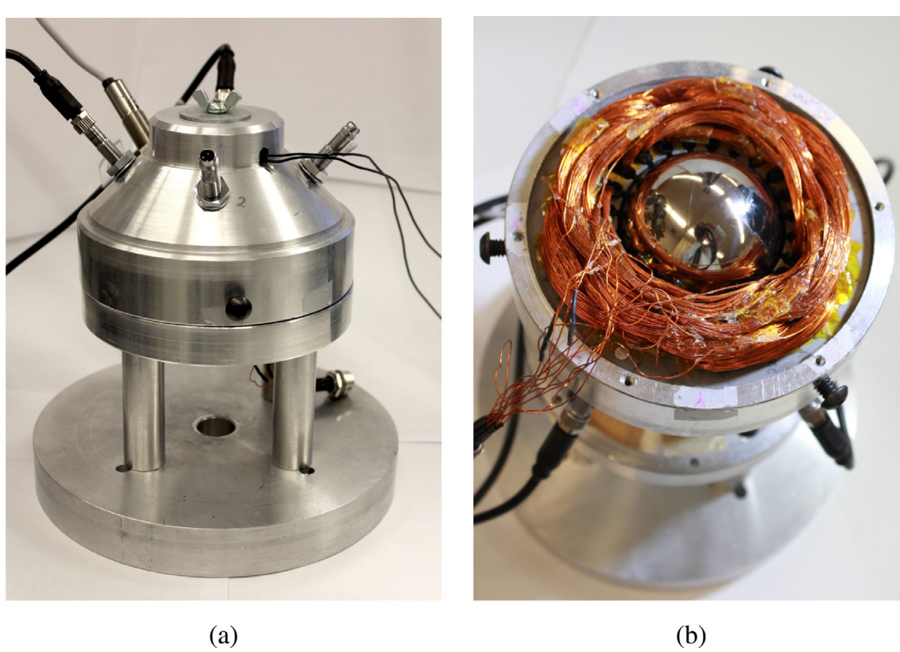

Fig. 2. Photographs of the 1D-MSRS. (a) Structure; (b) stator and rotor.