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HYSTERESIS MOTOR DRIVEN ONE AXIS MAGNETICALLY SUSPENDED REACTION SPHERE

Lei Zhou, Mohammad Imani Nejad, and David L. Trumper

Department of Mechanical Engineering

Massachusetts Institute of Technology, Cambridge, MA, 02139

INTRODUCTION

The Attitude and Orbit Control System (AOCS) plays an essential role in the flight control of a spacecraft. This system usually contains a minimum of three reaction wheels (often 4-5 wheels are used for optimization and redundancy [1]). By accelerating the appropriate wheels, the system can produce a zero-mean reaction torque about any axis to the spacecraft, which enables the spacecraft to maneuver on orbit. Meanwhile, the momentum generated by acceleration can be stored in the wheels.[2].

As an alternative to the reaction wheels, the idea of using a single magnetically levitated reaction sphere for satellite attitude control was proposed [3]. In this alternate version, the sphere can be accelerated about any axis by a spherical motor, making the attitude of the spacecraft in all axes controllable by a single device. Due to its symmetry, a sphere can always give the same inertia, independent of its rotational axis. As a result, using a reaction sphere may allow smaller size and mass. In addition, when assisted by magnetic suspension, the mechanical friction can be eliminated, and thus low steady-state power consumption may be possible. This also enables the device to work without lubrication and achieve greater operational lifetime.

The idea of reaction sphere was proposed as early as 1986 [3], however to our knowledge, the current technology is still far from a ready-to-commercialize state. One recent reaction sphere design presents a permanent magnet motor based reaction sphere designed by ESA [4]. This design uses tiled magnets on the rotor surface, which enables simpler angular position sensing and control. However, its complexity of the rotor structure may prevent it from being suitable for small satellites application, and the strength of the rotor limits its maximum rotational speed, which may limit the performance of the actuator.

Among many motor driving principles, the hys-

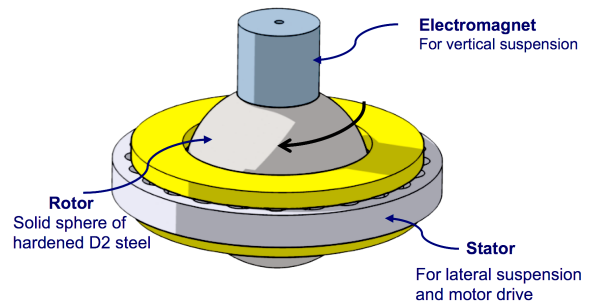


FIGURE 1. Design concept diagram of the 1D-MSRS.

teresis motor is well known for its simple structure, vibration-free operation, self-starting ability, and constant torque production. Another distinct feature of this motor is that its rotor can be made out of a single piece of hard steel, which allows the rotor to stand large stresses and thus makes this motor attractive for high-speed applications. However, to the best of our knowledge, the hysteresis motor has not yet been used in reaction wheels.

Aiming at the dual goal of exploring the design for a magnetically suspended reaction sphere and evaluating the performance of hysteresis motors for reaction wheels application, we focused this project on the development of a magnetically suspended reaction sphere with one-axis hysteresis drive (1D-MSRS). The hardware of the 1D-MSRS demonstrates a solid steel sphere magnetically suspended in all translation directions, and driven by a hysteresis motor about one axis. Figure 1 shows a diagram of the design concept of the 1D-MSRS.

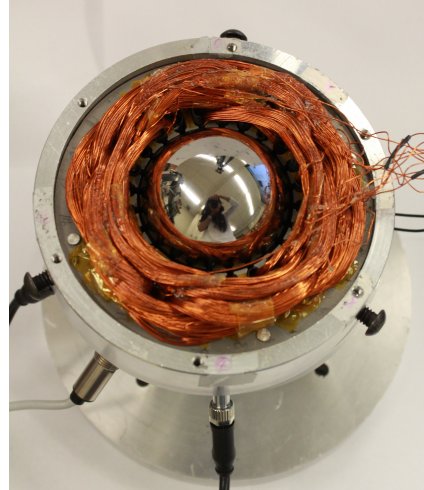
This paper presents the design characteristics and test results of the 1D-MSRS system. For more detailed analysis of the design, modeling, and control of the system see [5].

HARDWARE DESIGN AND INTEGRATION

The 1D-MSRS has a magnetically levitated spherical rotor that can rotate and store momentum about the vertical axis. Figure 2 shows the pho-



(a) Structure and sensors.



(b) stator and rotor.

FIGURE 2. Photographs of the 1D-MSRS hardware.

tographs of the hardware. In the 1D-MSRS system, the rotor is a 54 mm diameter sphere of hardened D2 steel. Four inductive sensors are placed around the rotor to measure the sphere's position in translational degrees of freedom. 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 line. It serves both for levitating the sphere in the horizontal plane and for torque generation simultaneously via a bearingless motor configuration. A reflective optical tachometer is used for speed detection of the reaction sphere.

The 1D-MSRS consists of several subsystems. They are: a single degree-of-freedom magnetic suspension system for the sphere's vertical suspension, a lateral suspension system for the sphere by mean of the bearingless motor, and a hysteresis motor for driving the sphere about the vertical axis. In the analysis of the 1D-MSRS, these subsystems are considered to be decoupled, that is, the interaction between the subsystems are considered to be negligible. In the following these subsystems are introduced.

VERTICAL SUSPENSION

The spherical rotor in the 1D-MSRS is magnetically suspended in the vertical direction by an electromagnet arranged at the north pole of the sphere.

In order to reduce the DC current in the actuator coil for the sphere's weight compensation, a thin-disk shape permanent magnet is placed in the

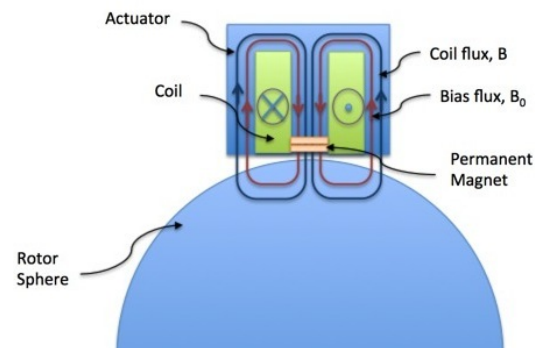


FIGURE 3. A cross section of the biased levitation actuation system

magnetic path of the suspension actuation system to add a bias DC flux. Figure 3 depicts the system for the sphere's vertical suspension.

LATERAL SUSPENSION

In the design of the 1D-MSRS, a bearingless motor is used to achieve a compact design. This motor uses two sets of three-phase windings on a single stator (for 1D-MSRS 4-pole and 2-pole). By correctly configuring and controlling the currents in these motor windings, the machine can generate a torque for spinning as well as radial forces for suspension using a single stator. In the 1D-MSRS system, the 4-pole winding is the motor winding, and the 2-pole winding is used for lateral suspension control.

A dynamic model is built to study the lateral suspension characteristics of the bearingless motor in 1D-MSRS. Here we only present the high level

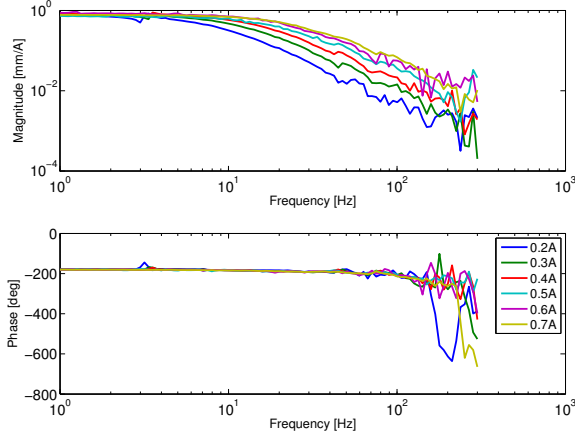


FIGURE 4. Experimentally measured plant frequency response for x -direction sphere suspension with different excitation amplitudes.

result, that is, the transfer function from the suspension winding current i_{2a} to the rotor's radial displacement $x(t)$ is:

$$\frac{X(s)}{I_{2a}(s)} = \frac{K_i}{ms^2 - K_s}. \quad (1)$$

Here m is the mass of the sphere, and the value of K_s and K_i are the negative stiffness [N/m] and the force constant [N/A] of the lateral suspension system respectively. They can be calculated by:

$$K_s = \frac{2}{\pi} \frac{Rl\mu_0 N_4^2 (\sqrt{3}/\sqrt{2}I_m)^2}{g_0^3} [N/m] \quad (2a)$$

$$K_i = \frac{\sqrt{3}}{\sqrt{2}} \frac{2\mu_0 RlN_2N_4}{\pi g_0^2} \left(\frac{\sqrt{3}}{\sqrt{2}}I_m\right) [N/A]. \quad (2b)$$

Here the value I_m is the zero-to-peak current amplitude of the 3-phase current in the 4-pole motor windings. The meaning of the nomenclatures and the detailed derivations of these results are presented in [5].

Equation 2 shows that the both K_s and K_i in the bearingless motor system are varying with the motor winding current amplitude I_m . This result can be verified by measuring the frequency response of the lateral suspension system of the 1D-MSRS under different excitation current amplitude. The measured Bode plots are depicted in Figure 4. This measurement was taken while under closed-loop control of the lateral suspension.

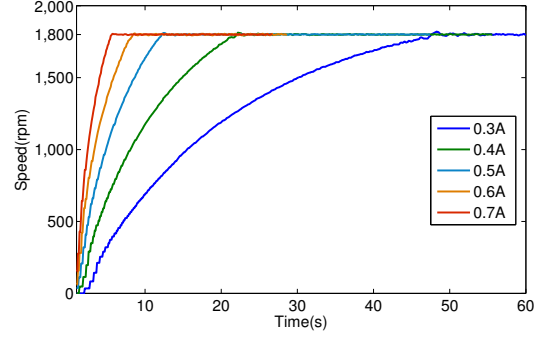


FIGURE 5. Acceleration curves of 1D-MSRS under different excitation current amplitude.

Since the motor excitation amplitude of the reaction sphere/wheel needs to vary according to the torque requirements, the lateral suspension controller needs to be able to stabilize the control loop under all excitation conditions. The detailed controller design for the lateral suspension in 1D-MSRS is presented in [5]. With the controller design, the lateral suspension loop of the reaction sphere kept a constant phase margin of 40° , while the cross-over frequency varies with the motor excitation amplitude.

HYSTERESIS MOTOR

One goal of this project is to evaluate the performance of hysteresis motor for reaction wheels application. A hysteresis motor operates by the magnetic hysteresis effect of its rotor material. Because the magnetization produced in the ferromagnetic material lags behind the magnetizing force, a torque is generated due to the rotor and stator field interaction. Although materials with better hysteresis properties exists, we selected D2 steel for the rotor of 1D-MSRS for the proof of our design.

Experimental data

The start up speed curve of 1D-MSRS is measured under different excitation conditions. Figure 5 presents the acceleration curves of the 1D-MSRS under different amplitudes of excitation current. Data shows that with 0.7 A excitation current, the sphere can reach the synchronous speed of 1,800 rpm within 6 seconds. Also, a starting torque of 8.15 mNm is demonstrated under 0.7 A exciting current.

The maximum synchronous rotational speed that the 1D-MSRS can reach is 200 Hz (12,000 rpm) in our lab. We believe that when running in vacuum the motor has the potential to reach higher speed.

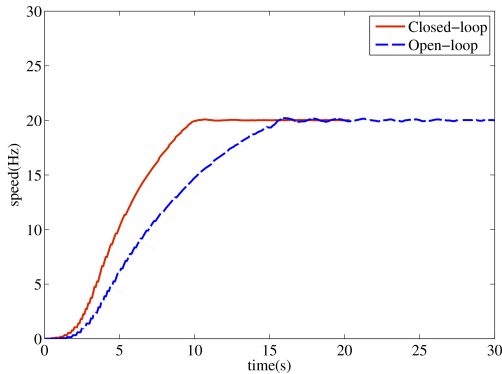


FIGURE 6. A comparison of experimental open-loop speed data and the closed-loop speed data of the 1D-MSRS during starting up.

Speed control of 1D-MSRS

In the speed plot shown in Figure 5, a speed fluctuation slightly above and below the reference speed can be observed when the motor speed first reaches the synchronous speed. This motor dynamics is known as hunting. It is undesirable when a hysteresis motor is used for the development of a reaction wheel or a reaction sphere, as it will introduce vibrations into the spacecraft.

To suppress the motor hunting, a feedback loop on the sphere's rotational speed is designed and implemented in the 1D-MSRS. In this control system, the sphere's speed is measured by an optical tachometer, and the control effort is the current amplitude that we supply to the motor windings. The controller design is introduced in [5] in detail.

Figure 6 shows the measured step response of the reaction sphere's rotational speed under open-loop and closed-loop operations, respectively. Note the hunting speed ripple in the open-loop speed data (blue). Data shows that the designed speed control scheme can effectively suppress the motor hunting and also enables faster acceleration.

CONCLUSIONS AND FUTURE WORK

The design and development of a hysteresis motor driven magnetically suspended one-axis reaction sphere is presented in this paper. Magnetic suspension, bearingless drive and hysteresis motor principles are used in the design for 1D-MSRS. An equivalent circuit model for hysteresis motor is used to analyze the dynamic behavior of the 1D-MSRS, and a speed control loop is built for the system to suppress hunting. The 1D-MSRS can run up to 200 Hz (12,000 rpm) with the existence of air drag, and a starting torque of 8.15 mNm is

generated with 0.7 A excitation current amplitude.

Future work should consider the design and development of a three-axis magnetically suspended reaction sphere (3D-MSRS). A brief discussion of the possible motor concepts and magnetic pole configurations for a 3D-MSRS is presented in [5]. The performance of the 1D-MSRS demonstrates that hysteresis motor has the potential for the circumstances where quiet operation and high speed are needed. We believe that this motor concept is promising for high speed, low vibration reaction wheel applications.

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