



Development of a spherical reaction wheel actuator using electromagnetic induction



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ARTICLE INFO

Article history:

Received 10 May 2014

Received in revised form 1 August 2014

Accepted 2 September 2014

Available online 16 September 2014

Keywords:

Satellite
Attitude control
Electromagnet
Levitation
Speed control
Spherical actuator

ABSTRACT

A spherical reaction wheel is a novel three-axis induction motor consisting of a spherical rotor and electromagnets. The electromagnets allow the rotor to levitate and to rotate about any desired axis without mechanical contact. A benefit of the actuator is to control the satellite for three-axis attitude using the single spherical reaction wheel. In this study, a prototype model of the spherical reaction wheel with a single rotating axis is developed, and a feasibility study on the actuator is conducted. The actuator system is designed through electromagnetic field analyses of the spherical rotor in order to evaluate the levitation force and torque. Dynamic performance tests are carried out under electromagnetic rotation and levitation conditions, and torque-speed characteristics are investigated. Using the test data, torque modeling and velocity control simulations are also performed. Finally, closed loop speed control tests are conducted on the experimental model. The model shows that the maximum torque and speed are 0.7 Nm and 13,500 rpm, respectively, and the speed control error is less than 4%.

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1. Introduction

Conventional control systems such as reaction wheel assemblies (RWAs) and control moment gyros (CMGs) have been used to quickly and accurately control the attitude of satellites. A typical reaction wheel assembly consists of a brushless DC motor and a rotor that is a variable-speed rotor suspended on ball or magnetic bearings with a fixed axis [1,27]. CMGs consist of a constant-speed or variable-speed spinning rotor and one or more motorized gimbal actuators that tilt the rotor's angular momentum in order to amplify the torque [22,25]. These actuator systems are capable of creating rotational torque and storing angular momentum on a single axis only. Hence, for satellites to operate in three axes of control, a minimum of three or more actuator systems, as well as their corresponding steering laws, are required, as shown in Fig. 1 (left) [33,32].

This paper focuses on a spherical actuator, which is a new form of actuator that is designed to generate control torque and momentum in three dimensions using the single actuator system as shown in Fig. 1 (right). It consists of a spherical rigid rotor and electromagnets that allow the wheel to levitate and rotate without mechanical contact between the rotor and stator. Resulting

from these benefits, the conventional single-axis drive systems can be replaced with a single spherical actuator. Therefore, satellites will be smaller and lighter, which will result in them being much more economical due to the reduction in weight and volume. In addition, the satellite lifetime can be expected to increase. The proposed actuator can be applied to small satellites such as CubeSat and micro-class satellites as well as general satellites [4]. As a result of the non-contacting mechanism, high quality satellite images can be ensured by a significant reduction of jitter sources such as micro-vibrations and gyroscopic precession induced when using the conventional actuators [16,15].

Initial research on this new type of control system for application in attitude control systems began in the early 1960s [8,18], but detailed and practical studies have been undertaken since the mid-2000s. In Japan, the mathematical analytical modeling was begun [10,24] and a 50 mm diameter spherical actuator was designed and tested for one degree-of-freedom (DOF) [11]. In Europe and the United States, some research on three-dimensional models has been undertaken at the conceptual design level, with experimental verification pending [17,20]. In its current state, the research in spherical actuators has yet to yield adequate rotation performance and speed control results.

Similar experiments have been conducted for purposes other than satellite ADCSs. The research on industrial electromagnetic driving spherical actuators has been undertaken in various research fields, such as the motor design, magnetic field analysis and

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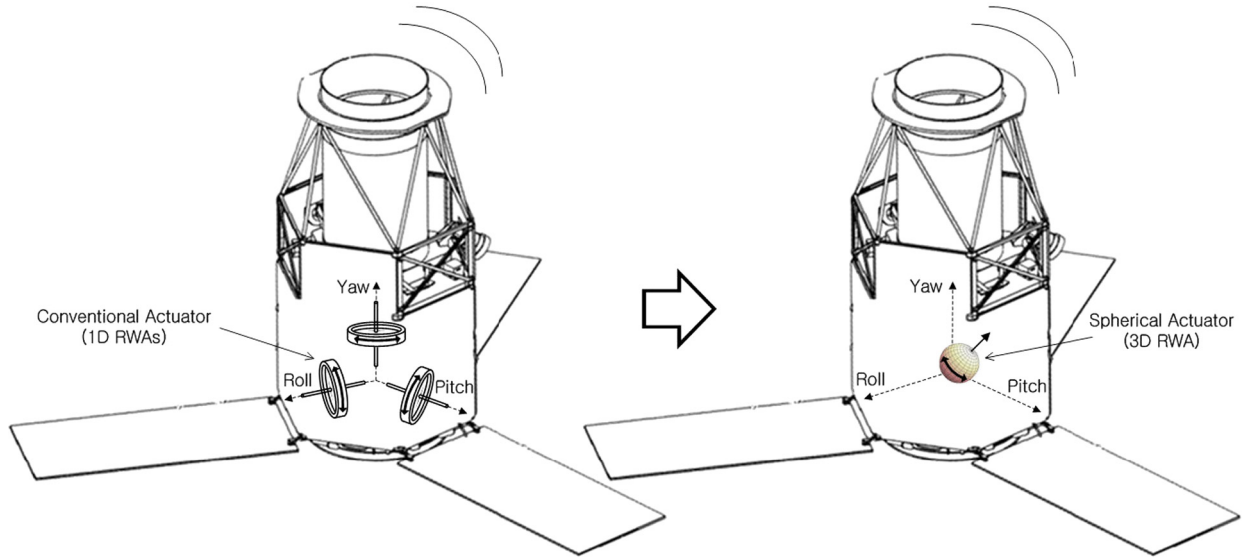


Fig. 1. Reaction wheel configurations of the conventional actuator and spherical actuator.

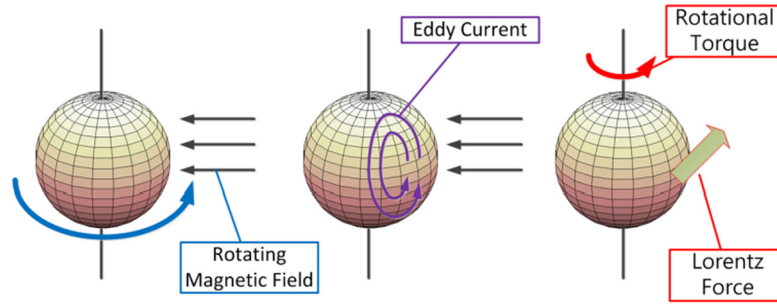


Fig. 2. Schematic of the rotation mechanism.

motion control [30,6,21,34,31]. Lee and Kwan [14] and Chirikjian and Stein [5] developed spherical stepper motors for robotic applications; Boletis et al. [3] and Wildmann et al. [28] conducted high velocity rotation experiments using a 1–4 mm diameter spheres at millions of rpm. A 2 DOF 50 mm diameter induction motor was also tested in Belgium [7].

This paper summarizes the design, performance, and speed control tests of a spherical actuator capable of magnetic levitation and rotation speed control. Particular emphasis is placed on explaining the rotational drive characteristic tests, determination of the rated torque and velocity, rotational drive modeling using a mathematical torque model of the induced electric motors, and control gain selection from the velocity control simulations. Finally, the velocity control tests of the manufactured test module are described.

2. Spherical actuator

2.1. Operational principles

The spherical actuator is operated using principles similar to those found in induced electric motors, as described in Fig. 2. As seen in the diagram, the rotating magnetic field around the stationary sphere induces an electric current on the surface of the metallic sphere; this is called an eddy current. This induced current then interacts with the rotating magnetic field, which results in a Lorentz force on the sphere's surface and then causes the rotational torque to spin the spherical rotor.

Even when the direction of the rotor's magnetic field is changed, the induced current will be generated and will be per-

pendicular to the field, which results in torque in the direction of the magnetic field. By controlling the rotational velocity, magnitude, and rotational axis direction of the magnetic field, the spherical rotor can be manipulated to spin in the desired direction and velocity. Using this method, a single spherical actuator can create torque and momentum in three dimensions and therefore control the attitude of satellites.

2.2. Spherical actuator design

The spherical actuator was designed by incorporating the modeling and analysis of the levitation magnetic field and rotating magnetic field around a ball, as depicted in Fig. 3. The total torque (\mathbf{T}) is obtained by integrating the Lorentz force (\mathbf{F}) induced on a surface element. These are briefly summarized for the rotation and levitation, respectively, as follows:

$$\begin{aligned} d\mathbf{F}_{\text{rotation}} &= |d\mathbf{l}|(\mathbf{i} \times \mathbf{B}) \\ &= -\sigma \delta B^2 r^3 \dot{\theta} \cos \theta \cos^2 \phi d\theta d\phi \begin{bmatrix} 0 \\ \cos \phi \\ \sin \phi \sin \theta \end{bmatrix} \end{aligned} \quad (1)$$

$$\begin{aligned} \mathbf{T}_{\text{rotation}} &= \int_{-\pi/2}^{\pi/2} \int_0^{2\pi} \mathbf{r} \times d\mathbf{F}_{\text{rotation}} d\theta d\phi \\ &= \pi \sigma \delta B^2 r^4 (\Omega - \dot{\theta}) \begin{bmatrix} 0 \\ 0 \\ \frac{3}{8}\pi \end{bmatrix} \end{aligned} \quad (2)$$

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