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Review of reaction spheres for spacecraft attitude control

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ABSTRACT

With respect to spacecraft attitude control, reaction spheres are promising alternatives to conventional momentum exchange devices for the benefits brought by their 4π rotation. Many design concepts of reaction spheres have been proposed in the past decades, however, developments of the driving unit and the bearing, as well as their combination remain great challenges. To facilitate research and push developments in this field, this paper provides a comprehensive review of reaction spheres. To some extent, an in-depth survey of multi-DOF (degree of freedom) spherical motors and possible bearings is provided, along with their advantages and weaknesses addressed. Some multi-DOF actuators for different applications, such as robotic joints, are investigated since they share many similar challenges and techniques with reaction spheres. The experimental performances of realized reaction spheres are listed and compared. Limits of current designs are identified and their causes are analyzed and discussed. Compared with existing summaries on multi-DOF actuators and some surveys done for specific reaction spheres' design, this paper provides the first thorough review on reaction spheres, considering approaches to excite and support the free 4π rotation.

1. Introduction

Attitude determination and control is of great importance to spacecraft. To implement scientific missions for earth observations and target trackings, stabilization or controls of the spacecraft's attitude is always required. Momentum exchange devices, such as reaction/momentum wheels and CMGs (Control Moment Gyros), are commonly used actuators and provide a higher control accuracy [1] than magnetorquers or thrusters. Usually, to achieve three-axis stabilization, at least three such devices are needed. Torques exposed on the spacecraft are separated into components, with each component counteracted by the corresponding wheel's acceleration or CMG 's gimballing [2]. This control strategy results in the cross coupling between each actuator's control loop since the torque decomposition depends on the body frame, which is rotating with the spacecraft while the attitude control is required with respect to an Earth-fixed or inertial frame. On the one hand, advanced nonlinear control strategies [3] are developed to handle the coupling effect. On the other hand, researchers proposed reaction spheres to counteract the total disturbance as a single actuator, where the torque decomposition and coupling would be avoided [4]. A reaction sphere could provide the conventional control torque by acceleration and the gyroscopic torque by tilting its rotation axis [5]. Therefore, the composite output of the reaction sphere could be about any desired direction, regardless of its transient orientation. In such a way, the minimum actuator number for three-axis stabilization can be reduced. It shows great benefits to spacecraft where hardware resources are limited. For redundancy, a backup sphere could be mounted on-board. In recent years, researchers proposed to replace the normal three-wheel assembly with three reaction spheres, enhancing the robustness and redundancy of the spacecraft's ADCS (Attitude Determination and Control Subsystem) via their changeable rotation axes [6]. This strategy is suitable for missions requiring high momentum storage capabilities rather than large torques. If non-functionality happens to anyone of the three, the remaining reaction spheres could adjust their rotation axes to counteract disturbances together and guarantee the mission's primary object will be achieved, such as earth observation of a certain region. Additionally, the changeable rotation axis turns the mechanical alignment issue into a software problem [7].

Reaction spheres were first proposed half a century ago [4] but the implementation was limited by technologies at that time. Nowadays, with increasing interest in miniaturized ADCS and advanced technologies on electronics, the design and development of reaction spheres receives more and more attention.

With respect to relevant literature reviews, summaries of multi-DOF (Degree of Freedom) actuators has been provided in [8–10]. However, a majority of these multi-DOF actuators have a limited rotation range since they are not required to perform 4π rotation. Besides, little consideration on bearings is included there. Investigations for specific reaction spheres' design are offered in [11–

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13] but with a limited review scope. This paper provides the look on reaction sphere designs, considering approaches to excite and support the free 4π rotation. Through analysis, the trend of reaction sphere development is provided. It is expected to facilitate research and push developments in this field.

The remaining sections are organized as follows. Section 2 provides a system level introduction to reaction spheres in the existing literature grouped per the driving mechanisms. For the implemented designs, the experimental performances of the prototypes are compared for an overview of current achievements. In Section 3, multi-DOF spherical motors based on different driving principles are investigated. Advantages and weaknesses of each category are analyzed and discussed, as well as how to integrate multi DOFs into a single motor. Section 4 discusses possible bearings to support reaction spheres, including their advantages, drawbacks and possible issue encountered in space applications. Based on the surveys, reaction spheres' excitation approaches are summarized in Section 5. Finally, conclusions are drawn in Section 6.

2. Reaction spheres

Since the first proposal in 1959 [4], researchers have proposed many design concepts for reaction spheres. However, they were seldom realized. Here, depending on their torque generation principles, we can distinguish these proposed concepts into four types which are based on induction motors, permanent magnet motors, hysteresis motors and piezo/ultrasonic motors respectively.

2.1. Induction motor-based reaction spheres

Time-varying magnetic field induces eddy currents in a conductive rotor. Lorentz forces experienced by the induced currents generate the spin torque. A benefit of an induction motor is that there are no determined poles on the rotor. Therefore, without mechanical constraints, the torque direction of an induction motor only depends on the revolving magnetic field. To excite rotations about arbitrary axes, a straightforward approach is combining rotation torques about three principle axes. Applying this approach to a spherical induction motor is, in principle, easy. Generating three independent revolving magnetic fields results in three independent torque components. Based on the superposition principle, the composite rotation torque, as well as the resultant rotational velocity could be about any direction. Additionally, if the torque generation is purely based on the induction motor, there is no need to measure the rotor orientation.

The first conceptual design was presented in [14] as an inertial sphere for the stabilization of a space telescope. The inertial sphere was a hollow aluminum sphere and driven by a rotating magnetic field around it. When driving torques about three principle axes were generated independently and simultaneously, the rotor would rotate about any given axis. Meanwhile, eddy currents excited by high-frequency AC (Alternating Current) coils provided position control for the actuator. The same configuration was also discussed in [15]. There, it was proposed to utilize interactions between the eddy currents and Earth's magnetic field to dump the inertial sphere's saturation passively.

Also based on an induction motor, a reaction sphere with electrostatic suspension was proposed in [16]. Three pairs of orthogonally arranged electrodes provided support and the rotor was placed at the equilibrium position. Additionally, three sets of induction windings were utilized to induce eddy currents in the rotor and drive the rotation. Only two sets of windings are shown on the left side of Fig. 1. An alternative configuration was described in [17,18], also adopting the combination of electrical suspensions and the induction driving. See Fig. 1 for comparison of the two designs.

In 1962, a spherical flywheel design was described in [19]. The spherical rotor was surrounded by three pairs of inductors about three

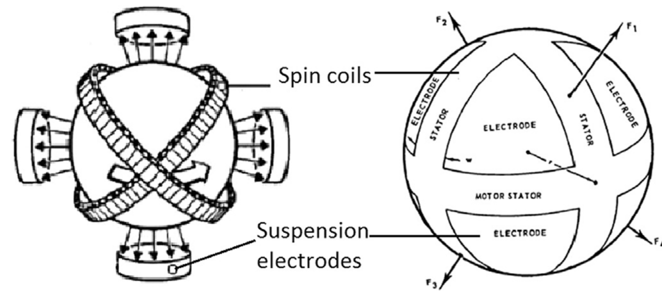

Fig. 1. Induction motors driven by three orthogonal winding sets: [16] (left) [17] (right).

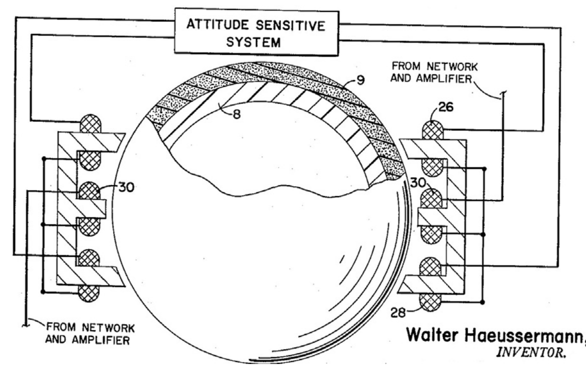

Fig. 2. Magnetic suspensions provided by the centering winding integrated in the inductors [19].

principle axes independently. Fig. 2 shows one pair of inductors. AC windings mounted on the inductors generated revolving magnetic fields. The rotor was driven by eddy currents induced inside the conductive material. The rotor could be supported by air bearings or magnetic forces provided by the tuned LC circuit integrated in the inductors. Actually, this configuration was also applicable to hysteresis motors where the rotation torque would be generated by the lagged magnetization axis. A similar driving configuration was introduced in [20]. A sealed air bearing system was utilized to support the rotor and to dissipate heat.

In [21], the spherical rotor was also actuated by three pairs of inductor segments orthogonally arranged. Each segment comprised a centering winding and a torquing winding, as illustrated in Fig. 3. Contactless support and centering of the reaction sphere were ensured by the automatic currents regulation in the three pairs of centering windings. The windings were energized with AC at a certain frequency and connected with capacitors, forming oscillating LC circuits operating near their resonance. Since the rotor was both magnetizable and conductive, eddy currents were induced by the centering windings. When torquing windings were energized with a 90° phase difference to the centering windings, forces experienced by the eddy currents would form driving torques.

To enable a conductive sphere's 3-DOF rotation, at least three inductors are needed. The slotted inductors could be arranged askew or

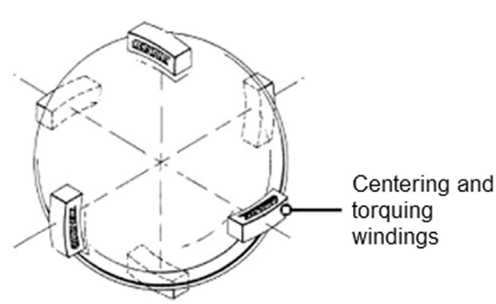

Fig. 3. Magnetically suspended reaction sphere [21].