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Invited Paper

Torque distribution of The Integrated Magnetically Suspended Inertia Actuator for attitude maneuvers

Yuanjin Yu [a,*,1], Jiancheng Fang [b], Zhaohua Yang [b]

[a] School of Astronautics, Beihang University, Beijing 100191, China
[b] School of Instrument Science and Opto-electronics Engineering, Beihang University, Beijing 100191, China

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ABSTRACT

The Integrated Magnetically Suspended Inertia Actuator (IMSIA), composed of three orthogonal fixed Magnetically Suspended Flywheels (MSFWs) and a Double Gimbal Magnetically Suspended Control Moment Gyros (DGMSCMG), can provide long-term high-precision torque and instantaneous great torque simultaneously. To reduce the electrical energy consumption, a novel torque distribution strategy yielding power optimization is investigated. The proposed scheme adopts the kinetic energy variation of the IMSIA as the cost function and obtains the distribution instructs of the actuators without changing the total torque of the IMSIA. Numerical simulation and tabletop hardware-in-the-loop simulation are carried out to verify the effectiveness of the new strategy. The results show that the new method obviously reduces the energy consumption compared with the traditional minimum-torque strategy.

1. Introduction

Most earth-observation satellites such as the *QuickBird*, *WorldView-1* and *WorldView-2* are expensive, complex and massive. Nowadays, the modern micro-satellites such as the *BIRD* (*Germany*), *KITSAT* (*Korea*) and *Tsinghua-1* (*China*) have been widely used for verifying the novel technology, and the micro-satellites will be very suitable for the future mission of earth-observation because of the merits of small size, low-cost, formulation facility and so on. For the earth-observation mission, the agile maneuver of attitude is necessary to improve imaging capacity or to meet the requirements of the imaging system payload. Various configurations of the attitude control system (ACS) for maneuver have been proposed in the last fifty years. The attitude actuator components are expected to provide long-term high-precision control torque for maintaining the high stability attitude and the instantaneous great control torque maneuvering the attitude agilely. It is well known that flywheel is commonly used for the attitude stabilization because of its high precision output torque. Without any additional actuator, the flywheel also can be directly used for the agile maneuver [1–3]. However, the output torque of the flywheel is usually relative small, and there exists an inherent drawback called the saturation problem. The saturation means that the flywheel speed will be accumulated to its maximum allowed speed limit. The saturation may occur frequently in the case of attitude maneuver requiring the long-term great torque. To solve the saturation problem of the flywheel, the flywheel speed should be desaturated by other types of actuators such as the magnetic torquer [4–6]. Some researchers interest in the application of the control moment gyros (CMG) instead of the reaction flywheel assemblies. Early in the 1970s, Liska et al.

* Corresponding author.
E-mail address: buaayyj@126.com (Y. Yu).

[1] Yuanjin Yu was born in 1985. He received the B.S. degree in automation at Huaqiao University, Quanzhou, China, in 2008, and the Ph.D. degree from Beihang University, Beijing, China, in 2015. He is currently the postdoctor of the School of Astronautics with Beihang University.

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proposed a strategy utilizing a double gimbal control moment gyros (DGCMG) for the high-accuracy attitude control of the orbiting telescope [7]. A two CMG cluster is validated as an experimental payload of the earth-observation micro-satellite, *BILSAT*-1 [8]. A four single gimbal control moment gyro (SGCMG) cluster in a pyramid configuration is used for the three-axis attitude control in [9,10]. Though the CMG can generate instantaneous great torque, it is difficult to obtain high-precision torque tracking. Thus it is hard to realize high-precision three-axis stabilization for the micro-satellite only using the CMG. To integrate the benefits of different actuators, the integrated actuators configuration is proposed. A kind of the integrated actuator containing SGCMGs and MomentWheels (MWs) is used for spacecraft attitude tracking control [11]. Another typical application of the integrated actuator composed of CMGs and flywheels (FWs) is the integrated attitude and power control system design [12,13], where the integrated actuator is not only used to control the attitude but also used to store the electrical energy. An appropriate integrated set of CMGs and FWs can meet the requirements of the attitude stabilization, agile maneuver and strictly constraints on power, mass and volume. In these applications of Refs. [11–13], the FWs and CMGs are actually used in different phases of the attitude control. These integrated actuators are necessary to equip with four SGCMGs and four FWs at least, and it is hard to meet the requirements of power, mass and volume. Meanwhile, the complex fault diagnosis and control approaches are needed to improve the reliability of these complex systems [14–17]. The integrated actuator equipped with only one DGCMG and three FWs is discussed, and the DGCMG and the FW are used simultaneously.

As the merits of non-contact, micro-friction, high precision and long life, the Active Magnetic Bearing (AMB) is applied to the inertial actuator. Furthermore, the vibration of the inertial actuator can be infinitely small with the active vibration control of the AMB [18–20]. The displacement, the rotary speed of the rotor and the current of the magnetic bearing are measurable for the magnetically suspended flywheel (MSFW), thus it is easy to implement the data-driven method for the reliability and safety [21–23]. Based on the controllable of the AMB, many researches extend the functions of the MSFW by tilting the rotor shaft [24–26]. These novel MSFWs own the ability of the attitude control in three axes and integrate the merits of the FW and the DGCMG. However, the maximal tilting angle of the novel MSFW is very small. Thus the integrated actuator with the double gimbal magnetically suspended CMG (DGMSCMG) and the MSFW, called the Integrated Magnetically Suspended Inertia Actuator (IMSIA), is very suited for the mission that requires high stability attitude and agile maneuver.

It is well-known that an appropriate torque distribution strategy for the actuators is a necessary condition to guarantee the performance of the closed-loop attitude control. Compared with the inertial actuator supported by mechanical bearings, the magnetic suspended actuator requires additional electrical power to suspend the rotational rotor. The energy saving strategy for the satellites with the magnetic suspended actuators is more significant than the mechanical suspended actuators. Ref. [27] developed a modified torque distribution strategy based on the minimum-torque solution for the redundant reaction wheels, where the modified method can reduce the energy consumption but the key rearranged matrix is not easy to determine. The purpose of this paper is to develop a novel torque distribution method to minimize the electrical power consumption of the IMSIA. The cost function is chosen as the norm of the kinetic energy variation and the distribution solution is easy to realize.

The paper is organized as follows. In Section 2, the expression of electric power of the IMSIA is given, which will be used for the cost function of the torque distribution strategy. In Section 3, the torque distribution strategy yielding power-optimal is proposed and proved. In Section 4, the numerical simulation is performed to validate the effectivity of the proposed method. In Section 5, the tabletop hardware-in-the-loop simulation is performed. A five degrees-of-freedom (DOFs) controlled MSFW is joined to the attitude control cycle. Finally, the conclusions are drawn in Section 6.

2. Problem formulation

Because the torque generated by the IMSIA relies on the orientation of the angular momentum, the coordinate frame definition of the MSFW and DGMSCMG is given first. Figs. 1 and 2 indicate the frame of the MSFW and DGMSCMG respectively.

As shown in Fig. 1, the *i*th MSFW body-fixed frame is given by w_i: $\{\boldsymbol{e}_{ix}, \boldsymbol{e}_{iy}, \boldsymbol{e}_{iz}\}$. The origin of the frame w_i is fixed on the mass center of the wheel. The wheel rotates about the axis $\boldsymbol{e}_{iz}$ with the speed Ω_{wi}. The axis $\boldsymbol{e}_{ix}$ is perpendicular to the axis $\boldsymbol{e}_{iz}$, and the axis $\boldsymbol{e}_{iy}$ follows the right-hand law.

As shown in Fig. 2, the frame of the DGMSCMG generally consists of three parts: the rotor body-fixed frame g_r: $\{\boldsymbol{e}_{rx}, \boldsymbol{e}_{ry}, \boldsymbol{e}_{rz}\}$ is fixed on the high speed rotor and does not rotate with rotor, where the axis $\boldsymbol{e}_{rz}$ is parallel to the spinning axis of the rotor. The axis $\boldsymbol{e}_{rx}$ is parallel to the rotation axis of the rotor house, and the axis $\boldsymbol{e}_{ry}$ follows the right-hand law. The rotor in the rotor house rotates about the axis $\boldsymbol{e}_{rz}$ with the constant speed Ω_g.

The inner gimbal fixed frame g_n: $\{\boldsymbol{e}_{nx}, \boldsymbol{e}_{ny}, \boldsymbol{e}_{nz}\}$ is fixed on the inner gimbal and rotates with inner gimbal, where the axis $\boldsymbol{e}_{nx}$ is parallel to the axis $\boldsymbol{e}_{rx}$. The axis $\boldsymbol{e}_{ny}$ is parallel to the rotation axis of the inner gimbal, and the axis $\boldsymbol{e}_{nz}$ follows the right-hand law. The angle α and angle velocity Ω_α describe the relative rotation between the rotor house and the inner gimbal.

The external gimbal fixed frame g_e: $\{\boldsymbol{e}_{ex}, \boldsymbol{e}_{ey}, \boldsymbol{e}_{ez}\}$ is fixed on the external gimbal, where the axis $\boldsymbol{e}_{ez}$ is perpendicular with the plane of the external gimbal. The axis $\boldsymbol{e}_{ey}$ is parallel to the axis $\boldsymbol{e}_{ny}$, and the axis $\boldsymbol{e}_{ex}$ follows the right-hand law. The angle β and angle velocity Ω_β describe the relative rotation between the inner gimbal and the external gimbal.

Based on the work-energy-rate principle [27,28], the rotational kinetic energy rate K of the three MSFWs and