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Output torque modeling of control moment gyros considering rolling element bearing induced disturbances

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ABSTRACT

Control moment gyros (CMG) have been widely used in spacecraft attitude control and large angle slewing maneuvers over the years. Understanding and suppressing high-frequency disturbances in CMG's output torques is a crucial factor to achieving the desired level of payload performance. Output torque modeling of a single gimbal CMG (SGCMG) with nonlinear rolling bearing supports is conducted in this paper. Taking the installation errors and micro-vibrations of the flywheel into account, three axis output torques of a SGCMG are derived based on Newton-Euler approach and theorem of moment of momentum. Dynamic model is then constructed to obtain the micro-vibration responses of the rotary flywheel. Mass imbalances of the flywheel, flexibility of supporting structures and nonlinearity induced by one pair of angular contact ball bearings are considered in the dynamic model. Especially for the rolling bearing, an improved load distribution analysis is proposed to more accurately obtain the contact deformations and angles between the rolling balls and raceways. Various factors, including the preload condition, surface waviness, Hertz contact and elastohydrodynamic lubrication, are included in the analysis. The bearing restoring forces are then obtained through iteratively solving the load distribution equations at every time step. Dynamic tests on a typical SGCMG supported by angular contact ball bearings are conducted to verify the output torque model. The effects of flywheel dynamic/static eccentricities, inner/outer surface waviness amplitudes, bearing axial preload and installation skew angles on the dynamic output torques are discussed. The obtained results would be useful for the optimal design and vibration control of the SGCMG system.

1. Introduction

A control moment gyro (CMG) consists of a spinning rotor (flywheel) and one (or more) motorized gimbals that tilt the rotor's angular momentum. As the rotor tilts, the changing angular momentum causes an output torque (also the gyroscopic torque) that rotates the spacecraft. Because of some superior properties, such as large torque amplification [1] and high power efficiency [2], CMG based attitude control systems have been widely used in various space applications [3–5]. When CMGs provide output torque for controlling the attitude of the spacecraft, undesirable high frequency torques with low amplitude appear during these operation due to various micro-vibration disturbances. These high-frequency output torques

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can seriously degrade the performance of instruments with high pointing precision and stability [6]. Therefore, understanding and controlling high-frequency output torques of CMGs becomes a significant problem for the modern high-performance spacecraft [7].

As the key component of the CMG, the rotary flywheel produces much of the disturbance, and has dominant effects on the high-frequency output torques of the CMG [8]. Most current research focused on appropriately modeling and analyzing vibrations of the rotary flywheel. Masterson et al. [9] proposed an empirical model to predict the vibration behavior of a wheel assembly in the Hubble Space Telescope. Liu, Maghami and Blaurock [10] considered the axial/rocking modes of the flywheel and gyroscopic torques on the wheel, and then established a dynamic model of the flywheel to analyze the jitter induced from both tonal and broadband disturbances. Narayan, Nair and Ghosal [11] discussed the dynamic coupling problem of a flywheel with its supporting brackets. For a cantilevered flywheel supported by a soft-suspension system, Zhou and Zhang [12,13] presented a comprehensive linear dynamic model to study the micro-vibrations induced by the mass imbalance of wheel and broadband noises. Later, the linear dynamic model has been successfully used for the design of both passive and intelligent flywheel vibration isolation system [14,15]. Zhang, Aglietti and Ren [16] analyzed the coupled micro-vibrations of a reaction wheel assembly including gyroscopic effects in its accelerant state. Addari, Aglietti and Remedia [17,18] carried out thorough experimental studies on a reaction wheel including the gyroscopic effects. Numerical simulations were also presented in order for comparisons and validations [18].

The above mentioned studies aimed to the flywheels in the reaction and moment wheel assemblies (R/MWAs). Although R/MWAs and CMGs both achieve reaction torque via high speed rotary flywheels, their operating principles are different [8]. R/MWAs provide control torque for spacecraft by adjusting he rotational acceleration of the flywheel, while CMGs generate output gyroscopic torques by gimballing the angular momentum vector of the flywheel. The rotation speed keeps constant in CMGs and it is much higher than that of R/MWAs (as high as 6000–10,000 rev/min) [8]. Thus, some researcher also paid a great deal of effort to study dynamic behaviors and vibration controls of the rotary flywheel in CMGs. Luo, Li and Jiang [19] conducted coupled dynamic analysis of a single gimbal CMG (SGCMG) cluster integrated with an isolation system. Their results showed that the gyroscopic effects produced by the rotary flywheel will stiffen or soften several of the structural modes of the coupled system. Recently, they also presented an innovative work on the optimum design of micro-vibration isolation for multiple flywheel system of spacecraft [20]. After analyzing the micro-vibration characteristics of the flywheel, a passive isolator for SGCMG using the viscoelastic material was put forward by Shi, Li and Luo [21]. Numerical simulations indicated that disturbances with frequency above 40 Hz can be isolated effectively by the viscoelastic material. Taking the static and dynamic imbalances and installation errors of the flywheel into consideration, Zhang and Zhang [22] conducted the disturbance characteristic analysis of CMGs. The constraint conditions of the CMG performance indexes were obtained to meet the requirements of attitude precision and attitude stabilization. Based on the dynamic model of the CMGs in a pyramid configuration considered static and dynamic imbalances of the flywheel, Zhang et al. [23] presented an active-passive integrated strategy for vibration control of CMGs. Through detailed simulations in both time and frequency domains, it was shown that remarkable attitude control improvement could be achieved by applying the proposed control strategy.

Most papers mentioned above considered the modeling of mass imbalances of the flywheel and flexibility of supporting structures and their effects upon the micro-vibrations of flywheel assemblies in CMGs or R/MWAs [10–23]. Rolling element bearings are the core supporting component, and play a decisive role in the performance, operation reliability and service life of CMGs. Currently, a linear spring-damper model has been widely adopted to describe the internal compliances of rolling element bearings [12–16,19–23]. Such treatment is obviously too ideal and could not reflect the imperfections and disturbances accurately. Some key factors, including the Hertzian contacts, bearing radial clearance, surface waviness, preload condition and so on, would significantly affect the dynamic behaviors of rolling element bearings and then the output torques of CMGs. Zhou et al. [24] first introduced the bearing irregularity and nonlinear stiffness into the dynamic model of a well-balanced flywheel. Simulation results indicated that the dynamic amplification is even greater than the mass imbalance when the bearing noise intersects with the translation mode at high rotational speed. Considering the nonlinear compliance of the internal bearing systems and the coupled motions of the rotating flywheel and the gimbal, Luo et al. [25] employed the energy method to develop a theoretical output torque model of a SGCMG. High frequency disturbances were found in the time history of output torques predicted by the theoretical model. In their model [24,25], both the nonlinear stiffness and bearing irregularity induced by the surface waviness were given by empirical equations, which might reduce the model accuracy.

Currently, most researchers believed that load distribution analysis should be utilized to iteratively solve the nonlinear bearing supporting forces. By applying elastic/geometric constraints between a rolling ball and radial roller bearings, Jones [26] first proposed a general load distribution model (Jones model) with five degrees of freedom considering gyroscopic moments and centrifugal forces of the balls. Tiwari et al. [27,28] greatly improved Jones' model by taking into account both radial clearance and Hertzian contact characteristics. Yhland [29,30] first pointed out that the waviness is the global imperfection on the surfaces of the bearing components, and conducted experimental measurements of waviness. Based on the work of Yhland [29,30], Jang and Jeong [31–34] introduced the bearing waviness into the Jones' model and carried out a series of work to analyze the effects of bearing waviness on the vibration forces and frequencies and on the stability of the rotating system. Later, Bai and Xu [35] proposed an improved load distribution model to study the effect of bearing waviness on the fluctuation of the cage speed. Cao and Xiao [36] developed a comprehensive model of the double-row spherical roller bearing. In their model, several excitations such as the waviness, clearance, surface defects were included. Babu et al. [37] extended the Jones' model to six degrees of freedom, and found that the effect of frictional moment on the vibrations of