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Coupled dynamic analysis of a single gimbal control moment gyro cluster integrated with an isolation system

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A B S T R A C T

Control moment gyros (CMGs) are widely used as actuators for attitude control in spacecraft. However, micro-vibrations produced by CMGs will degrade the pointing performance of high-sensitivity instruments on-board the spacecraft. This paper addresses dynamic modelling and performs an analysis on the micro-vibration isolation for a single gimbal CMG (SGCMG) cluster. First, an analytical model was developed to describe both the coupled SGCMG cluster and the multi-axis isolation system that can express the dynamic outputs. This analytical model accurately reflects the mass and inertia properties, the gyroscopic effects and flexible modes of the coupled system, which can be generalized for isolation applications of SGCMG clusters. Second, the analytical model was validated using MSC.NASTRAN software based on the finite element technique. The dynamic characteristics of the coupled system are affected by the mass distribution and the gyroscopic effects of the SGCMGs. The gyroscopic effects produced by the rotary flywheel will stiffen or soften several of the structural modes of the coupled system. In addition, the gyroscopic effect of each SGCMG can interact with or counteract that of others, which induce vibration modes coupled together. Finally, the performance of the passive isolation was analysed. It was demonstrated that the gyroscopic effects should be considered in isolation studies on SGCMG clusters; otherwise, the isolation performance will be underestimated if they are ignored.

1. Introduction

1.1. Micro-vibration problems

Micro-vibrations generated by on-board equipment in spacecraft, such as the reaction and momentum wheel assembly (R/MWA), control moment gyro (CMG), cryo-coolers and solar panel deployment actuators, can seriously degrade the performance of instruments with high pointing precision and stability [1]. Attenuating the micro-vibration disturbance becomes a significant problem for spacecraft with high-performance requirements, for example, GOES-N, GOCE, and Hinode (Solar-B) [2–5].

CMGs, which have been widely used as actuators for attitude control in spacecraft, are considered to be one of the most prominent disturbance sources. A CMG is composed of a high-speed rotary flywheel and a gimbal servo system. As the key component of the CMG, the rotary flywheel produces much of the disturbance [6]. Disturbance of the flywheel results primarily from the following factors: mass imbalance, bearing imperfection, and motor error [7,8]. Furthermore, the gimbal servo system generates random disturbances due to gimbal friction and motor ripple; however, the disturbances are at higher frequencies and with much smaller amplitudes than those induced by the rotary flywheel [9].

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During the past decades, many methods have been developed to reduce the micro-vibration disturbances from instruments. An effective way is to place an isolator between the vibratory source and the spacecraft, which can cut off the disturbance propagation [10–14]. Several isolation techniques have been devised and analysed. Honeywell designed a series of viscous fluid-damped passive isolators that have been used in many space missions, for example, the well-known Hubble Space Telescope [15]. Vaillon and Philippe [16] designed and tested an elastomer-based passive vibration isolator. The isolator can be used to isolate a disturbance source with an attenuation performance exceeding 20 dB above 25 Hz and 40 dB above 50 Hz. These aforementioned isolators are based on the passive viscosity dissipation mechanism and perform well at several interested frequencies in the high-frequency range. Because the flywheel of a CMG operates at a fairly constant speed, the disturbance force and torque harmonic remain relatively stationary in the frequency domain [9]. Therefore, a passive isolator can meet the vibration isolation requirements. Generally, isolation for CMGs must have multi-degrees-of-freedom for two reasons: first, the output disturbance of a CMG is closely related to the orientation of the flywheel; when the flywheel is at different gimbal angles, the output disturbance in each component axis is different [6]; second, CMGs are mounted together onboard a spacecraft in some type of configuration, such as the four- and five-pyramid, and then the output disturbances of the CMG cluster are multi-directional. Many multi-axis isolation systems have been investigated, where the Stewart–Gough active isolation system is the most widely used because of the great advantages in control purposes [17–22]. Zhang et al. [20–22] have conducted substantial studies in the area of vibration isolation for a CMG cluster in a pyramid configuration using the Stewart platform. The researchers designed isolation parameters and discussed the dynamic interaction between the isolation system and the flexible appendages that are attached to the spacecraft.

However, there are still problems that must be studied in the area of vibration isolation for CMG clusters. The first problem is that the isolation system should be designed in accordance with the mounting configuration of the CMG cluster that determines the mass and inertia distribution and disturbance characteristics of the CMGs [23]. There are many types of mounting configurations for CMG applications in practice, such as the four-pyramid configuration that uses four SGCMGs, the five-pyramid that uses six SGCMGs, etc. Different mounting configurations may present different dynamic characteristics, and therefore, it is advantageous to have a universal model that can be applied in the isolation analysis for a CMG cluster even when it is configured differently. The second problem is that the rotary flywheel produces gyroscopic effects, which induces dynamic interactions between the CMG cluster and the isolation system [24]. The gyroscopic effects can stiffen or soften the structural modes of the isolation system and consequently affect the isolation performance.

1.2. Contribution of this paper

To resolve the problems described above, the coupled dynamics between the CMG cluster and the isolation system are investigated in this paper. First, we developed a coupled dynamic model of a single gimbal CMG (SGCMG) cluster integrated with a multi-degree-of-freedom isolation system using the energy method. This model fully considers the dynamic interactions induced by the SGCMG mass and inertial properties, gyroscopic effects and internal compliance. Second, we validated the dynamic model based on the finite element technique using the software MSC.NASTRAN. Finally, using the proposed model, we calculated the dynamic responses of the coupled system when the gimbals are stationary and rotating. The performance of the isolation system was then analysed and discussed.

The paper proceeds as follows: Section 2 describes the micro-vibration of an SGCMG onboard a spacecraft. Section 3 describes the assumptions and defines the coordinates. Section 4 provides the modelling details of the SGCMG cluster integrated with a multi-degree-of-freedom isolation system. Section 5 presents examples and discusses the dynamic characteristics of the SGCMG cluster and isolation system. Section 6 summarizes the paper and draws the conclusions.

2. Micro-vibrations induced by an SGCMG

2.1. Description of the SGCMG

The SGCMG is widely used in attitude control due to its good trade-off between performance and cost. The double-end supported SGCMG is the most typical configuration, which is shown in Fig. 1. Table 1 gives the specifications of a mechanical bearing supported SGCMG. When the gimbal rotates ($\dot{\boldsymbol{\delta}}$), the SGCMG produces gyroscopic torque. For a cluster of SGCMGs, the total gyroscopic torque can be calculated by the following equation:

$$ {}^{0}\mathbf{T}_{\mathrm{o}} = -\sum_{i=1}^{N_{\mathrm{CMG}}} \dot{\boldsymbol{\delta}}_i \times \mathbf{h}_{\mathrm{CMG},i} \tag{1} $$

2.2. Flywheel mass imbalance

Flywheel mass imbalance is considered to be the most prominent disturbance source [7] and is caused by the misalignment of the flywheel with respect to the rotating axis, which generally cannot be completely avoided due to tolerances or imperfections during manufacturing [12]. In this study, we used small equivalent lumped masses to model the