Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Active-passive integrated vibration control for control moment gyros and its application to satellites

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ARTICLE INFO

Article history:
Received 18 September 2016
Received in revised form
20 December 2016
Accepted 5 January 2017
L.G. Tham

Keywords:
Vibration control
Control moment gyro
Attitude control
Truss structure
Dynamic model

ABSTRACT

The strategy of active-passive integrated vibration control on the truss enveloping control moment gyroscopes (CMGs) is presented and its characteristics of time domain and frequency domain are analyzed. Truss enveloping CMGs contains pyramid-type CMGs, which are enveloped by multiple struts. These struts can be employed to realize the active-passive integrated vibration control. In addition, the struts of the trusses can maintain the working space of CMGs. Firstly, the disturbance characteristics of CMGs are analyzed considering static and dynamic imbalances of the CMG's rotor; then, an active-passive integrated vibration isolation truss structure is developed based on its characteristics. This structure can restrain the CMG vibration as much as possible and reduce its influence on the photographic quality of optical payloads. Next, the dynamic model of the active-passive vibration isolation truss structure is established. The frequency domain analysis of this model shows that the active-passive integrated vibration control method can restrain the high-frequency vibration and also improve the characteristics of low-frequency vibration. Finally, the dynamic model for the whole satellite is built with this type of CMGs. The time domain simulations of satellite attitude control verify the attitude control improvements resulting from the CMGs vibration control strategy.

1. Introduction

Control moment gyroscope (CMG) is a common used actuator for attitude control of the satellite. It offers the advantages of large torque output and high control accuracy and is widely used in modern space missions [1,2]. Limited by its manufacturing process and assembly accuracy, CMG shows a high-frequency micro-vibration when working. If the micro-vibration is not effectively isolated, it strongly influences the orientation accuracy and stability of the satellite attitude, which will further affect the normal operations of sensitive payloads.

To isolate or control the vibration of the CMG effectively, its vibration characteristics should be analyzed first. Masterson [3], Robert [4], Zhou [5], Luo [6] and Li [7] built the dynamic model of CMGs respectively from experiences and theory analysis as well as studying of its vibration characteristics. These studies mostly focused on a single CMG rather than the vibration characteristics produced by a CMG configuration on a satellite. Christopher et al. [8] built the 4-CMG dynamic model of the three-sided pyramid configuration and analyzed the influence of the gimbal servosystem on the satellite

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http://dx.doi.org/10.1016/j.jsv.2017.01.002

pointing control accuracy. However, the analysis of the vibration characteristics for a specific CMG structure could clarify its characteristics in any directions. So the vibration isolation system can be designed targeted to the characteristics in different directions.

Recently, there are various methods used for CMG vibration isolation while passive vibration control is one of the most common. The Violet satellite [9] used single vibration isolation on every CMG to obtain high control accuracy. The series of WorldView satellites [10] with CMGs implemented the Octo-strut vibration isolation platform which was installed between the CMGs and the satellite body. The Pleiades-HR earth observation satellite [11] used the Stewart vibration isolation platform to isolate the high-frequency vibration of CMGs. For the theoretical study of the vibration isolation platform, Zhang et al. [12] designed an isolator with a spring-damper in three directions which was installed at the CMG outer gimbal axis to effectively reduce the disturbing force and torque. Zhang et al. [13] added an inner vibration isolator for CMGs, which showed great isolation effectiveness for CMG vibration. Taking the mass characteristics of struts into account, Zhang et al. [14] built a dynamic model of the Stewart vibration isolation platform and compared the CMG disturbance transmissibility characteristics between the two-parameter model and the three-parameter model. Luo et al. [15] built a dynamic model containing both CMGs and a vibration isolation platform; this model showed that the vibration isolation platform has an obvious attenuating effect for the high-frequency disturbance from the control torque. However, the passive vibration control method is only available for high-frequency vibration, and there are also difficulties in parameter selection for the vibration isolator.

In addition to the high-frequency vibration induced by the static and dynamic imbalances of the rotor, the CMG vibration also includes low-frequency vibration. The sources of low-frequency vibration include motor or reducer friction and installation errors. To improve the effect of vibration control, active vibration control can be added to form an active-passive integrated vibration control method. This method can effectively improve the low-frequency isolation effect of the vibration isolation system. The typical Stewart active-passive integrated vibration isolation platform systems include VISS [16] (Vibration Isolation and Suppression System) developed by the Honeywell company in 1999 and SUITE [17] (Satellite Ultraquiet Isolation Technology Experiment) developed by the CSA company in 2000. In a theoretical study, Zhang et al. [18] employed adaptive filter algorithms for active vibration control aiming at Stewart vibration isolation platform in non-cubic configuration. Liu et al. [19] used the adaptive PID control method and obtained a good isolation effect for vibration induced by flexible structures on a satellite. Chi et al. [20] used a voice coil motor as the vibration isolation platform actuator, and they used the $H\infty$ control method to analyze its amplitude-frequency characteristics and conducted experimental verification.

With the development of satellite miniaturization and quick response missions, some problems such as the complexity of traditional vibration isolation system, the space occupation on the satellite and weight problem have appeared. Therefore, the Honeywell Company proposed a CMGs truss structure [21,22] in 2002. Based on an integrated structure, this modular structure reduced the mass and volume of the entire system by using electronic components resulting from employing a normal circuit. However, for the vibration isolation of exposed truss structure CMGs, this company still used a traditional vibration isolation platform which made it difficult to show the advantages of structure compaction and little space usage. This paper proposes an improvement to the truss structure CMGs from this company. Some truss struts are designed to be active-passive vibration control struts. In this way, the isolation of CMG vibration can be achieved without occupying extra space.

For evaluating the improved performance of satellite attitude control by truss structure CMGs, a complete spacecraft dynamic model is necessary, and its dynamic characteristics need to be analyzed. The truss structure and the Stewart platform are kind of similar, because they both have less truss struts and large rigidity. The building methods of the dynamic models of parallel mechanisms and these of the spacecraft with CMGs can both be referred. For example, Xu et al. [23] used the Newton method to build a Stewart platform dynamic model combined with a satellite body, flexible structure and payloads. Xu et al. [24] built an analysis model of space truss structures and optimized the effectiveness of flywheel micro-vibration isolation through optimizing the installation locations of the viscoelastic dampers. Zhang et al. [25] built a dynamic model of rigid spacecraft with CMGs using the Newton-Euler method which considered the mass imbalances and installation errors of CMGs.

Therefore, this paper presents the characteristics of pyramid-type truss structure CMGs and proposes an active-passive vibration control strategy. This method aims to restrain various types of CMG vibrations to the utmost extent without affecting the output of CMG control torque. Section 2 builds a dynamic model of the CMGs in a pyramid configuration considered static and dynamic imbalances of the rotor, and analyses the disturbance characteristics of these CMGs. Section 3 proposes an active-passive integrated vibration isolation truss structure based on the disturbance characteristics. Section 4 builds a dynamic model of the truss structure. Section 5 analyzed the dynamic characteristics of vibration isolation truss structure and verifies the effect of the active control method. Section 6 builds the dynamic model of the whole spacecraft system and presents numerical simulations to verify the attitude control improvements from truss vibration isolation structure.

2. Vibration characteristics of the CMGs

As shown in Fig. 1, CMGs in a pyramid configuration are combined with four CMGs that are located at each midpoint of the bottom edges. The gimbal axis $z_{g0h}(h = 1, 2, 3, 4)$ is perpendicular to the four faces of a hypothetical pyramid. The