Chinese Journal of Aeronautics, (2016), **29**(1): 238–247

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Singularity problem of control moment gyro cluster with vibration isolators

Cui Yinghui, Zheng Gangtie *

School of Aerospace, Tsinghua University, Beijing 100084, China

Received 29 April 2015; revised 2 June 2015; accepted 7 June 2015
Available online 22 December 2015

KEYWORDS

Satellite;
Singularity;
Steering logic;
Torque error;
Vibration isolation

Abstract As powerful torque amplification actuators, control moment gyros (CMGs) are often used in the attitude control of many state-of-the-art high resolution satellites. However, the disturbance generated by the CMGs can not only reduce the attitude stability of a satellite but also deteriorate the performance of optic payloads. Currently, CMG vibration isolators are widely used to target this problem. The isolators can affect the singularity of the CMG system as they are placed between the CMGs and the satellite bus and provide additional freedoms to the CMG system due to their flexibility. The formulation of the output torque of a CMG is studied first considering the dynamic imbalance of its spin rotor and then the deformation angle as a result of the isolator's flexibility is calculated. With the additional freedoms, the influence of isolator on the singularity problem is studied and a new steering logic to escape from the singular states is proposed.

1. Introduction

As powerful torque amplification actuators, control moment gyros (CMGs) are often used in the attitude control of many state-of-the-art high resolution satellites. However, the disturbance generated by the CMGs, which is commonly called the torque ripple, is transmitted to the satellite structure and its optic payloads. Such disturbance can not only reduce the attitude stability of the satellite but also deteriorate the performance of its optic payloads. The agility of the high resolution satellite can also be affected as a longer time may be needed to settle the vibration.

Vibrations from a spinning flywheel (reaction wheel assembly, CMG) are generated in the form of axial forces and torques, in line with and about the spin axis, and also radial forces and torques, normal to the spin axis. Sources of these wheel disturbances are electromagnetics and electronics, such as torque motor ripple and cogging (torque), rotor and wheel static and dynamic imbalances (radial torques and forces), and imperfections in the ball bearings and raceways (axial and radial forces).[1,2] Currently, CMG vibration isolators are widely used to target this problem.[3–5] Three most common classifications of vibration isolators are passive, active and hybrid control.[6] Since the spin rotor of a CMG operates at a fairly constant speed, the disturbance force and torque harmonics remain relatively stationary in the frequency domain.[1] Therefore, a passive isolation can meet the vibration isolation

---

* Corresponding author. Tel.: +86 10 62783235.
E-mail addresses: youngheastyle@qq.com (Y. Cui), gtzheng@mail.tsinghua.edu.cn (G. Zheng).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.12.010
1000-9361

requirements.[5] A few papers have been published discussing the effect of vibration isolators on the performance of CMG/flywheel systems.[7,8] However, these researches took the vibration isolator as an isolation platform with all CMGs on it and hence the vibration isolators have no influence on the problem of singularity.[5–8] Since for many large satellites CMGs are mounted on different parts/positions, it is often not realistic to put all CMGs on a single vibration isolation platform, and the vibration isolator should be provided for each individual CMG.

On the other hand, an important problem of using a CMG system in the attitude control is the singularity.[9] When all individual CMG torque output vectors are perpendicular to the commanded torque direction, the system is in the state of singularity. In other words, in a singular state all the output torque vectors become coplanar and cannot span 3-D space. Many steering logics were studied and developed to avoid/escape the singular states and minimize negative effects on the satellite in the meantime.[7] The characteristics of the existing steering laws were summarized in Ref.[10].

Methods for solving the singularity problem published in literature can be classified into three categories,[11] i.e., gradient method, singularity robust (SR) inverse methods and global avoidance methods. The gradient method relies on the null motion, which is defined as CMG gimbal motions that generate no torque.[9] However there are some singular states called elliptic states cannot be escaped through the null motion.[12] The SR inverse methods, which are based on quadratic optimization, were proposed to escape from any kinds of internal singular states while allowing the torque error.[13–17] The gradient methods include path planning method, preferred gimbal angle method, etc. However, some of them are time-consuming or have limited angular momentum workspace.[18,19] Besides, some reconfiguration steering logics[7] are studied to accommodate the situation where some of the CMGs in the cluster fail, and hybrid steering logics[20] are discussed considering both the singularity escape and torque error.

As the isolators are placed between the CMGs and the satellite bus, their flexibility adds additional freedoms to the CMG system. Both the vibration and singularity are troublesome problem for a CMG-used satellite and none of the aforementioned papers presented specific conclusion on these problems simultaneously. Therefore, it is necessary to study the influence of CMG isolators on the singularity for the purposes of designing an isolator properly and avoiding negative effects on the attitude control. For the additional freedoms introduced by the vibration isolator's flexibility, more importantly, a new steering logic should be developed for escaping from singularities.

2. Modeling CMG system with isolators

2.1. Description of individual CMG isolation system

An individual CMG isolation system is composed of a single gimbal (SG) CMG and a passive isolator, whose task is preventing the satellite from vibratory forces or torque ripples created by CMG and in the meantime transmitting the useful control torque to the satellite. A uni-axial CMG isolation system is shown in Fig. 1, where m is the mass of CMG, x the translational motion component of CMG, c the damping coefficient of isolator, x_0 the translational motion component of base/satellite in x direction, k the stiffness parameter of isolator, $F_{\mathrm{E}}(t)$ the excitation/disturbance force, and m_{st} the mass of satellite. Dynamic equations of motion of this system are

$$m\ddot{x} + c(\dot{x} - \dot{x}_0) + k(x - x_0) = F_{\mathrm{E}} \tag{1}$$

$$m_{\mathrm{st}}\ddot{x}_0 + c(\dot{x}_0 - \dot{x}) + k(x_0 - x) = 0 \tag{2}$$

In the cases of CMG vibration isolation systems, the system shown in Fig. 2 can be used. It is called focal ring shaped vibration isolation system as introduced in Ref.[21]. The system model is defined as follows. It is composed of three or more identical mounts placed at the apexes of a regular polygon inscribed into a circle of radius r parallel to XOY plane with its center point (G) on the Z-axis. Principal axes Z_1, Z_2,... of all mounts are intersecting at point A on the Z-axis and are inclined by an angle ϕ to the XOY plane. Axes X_1, X_2,... of all mounts are tangential to the circle. Y_i (i = 1, 2, 3) is the axis that is vertical to the X_i and Z_i simultaneously. Principal stiffness coefficients of the mounts are k_X, k_Y and k_Z, along their respective principle axes X_i, Y_i and Z_i (i = 1, 2, 3). Point C.G. marked in Fig. 2 is the position of the center of gravity of the isolated object and it coincides with the origin O of the coordinate system. R is the distance between O and the ith mount, and θ is the inclined angle of the line connecting O and mount.

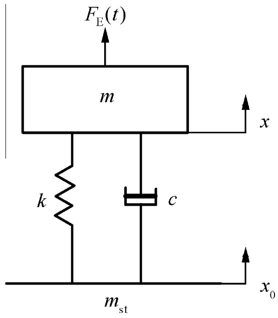

Fig. 1 Typical model of general uni-axial CMG vibration isolation system.

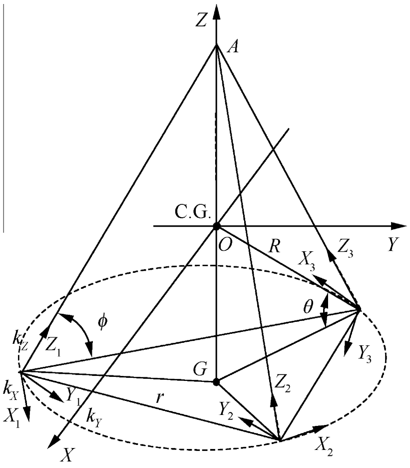

Fig. 2 Focal "ring-shaped" vibration isolation system.