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Modeling and analysis of a flywheel microvibration isolation system for spacecrafts

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Abstract

The microvibrations generated by flywheels running at full speed onboard high precision spacecrafts will affect stability of the spacecraft bus and further degrade pointing accuracy of the payload. A passive vibration isolation platform comprised of multi-segment zigzag beams is proposed to isolate disturbances of the flywheel. By considering the flywheel and the platform as an integral system with gyroscopic effects, an equivalent dynamic model is developed and verified through eigenvalue and frequency response analysis. The critical speeds of the system are deduced and expressed as functions of system parameters. The vibration isolation performance of the platform under synchronal and high-order harmonic disturbances caused by the flywheel is investigated. It is found that the speed range within which the passive platform is effective and the disturbance decay rate of the system are greatly influenced by the locations of the critical speeds. Structure optimization of the platform is carried out to enhance its performance. Simulation results show that a properly designed vibration isolation platform can effectively reduce disturbances emitted by the flywheel operating above the critical speeds of the system.

Keywords: Microvibration; Flywheel; Passive vibration isolation platform; Gyroscopic effects; Equivalent dynamic model

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1. Introduction

To satisfy high performance requirements relating to line-of-sight pointing accuracy of space observatory, remote sensing, laser communications and other high precision spacecrafts, an ultra-quiet spacecraft bus is imperative (Brugarolas et al., 2006; Doyle, 2007; Lee et al., 2011). However, the microvibrations induced by mechanical moving devices onboard spacecrafts, such as flywheels, solar array drive motors and cryo-coolers could undermine the stability of the bus seriously, causing deleterious effects on the pointing performance (Brugarolas et al., 2010; Oh et al., 2013). Therefore, more and more attentions have been turned to dealing with the microvibration problems of the spacecrafts in recent years (Lillie et al., 2010; Tan et al., 2005).

As a common actuator of attitude control system, when the flywheel rotates, it generates speed-related synchronal and harmonic disturbances due to wheel imbalance and other structure and assembling imperfections. Through numerous analyses and tests, flywheels have been identified as the dominant microvibration source of many spacecrafts, such as Chandra Observatory and James Webb Space Telescope (JWST) (Bronowicki, 2006; Pendergast and Schauwecker, 1998).

A great many efforts to reduce flywheel-induced microvibration onboard spacecrafts have been undertaken. Mostly, there are two approaches to the problem of microvibration caused by flywheels. One is to isolate the flywheel from the other parts of the spacecraft; the other one is to isolate sensitive payloads from the spacecraft

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bus (Preumont, 2011). An ad hoc passive isolator employing metal springs and viscous fluid dampers was developed to provide axial isolation for the reaction wheel assemblies (RWA) of Hubble Space Telescope (Davis et al., 1986). Component testing proved the isolator had two orders of magnitude reduction in force generated by an RWA. Pendergast and Schauwecker (1998) designed a reaction wheel isolator assembly (RWIA) to reduce the level of flywheel dynamic disturbances transmitted to the optical train of Chandra Observatory. Each RWIA was made up of a set of six machined spring elements with bonded viscoelastic material and has a 9 Hz cutoff frequency and a 5% modal damping to meet attenuation needs corresponding to wheel speeds above 500 rpm. Liu et al. (2008) conducted ground tests of the Solar Dynamic Observatory (SDO) and found that the speed of the reaction wheel would has to be limited within +/−400 rpm to mitigate its disturbance effects during the science mode if no vibration isolation measures are taken. To meet stringent pointing stability up to milli-arcsecond of JWST, a two-stage passive vibration isolation system is employed (Meza et al., 2005). The first stage is reaction wheel isolators between each reaction wheel and the spacecraft bus. The second stage is a 1 Hz isolator between the spacecraft bus and the optical payload. Kamesh et al. (2010, 2012) designed and tested a low frequency platform to act as a mount for reaction wheels. Zhou et al. (2011), Zhou and Li (2012), Zhou et al. (2012a) proposed a soft suspension design for a reaction/momentum wheel assembly. Unlike other research teams, they modified the internal suspension system of the flywheel to accomplish low disturbance outputs. Oh et al. (2004, 2006, 2011) investigated the characteristics of two types of isolators for momentum-wheel vibration. One of the isolators uses electro-rheological fluid, a type of smart material, to act as agent of semiactive isolation. The other one uses bio-metal fiber valve controlled semiactive damper to mitigate the vibrations. Makihara et al. (2006) also studied the semiactive technique for isolating observation devices from disturbances of momentum wheel using piezoelectric ceramics. Luo et al. (2013) proposed a vibration isolation approach for multiple flywheel system in arbitrary configuration based on Stewart platform and they found that there exist modes exchanging phenomenon when the flywheel rotates in some direction.

Despite quite a few vibration isolators have been proposed for flywheels, many of them did not consider the flywheel as a rotational system. This negligence tends to lead to some inaccurate results. In this work, a passive vibration isolation platform is studied as a prelude to a combined passive/active platform for isolating microvibrations generated by flywheels. By considering the rotational characteristics of the flywheels, we gained some useful insight into the vibration isolation problem of flywheels through a simplified equivalent dynamic model embedded with gyroscopic effects. Especially, we found that flywheels with different mass inertial properties will impose quite different impacts on the performance of the vibration isolation system, which had not been taken note of previously. This paper is organized as follows: Section 2 describes the platform, establishes the equivalent dynamic model of the vibration isolation system and analyses its eigenvalue characteristics theoretically when the flywheel is at rest and is running at full speed respectively. Section 3 verifies the dynamic model and examines the vibration isolation performance of the platform. Section 4 presents the conclusion.

2. Dynamic modeling

2.1. Description of the system and coordinates definition

A prototype of the flywheel vibration isolation platform proposed in this paper is shown in Fig. 1(1). The platform mainly consists of four identical zig-zag beams symmetrically connected to a circular plate, which is an interface between the flywheel and the platform. The flywheel is installed on the spacecraft through the platform, as is shown in Fig. 1(2). The platform is expected to act as a low pass filter, permitting low frequency attitude control torque to transmit to the spacecraft while blockading high frequency disturbances generated by the flywheel.

As is shown in Fig. 1, the four zig-zag beams of the platform are indexed anticlockwise from ① to ④ to act as reference directions for coordinate systems. Three coordinate systems are established to facilitate the study:

(1) $Oxyz$ is a platform-fixed coordinate system defined in the interface between the flywheel and the platform. The origin O is at the center of the circular plate. Ox and Oy are directed towards beam ① and beam ② in quadrature and Oz is in line with rotation axis of the flywheel. $Oxyz$ is used to describe direction of overall stiffness of the platform.
(2) O_mxyz is an inertial coordinate system with its origin set at the center of mass (CoM) of the flywheel and its three axes in line with that of $Oxyz$. The distance between O_m and O is denoted by h. O_mxyz is the reference coordinate system on which dynamic equation of the system is developed.
(3) $O_1x_1y_1z_1$ is a local coordinate system fixed on each beam and is defined in the connecting point between each zig-zag beam and the circular plate. The origin O_1 is at the geometry center of the beam. O_1x_1 and O_1y_1 are in the plane defined by the cross-section of the beam while O_1z_1 is directed along length direction of the first segment of each beam. $O_1x_1y_1z_1$ is used to describe direction of local stiffness of the beam.

2.2. Formulation of dynamic equation

A typical mechanical flywheel includes a rotor driven by a motor through bearings, all of which are enveloped in a housing. Considerable efforts have been made to model