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Hybrid isolation of micro vibrations induced by reaction wheels

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ABSTRACT

As the technology for precision satellite payloads continues to advance, the requirements for the pointing stability of the satellites are becoming extremely high. In many situations, even small amplitude disturbances generated by the onboard components may cause serious degradation in the performance of high precision payloads. In such situations, vibration isolators can be installed to reduce the vibration transmission. In this work, a hybrid vibration isolator comprising passive and active components is proposed to provide an effective solution to the vibration problems caused by the reaction wheel disturbances. Firstly, mathematical modeling and experimental study of a single axis vibration isolator having high damping and high roll-off rate for the high frequency region and active components that enhance isolation performance for narrow frequency bands are presented. This concept is then extended to multi-axis by forming Stewart platform and the performance is experimentally verified. The tests on a flexible testbed show effective vibration isolation by the proposed vibration isolator.

1. Introduction

A recent move towards the development of high performance observation and communication satellites (requires high pointing stability) and the use of large flexible structures (the structure is more vulnerable to vibration) has brought much emphasis on the vibration isolation of high precision payloads from the vibration disturbances that, although very small in amplitude, may still cause significant performance degradation [1–3]. Among the various sources of vibration disturbances on orbit, reaction wheels are reported as one of the most problematic disturbance sources [4–7]. The disturbances produced by a reaction wheel include fundamental harmonic disturbances and other sub/super harmonic disturbances [8]. The fundamental harmonic disturbances are caused by the static and the dynamic imbalance of the flywheel and are usually the largest disturbance. The sources of sub/super harmonic disturbances include bearing irregularities, motor imperfections and so on [9]. Measurements of the reaction wheel disturbances show that their amplitudes are proportional to the square of the wheel's rotation speed [10]. In order to meet extremely high pointing accuracy and stability requirements placed on the spacecraft to ensure mission success, vibration isolators are implemented to reduce the propagation of vibration disturbances from the reaction wheels [11].

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Several vibration isolators have been developed to reduce vibration disturbances from the reaction wheels. Viscous fluid based passive isolators called D-strut developed by Honeywell were used to isolate reaction wheel disturbances in Hubble Space Telescope [12,13]. In Advanced X-ray Astro-Physics Facility, passive isolators utilizing a bonded viscoelastic material (VEM) were implemented to reduce the transmission of reaction wheel disturbances [14]. In James Webb Space Telescope, vibration isolators using segmented constraining layer VEM were proposed to reaction wheel as well as to the optical payload to reduce vibration induced errors [15].

Aside from the aforementioned passive vibration isolators for reaction wheels, some semi-active and active vibration isolators were studied. Oh et al. [16] proposed a semi-active isolator using liquid-crystal type ER fluid and demonstrated the effectiveness of the proposed method for momentum wheel vibration isolation by numerical simulations. Oh et al. also proposed a variable damping isolator that uses bio-metal fiber (BMF) valve for changing damping values [17] and performed a single-axis isolation test using a flywheel [18]. Kamesh et al. [19] proposed a vibration isolator in folded beam configuration with piezoelectric actuators and sensors and some simulation results were presented. However, the active components were not included in their experimental study [20]. Similar type of active vibration isolator was also studied by Zhou and Li [21], but like Kamesh et al., the active components were excluded in their experimental study [22]. Several generic hybrid vibration isolators in hexapod configuration have been developed in various research groups [1,23–31], but the focus of their study has been mainly on control techniques. Davis et al. [32] proposed a hybrid D-strut isolator comprising passive D-strut isolator and electromagnetic actuator. Single axis test using Linear Quadratic Gaussian controller to achieve narrowband notch at the isolator's cutting frequency showed that the mount resonance can be actively lowered by more than a decade.

Although several passive vibration isolators have been developed for the purpose of reaction wheel disturbance reduction, few studies have focused on the development of a hybrid vibration isolator for the effective reduction of vibration caused by the reaction wheels. Considering the reaction wheel disturbance characteristics, the requirement for a vibration isolator for the effective reduction of vibration induced by the reaction wheel disturbances can be stated as follows:

- High roll-off rate: The amplitude of reaction wheel disturbances is proportional to the wheel speed squared ($|A| \sim f^2$) so the vibration isolator should have transmissibility that decreases with the square of the frequency ($|T| \sim 1/f^2$) for the effective vibration reduction.
- High damping (low magnification factor): Reaction wheels may operate at wheel speeds in which the frequencies of the induced disturbances match with the natural frequencies of the isolation system. High damping is required to reduce the large amplification at the resonances of the isolation system.
- Capability to enhance isolation performance at particular frequencies: Reaction wheels may produce disturbances that excite the structural modes of the spacecraft structure. In such cases, passive isolators may not be able to reduce the induced vibration below the requirement level. Active components can be added to enhance the isolation performance at the frequencies where the structural modes of spacecraft exist.

While passive isolators can be used to reduce the disturbances at high frequencies, even the reduced disturbances may cause significant vibration if the natural modes of the satellite structure are excited. In such cases, active control can be used to enhance the isolation performance in the problematic frequency bands. An example of this concept is shown in Fig. 1. Notch filter at the structural modes of the satellite can be used in the feedback loop to further reduce the vibration at these frequencies which may be significant even when the passive isolator is used.

In this paper, a hybrid vibration isolation platform is presented for the effective reduction of reaction wheel induced vibration. The developed vibration isolator is composed of (a) a passive three parameter vibration isolator having high

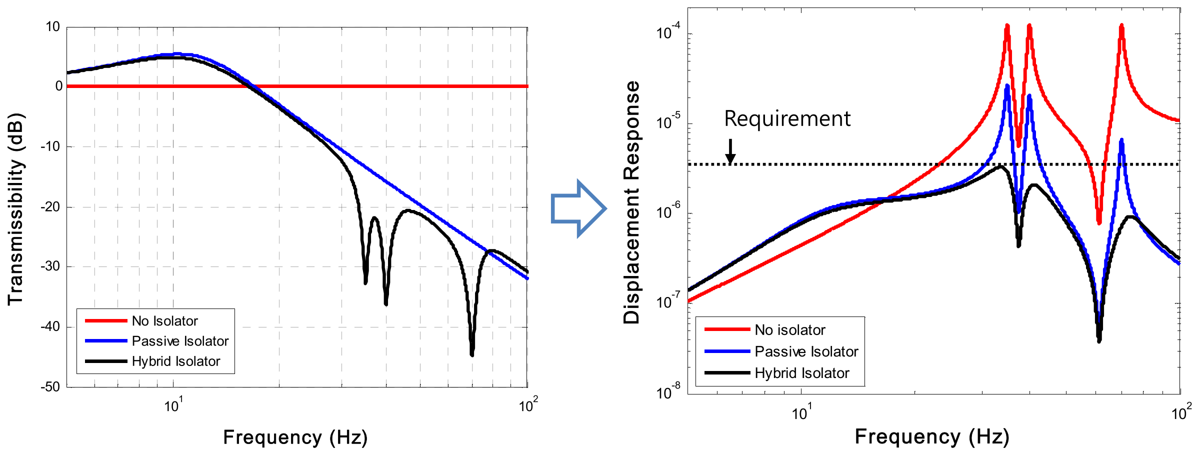

Fig. 1. Concept of the proposed hybrid vibration isolator.