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Review

Recent advances in micro-vibration isolation

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ABSTRACT

Micro-vibration caused by disturbance sources onboard spacecraft can severely degrade the working environment of sensitive payloads. Some notable vibration control methods have been developed particularly for the suppression or isolation of micro-vibration over recent decades. Usually, passive isolation techniques are deployed in aerospace engineering. Active isolators, however, are often proposed to deal with the low frequency vibration that is common in spacecraft. Active/passive hybrid isolation has also been effectively used in some spacecraft structures for a number of years. In semi-active isolation systems, the inherent structural performance can be adjusted to deal with variation in the aerospace environment. This latter approach is potentially one of the most practical isolation techniques for micro-vibration isolation tasks. Some emerging advanced vibration isolation methods that exploit the benefits of nonlinearity have also been reported in the literature. This represents an interesting and highly promising approach for solving some challenging problems in the area. This paper serves as a state-of-the-art review of the vibration isolation theory and/or methods which were developed, mainly over the last decade, specifically for or potentially could be used for, micro-vibration control.

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1. Introduction

The term micro-vibration usually refers to low-level mechanical vibration or disturbance in the microgravity environment, typically occurring at frequency from less than 1 Hz up to 1 kHz [1]. Therefore, micro-vibration can be created by mechanical systems located on spacecraft, for example, cryocoolers, thrusters, mobile mirrors, solar array drive mechanisms, and reaction/momentum wheel assemblies [2–5]. Due to very tiny environmental damping in aerospace, micro-vibration could persist for a long time. This will deteriorate the working environment of onboard instruments, for example, downgrading the precision of sensitive optical telescopes or the positional accuracy of space cameras. A typical example can be seen in the space interferometry mission (SIM), where a space-based interferometer with astrometry and imaging capability must meet an extremely harsh positional tolerance (of order of 1 nm across the entire 10 m baseline of the structure) to achieve astrometry requirements [6].

The main disturbance source of on-orbit spacecraft is often mechanical spinning devices such as reaction and momentum wheel assemblies [6–13]. Wheel assemblies are widely used in space technology to provide attitude control and momentum stability of a spacecraft. In general, the vibration disturbance from reaction and momentum wheels are mainly caused by static imbalance, dynamic imbalance, and bearing imperfection etc [8]. Static imbalance is caused by the offset of the center mass of the wheel spin axis, where disturbance resonant frequencies are equivalent to spinning frequencies of the wheels. Dynamic imbalance results from the misalignment of the principal axis and the rotating axis on the wheels, while bearing disturbances are caused by irregularities in balls, races and cage etc. [11].

Dynamic forces and moments generated by the imbalance and imperfection of rotating wheels can propagate in spacecraft structures. The disturbance resonant frequencies caused by the dynamic imbalance are smaller than the rotating frequencies. Compared to bearing imperfection, the imbalance of the flywheels has more impact on the generation of low frequency disturbance [11]. The main micro-vibration of onboard satellites focuses on the frequency range from 0.1 Hz to 300 Hz. Disturbances above 30 Hz are classed as high frequency whilst micro-vibration that occurs below this is deemed to be in the low frequency region [14]. The high frequency disturbance is mainly caused by momentum wheel assemblies, and low frequency micro-vibration by the reaction wheel assemblies. Due to rotating machines and their noise, micro-vibration could contain very different frequency components including harmonic, random, narrowband and broadband [15]. With the development of modern spacecraft with the characteristics of light-weight, flexible, large span and high precision, the influence of micro-vibration on the on-orbit spacecraft becomes more and more significant.

Many vibration isolation methods have been designed to protect high precision payloads from the impact of micro-vibration in onboard spacecraft. Typical isolation systems for space optical telescopes, referred to as vibration isolation and suppression system (VISS) and satellite ultra-quiet isolation technology experiment (SUITE) having been developed and utilized in spacecraft, can be seen in [16,17]. The VISS and SUITE consisting of six struts in a hexapod configuration are used as the support of the sensitive payloads or the disturbance sources of onboard spacecraft. Many other isolation systems are designed as support structures of payloads, which can isolate the micro-vibration transmitted from disturbance of the spacecraft to the sensitive payloads. The suppression of micro-vibration in the propagation path of disturbances has also been studied.

Overall, four kinds of isolation techniques can be classified for isolation of micro-vibrations of on-board spacecraft, e.g., passive, active, active–passive hybrid, and semi-active isolation. In this review, these four types of isolation methods will be discussed, respectively, including the isolation mechanism and characteristics, configuration design and features, advantages and disadvantages etc. Noticeably, a special section is given thereafter for some novel and emerging isolation methods by exploring nonlinear dynamics and benefits in vibration control. This review will serve as a state-of-the-art (although not comprehensive) summary of the vibration isolation theory and/or methods, that have focussed on micro-vibration control over the last decade.

2. Passive isolation techniques

Passive isolation techniques are commonly used in aerospace engineering providing high performance and stability, and requiring no external power [18–21], where the typical passive vibration isolation system is shown in Fig. 1. Vibration

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