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Design and experiments of an active isolator for satellite micro-vibration

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Abstract In this paper, a soft active isolator (SAI) derived from a voice coil motor is studied to determine its abilities as a micro-vibration isolation device for sensitive satellite payloads. Firstly, the two most important parts of the SAI, the mechanical unit and the low-noise driver, are designed and manufactured. Then, a rigid-flexible coupling dynamic model of the SAI is built, and a dynamic analysis is conducted. Furthermore, a controller with a sky-hook damper is designed. Finally, results from the performance tests of the mechanical/electronic parts and the isolation experiments are presented. The SAI attenuations are found to be more than −20 dB above 5 Hz, and the control effect is stable.

1. Introduction

For most satellites, on-board devices with moving/rotating mass, such as momentum or reaction wheels, flexible manipulator systems, cryocoolers, and other specialised devices, create micro-vibrations.[1–4] In the past, micro-vibrations with low amplitudes and frequencies up to approximately 1 kHz have often been neglected because of the low levels of induced disturbances.

Today, many satellites require very quiet environments to protect sensitive payloads, such as laser communication devices, astronomical telescopes, and micro-gravity experimental instruments. In order to achieve these stringent requirements, research on the attenuation of satellite micro-vibrations has become much more important. A variety of satellite designs and control architectures have been studied.[5,6] The most important aspect of satellite design and control is the vibration isolation between the precision payload and the disturbance base, which provides perfect transmissibility at low frequencies, greater isolation at high frequencies, and minimal amplification at all frequencies.

Commonly, passive isolation is regarded as the most mature technology for managing in-orbit vibration isolation. Ref.[7] discussed a two-layer vibration isolator assembly on the James Webb space telescope, which used viscoelastic damping with titanium springs and graphite/epoxy beams. Ref.[8] created a compact isolator for a space imager that was composed of three C-shaped metal springs with rubber dampers. Ref.[9] studied a viscoelastic damped ball joint and demonstrated its space applications, such as reaction wheel isolator struts. Ref.[10]

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developed a three-parameter isolator (D-strut) for a reaction wheel, in which the damping force was produced by a viscous fluid. Ref.[11] proposed a simple isolator, which consisted of a spring in parallel with an electromagnetic Maxwell unit. Passive isolation is necessary to limit the amplification at resonance but tends to reduce high-frequency attenuation. Furthermore, the damping materials are unable to maintain their properties in the harsh space environment because of their temperature dependence, making them insufficient for in-orbit micro-vibration isolation.

To overcome the disadvantages associated with passive isolation, active isolation has been widely studied for nearly two decades. Active isolation is usually conducted by two different types of isolators: hard active isolators (HAIs) and soft active isolators (SAIs).

HAIs use a stiff actuator (either piezoelectric or Terfenol-D) in series with a spring. Refs.[12–16] investigated various vibration isolation assemblies for precision payloads that employed piezoelectric HAIs, and Refs.[17–19] studied isolation assemblies with Terfenod-D HAIs. The HAI assemblies have proved to be effective for narrowband isolation. For broadband isolation, the control force of an HAI must be applied over a wide range of frequencies, leading to complex control algorithms and requiring powerful acquisition/operation electronics, high power consumption, and precision sensors, which are inappropriate for space applications.

SAIs generally use a soft actuator, typically a voice coil motor, in parallel with a soft spring. Although SAIs require that the payload mass be off-loaded during ground testing and satellite launching, they have lower corner frequency than HAIs, so they allow much lower frequencies to be isolated and consume less on-board resources in broadband isolation. Refs.[20–23] discussed spacecraft hexapod isolators, which were composed of voice coil motor SAIs with suspended permanent magnets. The main disadvantage of this configuration is that the permanent magnet, which is located on the bottom flexible joint, decreases the local mode frequency of the SAI, while inducing excessive stress on the flexible joint. Refs.[24–28] showed a more appropriately designed hexapod isolator with voice coil motor SAIs, in which the permanent magnet was fixed. In this configuration, the permanent magnet is attached to the base, and the membrane performs the functions of both the axial spring and the bottom flexible joint. Refs.[29,30] demonstrated the concept of a disturbance-free payload architecture for active isolation as well as precision steering of a payload, which was controlled by non-contact voice coil motor SAIs. Ref.[31] fabricated several active vibration isolation assemblies for international space station micro-gravity experiments, which were controlled by the levitation of various electromagnetic SAIs. Although the isolation assemblies with non-contact or levitation SAIs exhibited good performance, the complexity of the system design and controls decreases their reliability and restricts applications on unmanned satellites.

Thus, previous work has shown that an SAI is more suitable for satellite vibration isolation in regard to isolation performance, technology maturity, and consumption of on-board resources. However, few studies have focused on the low-noise design of an SAI system for micro-vibration as well as SAI vibration isolation experimental verification with micro-vibration excitation. In this paper, a voice coil motor SAI with a fixed permanent magnet was studied. There were one active degree-of-freedom (DOF) along the axis of the SAI and five passive DOFs, making the SAI applicable to not only localised (single-axis) isolation but also systematic (multi-axis) isolation when forming an isolation mount (e.g., tripod, hexapod, or octopod). In addition to the SAI system design and analysis, this paper reports on (1) the six DOFs stiffness calculation of the SAI membrane in large deformation, (2) the development of a low-noise linear driver for the SAI with a high-speed buffer, and (3) the SAI micro-vibration isolation experiments in frequency domain and time domain to verify the control effect and stability.

This paper begins with a discussion of the demands of satellite micro-vibration isolation and a summary of the isolation approaches that have been used or studied. Next, the design, analysis, and manufacture of the mechanical unit and the low-noise linear driver of a voice coil motor SAI are studied. Then, rigid-flexible coupling dynamic modelling of the SAI based on the Catia-Patran/Nastran-Adams software platform and an analysis of the SAI are conducted, and a sky-hook damper for active control is designed and simulated. Finally, experimental results of the SAI are shown, including driver noise, dynamic response, and frequency/time domain isolation.

2. Design and manufacture of SAI

2.1. Mechanical unit

Fig. 1 shows the schematic of the mechanical unit of the SAI. As shown in the figure, a permanent magnet, the heaviest part of the mechanical unit, is attached to the base. A single membrane performs the functions of both the spring for axial compliance and the U-joint. A rod is attached to the central point of the membrane, supports the coil on the left side and connects to the flexible joint on the right side, which in turn is connected to the payload as a ball joint. In this design, the rod axis is allowed to rotate with respect to the magnet at the central point of the membrane. This capability results in an increase in the magnetic gap of the voice coil motor, which slightly decreases the force sensitivity. The one active DOF on the SAI is the axial movement of the coil, and the five passive DOFs are the rotation and torsion of the membrane and the flexible joint. Figs. 2 and 3 show a cutaway view and a photo of the mechanical unit.

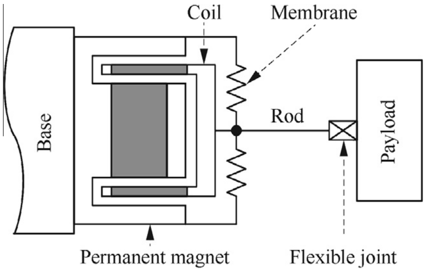

Fig. 1 Schematic of mechanical unit.

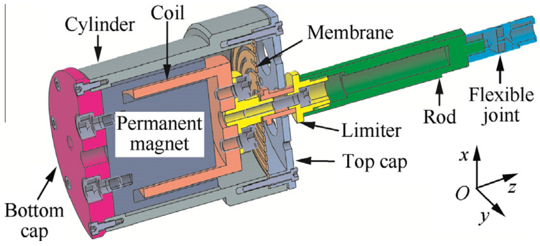

Fig. 2 Cutaway view of mechanical unit.