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Dynamic isotropic design and decentralized active control of a six-axis vibration isolator via Stewart platform

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ABSTRACT

the six-axis vibration isolation system is essential for high-precision space systems. Its architecture is always designed based on the cubic-configuration Stewart platform, whose six flexible modes generally have different natural frequencies resulting in multiple resonances at various frequencies such that a uniform capability of vibration isolation cannot be achieved for the six flexible modes. To solve this problem, the dynamic isotropic design of the isolator is studied to make the six nonzero natural frequencies identical. The free-floating state of the isolator is taken into account and six design criteria of the dynamic isotropy are obtained. The internal relation between the dynamic isotropy and the kinematic isotropy is revealed and discussed. A decentralized active controller is then investigated for the isolator of dynamic isotropy. The controller decouples the six-axis vibration control into six identical control of a single-axis vibration isolator. The same control gains in each single-axis isolator reaches the optimum simultaneously for all the flexible modes such that a best performance of vibration isolation can be achieved. Finally, we present an example of an isolator of dynamic isotropy. With the proportional plus integral compensator, the uniform corner frequency and optimal active damping can eventually be achieved.

1. Introduction

A super quiet environment is indispensable to the space systems with high-precision instruments, e.g. the space interferometers and the laser communication equipment, which are required to reach the motion stability of nanoscale [1–2]. One of the most important techniques used to attenuate the micro vibrations of the instruments is to install a vibration isolation system between the disturbance sources and the instruments [3–5].

A six-axis vibration isolation system can be designed based on many kinds of six-DOF architectures [6–9]. Among them, the common ones are parallel mechanisms, especially the Stewart platforms, due to their high ratio of stiffness to mass, strong dynamic performances and high accuracy. The vibration isolator can be mounted at the interface between the spacecraft bus and the attitude control module, allowing the low frequency attitude control torque to be transmitted, while filtering out the high frequency disturbances generated by the unbalanced centrifugal forces in the reaction wheels. Also the vibration isolator may be used at the interface between the spacecraft bus and the independent telescopes to be stabilized. It consists of an upper plate, a lower plate and six identical legs as the single-axis vibration isolators. The researches on this

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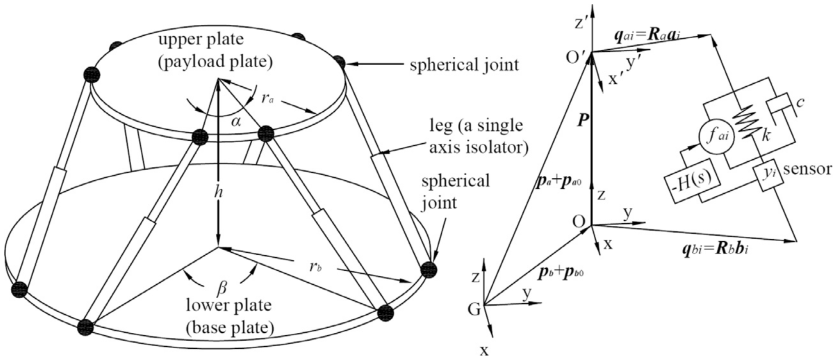

Fig. 1. Geometrical description of a six-axis micro-vibration isolator.

area have been carried out during the last two decades. A special-configuration Stewart platform, called the cubic Stewart platform, was firstly proposed as the architecture of the six-axis isolation system [10]. Later, the design [11], experiment [12], modeling [13–14], analysis [15] and active control [16–17] of the cubic Stewart platform had been researched constantly to the present. However, the Stewart platforms of this type always have different natural frequencies of the flexible modes, making it impossible to achieve a uniform capability of vibration isolation for six flexible modes. If the six flexible modes have different natural frequencies, the single gain of the feedback controller can only reach an optimal value for a certain mode or has to be adjusted to achieve a compromise in the suspension performance for the six modes. The best performance will be achieved if the system is designed in such a way that the modal spread, ($\omega_{\max}/\omega_{\min}$), is minimized. One cubic Stewart platform was designed with a modal spread of 2.2 [18]. Another cubic Stewart platform was designed with six flexible modes: 3.02, 3.02, 3.26, 6.66, 7.27 and 7.27 Hz, which limited the modal spread to 2.4 [19]. This paper aims to solve the problem, called the dynamic isotropic design to obtain a uniform capability of vibration isolation when a decentralized active control is employed.

Ma and Angeles [20] were the first to define the dynamic isotropic index and perform the isotropic design of the Stewart platform. Jiang et al. [21, 23–24] and He et al. [22] then studied the isotropic design of the Stewart platforms with full or redundant actuation. However, these results are not applicable for vibration isolation system in space since the system's free-floating state has not been taken into account. Therefore, in this paper, we will consider the free-floating state of the system in design and employ a decentralized active control based on force feedback to decouple the MIMO system into six identical single-axis active vibration isolator. The problem of dynamic isotropic design of a six-axis vibration isolator via Stewart platform working in the free-floating state will be solved for the first time. Moreover, we will discuss the internal relation between the dynamic isotropy and the kinematic isotropy. To take the advantages of the dynamic isotropy, a force-feedback decentralized control will be proposed to make the system possess a uniform capability of vibration isolation for all flexible modes. The main contributions of this paper include: (1) the dynamic isotropy of six-axis vibration isolator working in the free-floating state is realized for the first time and the design criteria are derived analytically; (2) the comparison of dynamic isotropy and kinematic isotropy reveals their internal equivalence in some sense to deeply illuminate the significance of dynamic isotropy; (3) under the condition of dynamic isotropy, a force-feedback decentralized active controller is designed to make the system possess a uniform capability of vibration isolation for all flexible modes; (4) the proportional plus integral compensator is given to demonstrate the uniform corner frequency and optimal active damping for all flexible modes.

We will firstly establish the dynamic model of the system, derive all the natural frequencies in analytic form in Section 2 and educe the design criteria of dynamic isotropy in Section 3. In Section 4, a decentralized active control is then employed to decouple the system of dynamic isotropy and to obtain the uniform capability of vibration isolation. An example of a six-axis isolator will finally be presented in Section 5.

2. Dynamic modelling

2.1. Six-axis vibration isolator via Stewart platform

As shown in Fig. 1, the six-axis micro-vibration isolator based on the Stewart platform consists of an upper plate (payload plate), a lower plate (base plate) and six legs (single-axis isolators including actuators and sensors), which are connected by spherical joints. The radius of the upper circle is r_a and that of the lower plate is r_b. The actuators with an equivalent stiffness k and a damping c in the six legs are the active joints of the system and their output forces are denoted by f_{a1}, …, f_{a6}. The six independent single-axis translations of the actuators can generate six-dimensional movement of the upper plate relative to the lower one.