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Post-capture vibration suppression of spacecraft via a bio-inspired isolation system

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ABSTRACT

Inspired by the smooth motions of a running kangaroo, a bio-inspired quadrilateral shape (BIQS) structure is proposed to suppress the vibrations of a free-floating spacecraft subject to periodic or impulsive forces, which may be encountered during on-orbit servicing missions. In particular, the BIQS structure is installed between the satellite platform and the capture mechanism. The dynamical model of the BIQS isolation system, i.e. a BIQS structure connecting the platform and the capture mechanism at each side, is established by Lagrange's equations to simulate the post-capture dynamical responses. The BIQS system suffering an impulsive force is dealt with by means of a modified version of Lagrange's equations. Furthermore, the classical harmonic balance method is used to solve the nonlinear dynamical system subject to periodic forces, while for the case under impulsive forces the numerical integration method is adopted. Due to the weightless environment in space, the present BIQS system is essentially an under-constrained dynamical system with one of its natural frequencies being identical to zero. The effects of system parameters, such as the number of layers in BIQS, stiffness, assembly angle, rod length, damping coefficient, masses of satellite platform and capture mechanism, on the isolation performance of the present system are thoroughly investigated. In addition, comparisons between the isolation performances of the presently proposed BIQS isolator and the conventional spring-mass-damper (SMD) isolator are conducted to demonstrate the advantages of the present isolator. Numerical simulations show that the BIQS system has a much better performance than the SMD system under either periodic or impulsive forces. Overall, the present BIQS isolator offers a highly efficient passive way for vibration suppressions of free-floating spacecraft.

1. Introduction

The past two decades witnessed a growing trend of on-orbit servicing (OOS) missions duo to the introductions of new technologies to the design of modern satellites. It will become popular to conduct on-orbit refueling, assembly and retrieval of malfunctioning satellites in future space operations [1–4]. Besides, the removal of space debris is also becoming an urgent task [5–8], due to the increasing threat posed to the near-Earth space activities by the rapidly increasing amount of space debris.

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For the aforementioned missions, the on-orbit capture operation plays a fundamental role. In the capture process shown in Fig. 1, the chasing satellite is expected to approach the target in a manner that at the time of collision the relative velocity between the end-effector, i.e. capture mechanism, and the target vanishes. In practice, however, there always exists an impact which results in undesirable vibration and drifting motions for the satellite platform [9], especially for capturing an uncooperative target that lacks partial state information. If the target is a satellite, its moving parts turn out to be vibration sources for the whole system after capture.

In general, post-capture vibrations of the satellite platform are primarily stimulated by two types of vibration sources, the high frequency periodic excitations and the impact excitations. The former arise from the moving payloads mounted on the target, including the reaction flywheel, the propulsor, the driving mechanism of solar panel, for which the induced vibrations are mild. A vibration experiment was conducted in China's four remote sensing satellites [10], which demonstrates that the dominate vibration sources are from reaction flywheels and radiometer, mainly distritbuted over 50–200 Hz with a maximum vibration acceleration being 57 mg. The latter vibration sources are due to collisions with the targets, e.g. space debris or spacecraft waiting for service [11]. No matter what kinds of excitations, the satellite platform should stay stable, otherwise the pointing accuracy and the performance of precision instruments will be damaged.

Micro-vibration control is a challenging problem in engineering, especially for spacecraft with high precision instruments whose vibration magnitude is strictly required. Although the vibration sources are not strong, micro-vibration may last for a long time because of the low damping and micro-gravity space environment [12]. In general, there are three isolation methods namely, the passive, active and semi-active control methods, among which the passive one is mostly used. A typical passive control method for vibration isolation is to use the linear spring-mass-damper (SMD) isolator. The pioneer work is attributed to Ref. [13], in which the properties of the SMD under repetitive impact were exhaustively analyzed both theoretically and experimentally. Normally, increasing the linear damping in SMD system leads to a smaller resonant amplitude, but may result in a worse isolation performance beyond the resonant range, which is a major drawback for the SMD isolator. On the other hand, the resonant frequency is expected to be smaller so that the excitation frequencies can be far away from the resonant frequency, thus leading to a weaker vibration. The resonant frequency in linear system is determined by $\sqrt{k_{eq}/m_{eq}}$, where k_{eq} and m_{eq} represent equivalent stiffness and mass respectively. However, a smaller resonant frequency implies a smaller system stiffness k_{eq} or a larger mass m_{eq}, which are corresponding to unwanted lower loading capacity or heavier satellite. To conquer these limitations, the quasi-zero-stiffness (QZS) isolator is proposed in Ref. [14], which can realize ultra-low stiffness, zero stiffness, or negative stiffness via carefully choosing structural parameters. The QZS isolator shows a better performance than the traditional SMD isolator in the vicinity of the equilibrium point due to its quasi-zero stiffness property. A variety of studies are carried out to the applications of the QZS [15–21]. However, it is reported that very complex nonlinear behaviors such as bifurcation and chaos may occur due to strong nonlinear stiffness [22,23]. Moreover, the QZS is prone to instability and low loading capability at equilibrium in case of negative stiffness [24].

In order to obtain an efficient isolation performance, a series of active vibration control methods are proposed which can achieve excellent performance for low frequency vibration, and simultaneously with sufficient loading capacity and robustness. Thayer et al. [25] designed several active control Stewart platforms using very soft axial stiffness, and a 20–25 dB vibration reduction performance was achieved in all six degrees of freedom over the bandwidth 5–20 Hz. Anderson et al. [26] studied a piezoelectric-based active vibration isolation control method for pico-satellite. Ground experiments show that effect of small vibrations on spacecraft instrument effectiveness can be significantly reduced. Wei and coauthors proposed a novel adaptive model-free active control method, which is capable of handling uncertain large-scale nonlinear systems [27–29]. Nevertheless, the need for including sensors and actuators in active controls significantly increases the system size, weight, and complexity, and therefore increases cost and potential failures. The semi-active method can be treated as a compromise between the passive and active methods. Semi-active techniques using electro-rheological fluids [30], magneto-rheological fluids [31], and some smart materials [32] have been extensively investigated. Although effective, the semi-active method has a complicated structure as well.

In the past five years, the passive nonlinear vibration control method has regained a growing attention due to its high reliability, easy implementation and low cost. A scissor-like structure (SLS) or later referred to as X-shaped structure, which exploits the benefits of nonlinear damping and nonlinear stiffness induced by geometrical relationships of the rods, rotation joints and springs, was proposed and further developed by Jing and his coworkers [18,33–38]. It is demonstrated that the SLS isolator can overcome major disadvantages of the traditional SMD, the QZS and the active control vibration isolators. The SLS system can achieve better nonlinear vibration isolation using pure linear spring and damper elements. Besides, its nonlinear damping and stiffness can be flexibly designed by changing system parameters. In all existing studies of SLS isolators, however, the isolation systems are properly constrained, and the vibration sources are given base excitations. For suppressing the micro-vibrations of the free-floating spacecraft, it is necessary to set up a new isolation system which can deal with various external forces.

Biological structures enjoy excellent efficiency benefiting from millions of years of biological evolution, thus it is a wise way to learn concepts from nature [39]. Kangaroos are the only large animals to use hopping to travel. They can jump 9 m far in a single leap, with a maximum hopping speed up to 70 km/h. One of the reasons for this fast and smooth way of travel is attributed to their legs that can efficiently absorb strong impacts resulting from collisions with ground. Inspired by the smooth motion of a running kangaroo, a quadrilateral shape structure is designed in Fig. 2(b) as a basic unit for constructing the bio-inspired quadrilateral shape (BIQS) isolation system in Fig. 3. The quadrilateral shape structure is one kind of the