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A novel quasi-zero-stiffness strut and its applications in six-degree-of-freedom vibration isolation platform

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ABSTRACT

Generally, existing isolators with quasi-zero stiffness (QZS) are designed for mitigating transmission of vertical translational excitations, but vibration isolation in multiple directions is much more desirable and useful. The major contribution of this paper is extending the QZS vibration isolation method from one degree of freedom (DOF) to all six DOFs, by using a novel QZS strut to construct a 6-DOF QZS vibration isolation platform. Firstly, the design concept of the QZS strut is proposed, and then a pyramidal 3-QZS-strut isolator is assembled. Finally, a 6-DOF QZS platform is achieved by using such isolators as supporting mounts. The equations of motion of this platform are established, and solved by the Harmonic Balance method to obtain amplitude-frequency relationships. Moreover, the performance of vibration isolation is evaluated in terms of force/moment transmissibility. Compared with the linear counterpart, the 6-DOF QZS platform has broader bandwidth of vibration isolation starting from lower frequency, and possesses higher effectiveness in low-frequency range, most importantly, in all six DOFs.

1. Introduction

Recently, a category of vibration isolators with quasi-zero stiffness has been proposed to overcome the drawback of traditional linear passive isolators [1,2]. Specifically, the QZS isolator not only can attenuate transmission of low-frequency excitations, but also possesses high static stiffness to prevent the system from producing large static deflections. The vital component of a QZS isolator is the negative-stiffness mechanism. There exist several formulas to realize a negative-stiffness mechanism [1,2]. The earliest form might be the oblique-spring mechanism [3], which was often utilized as a theoretical model for performance evaluation of the QZS isolator [4–7]. To avoid possible bulking of oblique springs, its alternatives can be a planar spring [8], or an oblique link connecting horizontal spring [9]. Other means of negative stiffness include: cam-roller-spring mechanism (CRSM) [10,11], bi-stable structures [12–16], magnetic springs [17–21], and scissor-like structures [22,23]. All these investigations indicate that the QZS isolator can perform a good function of low-frequency vibration isolation.

Generally, most of the exiting QZS isolators were designed for mitigating the transmission of vertical translational excitations. However, in many engineering fields including high-technology manufacturing [19,24], high precision

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measurement [25] and micro-vibration control in spacecraft [26,27], multi-direction isolation with high effectiveness is desired to reduce vibration transmission in multiple directions. Hoque et al. [28] developed a 6-DOF hybrid vibration isolation system, which was a combination of an active negative suspension and an active-passive positive suspension with a passive weight support mechanism. Wang and Liu [24] proposed a 6-DOF hybrid micro-vibration isolation platform consisting of passive air springs and magnetostrictive actuators. To attenuate micro-vibration in multiple directions resulting from the reaction and moment wheels on board of spacecraft, Zhou and Li [26] designed and analysed an intelligent vibration isolation platform.

It can be observed from the above works that researchers often resort to active control for multi-direction vibration attenuation. To the best of our knowledge, the designs and studies of passive multi-direction QZS isolators are rarely reported. Sun and Jing [29] designed a 3-DOF QZS isolator in the form of a scissor-like structure. Platus [12] proposed a compact 6-DOF QZS isolator with buckled Euler beams. Zhu et al. [30] developed a 6-DOF QZS/ZS isolator using magnetic levitation. Wu et al. [31] used X-shape structures as the legs to assemble a 6-DOF QZS Stewart platform.

The major contribution of this paper is extending the QZS vibration isolation method from one direction to six directions. The design concept of a novel compact QZS strut is proposed based on the CRSM that has been validated by experimental tests in our previous work [10]. A pyramidal isolator consisting of such three QZS struts is assembled to be a mount to symmetrically support a platform, leading to a 6-DOF QZS vibration isolation platform. The static and dynamic characteristics of this platform are studied, and its isolation performance is theoretically and numerically evaluated in terms of force and moment transmissibility.

The aim of this paper is to show a procedure for creating a 6-DOF QZS vibration isolation platform by using the proposed QZS struts, rather than an experimental study based on a fabricated prototype. In the present study, some assumptions should be noted, which are listed as follows: (1) The deformations of struts are far smaller than the length of the strut, and thus can be approximated by the first order Taylor polynomial. (2) All the QZS struts are identical to each other, and all the inclination angles of the struts with respect to the vertical direction are the same at the static equilibrium. (3) An equivalent constant viscous damping model is assumed for the proposed QZS platform. The actual damping needs to be obtained by experimental measurement on an actual prototype to be built later.

2. QZS strut

2.1. Conceptual model of the QZS strut

A schematic diagram of the QZS strut is shown in Fig. 1. Rigid rod (2) with a cam (9) can only slide along the axial direction guided by two linear bearings (6), which are fixed on sleeves (3). Flexible beams (7) with rollers (8) are fixed on holders (10), which are also fastened on sleeve (3) by screws. There are three flexible beams fixed on annular holders (10) at equal intervals. A coil spring (4) is installed at the end of the strut, and is fastened on the end of rod (2). An adjustor (5) is designed to tune up the compression of coil spring (4) to handle different levels of payload. To assemble a vibration isolation platform by using such QZS struts, ball joints (1) are set at two ends of the strut.

2.2. Static analysis

The schematic diagram of static analysis is shown in Fig. 2. The QZS characteristics are fulfilled by means of a Cam-Roller-Spring Mechanism proposed in our previous work [10]. When the strut is subjected to a payload F_P, the connecting line between the centres of the semi-circular cam and the roller is perpendicular to the axis of the strut, leading to a static

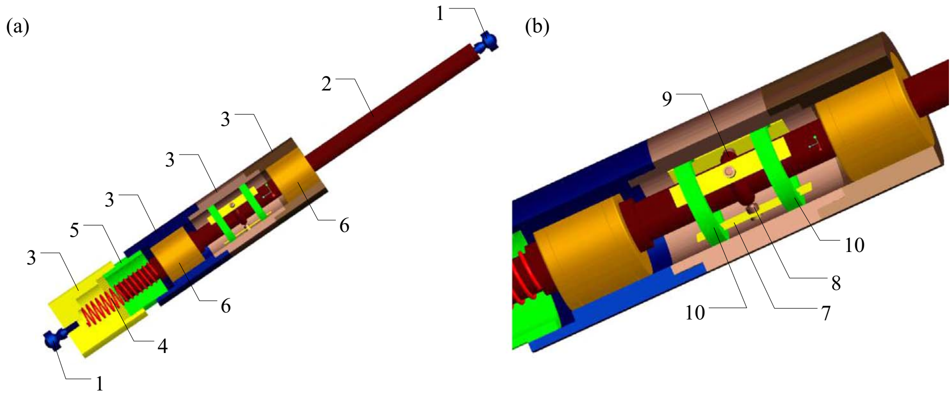

Fig. 1. Schematic diagram of the QZS strut at the static equilibrium position. (a) Internal configuration; (b) a partially enlarged view. 1 ball joint, 2 rod, 3 sleeve, 4 coil spring, 5 adjuster, 6 linear bearings, 7 flexible beam, 8 roller fixed on the beam, 9 cam fixed on the rod, 10 holder of flexible beams.

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