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Multi-direction vibration isolation with quasi-zero stiffness by employing geometrical nonlinearity

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ABSTRACT

The study proposes a novel vibration isolator with 3D quasi-zero-stiffness (QZS) property. The remarkable feature of the proposed system is to apply symmetrically scissor-like structures (SLS) in the horizontal directions, together with a traditional spring-mass-damper system assembled vertically with positive stiffness. With the mathematical modeling of the proposed system, it is shown that the stiffness and damping properties are nonlinear due to nonlinear geometric relations within the SLSs and both can be adjusted via structural parameters of the system. Theoretical analysis with the harmonic balance method reveals that the system can demonstrate QZS property in 3 directions, and can achieve much better 3D vibration isolation performance, including high-static and quasi-zero-dynamic stiffness, and much larger displacement range around equilibrium, compared with an existing QZS system in the literature. The results provide a novel and significant multi-direction vibration isolation method using structural nonlinearity with noticeable performance but using only passive elements.

1. Introduction

Considerable research activities have been conducted in vibration isolation by using passive/active components for multi-direction vibration suppression. Usually, different designs of structure and control methods could demonstrate very different vibration suppression effect due to different vibration isolation mechanisms adopted, for example, energy transferring between different vibration modes [1,2], vibration suppressing with absorbers [3–5], or utilizing semi-active/active vibration control methods etc. [6–8]. In most cases, better isolation effect can be obtained by using elements with smaller restoring forces which result in smaller natural frequency of the system [9–15]. Passive vibration isolation is often more preferable in practice. However, passive vibration isolators for multi-direction excitation with excellent isolation performance over larger frequency region have always been a hot and hard research topic in the literature.

Quasi-zero-stiffness (QZS) systems have been studied in the literature for various vibration isolation purposes [16–20] to improve working environment for users or provide better surroundings for precise and sensitive instruments. Vibration isolation

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with the QZS stiffness is often focused in practice to improve comfort or safety of the systems under study. To overcome disadvantages such as large value of natural frequency and large static deflection of traditional mass-spring isolators with linear springs and dampers, oblique or horizontal springs are added. Due to the nonlinearity introduced by oblique springs with/without pre-deformation, the system can obtain a high static stiffness, and low natural frequency induced by the small dynamic stiffness. However, one-direction QZS isolators has its limitation in application. The first one could be that its stability is difficult to control. Several critical parameters in the existing QZS systems should be very carefully chosen to avoid instability of static equilibrium induced by the negative linear stiffness [21–23]. Secondly, strong nonlinearity existing in the existing QZS systems could induce the bifurcation phenomenon (e.g., jumping) or quasi-periodic response. Moreover, existing QZS systems in the literature cannot achieve multi-direction vibration isolation simultaneously.

Recent advances show that nonlinearity could take a very positive effect in vibration control [24–29,31]. A scissor-like structure (SLS) is proposed in [29] to achieve the QZS property in vibration isolation, which has obvious advantages including excellent isolation effect and much better equilibrium stability. Preliminary theoretical results about the SLS system as an isolator in one direction clearly indicate that the SLS has significant isolation effect because of its adjustable nonlinear stiffness and damping properties induced by geometrical nonlinearity of the structure [29]. Moreover, the SLS has good static stability and load capacity because its linear stiffness coefficient is always positive and nonlinear stiffness coefficients can be adjusted to different values conveniently. Importantly, because the nonlinearity of the SLS is induced by its geometrical relationship, it is easy to avoid the occurrence of jumping phenomena via parameter design.

Considering the advantages of the SLS and QZS systems mentioned above, in this study, the SLS is integrated with a traditional mass-spring-damper (MSD) system to construct a novel powerful and compact Multi-Direction Quasi-Zero-Stiffness (MSQZS) system. The SLSs are applied in orthogonal to the MSD system (with positive stiffness). The proposed MDQZS system has nonlinear stiffness and damping characteristics in three directions, which are all adjustable and can achieve superior vibration isolation using only pure linear and passive elements in the system with a simple and flexible installation structure. This system could provide an effective solution to many engineering problems for excellent vibration suppression and sustainable development.

The paper is organized as follows. The structure of the MDQZS system, mathematical modeling, and vibration solutions solved by the Harmonic Balance Method (HBM) [30] are conducted in Section 2. Then, the nonlinear stiffness and damping properties and the isolation effectiveness under different structural parameters are studied in Section 3. The comparisons of the MDQZS system utilizing the SLS and the existing QZS system in the literature are discussed in Section 4. A conclusion is drawn thereafter.

2. The Structure and modeling

2.1. Structure diagram

Fig. 1 is the 3-D structural diagram of the proposed vibration isolation system, which can be used for isolation of three-direction vibration. The isolation object is connected with the base by four n-layer scissor-like structures (SLSs) assembled symmetrically in the x and z directions. In order to keep the loading capacity, only a linear spring and damper are used in the vertical direction. The assembly process of the proposed structure is firstly to connect the isolation platform and the base with vertical spring and damper; secondly to assemble the SLSs symmetrically in the x and z directions; and thirdly to apply the pre-extension to springs in each SLS. Because the effect of SLSs in the x direction is the same as the z direction, the analysis of the three-direction vibration isolation can be simplified to the study of two-direction (x- and y-directions) problem as shown in Fig. 2.

In Fig. 2, the mass of isolation object is M. In the horizontal left- and right-side SLSs, the same springs and dampers are assembled in one layer. The stiffness of the vertical spring is k_1 and the damping coefficient of the vertical dampers is c_1. The original length of the vertical spring is l_1. In the two horizontal SLSs, the stiffness of the springs is k_2, the damping coefficient

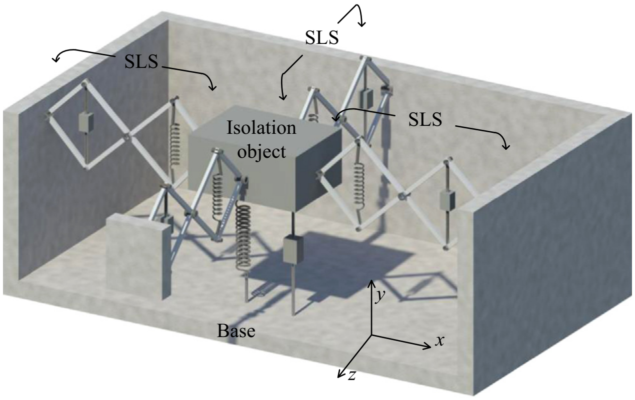

Fig. 1. Three-dimension structural diagram of the proposed multi-direction isolation system.