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Analysis and design of a nonlinear stiffness and damping system with a scissor-like structure

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ABSTRACT

An *n*-layer Scissor-Like Structured (SLS) vibration isolation platform is studied in this paper, focusing on the analysis and design of nonlinear stiffness, friction forces and damping characteristics for an advantageous vibration isolation performance. The system nonlinear stiffness and damping characteristics are theoretically investigated by considering the influence incurred by different structural parameters, friction forces and link inertia. Since stiffness and damping properties are both asymmetrical nonlinear functions, and Coulomb friction is piecewise nonlinear function, Perturbation Method (PM) and Average Method (AM) are applied together to achieve better solutions. The vibration isolation performance of the SLS platform is compared with known quasi-zero-stiffness vibration isolators in the literature, and a typical application case study as a vehicle seat suspension is also conducted, subjected to different load masses, and base excitations. The results show that much better vibration isolation performance and loading capacity can be easily achieved with the SLS platform by designing structural parameters, and the scissor-like structure provides a very powerful, practical and passive solution to design and realization of beneficial nonlinear stiffness and damping characteristics in vibration control.

1. Introduction

Vibration isolation is extensively applied in various engineering practice from vehicle ride comfort improvement [1], protection of high-precision machinery [2], to space lunch or on-orbit vibration control [3]. Performance requirements for vibration isolation or suppression usually include several aspects, which are isolation effect (or transmissibility), loading capacity, energy cost, and complexity of implementation. Active control can achieve much better isolation performance but cost energy [3,4]. Semi-active control methods would be much better in saving energy. But similar to active control, special control units are usually needed in semi-active control which often increase isolator weight and development complexity.

It is particularly noticed that, some passive vibration control methods in the literature are designed by employing various structure properties and thus better vibration isolation performance is achieved. For example, a vibration isolation structure whose linear stiffness is close to zero called quasi-zero-stiffness vibration isolator (QZS-VI) is investigated in [5–13]. The QZS-VI can obtain a high static stiffness but small dynamic stiffness, which results in low natural frequency and small static

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displacement. Because the linear stiffness of the QZS-VI can be designed close to zero by properly choosing structural parameters, it is potentially advantageous in many practical applications [6,7]. However, obvious disadvantages of the class of QZS-VIs are the easiness to lose stability, low loading capability and potential bifurcation effect at equilibrium due to negative linear stiffness [8,12,13]. The other noticeable vibration system is designed by using a one-layer truss structure which is applied in seat suspension systems [14–16]. Considering that the most sensitive frequency range in vertical vibration for seated human body is in 4 to 9 Hz [17,18], the authors use additionally an air-spring and hydraulic shock-absorber to provide load force and vibration isolation from base excitation. Moreover, an active controller is designed in [14,15] with the same structure to improve ride comfort and vibro-isolation properties for different loading mass. The results show that this truss structure can obviously improve vibro-isolation performance of seat suspension.

Some recent studies indicate that nonlinear stiffness and damping are very beneficial in vibration control for both low and high frequencies [19–24,39]. For example, the research results in [25–27] show that MR dampers and pneumatic springs are very versatile in providing advantageous and adjustable damping and stiffness characteristics for vibration control. Considering that many practical systems have inherent nonlinearity, a fundamental question is whether it is possible to exploit those inherent nonlinearities in structures or control units to realize much better vibration isolation performance, without much energy cost or with only passive elements. The QZS-VIs mentioned before are good examples to this aim, but their limitations should be overcome for a much better engineering resolution.

Therefore, an n-layer scissor-like structured (SLS) platform is studied in this paper to explore new design of nonlinear vibration isolation systems by employing beneficial nonlinearity in stiffness and damping characteristics incurred by structures. In engineering practice, various structures of special characteristics or functions may be designed for different purposes. Scissor-like-elements have been used as self-deployable structures in the literature manipulated with active control [29,30]. Due to nonlinear geometric relations within pantographic structures, a homogenized model is studied for the external contact action at extremities of thin-walled twisted tubes [30,31], which can overcome the limitation of classical continuum mechanics in microstructure. The SLS platform has been proposed and studied recently in [38,28]. Only some preliminary modeling and simulation results are presented in [38], and in [28] system modelling is conducted without considering mass of connecting rods and corresponding friction forces.

In this study, for the n-layer SLS vibration isolation system, the Coulomb friction [32,33] and mass of connecting links are all carefully considered in system modeling and performance analysis. Different from the results in [28], the influence incurred by joint or contract frictions and link inertia on system equivalent mass, stiffness and damping of the SLS platform are theoretically analyzed. Some preliminary experimental analysis is also conducted to verify the excellent vibration isolation performance of the platform. It is shown that (a) the inherent nonlinear stiffness and damping characteristics of the SLS system can achieve superior vibration isolation using only pure linear and passive elements in the system with a simple and flexible installation structure; (b) the friction and inertia effects can all be minimized by choosing appropriately structure parameters; (c) the SLS platform can achieve much better quasi-zero stiffness property, without those disadvantages of the existing QZS-VI systems (such as strong nonlinearity and poor loading capacity) and drawbacks of the seat suspension system with active control in the literature.

The paper is organized as follows. The schematic structure of an n-layer SLS platform is introduced in Section 2 and mathematical modeling is conducted in Section 3. Then, the nonlinear stiffness, equivalent friction force and damping properties under different structural parameters are studied in Section 4. An effective solving method is also provided in this paper which is combined the Perturbation Method (PM) and Average Method (AM) [34–36] in Section 5 and the self-locking phenomenon induced by the Coulomb friction is analyzed. Comparisons and application studies of the SLS platform are discussed in Section 6. Some experimental results for the response of the platform under random impact excitation are shown in Section 7. A conclusion is drawn thereafter.

2. The *n*-layer SLS platform

Consider the platform with n-layer scissor-like structure in this section. Fig. 1 is the diagram of a 3-layer SLS system. Each layer of the structure is constructed by connecting rods and corresponding rotating joints. The mass of the connecting rods is taken into consideration but the mass of corresponding rotating joints is ignored since the mass of joints is often much smaller than rods. The supporting joints in the left bottom and top layer can be freely sliding along pre-designed horizontal tracks. Obviously, the properties of contacting surface on these sliding tracks and in rotating joints can be designed for different damping properties. Potentially, some linear springs can be used as indicated to achieve the stiffness of the system.

Because the platform is symmetric, it can be simplified as a plane problem as shown in Fig. 2, which demonstrates the front view of the n-layer platform. The mass of the isolation object is denoted by M_1. The connecting rods have the same length denoted by $2l$ and the assembly angle with respect to the horizon line is represented by θ. More practically, the stiffness of the spring in the first layer in horizontal direction is supposed to satisfy a property $f = k_l(\cdot)$. The friction coefficients of rotational motion and horizontal motion are set as c_1 and c_2, respectively. Additional dampers in y and x direction are considered shown in Fig. 2. Two linear dampers, i.e., Damper 1 and Damper 2, are assembled in horizontal and vertical vibration directions, which are much simpler to implement than some complex nonlinear control methods using feedback signals. Damper 1 only affects the vibration in vertical direction and its effect is the same as the case assembling it in the center of the platform. Damper 2 is assembled in the bottom layer to generate nonlinear damping. All the structural parameters are listed in Table 1 in Appendix A.