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Vibration isolation using a hybrid lever-type isolation system with an X-shape supporting structure

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ABSTRACT

This study presents some novel results about analysis and design of low-frequency or broadband-frequency vibration isolation using a hybrid lever-type isolation system with an X-shape supporting structure in passive or semi-active control manners. It is shown that the system has inherent nonlinear stiffness and damping properties due to structure geometrical nonlinearity. Theoretical analysis reveals that the hybrid isolation system can achieve very good ultra-low-frequency isolation through a significantly-improved anti-resonance frequency band (by designing structure parameters). Noticeably, the system can realize a uniformly-low broadband vibration transmissibility, which has never been reported before. Cases studies show that the system can work very well with good isolation performance subject to multi-tone and random excitations. The results provide a new innovative approach to passive or semi-active vibration control (e.g., via a simple linear stiffness control) for many engineering problems with better ultra-low/broadband-frequency vibration suppression.

1. Introduction

Vibration control is often a critical and difficult issue in many engineering practices. A typical example can be seen in micro-vibration control of on-orbit spacecraft. Micro-vibration can be produced by various mechanical parts in on-orbit spacecraft such as cryocoolers, mobile mirrors, and reaction/momentum wheel assemblies, mainly appearing in the frequency range from less than 1 Hz up to 1 kHz [1,2]. Because of the tiny environmental damping in aerospace, micro-vibration may exist for a long time, which can thus degrade working environment of sensitive instruments in onboard spacecraft. Usually, passive isolation techniques are commonly employed to suppress vibration [3–6]. The vibration energy can be dissipated through passive damping, and high frequency disturbances can be suppressed by the designed low dynamic stiffness of isolator systems. Passive vibration isolation is known for its high reliability, easy implementation and low development cost, while may not be effective for low frequency vibration.

Recently, some nonlinear vibration isolation methods have been developed in the literature [7–15,22–26], which demonstrate excellent vibration isolation performance both in high and low frequency range, i.e., high static but low dynamic stiffness. This can be achieved through nonlinear stiffness design of a isolation system leading to different nonlinear stiffness properties such as quasi-zero stiffness [7–11] and negative stiffness [14,15]. However, in some cases complicated nonlinear phenomena could also happen if system parameters are not well designed, incurring potentially worse stability problems. Recently, a passive scissor-like structured isolation system was proposed and studied in [33,16], where an excellent high-static-low-dynamic stiffness property can be achieved by flexibly designing structural parameters.

To address low frequency vibration isolation, active control methods are often used [17–21]. Different isolation systems with different active control strategies can be designed for various requirements of low frequency vibration isolation. Although excellent low frequency isolation performance could be obtained through active isolation techniques, high energy cost, high development expense, actuation saturation, stability issues, and/or complexity in implementation etc. could occur. Alternatively, the semi-active control method can be employed to realize excellent vibration transmissibility at resonant frequency and above through some simple nonlinear damping systems [22–26]. But ultra-low frequency vibration control may still be a problem that cannot be addressed with pure damping control methods.

System inertia can be changed in a lever-type isolation system, which can reduce resonant frequency and produce an anti-resonant frequency [27–29]. Since the anti-resonant frequency can be designed into low frequency region (smaller than the resonant

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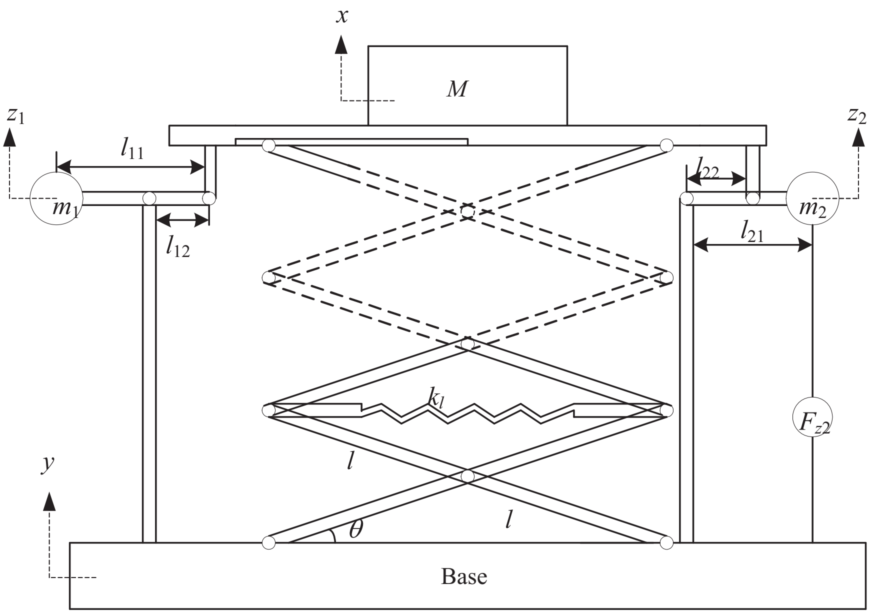

Fig. 1. The hybrid SLS lever-type vibration isolation system.

frequency), the ultra-low frequency isolation effect can therefore be achieved with the lever-type isolation system [27]. The inertia force with the system can be increased by changing mass ratio and lever length ratio, which can be employed to reduce the supporting spring force. Therefore, the dynamic stiffness of the system can be reduced but a relative high static stiffness maintained [29]. However, only designing system inertia as mentioned, the difference between the resonant and anti-resonant frequencies is relatively very small, and thus the ultra-low-frequency isolation performance is rather limited. It is noticed that Jo and Yabuno [30,31] proposed a new type of vibration absorbers utilizing quadratic nonlinear coupling to reduce the vibration amplitude. The main idea of the vibration reduction is based on mode coupling such that the vibration amplitude only around the natural frequency of the master vibration system can be reduced [30].

In this paper, a novel X-shape structure strengthened hybrid lever-type vibration isolation system is investigated, which combines the features of the scissor-like structure and lever-type structure together, and is aimed at exploring inherent structure nonlinearity for superior low-/broadband-frequency vibration isolation/control performance in passive and/or semi-active manners. The mathematical modeling of the system is conducted with the harmonic balance method (HBM) for analysis of the nonlinear dynamics to derive the vibration transmissibility. It is systematically shown that this hybrid isolation system can demonstrate much better ultra-low frequency vibration isolation with designable anti-resonance frequency and lower transmissibility in a relative larger frequency range by designing structure parameters. Noticeably, the system can also achieve obvious vibration suppression covering the full frequency range with proper structure parameter selection and a simple linear stiffness feedback control. These advantageous performances should be of more significance in engineering practice. To demonstrate the effectiveness of the proposed hybrid structure system, vibration isolation subject to multi-tone and random excitations at the base is also demonstrated as case studies.

The rest of this paper is organized as follows. The design of X-shape structural hybrid lever-type isolation system is introduced in Section 2. The mathematic modeling and analysis are carried out in Section 3, where the inherent nonlinearity is discussed in detail. Then, vibration isolation performance with parameter sensitivity analysis is studied in Section 4. Section 5 shows dynamic responses of the novel hybrid lever-type isolation system under multi-zone and random excitations. Finally, a conclusion is drawn.

2. The X-shape structured hybrid lever-type isolation system

The hybrid lever-type vibration isolation system supported by an X-shape structure is shown in Fig. 1. The supporting structure is an n-layer scissor-like or X-shape structure with horizontal spring [16]. Each layer has two rods combined with one joint, and length of each rod is $2l$. Angle of the rod with respect to horizontal line is θ, and the angle displacement of the joints is represented by ϕ. The restoring force in the horizontal spring is linear with a stiffness k_l. The n-layer X-shape structure can provide high static and low dynamic stiffness [16], which is very important to obtain good and stable isolation both in the low and high frequency range.

The absolutely motions of the isolation body M and base are represented as x and y. $z_1(t)$ and $z_2(t)$ are the absolutely displacements of the attached mass m_1 and m_2 in the levers type I and type II [27,28]. The mass m_1 is located on the type I lever, where the lever ratio $\alpha_1 = l_{11}/l_{12}$, while, type II lever is attached to m_2, which has the lever ratio $\alpha_2 = l_{21}/l_{22}$. The simple linear stiffness feedback control is applied to the mass m_2, i.e., $F_{z2} = -k_{z2}z_2$.

3. Mathematical modeling and analysis

Due to function of the levers, the motion of the two attached mass m_1 and m_2 can be expressed as:

$$z_1 = \alpha_1 y - (\alpha_1 - 1)x, \quad z_2 = \alpha_2 x - (\alpha_2 - 1)y. \tag{1}$$

So the kinetic energy of the hybrid isolation system is written as,

$$T = \frac{1}{2}M\dot{x}^2 + \frac{1}{2}[m_1(\alpha_1 - 1)^2 + m_2\alpha_2^2]\dot{x}^2 - [m_1\alpha_1(\alpha_1 - 1) + m_2\alpha_2(\alpha_2 - 1)]\dot{x}\dot{y} + \frac{1}{2}[m_1\alpha_1^2 + m_2(\alpha_2 - 1)^2]\dot{y}^2, \tag{2}$$