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Simulated and experimental studies on a high-static-low-dynamic stiffness isolator using magnetic negative stiffness spring

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ABSTRACT

For the purpose of isolating the low frequency vibration, a magnetic vibration isolator with the feature of high-static-low-dynamic stiffness (HSLDS) is developed in this paper, which is constructed by combining a magnetic negative stiffness spring (MNSS) with a spiral flexure spring (SFS) in parallel. The MNSS comprises three magnetic rings configured in attraction and is utilized to reduce the resonant frequency of the isolator. Then an analytical expression of magnetic negative stiffness (MNS) of the MNSS is deduced in terms of the current model, and an approximation to the MNS is further sought. To support the object, the axial positive stiffness of SFSs, which can behave with a smaller static deformation if a specified weight is applied, is analyzed with finite element method (FEM). After that, the governing equation of the isolator is established and solved via harmonic balance method (HBM). Finally, an experimental prototype is developed and tested. The experimental results demonstrate that the MNSS can reduce the resonant frequency of the isolator to expand the isolation frequency band to low frequency range; and the theoretical calculations and experimental results shows a good agreement.

1. Introduction

Linear vibration isolation system is useful when the resonant frequency is far below the excitation frequency. Whereas it is limited to the application of moderate environmental disturbances. Due to the severe disturbances such as shocks, impact loads and random motions are frequently encountered in engineering and the low frequency components are often contained as well, the requirement for vibration isolation have become increasingly rigorous [1]. However, the present passive vibration isolation systems are unable to work well if the low and ultra-low frequency isolations are required.

According to the linear isolation theory, the vibration attenuation occurs above $\sqrt{2}$ times of the resonant frequency ω_n of the system [2,3]. Thus, the isolation frequency band can be expanded as long as the resonant frequency is reduced, which can be realized by either reducing the stiffness or increasing the mass of the object. Whereas reducing stiffness will cause larger static deformation and degrade the stability of the isolator, while the mass of object is usually unchangeable in practice [4,5]. Consequently, how to achieve the effective isolation in low or ultra-low frequency ranges is always a challenge in the subject of linear vibration isolation. In recent years, the nonlinear passive vibration isolators constructed by combining positive stiffness element in parallel with a negative stiffness element have been proven to be a wonderful manner to broaden bandwidth for low frequency vibration suppression [1,6]. These isolators commonly feature with high-static-low-dynamic stiffness, where high static stiffness is used to support payload and low dynamic stiffness is employed to improve the performance of low frequency isolation.

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By now, many studies have been conducted to attain the HSLDS property. Carrella [7] exploited two oblique springs as negative stiffness mechanism to incorporate with a vertical spring to design a quasi-zero stiffness (QZS) isolator; and both force and displacement transmissibilities are latterly investigated in [8,9]. Similarly, Xu [10] further used this type mechanism to construct a QZS isolator by using four inclined springs rather than two springs. By using inclined rods instead of oblique springs, Ahn et al. [11,12] adopted the inclined rods in series with horizontal spring to attenuate the vibration of vehicle seat. Since the negative stiffness characteristic can also be yielded by the bucking phenomenon, the behavior of the buckling beams under axial load are employed to realize low frequency isolation in horizontal direction by Platus [13]. Fulcher [14] further used this kind of buckling-beam negative stiffness mechanism to design a vibration isolator for investigating passive shock and vibration isolation. More recent studies involving the buckled beam corrector were completed by Huang et al. [15,16]. In their work, both the stiffness and load imperfections are included to analyze the isolation performance of the isolator. Besides, A QZS isolation system using scissor-like structure was developed with an added benefit of nonlinear damping by Sun [17,18]. However, some limitations within the above isolators may hinder their wide application. For example, an oblique pre-stressed springs, pre-stressed rods, or buckling beams exhibit negative stiffness only when displaced beyond a certain limit. It means those negative stiffness mechanisms are insensitive to micro displacement. In addition, a buckled beam may present asymmetrical negative stiffness about the operating point.

Compared with the negative stiffness mechanisms like oblique springs, inclined rods and buckling beams, magnetic and electromagnetic technologies have provided another way to realize the HSLDS property. Both the positive and negative stiffness properties can be realized by magnetic structures. Thus, the application of magnetic techniques in the design of HSLDS isolator has been investigated. Carrella [19] used three magnets configured in attractive interaction to provide negative stiffness and designed a HSLDS vibration isolator. While Xu et al. [20] investigated a QZS isolator by configuring the magnetic springs in repulsion to offer negative stiffness for low frequency isolation. Then the cubic and annular magnets arranged in repulsive interaction are also utilized to fabricate negative stiffness element for reducing the resonant frequency of the isolation system by Wu and Shan [21,22]. In contrast, the magnetic spring acts in repulsion with positive stiffness, and the negative stiffness produced by rubber membrane is presented in [23]. With the application of magnetic levitation, Robertson [24] carried out a research on the vibration isolator by using only a pair of fixed magnets to support middle magnet to obtain the characteristic of quasi zero stiffness. To achieve the online tuning for negative stiffness, Zhou [25] designed a electromagnetic isolator with HSLDS property via controlling the magnitude of the current applied to the coils.

In this paper, a passive magnetic isolator with HSLDS feature is developed by connecting a SFS with a MNSS in parallel to explore a new design for low frequency isolation. To make the current isolator more compact and own relative larger load capacity, a new design of the spiral flexure spring (SFS) is developed to support the specified object, which is different from the positive stiffness element used in the previous studies, where the elastic supporting elements in [7–10] and [14–16] are all mechanical spring. With the increase of the load capacity of SFS, a smaller static deformation of SFS will be generated when a relatively heavier object is applied. This is desired for low frequency isolation and overcomes the shortcoming of low load capacity existed in [19]. The MNSS including three magnetic rings configured in attractive interaction is developed to reduce the resonant frequency of the isolator. Compared with the existing negative stiffness mechanisms like oblique springs, pre-stressed rods or buckled beams, the proposed MNSS is sensitive to micro displacement and can work effectively during the experimental tests. Also the proposed MNSS can produce a larger magnitude and more flattened MNS with only a small size of MNSS in comparison with the negative stiffness mechanism employed in [19]. Besides, MNSS has the distinct advantages such as faster response, no contact, and small size that would make present isolator mare compact and low space occupation rate over the previous studies. Because of the usage of magnets, the semi-active or active approaches can be incorporated with the present MNSS. In such a configuration, a low dynamic stiffness is obtained and a relatively large load capacity is remained.

The rest of this paper is organized as follows: Section 2 describes the configuration of the proposed HSLDS isolator. The characteristics of the MNS of MNSS are investigated in detail in Section 3. In Section 4, the FE analysis of SFS is carried out to provide a guidance to the design of SFS. Then, the governing equation of the isolator is developed in Section 5. To verify the performance of the designed isolator, experiments are conducted in Section 6. Finally, some conclusions are summarized in Section 7.

2. Configuration of the high-static-low-dynamic stiffness isolator

The configuration of the proposed HSLDS isolator is presented in Fig. 1(a). It is constructed by using the mechanism of combining a negative stiffness element with a positive stiffness spring in parallel, where the positive stiffness provided by a specially designed SFS is applied to support an object with a small static deformation; while the magnetic negative stiffness (MNS) produced by MNSS is employed to cancel the positive stiffness of SFS for reducing the resonance frequency of the isolator.

As shown in Fig. 1(a), the isolator is mainly composed of a SFS, an object, a rigid rod and a MNSS. Besides, other subsidiary parts are used as well, which include a copper plain bearing, a mounting base, two magnet holders, two cases, two covers, and several bolts. Except MNSS, all the components mentioned above are made of aluminum for its small permeability. Fig. 1(b) displays the layout of SFS, which is fixed at its outer boundary by two cases and considered as a load-bearing component to provide positive stiffness in the axial direction. For the sake of reducing the resonant frequency of the isolator, the MNSS is composed of three magnetic rings magnetized axially, and they are configured coaxially in attractive interaction as depicted in Fig. 2. The two outer ends magnetic rings represented by symbol 2 are mounted into the chambers of the magnet holders, then the magnet holders are fixed with two cases. While the central magnetic ring 1 is installed into the chamber of SFS. The mounting distance between the outer magnetic rings and central magnetic ring in z direction is l. Flexibly, l can be tuned manually to adjust the MNS properties