A Novel Bridge-Type Compliant Mechanism with Metastructures for Broadband Vibration Suppression

Xiaomeng Jiang, Zhong Chen, Wenqiang Cao and Xianmin Zhang

Abstract Vibration suppression on precision equipments always attracts great attention in industry and academic field. In order to reduce the vibration, many measures are taken in the past few decades. In general, vibration suppression can be classified as either active or passive mode. However, both of them achieve their own vibration-suppression function by attaching external members, which has some shortcomings of the complexity of production assembly. In order to improve vibration-suppression performance of a compliant amplifier, a novel compliant mechanism with metastructures is designed. The metastructures as shock-absorbed unit inserted in the amplifier's members can have capabilities of vibration suppression for their host structures. The different configurations of the metastructures in the host members are presented. Their frequency response functions are obtained using ABAQUS software, respectively. Through comparisons between their response functions, it indicates that the vibration-absorbing metastructures orienting along horizontal direction, which vibration-suppression direction is consistent with the output direction, have excellent performance of broadband suppression when their natural frequency keep highly coincident with the first order modal frequency of the compliant mechanism.

Keywords Broadband vibration suppression · Metastructures

1 Introduction

As we know, the needs for precision equipments become more and more urgent than ever due to the development of modern industry, such as medical, industrial, aerospace, biotechnology and other fields, which all are payed attention on the

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influence of equipment vibration to their precision [1, 2]. In order to achieve the purpose of vibration suppression, a large number of researches are conducted. The major measures to reduce vibration can be classified as active and passive vibration control [3]. Active vibration control need some embedded actuators for vibration suppression, which energy consumptions depend on external energy. Passive vibration control don't need external energy, actuators and a control system, but usually adopt additional damping structure to consume vibration energy. Unfortunately, both of them are taken after the structure is fabricated, which will increase the complexity of the production assembly and reduces the production efficiency. Besides, they cannot be applied to some smaller size of structures.

With the development of 3D printing technology [4], especially the publication of the 3D printing of pure metal [5], a suitable solution can be adopted is to design a vibration-absorbing metastructure, a kind of oscillators, which are designed uniquely to be insert to its host structure. Usually the metastructures are designed and fabricated as a whole. And there are large numbers of researches and applications focusing on the vibration suppression with metastructures recently [6, 7]. Hobeck et al. [3] designed a rod inserted into the beam to implement the vibration suppression of the beam with some rods [8]. Xiao et al. extended to study the flexural wave propagation in locally resonant beams with multiple periodic arrays of attached spring-mass resonators [9]. Zhu et al. [10] adopted a uniquely designed array of chiral oscillators to achieve the broadband vibration suppression [10]. Sun studied theoretically broadband damping characteristics of partial array of resonant beam [11]. Baravelli et al. presented a structural concept for high stiffness and high damping performance by designing the resonating lattice to resonate at selected frequency [12]. Brittany presented an experimental study of optimized numerical simulations on a metastructure created for the purpose of broadband vibration suppression [13].

However, the above mentioned researches only use some simple structures like cantilever beam, that whether it can be applied in a complicated structures may be further investigated. So the paper focuses on broadband vibration suppression with metastructures for a complicated structure: a bridge-type compliant mechanism. In order to realize broadband vibration suppression of the compliant amplifier, the paper puts forward some configurations of vibration-absorbing metastructure, and verifies their performance of broadband vibration suppression based on ABAQUS software, respectively.

2 Structure Design

In order to analyze the vibration-suppression effect of the absorbers, this paper presents a design which is to insert the absorbers into a stiff body at the output end of a bridge-type compliant mechanism. all the absorbers are same, a kind of metastructure, and every absorber is designed as a cantilever beam with a tip mass as illustrated in Fig. 1c. if hollowing directly the output end of the mechanism for adding the absorbers, it will reduce its stiffness. Hence, a clapboard is added inside of the output member, as shown in Fig. 1a, b.

The vibration-suppression effect of the absorbers is heavily influenced by the consistence of first order modal frequency between the absorber and the compliant amplifier with the absorbers which has the compact size, 40 × 21 mm. All of the absorbers and the complaint amplifier are made of stainless steel, which the elastic modulus and the Poisson's ratio equals to 2.06×10^{11} Pa and 0.3, respectively. The first order vibration mode of the compliant mechanism with the absorbers usually is a kind of back-forward motion of the output member along the output direction. Hence, in order to meet the requirements, the dimensions of the absorbers are designed carefully for adjusting its first order natural frequency. According to the analysis, the dimension 1–6 of the absorber equals to 0.15, 0.46, 2, 1.5, 2 and 3 mm, respectively. The four absorbers are fabricated in the output member of the compliant amplifier. Meanwhile, their dimensions are kept in consistence to reduce influences in evaluation of vibration suppression and make it more easily fabricated.

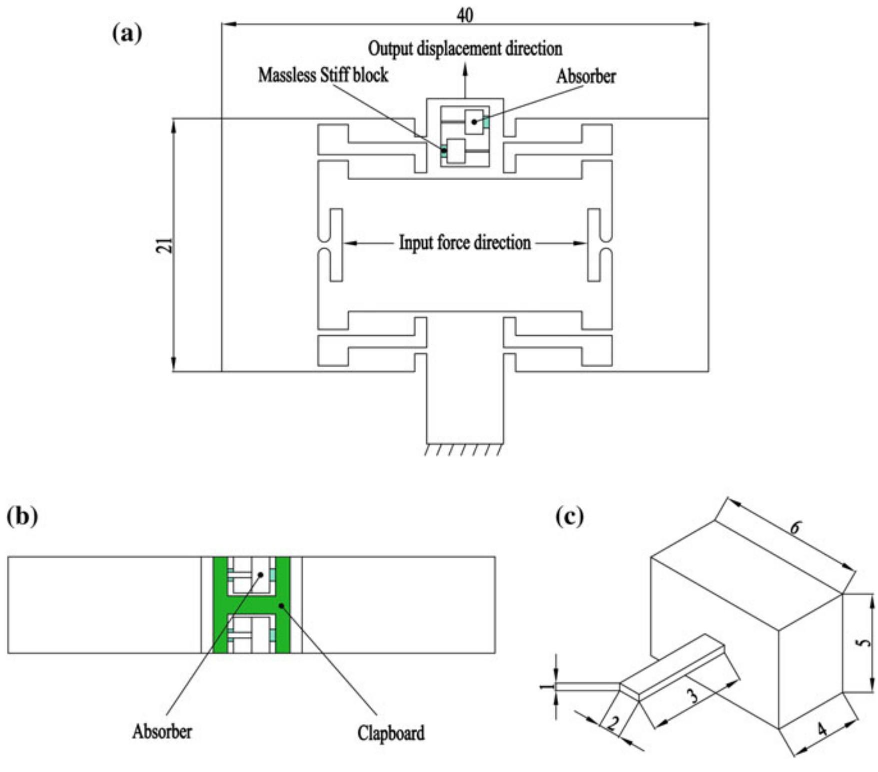

Fig. 1 Bridge-type compliant mechanism with absorbers in **a** the front view and **b** the top view and **c** its embedded absorber

3 Evaluation of Vibration Suppression

3.1 Preliminary Vibration Suppression

In order to evaluate the vibration suppression effect using the absorbers embedded in the compliant mechanism, two kinds of configurations of the absorbers are set beforehand, which include absorbers in blocked as Fig. 1a and absorbers in free as removing the massless stiff blocks from Fig. 1a. When implementing dynamical analysis, the blocks are set at massless stiff state, and these blocks can restrain the vibration of the absorbers. Then their frequency response functions are obtained using scanning stimulus in ABAQUS software, as fixing the lowest end of the mechanism, then loading a stimulus unit-force in different frequencies in scanning mode on the input end of the mechanism, and recording the output displacements. Comparisons of these frequency response functions are conducted, as shown in Fig. 2.

From Fig. 2, we can observe that the vibration at the design frequency of 1097 Hz is suppressed, which is the first order modal frequency of the mechanism in blocked state. And the shock absorption bandwidth is about 90 Hz. The result suggests that the four absorbs, which are not blocked, can eliminate the peak of the output displacement at the design frequency and effectively suppress the vibration of the whole mechanism in a certain bandwidth.

3.2 Superimposed Vibration Suppression

In above section, it has been proved that the absorbers embedded into the bridge-type compliant mechanism have a good performance of vibration suppression. However, whether the bandwidth of vibration suppression of the absorbers can be enhanced by inserting more absorbers to the other rigid bodies of the mechanism is unknown. However, the output end of the mechanism has no more

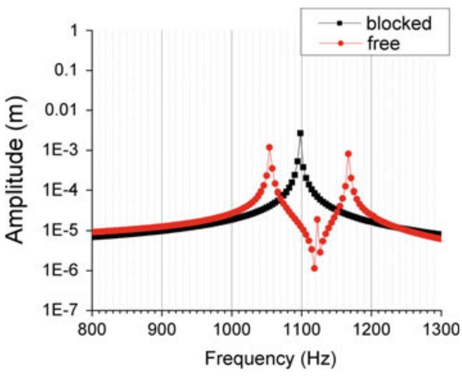

Fig. 2 Frequency response function of the output end of the mechanism in free and blocked state

space to configure more absorbers. Only both side rigid blocks can be used to embedded more absorbers. In order to keep its static performance of the mechanism unchanged, eight symmetrical absorbers are embedded into the both side bodies. It is obvious that the side beams vibrate along the direction of the input force more easily than along output direction, but it is still necessary to evaluate the performance of vibration suppression under different orientations of the absorbers when embedded in the both side beams.

Thus, there are two different layouts of the absorbers in horizontal and vertical orientations, which remain along input axis and output axis, respectively. In order to confirm exactly which layout has better performance of vibration suppression, many dynamical simulations are implemented under different condition of absorbers as shown in Fig. 3. In Fig. 3 there are eight configurations, which *horizontal-all blocked* means that all absorbers are blocked, *horizontal- side blocked* means that only the absorbers in both side beams are blocked, *horizontal-half blocked* means that only half of the absorbers in any side beam are blocked, *horizontal-all free* means that all absorbers in both side beams are free, and other configurations in vertical orientation like that in horizontal orientation.

Like the above section, their frequency response functions are obtained under configuration (b), (c), (d) in horizontal orientation and (f), (g), (h) in vertical orientation, respectively, as shown in Fig. 4.

From Fig. 4a, b, c, we can get information of bandwidth of vibration suppression of *horizontal-side blocked*, *horizontal-half blocked*, and *horizontal-all free* which are approximately 90, 120, and 145 Hz. And this indicates that it can enhance the performance of vibration suppression by adding more absorbers to the mechanism when the absorbers in the side beams are inserted along horizontal orientation. However, from Fig. 4d, e, f, the bandwidth of vibration suppression of *vertical-side blocked*, *vertical-half blocked*, and *vertical-all free* are approximately 90, 90, and

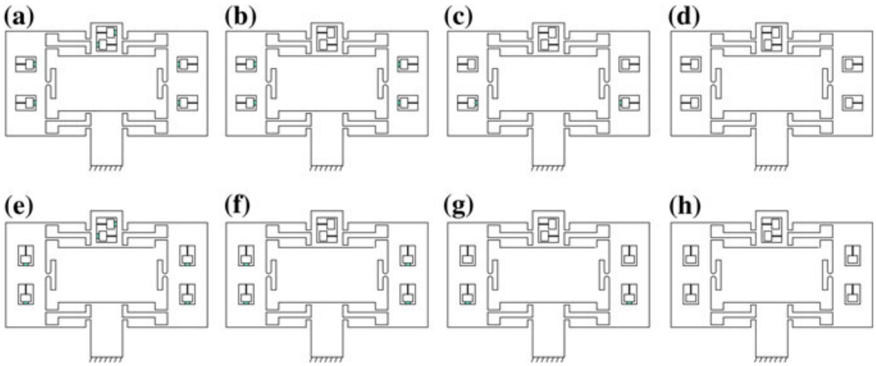

Fig. 3 Bridge-type compliant mechanism with absorbers in different free or blocked state: **a** horizontal-all blocked **b** horizontal-side blocked **c** horizontal-half blocked **d** horizontal-all free **e** vertical-all blocked **f** vertical-side blocked **g** vertical-half blocked **h** vertical-all free

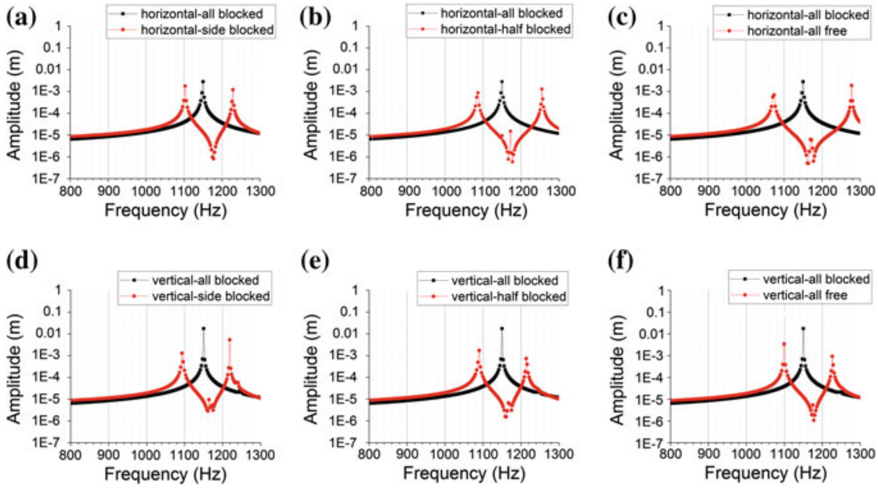

Fig. 4 Comparisons of the frequency response functions under the different configurations of the absorbers

90 Hz. And this indicates that it cannot enhance the performance of vibration suppression after inserting more absorbers to the mechanism when the absorbers in the side beams are inserted along vertical orientation.

3.3 *Further Discussions*

In above two sections, it has been discussed whether the bridge-type compliant mechanism which embeds some absorbers can have a better performance of vibration suppression and whether it can enhance the performance of vibration suppression when inserting more absorbers to the host mechanism. But all of them are based on the following premise that the absorbers must approximately keep same of first order modal frequency with the bridge-type compliant mechanism. Thus, if changing the first order frequency of the absorbers, it will lead to a little impact on the first order modal frequency of the mechanism. Will the vibration-suppression effect of the absorbers be weaken? Aiming at the issue, the following discussions are carried out.

According to Sect. 3.1, a best performance of vibration suppression is obtained when the absorbers are configured as in Fig. 3d. So we choose the model in Fig. 3d to start a discussion firstly. By changing the dimension 1 and the dimension 2 in Fig. 1c, the first order modal frequency of the absorber can be changed as we need. And their frequency response functions are obtained while the dimension 1, 2 are changed, as shown in Fig. 5, which include four kinds of models, *free1–free4*. From Fig. 5, it is obvious that the absorbers with different dimension 1, 2 have a

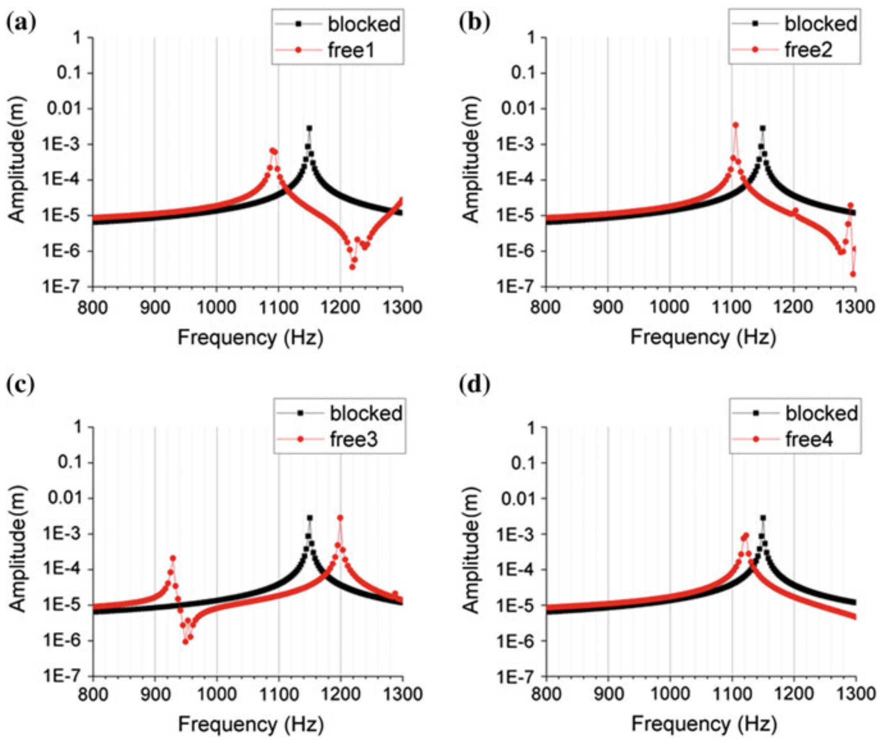

Fig. 5 Comparisons of the frequency response functions when changing the natural frequency of the absorbers

little impact on the first order modal frequency of the bridge-type compliant mechanism. So we can evaluate the performance of vibration suppression when dimension 1, 2 of the absorber are changed.

After analyzing all frequency response functions in Fig. 5, we can easily draw a conclusion that performance of vibration suppression of the absorbers depend on its first order modal frequency. And it becomes more and more weak, when its first order modal frequency deviates more heavily from the design frequency of the bridge-type compliant mechanism. Even when the frequency deviation increase at a certain extent, its vibration-suppression effect will disappear.

4 Conclusion

The paper analyzes the performance of vibration suppression of the absorbers, a kind of metastructure, embedded into a bridge-type compliant mechanism. When the first order modal frequency of the absorbers equals to the one of the compliant amplifier, the absorbers can reach best performance of vibration suppression. Their vibration-suppression effect can be enhanced by adding more absorbers into both side beam of the mechanism in horizontal orientation. And their vibration-suppression effect has a key relation with deviation degree between first order modal frequency of the absorbers and their host structure. When their first order modal frequency deviates more largely from the design frequency, their effect will become weaker until it has no vibration-suppression effect nearly.

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