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Technical note

Experimental investigation of vibration damper composed of acoustic metamaterials

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ABSTRACT

The membrane type acoustic metamaterials have been recently proposed and described in our research team. The present paper presents the experimental results of the vibration damper composed of acoustic metamaterials attached to a rectangular steel plate with free edges, which can be considered as an application extension of the structure. The results of frequency response function (FRF) of the system show that such vibration dampers could reduce the vibrating plate resonance magnitudes by up to 42 dB (averaging 27.1 dB) while providing overall vibration reduction of 24.7 dB in the frequency range of 100–1200 Hz, in comparison with the response of the free plate. However, the mass ratio between the structure and the plate is about 6.1%. Thus, the measurements demonstrate the possibility of its use in practice, such as the aerospace vehicles. Besides this, the vibration reduction experiment of a commercial rubber plate is also conducted, for the comparison purpose with the acoustic metamaterials structure. The final comparison results indicate that the performance on the vibration absorption of the 4 stacked samples is even better than the commercial rubber plate either in the relatively lower frequency range (100–500 Hz) or in the relatively higher one (500–1200 Hz).

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1. Introduction

Damping of unwanted structural vibrations remains a major issue in many branches in engineering. To achieve a desired performance of many engineering systems, vibration control in general can be achieved passively, actively, or semi-actively [1–3]. Due to the reliability of performance and limited required maintenance, passive vibration control treatments are frequently the preferred remedy. In this paper, the focus is on passive control. There are many methods of passive damping of structural vibrations, the most common of which being attaching unconstrained damping layer or constrained damping layer (CDL) to the surfaces of vibrating structures resulting in increase of structural wave attenuation [4,5]. Moreover, impedance changes at discontinuities, for example by added stiffness, mass or section change, may be used to introduce reflection and thereby reduce transmitted power of the flexural waves. As the example of such practical application, an efficient method of reducing flexural vibrations in plates with attached wedges of power law profile based on the so-called "acoustic black hole effect" has been recently proposed and developed [6,7], which can be applied to the damping of excessive resonant vibrations in turbine and fan blades [8].

However, these treatments are ineffective at low frequencies and the classical dynamic vibration absorber (DVA), may be an alternative solution in this case [9]. A large number of works reported in the literatures have considered the design and optimization problems of the different forms of DVA devices focusing on either single-mode attenuation [10–12] or broadband performance [13–16]. It is also possible to use piezoelectric patches along with passive, resonant electronic circuits to form vibration dampers [17].

An on-going aim of passive control materials is to simultaneously achieve low and high frequency structural vibration attenuation while contributing only a small mass to the host structure. For applications in transportation, e.g. in maritime or aerospace vehicles, the minimization of weight is desirable, meanwhile, broadband passive vibration attenuation are equally important objectives. In this circumstance, the distributed vibration damper has been an alternative solution, featuring viscoelastic or poroelastic spring layers along with some form of distributed mass [18–20].

In this paper, a new vibration control structure mainly composed of the acoustic metamaterials is presented. In earlier research [21], a thin-film acoustic metamaterials sample, comprising an elastic membrane decorated with asymmetric rigid platelets, can reach almost unity absorption at selective resonance frequencies ranging from 100 to 1000 Hz. The new aspect of this

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idea, which is initially used for low frequency sound absorption, is to apply such absorbing sample to plate to achieve maximum vibration reduction at the resonant frequency of the structure. Although it is regarded as a tuned system in the case of the sound absorption phenomenon, it can also be designed to be effective over a broad frequency range due to its multiple close eigenmodes of the metamaterials [21]. More recently, we proposed a type of miniature low frequency vibration dampers based on decorated membrane resonators. At frequency around 150 Hz, it can limit its maximum resonance quality factor to 18 [22].

The aim of this paper is to present the preliminary findings of the experimental investigation of a damping system composed of the acoustic metamaterials. As will be demonstrated, the results of these experiments show that, a significant reduction of resonant peaks can be observed covered by 4 stacked sample damper, in comparison with the free plate response. This implies that vibration-damping systems utilizing the acoustic metamaterials are efficient and suitable for practical applications (see Table 1).

2. Background information

Dissipating vibration energy by the viscosity in solid is only referring to the internal relative motions. The relevant dissipative power is, therefore, [23]

$$\dot{E} = \omega^2 \sum_{iklm} \eta_{iklm} \int_{\Omega} u_k \frac{\partial^2 u_l}{\partial x_i \partial x_m} dV. \tag{1}$$

where the tensor η_{iklm}, of rank four, is the uniform viscosity tensor of material, and vector u the local displacement. The integral is over the space Ω occupied by material. The difficulties for low frequency dissipation is clear from the quadratic term of circular frequency ω^2.

The acoustic metamaterial was conquering this low frequency absorption difficulty by utilizing the local resonance phenomena in metamaterial. Properly designed low frequency resonant modes localized in small scale can provide extremely large second derivative $\partial^2 u_l/(\partial x_i \partial x_m)$ for displacement in Eq. (1), therefore, possibly achieve large dissipative power $\dot{E}$ [21]. Of course, this working principle is not necessary to be restricted in the acoustic process; the extension on solid vibration is natural.

However, the issues for wave absorption are not only about dissipating waves inside of the damper, but also impedance match – only properly matching the wave impedance in the medium can maximally reduce the reflection waves and introduce most of the energy into the damper. Therefore, the medium impedance for solid and air would be the major differences between acoustic and vibration dissipation problem. However, benefiting from its resonant features, the effective impedance of metamaterial is highly dispersive; one can almost found all the possible values of impedance in the small region of frequency around the system's resonance. Thereby, by only using the similar design as the air-based metamaterial damper, one can achieve the high absorption for the vibration process around the system's resonances as well. The dispersive properties of metamaterial also explain the small weight of the damper comparing to the conventional absorbing material, since large effective impedance is also indicating heavy effective mass much larger than its real mass.

Table 1
Comparison result of the eigenfrequency of the free plate.

Material	Mode	Frequency (FEA) Hz	Frequency (experiment) Hz	Percent Error
Steel	1	135.4	135.4	0
	2	160.6	162.1	0.93
	3	296.7	297.6	0.3
	4	390.0	389.9	0.026
	5	466.3	468.1	0.38
	6	608.5	608.5	0
	7	648.7	648.1	0.092
	8	809.1	809.1	0
	9	896.5	899.5	0.33
	10	910.1	907.1	0.33
	11	995.6	993.4	0.22
	12	1038.1	1038.1	0
	13	1184.4	1181	0.29

3. Experimental results

In this section, a simple decorated membrane resonator is investigated first to verify the damping mechanism, which can be modeled by resorting to the dynamic effective mass parameter, then multiple platelets damper is also examined, such multi-plate dampers have many vibration eigen-modes and serve as multiple frequency dampers, therefore we naturally extend this structure to multiple ones, just as the picture shown in the part of Section 3.2, to obtain the vibration suppression effect over broad-band frequency range.

3.1. Single and multiple platelets dampers

A typical single platelet damper consists of a rigid frame, an elastic membrane fixed onto the frame, and a platelet fixed on the membrane. In applications, the frame of the damper is in direct contact with the host structure. Therefore, the interaction between the host structure and the damper at the contact can be fully captured by the dynamic effective mass [24] ($\tilde{m} = m_R + im_I$) of the damper ($i = \sqrt{-1}$) relative to the frame, as the force $\tilde{F}$ exerted on the host structure by the damper is simply given by $F(t) = -\tilde{m}\omega^2 \tilde{A}(t)$, where $\tilde{A}$ is the oscillation displacement of the host structure at the contact (and the rigid frame of the damper), and ω is the vibration frequency. As the power dissipation by the damper is given by $P_{Diss} = -\frac{1}{2} m_I \omega^3 |A|^2$, maximum dissipation occurs when m_I reaches negative maximum values. The force from the membrane on the frame also reaches maximum.

To measure the effective mass of a sample damper, the sample hard frame was mounted on the platform of a force sensor, which was mounted on an accelerometer. The other end of the accelerometer was attached onto a vibration shaker. The acceleration of the sample frame was the same as that of the accelerometer

Fig. 1. Single platelet damper.

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