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Wave energy control using asymmetric dual acoustic black holes with width variation

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ABSTRACT

The acoustic black hole (ABH), a wedge-type structure with power-law thickness, has been developed for light-weight vibration damping in thin structures. Recently, a space efficient concept of a spiral ABH was reported based on a geometrical modification on the ABH baseline into the spiral shape. In this study, we propose another two simple modifications and investigate advantages of using the modified ABHs. One of the modifications is attaching dual ABHs to a beam, which results in enhancement of the damping performance compared to the conventional case of the single ABH. The other is gradually decreasing the width-profile of the ABH to zero towards the ABH tip, and the width-varying ABH focalize the elastic waves near the tip with higher energy density than that of the standard ABH. Numerical results show that the resonant peaks of vibration response in the dual ABHs case are reduced up to 4.3 dB compared to the single ABH case. In addition, the damping performance of the dual ABHs can be more increased by making a difference in the ABH length between the dual ABHs. In the case of the width-varying ABH, the highly focused waves are near-perfectly attenuated by only a small amount of damping material and it could achieve damping performance similar to the standard one, so the installation weigth of the ABH can be saved by modifying the width-profile. When we utilize the width-varying ABH for vibration amplification, the vibration response in a beam only are increased up to 30.1 dB, indicating that the width-varying ABH can be applied to ultra-sensitive vibration detection by focalizing the elastic waves in the original structure into the ABH tip.

Keywords: Acoustic black hole, Elastic wave, Wave focalization
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1. INTRODUCTION

The concept of an acoustic black hole (ABH) was first proposed by Mironov [1]. Ideally, when the thickness of a wedge structure is gradually reduced to zero according to the power-law of $h(x) = \varepsilon x^m$ $(m \geq 2)$, the group velocities of incident elastic waves approach to zero and the amplitude of vertical displacement becomes infinite at the wedge tip, resulting in zero wave reflection and high energy concentration at the tip. However, a finite tip thickness in real manufactured wedges causes inevitable wave reflections [1-3]. Krylov et al. suggested attaching only a small amount of damping material to near tip, and confirmed that that the focalized wave energy could be near-perfectly attenuated by the damping material treatment – the so-called an ABH effect [2,4,5].

Several studies have been conducted to investigate the ABH effect with geometrical modifications on the ABH. Lee and Jeon proposed a space-efficient form of ABH by rolling the baseline into an Archimedean-spiral configuration and numerically showed that the spiral ABH could achieve vibration damping as effective as the standard ABH [6]. Tang and Cheng changed the thickness profile, and the modified thickness profile provided an enhancement of the ABH effect in their numerical simulations [7].

In this study, we propose two simple modifications and investigate advantages of using the modified ABHs. By attaching dual ABHs to a beam, we increase the damping performance of the ABH compared to the conventional case of the single ABH. In addition, we further enhance the damping performance of the dual ABHs by making the length difference between the dual ABHs. Another modification is smoothly decreasing the width-profile of the ABH to zero towards the ABH tip, and elastic waves with higher energy density can be concentrated near the tip of width-varying ABH than the standard ABH case. We utilze the width-varying ABH in vibration damping and amplification, and advantages of using the width-varying ABH are discussed.

2. Geometry, material, and Method

2.1 Geometry and material of dual ABHs and width-varying ABHs

Figure 1 shows the side view of the dual ABHs with a beam and the plan views of the width-varying ABHs. The dual ABHs, shown in Fig. 1(a), are classified into two groups. One is symmetric dual ABHs whose two ABHs have same legnth. The other is asymmetric dual ABHs with different ABH length. The dual ABHs are connected to a simple beam (dimension: 180x30x6 mm^3) and each ABH has same power of the thicknessp profile (m=2.2) and tip thickness (0.5 mm). The width-profile of the width-varying ABH depicted in Fig. 1(b) linealy decreases to zero and its plan view is a delta shape, so the ABH is referred to as a delta ABH. In order to more highly focalize wave energy near the tip of the width-varying ABH, we make the tip region narrower and its planview is shown in Fig. 1(c). The width-varing ABH, depicted in Fig. 1(c), is referred to as a concave ABH. In Fig. 1(b) and (c), the width-vayring ABHs are attached to the same beam as mentioned above. Each ABH has same length of 120 mm and thickness profile (m = 2.2, ε = 0.2973 m$^{-1.2}$, and tip thickness = 0.2 mm). The substrate material is aluminum, and the material properties of aluminum are listed in Table 1.

Table 1 – Material properties of aluminum

Material	Young's modulus	Mass density	Poisson ratio	Loss factor
Aluminum	71.7 GPa	2810 kg/m^3	0.33	0.4 %

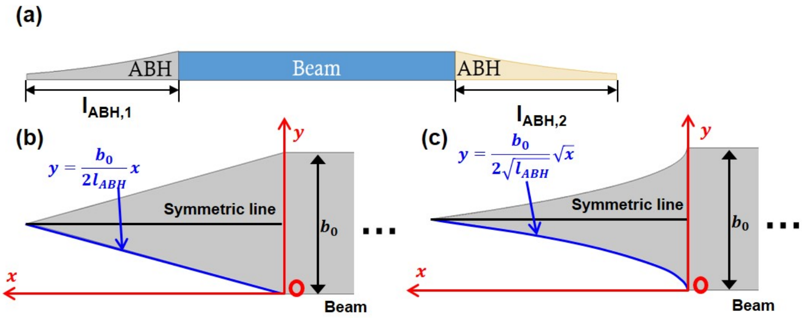

Figure 1: (a) Side view of dual ABHs with a simple beam. (b) Plan view of delta ABH attached to a beam. (c) Plan view of concave ABH with a beam.

2.2 Numerical method

We performed three-dimensional numerical simulations to investigate the frequency response of a simple beam or the beam with an ABH under a unit harmonic force excited at the center point of the beam by using FEM software, COMSOL Multiphysics V5.2a. The governing equation is the Navier's equation, and free boundary conditions are given along all faces and edges of the beam structures. The studied frequency range is from 20 Hz to 7,000 Hz and the frequency resolution is 2 Hz.

3. Results and discussions

3.1 Vibration damping using dual ABHs

In this section, we investigate the damping performance of the dual ABHs. Figure 2(a) compares the driving point mobility of the beam only and the beams with single ABH and symmetric dual ABHs. Each ABH has same length (180 mm), thickness profile (m = 2.2, ε = 0.111 m$^{-1.2}$, and tip thickness = 0.5 mm), and damping material treatment treatment near the ABH tip. The dimensions of damping material are length of 12 mm and thickness of 3 mm and its material properties are the Young's modulus of 10 MPa, the mass density of 1000 kg/m^3, the Poisson ratio of 0.45 and the loss factor of 10%. As shown in Fig. 2(a), the peak amplitudes of the dual ABHs case decreased about 2.5 dB and 4.3 dB near the 1st and 2nd resonant frequencies of the beam only, respectively. From the results, it can be seen that the damping performance can be enhanced compared to the conventional case of the single ABH by using the dual ABHs. In order to further increase the damping performance of the dual ABHs, we change the $l_{ABH,2}$ from 135 mm to 225 mm while $l_{ABH,1}$ is fixed with 180 mm. As shown in Fig. 2(b), the peak reductions of the dual ABHs varies periodically with respect to the $l_{ABH,2}$. The peak reduction of the asymmetric dual ABHs with $l_{ABH,2}$=135 mm further increases about 7.4 dB compared to the symmetric dual ABHs even though the ABH length decreases about 25%, i.e. the ABH mass is reduced about 25%.

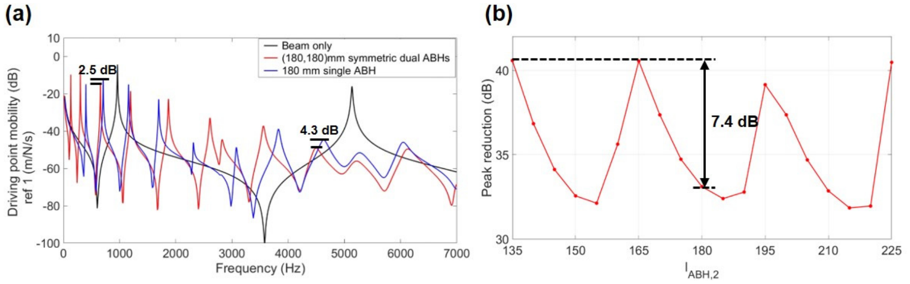

Figure 2: (a) Driving point mobility of a beam only and the beams with single ABH

and symmetric dual ABHs. (b) Peak reductions of dual ABHs with different $l_{ABH,2}$ *near 5 kHz.*

3.2 Vibration damping using width-varying ABHs

In this section, we investigate the effects of width variation on the damping performance by comparing the damping performance between the standard ABH and the width varying ABHs shown in Fig.1(b) and (c). Figure 3(a) compares the driving point mobility of the beam only and the beams with the standard ABH and the delta ABH. Each ABH has same ABH length and thickness profile, but different width-profile. In the results, there is no significant difference in peak reductions between the ABHs, indicating that the width variation does not considerably affect the ABH effect. One of advantages of using the delta ABH is that it can save the installation weight of the ABH because the mass of the delta ABH is about 66% of the standard ABH. In order to further save the ABH mass, we investigate the damping performance of the concave ABH whose mass is only 50% of the standard ABH. As shown in Fig. 3(b), the damping performance of the concave ABH is similar to that of the standard ABH, indicating that the concave ABH can be a more lightweight alternative for the standard ABH.

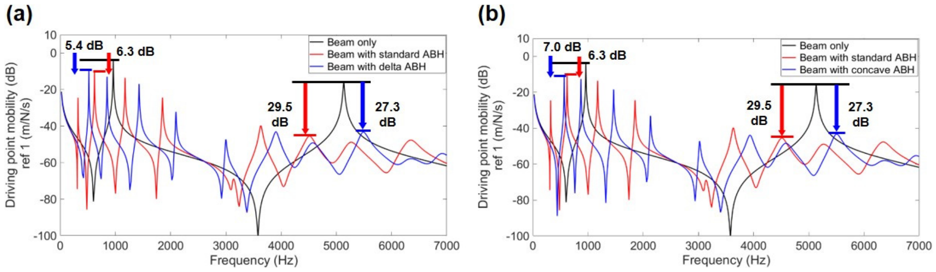

Figure 3: Driving point mobility of (a) a beam only and the beams with the standard ABH and the delta ABH, (b)beam only and the beams with the standard ABH and the concave ABH.

3.3 Vibration amplification for sensing

In this section, we use the width-varying ABH for vibration amplification, and discuss the possibility to utilize it in ultra-sensitive vibration sensing. By comparing the cross point accelerance between the beam only (dimensions: 180x30x5 mm^3) and the beam with the delta ABH, we investigate the amplification performance. The delta ABH has length of 120 mm and the thickness profile (tip thickness = 0.2 mm, m = 2.2, and $\boldsymbol{\varepsilon}$ = 0.2973 $m^{-1.2}$). Figure 4(a) shows the measurement point, at which the vibration response is maximum, of the point accelerance. As shown in Fig. 4(b), the amplitudes of the resonant peaks of the beam with the standard ABH are increases up to 13.7 dB compared to the beam only. The wave energy is focused near the ABH tip by the thickness profile, resulting in the wave amplification. In the case of the delta ABH, waves are focalized with higher energy density than that of the standard ABH due to its much narrower tip region, so larger amplifications are achieved up to 30.1 dB. The enormous amplification of the vibration response can be utilized in detecting an undetectably tiny vibration of which amplitude is smaller than sensor threshold. In addition, the delta ABH increases the number of peaks, indicating that it can enhance the sensitivity in a broad frequency range.

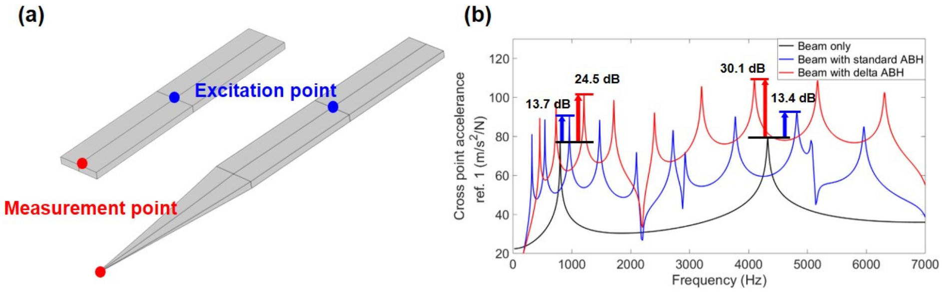

Figure 4: (a) Schematics of the measurement point and the excitation point of the cross point accelerance. (b)Cross point accelerance of a beam only and the beams with the standard ABH and the delta ABH.

4. CONCLUSIONS

In this study, we proposed two modifications on the ABH and investigate advantages of using the modified ABHs. One modification was attaching dual ABHs to a beam. Using dual ABHs, we could achieve better damping performance compared to the single ABH. In addition, we further increase the damping performance using the concept of asymmetric dual ABHs. The other modification was smoothly decreasing the width-profile to zero towards the ABH tip. Using the width-varying ABH, it was possible to save installation weight of the ABH by half. On the other hand, when the width-varying ABH was used for vibration amplification, the resonant peaks increased up to 30.1 dB compared to a reference beam without the width-varying ABH, indicating that it can be applied to ultra-sensitive vibration detection.

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