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Investigations on flexural wave propagation and attenuation in a modified one-dimensional acoustic black hole using a laser excitation technique

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ABSTRACT

Acoustic Black Holes (ABHs), as a new type of passive structure for vibration damping enhancement and noise attenuation, have been drawing increasing attentions of many researchers. Due to the difficulty in manufacturing the sharp edges required by the ABH structures, it is important to understand the wave propagation and attenuation process in the presence of damping layers in non-ideal ABHs with a truncated edge. In this paper, an analytical expression of the wave reflection coefficient in a modified one-dimensional ABH is derived and a time-domain experimental method based on a laser excitation technique is used to visualize the wave propagation. In the experimental studies, the flexural waves in the ABH were excited by a scanning pulse laser and measured by a Laser Doppler Vibrometer (LDV). The incident wave and reflected wave were separated from the measured original wave field and the decrease of the wave velocity in the ABH was exhibited. The reflection coefficient was calculated from the ratio of the amplitude of the reflected wave to that of the incident wave for different ABH parameters and different thicknesses of the damping layer. The measured reflection coefficients were used to identify the unknown coefficients in the theoretical formula. The results confirm that there exists an optimal thickness for the damping layer, which leads to the minimum wave reflection. Based on the laser-induced visualization technique and various signal processing and feature extraction methods, the entire process of the wave propagation in a non-ideal one-dimensional ABH structure can be visualized and scrutinized.

1. Introduction

Recently, acoustic black holes (ABHs), as a new type of passive structure for vibration damping enhancement and noise attenuation, have drawn the attention of many researchers. The concept of the ABH was initially proposed by Mironov and Krylov in one-dimensional plates containing a power-law-profiled wedge, towards which the propagating flexural waves are slowed down [1–3]. When the power-law thickness profile, $h(x)$, satisfies

$$h(x) = \varepsilon x^m \quad (m \geqslant 2), \tag{1}$$

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in which x is the distance from the edge, ε is a constant scale factor, and m is a rational number, the flexural wave cannot reach the sharp edge and be reflected back in the ideal zero-thickness scenario. This leads to a drastic wave compression and energy trapping within the tapered wedge area. This phenomenon has been exploited to achieve efficient damping for flexural waves in plate-like structures using both one-dimensional and two-dimensional ABHs with a very small amount of damping materials covering the sharp edges [4]. The benefit of the wave manipulation through ABH effect is obvious. In terms of the energy utilization, the strong energy concentration facilitates and enhances the efficiency of the energy harvesting [5,6]. In terms of vibration and noise suppressions, it would be more advantageous and efficient to apply energy dissipation means such as coated damping layers only to the specific energy concentration areas, which is especially important in light-weighted structures used in aeronautical and automotive applications [7–11].

However, an ideal ABH structure is difficult to be realized due to the existing machining capability. Even in the ABH structures of composites, which are usually manufactured by layering up prepreg, ideal profiles are still difficult to be realized due to the thickness of prepreg. On the other hand, ideal ABHs are not suitable for real-world structures due to their intrinsic weakness in structural integrity and strength. Fabricated real-life wedges are always truncated to a certain residual thickness, which adversely affects their performance as 'black holes'. Without additional damping treatment, the typical values of the reflection coefficient in such materials as steel can become as large as 50–70%, which makes it impossible to use such wedges as practical vibration dampers. Although the situation can be improved by covering the wedge surfaces near the edges by thin absorbing layers [12–16], methods, be it theoretical or experimental, allowing for systematic analyses and the time-domain wave visualization are still very much limited.

Among existing theoretical and numerical studies, the geometrical acoustic approach was first proposed to analyze the flexural wave propagation in tailored wedges and to calculate the reflection coefficients under the hypothesis that the influence of the stiffness and the mass of the damping layer on the local dynamics of the ABH is negligible [17]. Under the umbrella of the geometrical acoustics, the reflection coefficient was analytically expressed as simplified formulae to taking into account the effect of a thin absorbing film for different power-law profiles of order m=2, 3, 4 and for a sinusoidal profile [12–14]. A different approach which is not limited by the hypotheses of the geometrical acoustics has been proposed by Georgiev et al. for beam structures using an impedance method [18], which in turn leads to a Riccati equation. This approach can only deal with a semi-infinite structure with the ABH on the edge, which is obviously different from the practical structures with finite size and real boundaries. On the other hand, most existing approaches consider the effect of a thin damping layer through Ross-Unar-Kerwin (RUK) model [19], which assumes the thickness of the damping layer is much smaller than that of the wedge. In practice, however, the thickness of even an extremely thin damping layer would be comparable to that of the wedge tip, where ABH effect is the largest, which suggests the importance of considering more practical cases. Besides, the optimal damping layer thickness depend on many factors, such as the tip thickness, the location, and the size [12–16]. In this regard, Tang et al. [20] show that the full coupling between the damping layers and the ABH taper can be taken into account using a semi-analytical model based on a Euler-Bernoulli beam. By using Mexican hat wavelet functions to approximate the flexural displacement, the governing equations are obtained using Lagrange's equations. The proposed model provides an efficient way to study the ABH feature and the effect of damping layers using a more realistic ABH-featured beam. However, in almost all the above works, frequency-domain approaches were used.

In addition to the theoretical studies, experimental investigations on ABH have also been conducted using a variety of beam-like and plate-like structures [4,9,11,15,21–23]. Bowyer investigated the effects of the different manufacturing processes and the tolerances on the vibration damping in structures with power-law-profiled edges [24]. Two-dimensional structures like rectangular plates, elliptical plates and circular plate with tapered indentations (pits) of power-law profile machined on the plates were also experimentally investigated [7,8–13]. Until now, with nearly no exception, all the experimental investigations on ABHs are carried out in the frequency domain, based on metrics such as frequency response function or point mobility. These experimental studies have confirmed the high efficiency of ABH for vibration damping enhancement. Although the ABH effect on the steady vibration response can be illustrated, the wave propagation process, which is very important for understanding the energy trapping process as well as the influence of various geometrical and structural imperfections of the structure, cannot be revealed. Despite the popular use of frequency-domain methods in engineering applications, time-domain methods are more attractive and insightful in revealing time-varying phenomena. Besides, as a more direct indicator of the ABH phenomenon, the reflection coefficient can provide invaluable information on the design of practical ABH structures, if it can be directly measured experimentally. One of the possible ways is the use of laser-based wave generation technology [25–28]. Yan investigated the effect of ABH structure on Lamb modes using laser-generated Lamb waves [27]. Huang also researched the wave energy focalization in a modified ABH structure using laser excitation technique [28]. The time-domain technique using laser excitation not only helps to understand the energy trapping effect of ABH qualitatively, but also provides a quantitative means to evaluate the ABH effect and to study the influence of parameters. A Kundt-like method was proposed by Denis for measurement of the reflection coefficient of a beam termination, but it cannot be used to show the wave propagation process of the ABH effect [29].

In order to achieve better understanding of the ABH effect and the calculation of the reflection coefficient directly, a time-domain experimental method is proposed to study some fundamental issues, including wave velocity decrease, wave package compression, edge reflection and attenuation along the propagation path. In the proposed method, the flexural wave in the ABH is generated by a scanning pulse laser and measured by Laser Doppler Vibrometer (LDV). Signal processing on the measured time-domain is then carried out for wave separations. Based on the laser-induced visualization technique and various signal processing and feature extraction methods [30], the entire process of the wave propagation in a non-ideal