ARTICLE IN PRESS

Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Embedded Acoustic Black Holes for semi-passive broadband vibration attenuation in thin-walled structures

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ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form
17 October 2016
Accepted 19 October 2016
Handling Editor: A.V. Metrikine

Keywords:
Acoustic Black Hole
Vibration attenuation
Wavenumber sweep
Broadband

ABSTRACT

We explore the use of structure-embedded Acoustic Black Holes (ABH) to design thin-walled structural components exhibiting broadband vibration attenuation characteristics. The ABH is a geometric taper with a power-law profile fully integrated into the structural component and able to induce a smooth and progressive decrease of both the velocity and the wavelength of flexural waves. Previous studies have shown these characteristics to be critical to enable highly efficient vibration attenuation systems. The performance of ABH thin-walled structures is numerically and experimentally evaluated under both transient and steady state excitation conditions. Both numerical and experimental results suggest that the proposed approach enables highly efficient and broadband vibration attenuation performance.

1. Introduction

Structural vibration control has been a long standing challenge on the path to maximize the performance of mechanical, aerospace, and civil engineering systems [1]. The vibration environment strongly affects the safety and durability of the host structure as well as its spectrum of applications and operating conditions. As an example, in manufacturing applications mechanical vibrations affect both the fabrication rate and quality of the end product. In aerospace and mechanical applications, vibrations are the primary factor inducing damage initiation and propagation as well as a predominant source of noise which ultimately impact the end-user comfort. In civil engineering, environmental and operational loads combined with the large size of the structure can induce nonlinear vibrations and highly coupled fluid–structure responses that, if not properly attenuated, can lead to catastrophic events. During the past several decades, a variety of approaches have been explored to reduce or control these harmful vibrations. For detailed reviews of these methodologies the reader is referred, as an example, to [2–4].

From a general perspective, vibration attenuation and control techniques are typically classified into passive and active. The passive treatments are light, easy to install and to maintain, and relatively inexpensive but yield limited vibration reduction and suffer from a narrow operating bandwidth. The active techniques provide a much larger operating bandwidth and overall adaptive characteristics to variable external conditions but are associated with increased cost and complexity, and higher probability of malfunctions. Hybrid methodologies have also been explored in order to combine some of the benefits of passive and active techniques. The attention to hybrid systems has been somewhat revitalized during the last

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http://dx.doi.org/10.1016/j.jsv.2016.10.029

decade due to the interest in harvesting the energy associated with operational or environmental induced vibrations. In fact, structural vibrations have become one of the most natural source of energy to generate small but continuous amount of electrical energy necessary to power the increasing amount of electronics used in modern structural systems. Interestingly, these vibration-based energy harvesting systems suffer similar limitations to passive vibration control treatments, that is a relatively low efficiency and narrow operational bandwidth. This aspect is even more limiting for energy harvesting if we consider that environmental and structural vibrations are broadband in nature, therefore resulting in low spectral energy density. To some extent, this similarity between the two systems is not surprising considering that in both the ultimate goal is to extract mechanical energy from the system. Many approaches have been investigated to enhance the performance of mechanical energy extraction systems under broadband excitation. Techniques ranged from tunable resonators to multi-stable and nonlinear systems. Comprehensive reviews for energy harvesting applications can be found in [5–7].

A different approach to the general problem of broadband vibration control was originated by the seminal study performed by Mironov [8] on the propagation of acoustic waves in a non-reflecting wedge. He observed that, when acoustic waves propagate in a power-law tapered wedge (having an exponent greater than 2 and satisfying the smoothness condition), the wave slows down without giving rise to any reflection. In the ideal case, corresponding to a vanishing thickness at the tip of the wedge, the wave would approach zero phase velocity. Following Mironov's intuition, Krylov [9] introduced the concept of an Acoustic Black Hole (ABH) which essentially forges the idea of a non-reflecting wedge in a three-dimensional element. Krylov's studies started a whole line of research targeted to the attenuation of structural vibration via embedded ABH elements. Since then, many researchers have explored the design and the dynamic performance of structures with different types of ABH tapers. O'Boy [10] investigated the reduction of flexural vibration in plate structures induced by ABH effects. He found that the ABH profile can be used as an effective vibration damper in plate structures over a broad frequency range. Bowyer [11] experimentally investigated the damping of flexural vibrations using tapered indentations of power-law profiles on rectangular plates. These indentations were proven to be effective as vibration dampers. Georgiev [12] studied the damping of structural vibrations in beams and elliptical plates with embedded ABHs. He numerically and experimentally confirmed the importance of the absorbing layer in the overall design of the vibration dampers and performed a parametric study to determine the optimal geometrical and material properties of the absorbing film. Gusev [13] found that propagating waves on ABH tapered plate can exhibit hysteretic nonlinearity. This theory showed that the nonlinear absorption causes complete attenuation of the wave in the ABH. Conlon [14] studied the modal loss factor and the structural-acoustic properties of thin plate structures with multiple embedded ABHs. Yan [15] evaluated the structural characteristic of ABH using laser generated Lamb waves. Denis [16] measured the reflection coefficient of an ABH termination while Zhu [17] used the ABH as a fundamental unit cell to create phononic plates with unique dispersion and propagation characteristics. Zhao [18,19] suggested an ABH tailored host structure for efficient vibration-based energy harvesting showing that both the harvesting efficiency and the operational bandwidth could be increased drastically.

The main objective of this paper is to present a numerical and experimental study to assess and quantify the broadband semi-passive vibration characteristics of ABH dynamically tailored structures with piezoelectric transducers. This paper is a follow-up study to [18,19] in which the emphasis was given to understanding the role of ABH embedded tapers from the perspective of vibration-based energy harvesting. The present study instead illustrates, both qualitatively and quantitatively, some important characteristics of the dynamic response of ABH-tapered structures from a vibration attenuation perspective. In this regard, the following study uses the same geometric configuration and experimental setup as [19] in order to provide vibration attenuation data that are fully consistent with the previously published energy harvesting data. In reference to the existing literature and to previous studies from the authors, this paper presents the following contributions:

1. The dynamic response of semi-passive ABH structures is predicted by developing three-dimensional finite element models that account for the fully coupled electro-mechanical response of the system; the excellent qualitative agreement with published experimental results [19] reveal the feasibility of capturing the main features of electro-mechanically coupled ABH-structures for system design and performance evaluation.
2. The current study provides one of the first set of numerical and experimental results assessing the performance of semi-passive vibration attenuation systems in ABH structures. These datasets will serve as a useful reference for future numerical and experimental studies on vibration reduction in ABH structures.
3. Performance optimization is accomplished directly on experimental vibration data. The data are consistent and directly comparable with those collected for energy harvesting applications [19]. We believe that these results provide a useful reference in support of future multi-functional structural designs.

In the following, we first review the general idea of structural dynamic tailoring as an approach to improve vibration attenuation and to achieve broadband operating conditions. Then, we perform a numerical study based on 3D finite element simulations in order to evaluate the performance of geometrically tapered thin-walled structures for piezoelectric-based vibration attenuation. Finally, we present an experimental investigation and a performance optimization study aiming at validating the overall design approach and at quantifying the vibration suppression effect.