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Passive constrained viscoelastic layers to improve the efficiency of truncated acoustic black holes in beams

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ABSTRACT

Power-law profiles at the edges of beams and plates have proved to be a very efficient way to attenuate vibrations. In an ideal scenario, for a profile with zero end thickness, the energy of flexural vibrations would never reflect from the boundaries, giving place to the Acoustic Black Hole (ABH) phenomenon. In practice, however, the edge must be truncated which results in a non-zero reflection coefficient. To partially mitigate this problem, a viscoelastic layer (VL) is typically placed at the tip of the ABH termination to compensate for the effects of truncation. Instead, in this work it will be shown that one can achieve better results by resorting to passive constrained viscoelastic layer (PCVL). The latter consists of a sandwich made of a viscoelastic layer (VL) plus a constrained layer (CL). An analytical model is developed to describe the performance of a truncated ABH beam with PCVL, where the displacement fields are expanded by means of Gaussian functions. The model is validated through finite element (FEM) simulations and experiments. It is observed that a truncated ABH beam with PCVL at the tip performs better than an ABH beam with an unconstrained VL, even if they add equal mass to the system.

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1. Introduction

In the past two decades, acoustic black holes (ABH) in vibroacoustics have revealed as a potential means of vibration suppression in beams and plates [1–4], with applications in lightweight shell structures. A one-dimensional ABH can be achieved in a beam that is composed of a uniform section and a wedged tip with a decreasing power-law profile. Analogously, two-dimensional ABHs can be attained in plates with power-law tailored boundaries, or with embedded cuneate areas [5].

Because of the specific thickness profile at the tip, the velocity of a flexural wave propagating in an ABH beam will shift down without reflection, in the ideal scenario of a zero-thickness wedge. Meanwhile, its travelling time will tend to infinity as the local thickness diminishes, owing the phase velocity to decay to zero and the energy to focalize at the tip end. This interesting effect not only can be successfully exploited for vibration attenuation in beams and plates [6], but also, and consequently, for noise radiation control [5,7], as well as for harvesting energy in cuneate areas of plates [8,9].

However, ideal ABHs cannot be constructed and the wedges must be truncated at some point. This brings adverse effects on the performance of the ABHs [10]. Even if the cut-off thickness is minimal (which is hard to manufacture in practice, see e.g. [11,12]), both theory and experiments show that the energy absorption effect strongly diminishes because of the

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truncation. To partially remedy this situation viscoelastic layers are typically placed at the end of the tip [6], its precise location and shape being a topic of current research (see e.g. [13]). Some further enhancement can be achieved by placing an extended platform of uniform thickness at the tip of the ABH wedge [14,15]. It is also worthwhile mentioning that some alternative strategies have been recently proposed, such as rolling the ABH wedge into a spiral [16], yet the use of viscoelastic layers is by far the most common option to mitigate the truncation effects in beams and plates [12,17,18].

In this work it is proposed to replace the standard viscoelastic layer with a *passive constrained viscoelastic layer* (PCVL) treatment [19–21], which, as it will be shown, clearly improves the efficiency of the ABH. A PCVL consists of a viscoelastic layer (VL) sandwiched by a constrained layer (CL). When applied to a standard beam (or plate), the VL consumes energy via its cyclic shearing movement [22], which exhibits a much better damping effect than that of the unconstrained configuration [23–26]. To the authors' knowledge, applying PCVL treatments to mitigate the truncation effect on ABHs has not previously been investigated.

To analyze the performance of the PCVL on the ABH we need to resort to some analytical or numerical approach. In fact, several procedures have been proposed in literature to examine the ABH effect. For instance, the geometrical acoustic methodology was initially utilized to investigate the bending wave propagation in a wedge-shaped beam, and to compute the corresponding coefficient of reflection [27]. However, in truncated ABHs the thickness of the damping material is comparable to that of the edge, which conflicts with the premises of geometrical acoustics, leading to inaccurate results [28]. In contrast, structural impedance methods can circumvent the premise of neglecting the damping element thickness, yet only semi-infinite structures have been considered so far [6]. Transfer matrix approaches have also been proposed to analyze the ABH effect e.g., in duct terminations [29–31]. Recently, an analytical method has been suggested to characterize a finite length beam with a symmetric ABH profile, which resorts to a wavelet decomposition to reconstruct the displacement field [13,14]. The model can take into account different distributions of viscous damping elements at the truncation, as well as boundary conditions at the regular end of the beam, by means of translational and rotational springs [32]. In the present work we rely on the analytical approach in [13,14] to characterize the ABH with PCVL. Yet, our model presents some substantial differences with respect to that in [13], because we consider the case of an asymmetric ABH wedge that needs to account for the motion of the three different coupled layers, namely the bare beam, the viscous layer and the constrained layer. Also, the Gaussian expansion method (GEM, see e.g. [33–36]) is favored over wavelet factorization to expand the layer displacement fields. This is so to prevent the numerical difficulties encountered when building the system mass matrix in [13].

The paper is organized as follows. In Section 2 we present all theoretical developments. First, the Lagrangian of the ABH beam with PCVL is constructed, from which the equations of motion are derived. It is next shown how to build a basis of Gaussian shape functions to approximate the layers' displacements, and describe wave propagation in the beam. Section 3 is devoted to the validation of the previous model by means of the finite element method (FEM) and of experimental testing. Section 4 exposes thorough numerical simulations to analyze the performance of the truncated ABH, and the benefits of using the PCVL in comparison with conventional viscoelastic treatments. Conclusions close the paper in Section 5.

2. Analytical model for the ABH beam with PCVL

2.1. The equation of motion

Let us consider a beam with an ABH termination profile partially covered with a PCVL patch, its CL and VL components having the width of the bare beam (see Fig. 1). Henceforth, variables and magnitudes related to the beam, the VL and the CL, will be respectively identified by subscripts b, v and c. The beam comprises the interval $[x_0, x_{b2}]$ and the ABH profile the interval $[x_0, x_{b1}]$. The PCVL expands from x_{v1} to x_{v2} (see Fig. 1). The thickness of the bare beam is given by

$$h_b = \begin{cases} \varepsilon x^2, & x_0 \le x \le x_{b1} \\ h_{Uni}, & x_{b1} < x \le x_{b2} \end{cases} \tag{1}$$

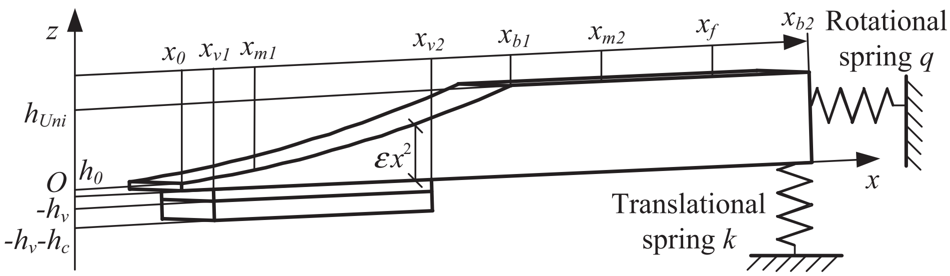

Fig. 1. Scheme of an ABH beam with PCVL.