



Scattering effects induced by imperfections on an acoustic black hole placed at a structural waveguide termination



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ABSTRACT

The so-called “acoustic black hole” (ABH) effect is a passive vibration control technique based on the flexural waves properties in thin structure of varying thickness. A usual implementation consists in using a plate with tapered extremity with a power-law profile, covered with a thin damping layer. The inhomogeneity of the structure leads to a decrease of flexural wave speed and an increase of their amplitude, therefore resulting in an efficient energy dissipation if damping layer is placed where the thickness is minimal. The manufacture of an efficient extremity is difficult because of the small thickness, and often generates imperfections and tearing. Moreover, previous works suggest that multiple flexural modes are propagating across the width of the ABH tip. A model of an ABH multimodal waveguide taking into account an imperfect termination is developed. It shows that an elementary imperfection can affect the reflection coefficient of the extremity and reduce it. Scattering and propagation properties of the extremity are also studied. An incident mode excites several modes that are localised in the tapered region and local resonances explain the drops in the reflection coefficient. Experimental evidence of the influence of the imperfection on the reflection coefficient is provided. A key result of the paper is that manufacturing imperfections are not detrimental to the ABH effect.

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1. Introduction

The control of unwanted vibrations is important for reliability, stability and comfort in many industrial applications [1]. Indeed, vibrations can generate radiated noise [2] but are also a source of structural damage [3]. Most of the classical vibration control methods involve surface damping treatment. The efficiency of these methods has been widely proven, but a major drawback is that they involve an increased mass of the treated structure. This is a concern in many engineering domains for economical or ecological cost. The development of passive vibration control techniques without added mass is interesting in this matter.

The Acoustic Black Hole (ABH) effect [4–6] is a passive vibration control technique taking advantage of bending wave properties in structures of decreasing thickness in order to attenuate the reflections at the edge, and consequently decreasing the resonant behaviour. An example of such boundary damping is given in the pioneer work of Vemula et al. [7] which proposes to use a graded impedance interface at the edges of a beam, consisting in the association of several pieces of beams made with different materials. The results show that lower reflectivity is caused by energy dissipation within the

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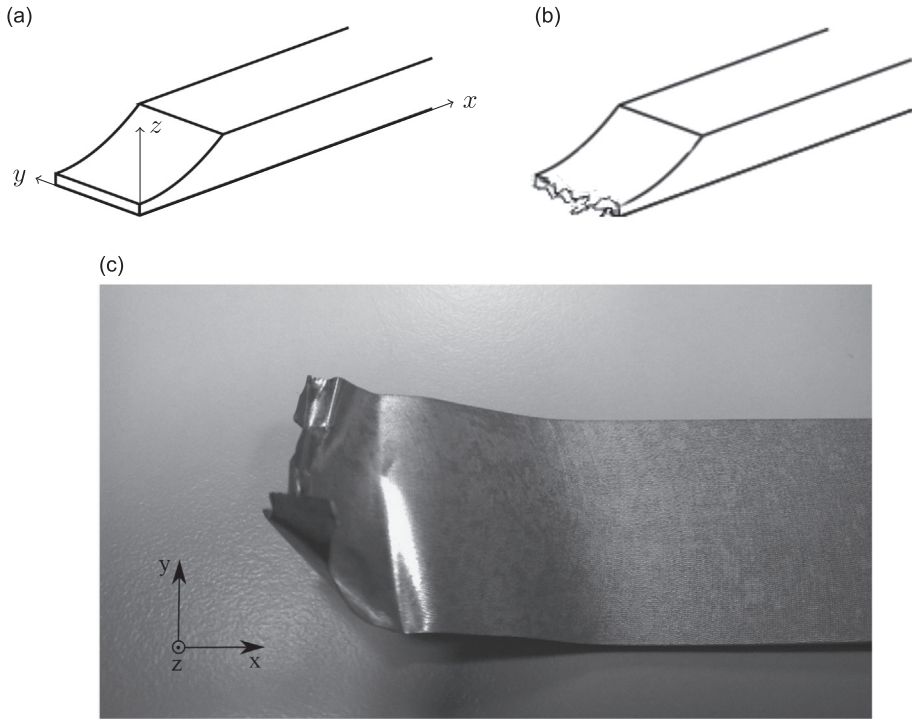


Fig. 1. (a) Nominal shape of the ABH termination (perspective view), (b) scheme of imperfect ABH termination and (c) picture of imperfections taking place at the tip of an ABH extremity (top view). Deformations come from stress relaxation during machining.

composite material at the free end coupled with relatively large amplitude vibrations caused by the impedance gradation. In the ABH effect, as first described by Mironov [8], the thickness of a beam edge decreasing smoothly to zero cause flexural waves to slow down and stop without being reflected. The condition of sufficient smoothness can be fulfilled by a power-law thickness profile $h(x)$ in the form:

$$h(x) = \epsilon x^m, \quad (1)$$

where x is the spatial coordinate and $m \geq 2$ (see Fig. 1(a)). If the thickness is strictly zero at the edge [8], it can be shown that the time taken by a wave to reach the edge becomes infinite. For a practical structure with a finite thickness, the reflection coefficient tends to zero with the decrease of the residual thickness at the tip of the tapered profile. It is however shown that manufacturing processes are such that this residual thickness can never be small enough for the effect to be attractive.

As it is shown by Krylov et al. [4,5] in the framework of geometrical acoustics, the negative effect of the finite thickness at the edge can be compensated by covering the profile with a thin damping layer. A low reflection coefficient can be obtained for the ABH termination. This model has been refined by Georgiev et al. [6] by using an Euler–Bernoulli beam modelling. In this work, reflection and impedance matrices along the tapered beam are computed solving a Riccati equation. Practical rules for determining the optimal geometrical and material properties of the damping layer [9] are found using this model. Further investigations from Denis et al. [10] show that the small thickness of the extremity induces a local plate behaviour in a beam with an ABH extremity, and that a two-dimensional behaviour has to be taken into account to model the tapered zone; local transverse eigenmodes can be found in the beam structure. Note that two-dimensional ABH has also been described in the literature: circular ABH used as plate vibration damper has been firstly proposed by Gautier et al. [11] and studied both experimentally [11–13] and theoretically [14–16].

Most of the literature [4,6,10] considers a perfect tapered extremity: the free edge is considered straight and normal in the direction of propagation x . The consequence is that an incident plane wave propagating along the x -axis remains plane and that the reflected wave is also strictly plane. Thus there should be no excitation of the trapped eigenmodes mentioned in [10]. However the practical realisation fails the assumption of perfect edge because the manufacture of such small thicknesses is difficult and leads to irregular and teared extremities (see Fig. 1(b) and (c)). Moreover, it is observed that the wave field is not unidimensional for some frequencies [17,18]. Bowyer et al. [12] study experimental imperfections of ABH by comparing an imperfect termination and a shorter thus thicker perfect termination. From this experimental comparison, they conclude that even imperfect, a thinner extremity has a better damping performance. It is proposed in this paper to observe what effects are induced by imperfections for a given thickness at the end to gain design insight needed for enhancing and optimising ABH performance.

A model of the inhomogeneous plate seen as a multimodal waveguide is developed in Section 2. It is numerically solved in order to compute the couplings in the waveguide. Section 3 presents typical results from the model and proposes an

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