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Enhanced Acoustic Black Hole effect in beams with a modified thickness profile and extended platform

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ABSTRACT

The phenomenon of Acoustics Black Hole (ABH) benefits from the bending wave propagating properties inside a thin-walled structure with power-law thickness variation to achieve zero reflection when the structural thickness approaches zero in the ideal scenario. However, manufacturing an ideally tailored power-law profile of a structure with embedded ABH feature can hardly be achieved in practice. Past research showed that the inevitable truncation at the wedge tip of the structure can significantly weaken the expected ABH effect by creating wave reflections. On the premise of the minimum achievable truncation thickness by the current manufacturing technology, exploring ways to ensure and achieve better ABH effect becomes important. In this paper, we investigate this issue by using a previously developed wavelet-decomposed semi-analytical model on an Euler-Bernoulli beam with a modified power-law profile and an extended platform of constant thickness. Through comparisons with the conventional ABH profile in terms of system loss factor and energy distribution, numerical results show that the modified thickness profile brings about a systematic increase in the ABH effect at mid-to-high frequencies, especially when the truncation thickness is small and the profile parameter m is large. The use of an extended platform further increases the ABH effect to broader the frequency band whilst providing rooms for catering particular low frequency applications.

1. Introduction

Suppression of structural vibration while maintaining its light-weight is important for various industrial applications. The Acoustics Black Holes (ABH) effect results from the manipulation of bending wave propagation inside a thin-walled structure through thickness changes. With a tailored power-law thickness variation, the phase velocity of the bending wave gradually reduces to zero in the ideal scenario, resulting in zero wave reflection and high energy concentration at the wedge tip [1–3]. ABH effect attracts increasing attention as a promising passive vibration control method because vibration energy can be channeled and only a very small amount of damping materials is required at the energy focalization region to achieve efficient damping to flexural waves [4–9]. It also shows appealing potential in sound radiation control [10,11] and energy harvesting [12,13] due to the high energy concentration within a confined area.

Krylov et al. [3] showed that the inevitable truncation (the residual thickness at the wedge tip) resulting from the manufacturing difficulty would significantly compromise the ideal ABH effect by generating wave reflections. To maximize

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the ABH effect, however, the ultimate pursuit of extremely thin wedge tip is of high cost and harsh demand for the precision machining and would also lead to tip damage of tearing and irregularities. Although Bowyer et al. [14] experimentally showed that the damage on the wedge tip does not notably affect the ABH effect; Denis et al. [15] reported that the imperfect wedge tip would reduce the reflection because of the resultant scattering effects; structures with ultra-thin or damaged tips however can hardly be applied in industry due to the structural strength problems. Therefore, on the premise of the minimum achievable truncation thickness by currently available manufacturing technology, ways maximize the ABH effect need to be explored.

Motivated by this, Bayod [16] proposed a modified thin wedge with extended constant thickness to achieve better vibration damping compared with conventional wedge. Experiments and FEM analyses were carried out to confirm this concept. Probably due to the lack of simulation tools, however, no deep explanation and parametric studies were provided in that work to guide the design of the modified wedge. Meanwhile various modified wedge thickness profiles were also proposed [13,17]. Although similar ABH effect as the conventional profile was observed, the effect of various parameters defining the modified profiles still needs to be systematically analyzed and quantified. On the other hand, nearly all the references mentioned above focused on the ABH effect at relatively higher frequencies. Possible extension of the ABH effect to lower frequencies is still a great challenge and is of particular importance for applications in energy harvesting and noise control. It is understandable the none of the above could be done without a reliable and flexible simulation tool.

In this paper, we focus on seeking ways to achieve better ABH effect on the premise of the minimum achievable truncation thickness and the possibility of applying ABH effect at low frequencies. Firstly, an Euler-Bernoulli beam, with modified thickness profile, $h(x) = \varepsilon(x - x_0)^m + h_0$ and an extended platform, is studied using a previously developed wavelet-decomposed model [18,19]. Then, the effect of the additional thickness h_0 and the extended platform is systematically discussed through numerical simulations. Particularly, we investigate the effect of the profile parameters on the average system loss factor for different additional thicknesses and lengths of extended platform. A particular focus is also put on exploring the beneficial effect of the extended platform in the low frequency range. Finally, conclusions are drawn.

2. Modelling of a beam with a modified thickness profile and extended platform

We consider an Euler-Bernoulli beam composed of a uniform portion with a constant thickness h_b from x_{b3} to x_{b4}, and an ABH portion with a modified thickness profile, $h(x) = \varepsilon(x - x_0)^m + h_0$, from x_{b2} to x_{b3} (Fig. 1). When x_0 and h_0 are both equal to zero, it retreats to the conventional power-law thickness profile, *i.e.* $h(x) = \varepsilon x^m$. A platform of uniform thickness $h(x_{b2})$ is extended from the truncation point x_{b2} to point x_{b1}. The beam is excited by a point force $f(t)$ at x_f and is covered by two damping layers with variable thickness $h_d(x)$ from x_{d1} and x_{d2}. The whole system is symmetrical with respect the mid-line of the beam. The extended platform end of the beam is free and the other end is elastically supported by artificial translational and rotational springs [20,21], the stiffness of which can be adjusted to achieve various boundary conditions. The damping of both the beam and the damping layer are taken into account through complex stiffness E, *i.e.*, $E = E(1 + i\eta)$, where η is the damping loss factor, assigned differently to the beam and the damping layer. A previously developed wavelet-decomposed mothed based on Lagrange's equation is used to obtain the vibration response [18,19].

For the benefit of readers, the modeling principle is briefly recalled. The displacement field of the beam based on Euler-Bernoulli beam theory is expressed as

$$\{u, w\} = \left\{ -z\frac{\partial w}{\partial x}, w(x, t) \right\} \tag{1}$$

where the vector $\{u, w\}$ represents the displacement of a point either on the beam or on the damping layers based on the assumption of perfect bonding between them. The transverse displacement w can be expanded as

$$w(x, t) = \sum_i a_i(t)\varphi_i(x) \tag{2}$$

where $\varphi_i(x)$ are the assumed admissible functions and $a_i(t)$ the complex unknowns to be determined. As demonstrated in Ref. [18], the Mexican hat wavelets (MHW) [22,23] are particularly suitable, compared with power series, to characterize the present rapid wavelength fluctuation along the beam, owing to the appealing properties of the wavelets in terms of scaling

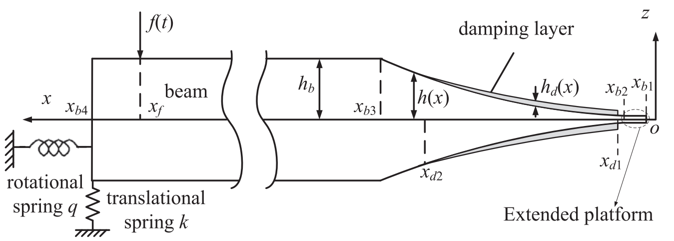

Fig. 1. An Euler-Bernoulli beam with symmetrical modified power-law profile and extended platform.

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