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ENHANCED ACOUSTIC BLACK HOLES (EABH) BASED ON TUNED DAMPING PROPERTIES OBTAINED BY THERMAL CONTROL

G. Raybaud¹ A. Pelat¹ M. Ouisse² F. Gautier¹

¹ LAUM, Université du Mans, Le Mans, France

² FEMTO-ST, Département Mécanique Appliquée, Université Bourgogne Franche-Comté, Besançon, France
guillaume.raybaud@univ-lemans.fr

ABSTRACT

The design of lightweight and stiff structures with attractive vibration damping properties is a major issue in mechanical engineering. The insertion of Acoustic Black Holes (ABH) is an innovative technique that consists in locally reducing the thickness of the structure and coating it with a viscoelastic film. In the particular case where the damping layer provides a perfect adjustment of the losses, the reflection coefficient R of the resulting system is zero at the resonance of a trapped mode localized in the ABH profile. This phenomenon is reached when the critical coupling conditions are fulfilled. However, the precise amount of losses is particularly difficult to tune by using only classical viscoelastic layers. It is here proposed to control it by using a thermal active system acting in a shape memory polymer (SMP).

The goal of the paper is to investigate several enhanced ABH (eABH) in beams for which the damping and the stiffness are controlled by a thermal profile. For each eABH configuration, the trajectory of the zeros of R is studied in order to approach the critical coupling conditions.

1. INTRODUCTION

For reasons of reliability and comfort, controlling the vibration of structures is a major issue in mechanical engineering. In addition, lightening structures is also important, which makes them more sensitive to vibrations. Combining these two objectives results in designing lightweight, stiff and damped structures. The Acoustic Black Holes (ABH) are an innovative technique which can respond to this problematic.

An ABH consists in locally reducing the thickness and coating it with a viscoelastic film. This induces a heterogeneity of the stiffness and the damping in the medium which slows down and dissipates the bending waves. Inserting an ABH at a beam extremity (one dimensional ABH) ideally creates an anechoic termination. [1-4].

The reflection coefficient R of the resulting beam termination decreases with frequency and displays typical arches for which each drop corresponds to the resonance of a trapped mode localized in the ABH profile. In particular, it can be shown that a drop of R can perfectly vanish when the amount of losses is well adjusted so that critical coupling conditions are fulfilled [5].

However, the precise amount of added damping for fulfilling the critical coupling conditions is particularly difficult to tune by using only classical viscoelastic layers. It is here proposed to control it by using a thermal active system acting in a shape memory polymer (SMP), for which the damping and the stiffness strongly depend on the temperature [6]. An ABH with a SMP layer under uniform thermal field has already been experienced and has shown its benefit [7]. This system constitutes an enhanced ABH (eABH).

The goal of the paper is to investigate several eABH under thermal profiles. The eABH of this study consists in an architected SMP layer controlled in temperature along the ABH tip. For each eABH configuration, the trajectory of the zeros of R induced by a change of the local temperature is studied in order to adjust the amount of losses and approach the critical coupling conditions.

2. STUDY PERIMETER

2.1 System under study

The studied eABH is a quadratic profile beam of length x_{ABH} ending with an extruded tip from x_T to 0 of residual thickness h_T (see Tab. 1). The truncation length x_T is fixed for manufacturing reasons. The damping layer is a manufactured SMP (tBA/PEGDMA) of thickness h_{SMP} . Five zones of equal length are independently thermally controlled (see Fig. 1). The aluminum holding beam has a thickness h_0 and a width b . This system allows to simulate a damping layer with a discrete property gradient.

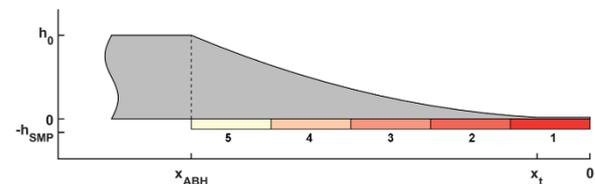


Figure 1. Schematic diagram of the eABH system. The temperatures of zones 1-5 can be controlled independently.

Parameters	Numeric value
x_{ABH}	15 [cm]
x_T	2 [cm]
h_0	5 [mm]
h_T	89 [μm]
h_{SMP}	2 [mm]
b	2 [cm]

Table 1. Geometric parameters of the eABH system.

2.2 Numerical model: Impedance Matrix Method

The reflection coefficient R is computed using the Impedance Matrix Method which consists to numerically compute the impedance Z from the free end of the beam to the abscissa where R needs to be found. This method uses the Riccati equation (verified by Z), leaning on the transition matrix H written as follow,

$$H = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1/EI \\ -\rho S \omega^2 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad (1)$$

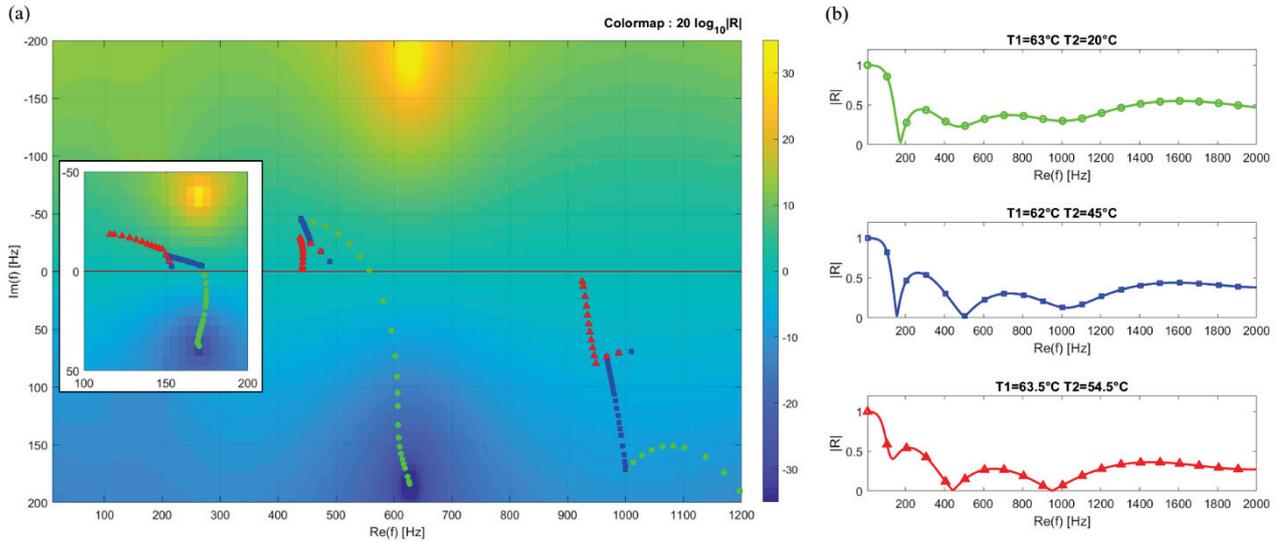


Figure 2. (a) Complex frequency plan of R ($20 \log|R|$) highlighting the poles and zeros (yellow and blue spots) for a configuration where the SMP is at room temperature. The green, blue and red trajectories represent the complex frequency of the zeros for several temperature settings. The three colors correspond to three targeted configurations. (b) Values of R along the real frequency axis at the 3 configurations (last marker of each color trajectory on (a)). T_1 and T_2 are the temperature of the zone 1 and 2 of the SMP layer (see Fig. 1).

3. PARAMETRIC INVESTIGATION

The goal of this paper is to show the level of control that the system provides. By including a thermal gradient along the ABH termination, new degrees of freedom are added.

3.1 Heating 1 zone

Firstly, only the temperature of the first zone (T_1) is increased until the conditions of critical coupling are

where ρ is the mass density, E is the storage modulus, S is the cross section and I is the moment of inertia. Then Z is expressed as

$$\frac{\partial Z}{\partial x} = -ZH_1 - j\omega ZH_2Z + \frac{H_3}{j\omega} + H_4Z. \quad (2)$$

Finally, R can be written as a function of Z and the matrix E whose columns are eigenvectors of H :

$$R = [j\omega ZE_2 - E_4]^{-1}[E_3 - j\omega ZE_1]. \quad (3)$$

Using this method allows to compute R in the complex frequency plan (see Fig. 2). Sets of poles and zeros (respectively yellow and blue spots) corresponding to the resonances of the ABH termination are visible on this plan. In the following, the focus is on the trajectory of the first zeros for several temperature profiles. The thermal field is supposed to be uniform and distinct for each zone of the SMP layer. The equivalent parameters of the system are computed in Eqn. (1) using the RUK mixing law [8].

reached on the first zero: $T_1=63^\circ\text{C}$ (see Fig. 2, green trajectory). The second zero crossed the real frequency axis.

3.2 Heating 2 zones

Then, keeping $T_1=63^\circ\text{C}$, T_2 is increased. By small adjustment, $T_1=62^\circ\text{C}$ and $T_2=45^\circ\text{C}$, the first 2 zeros approach the conditions of critical coupling (see Fig. 2, blue trajectory). Furthermore, the third zero has gone closer to the real frequency axis. Again, with small

adjustments, $T_1=63,5^\circ\text{C}$ and $T_2=54,5^\circ\text{C}$, a configuration completing the critical coupling on the second and third zeros can be found (see Fig. 2, red trajectory). Thus, it is possible to reach the critical coupling on 2 zeros using the first 2 heating zones.

3.3 Heating 3 zones

Unfortunately, this is not simple to say that n zeros can be critically coupled using n heated zones (i.e. considering a continuous gradient). No configuration of 3 perfect critical couplings is found. In the contrary, by increasing T_3 , the zeros appear to move away from the real frequency axis. On the other hand, the ratio of the thickness of the SMP over the thickness of the beam at the third zone location is very small and it will be worst for the fourth and fifth zones. This leads to a minor effect of the last zones compared to the first and second zones. That is why T_4 and T_5 are finally not considered.

4. CONCLUSION

The thermally controlled eABH allows a high control on the first zeros of its reflection coefficient. Indeed, it is possible to precisely reach the conditions of critical coupling on 1 or 2 zeros of R by tuning 1 or 2 heating zones. That corresponds to a perfect absorption of 1 or 2 resonances of the system.

For a quadratic ABH, tuning the first zeros tends to tune more or less all the others, which allow to reach a very low value of R on a wide frequency range.

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