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Published in:
Journal of Physics: Conference Series

DOI (link to publication from Publisher):
10.1088/1742-6596/2647/23/232003

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Avetisov, S., Pelat, A., Gautier, F., & Sorokin, S. (2024). Adaptation of the HQ device for suppressing wave propagation in elastic beams. *Journal of Physics: Conference Series*, *2647*(23), Article 232003. https://doi.org/10.1088/1742-6596/2647/23/232003

Journal of Physics:
Conference Series

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To cite this article: S. Avetisov *et al* 2024 *J. Phys.: Conf. Ser.* **2647** 232003

Journal of Physics: Conference Series **2647** (2024) 232003 doi:10.1088/1742-6596/2647/23/232003

Adaptation of the HQ device for suppressing wave propagation in elastic beams

S.Avetisov[1], A.Pelat[1], F.Gautier[1] and S.Sorokin[2]
[1]LAUM UMR CNRS 6613, Avenue Olivier Messiaen, 72085 Le Mans Cedex 09, France
[2]Department of Materials and Production, Aalborg University Fibigerstraede 16, DK 9220 Aalborg, Danemark

E-mail: `stepan.avetisov@univ-lemans.fr`

Abstract. In this work, we study the application of the Herschel–Quincke (HQ) principle to the case of bending waves in a beam structure. This type of device is well known in acoustic tubes where an HQ filter consists of the bifurcation of a primary tube into two tubes of different lengths placed in parallel. The resulting phase shift creates a destructive interference and so a zero transmission at selected frequencies. To adapt this principle to bending vibrations, a homogeneous solid beam is divided into two different strands with different thicknesses and of same length, so that the phase difference created between these two strands of different wave celerities also leads to the same interferential effects. A Timoshenko wave model is derived to analyse the scattering properties of such HQ filter for bending and longitudinal waves. The results are well confirmed by the reference finite element simulations.

1. Introduction

The development of new concepts able to mitigate the vibration fields in mechanical structures under lightweighting constrains is a very ongoing research topic with applications in the fields of transportation, aerospace engineering and energy. In this context, this study is inspired by the so-called Herschel-Quincke (HQ) filters that have been exclusively studied for guided acoustic waves since the early work of Stewart [1], [2]. The objective of this study is to evaluate the potential of the HQ filter principle to attenuate vibrations due to bending waves that propagate along beams. The HQ principle has been studied by many scientists [3], [4]. In the acoustic context, the basic device is composed of a main pipe and a tube parallel to the latter, called the HQ tube. The HQ tube placed in parallel with the main tube is of different dimension with respect to the latter. The length of the HQ tube is generally larger. The objective is to create a phase shift between the wave propagating in the main tube and the wave propagating in the tube in parallel. This phase shift, due to the difference in length between the paths taken by the two waves, causes destructive interference to appear between them. These interferences cause attenuation of certain frequency bands. It can be written that the interferences cancel the transmission in the pipe when the phase difference between strand 1 and strand 2 satisfies one of the equations

$$\Delta\phi = \phi_1 - \phi_2 = (2n+1)\pi, \tag{1}$$

as described in [2]. It is observed that frequencies for which such this condition is satisfied lead to strongly attenuated transmitted waves. The main idea of this paper is to transpose the HQ concept, to beams and to see how the effect remains effective despite the existence of evanescent bending waves. In section 2, an analysis of the effect of the HQ filter is proposed by means of a semi-analytical wave based model. Typical results and a numerical validation are presented in section 3.

2. Wave based model of the HQ filter

In a beam, an HQ filter is made in practice by means of a two strands of adjustable thicknesses, which allows to control the celerities of the bending waves (see Fig.1). A wave model of the system is developed considering both the Timoshenko beam equations for the description of the bending motion and a wave equation to describe longitudinal motion. Assuming harmonic time factor $e^{-j\omega t}$, the solutions for the bending displacement $w(x)$, the slope of the cross-section $\theta(x)$ and the longitudinal displacement $u(x)$, x being the axial coordinate satisfies to

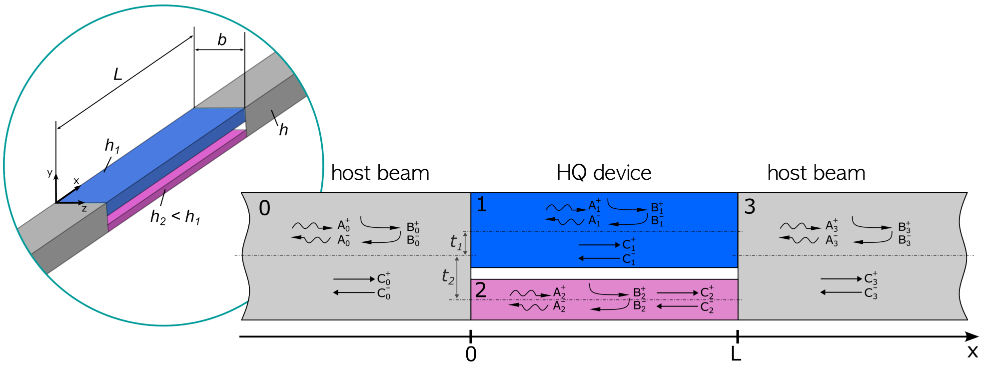

Figure 1. sketch up of a HQ filter embedded within an infinite host beam. The device involves two parallel beams of varying thicknesses but equal lengths.

$$
\begin{cases}
\kappa GS\left(\dfrac{\partial^2 w}{\partial x^2} - \dfrac{\partial \theta}{\partial x}\right) - \rho S\omega^2 w = 0, \\
EI\dfrac{\partial^2 \theta}{\partial x^2} + \kappa GS\left(\dfrac{\partial w}{\partial x} - \theta\right) - \rho I\omega^2\theta = 0, \\
\dfrac{\partial^2 u}{\partial x^2} - \dfrac{\omega^2}{c_L^2}u = 0.
\end{cases}
\tag{2}
$$

where $\gamma(x,t) = \dfrac{\partial w}{\partial x} - \theta(x,t)$ is the shear angle, S is the area of the cross-section, ρ is the beam material density, $E = E_0(1 + j\eta)$ is the complex Young's modulus with E_0 the elastic constant and η the material loss factor, ν is the Poissons's ratio and $G = \dfrac{E}{2(1+\nu)}$ is the shear modulus. The bending stiffness is given by $EI = E\dfrac{bh_n^3}{12}$ and $\kappa = \dfrac{10(1+\nu)}{12+11\nu}$ is the shear deformations coefficient for the rectangular cross section considered in the study. A harmonic wave $w(x) = A_0^+ e^{jkx}$ propagating in the direction of increasing x is incident on the HQ device. All the fields can be represented using wave expansions in the subdomains 0,1,2,3 (see Fig. 1).The continuity relations for all kinematic and force variables (displacement, slope, bending moment and shear force) and the Sommerfeld conditions at $x = \pm\infty$ provide wave amplitudes and the relationship between the bending and the longitudinal wave in all subdomains. These wave amplitudes are used to calculate the reflection and transmission coefficients for the bending waves (where the amplitude of the longitudinal wave has an effect on this parameter) as

$$\boldsymbol{R} = \frac{A_0^-}{A_0^+}, \quad \boldsymbol{T} = \frac{A_3^+}{A_0^+}. \tag{3}$$

3. Numerical Simulations of the Reflection and Transmission coefficients

Numerical simulations of the reflection and transmission coefficients obtained by the wave based model are provided in Fig. 2. The host beam and the HQ filter are defined by the parameters given in table 1. The HQ filter is intrinsically characterised by the R and T coefficients, which describe its response to an incident wave travelling from left to right. The results are validated using a comparison with those obtained using a finite element code in the solid mechanics COMSOL software package. For this calculation, the host beam is terminated by a perfectly matched layer describing Sommerfeld conditions for $x = \pm\infty$. The excitation is provided by a transverse force applied at $x = -0.2$m. The mesh is chosen to obtain a convergent solution (3 elements in the thickness and width of the beam and a mesh of 1cm along the beam). The transverse displacements of two upstream points ($x < 0$) and two downstream points ($x > L$) are used to identify the wave coefficients and evaluate the scattering coefficients of Eq.(2). In Fig. 2, the magnitudes of R and T reveal some frequencies at which the reflection or transmission of waves reaches zero or one. This is the signature of the HQ filtering effect. The frequencies leading to zero transmission are particularly interesting: in this case, the presence of destructive interference highlights the cancelling effect of the the HQ filter. This result demonstrates the pertinence of the HQ idea when applied to bending vibrations. A good agreement is found between the R and T results obtained by the FEM, considered as a reference and the results obtained by the wave based model using coupled Timoshenko and longitudinal waves. It confirms the validity of the approach. If the longitudinal waves are ignored (reduced model), R and T are significantly changed. Significant differences are observed between the FEM reference results and the ones obtained with this reduced model. However, both the full and the reduced models predict the same zero transmission frequencies.

Table 1. Geometric and physical parameters .

E_0	ρ	ν	η	L	b	h_1	h_2	h
70GPa	2700kg/m^3	0,3	0	200mm	10mm	5mm	2,5mm	10mm

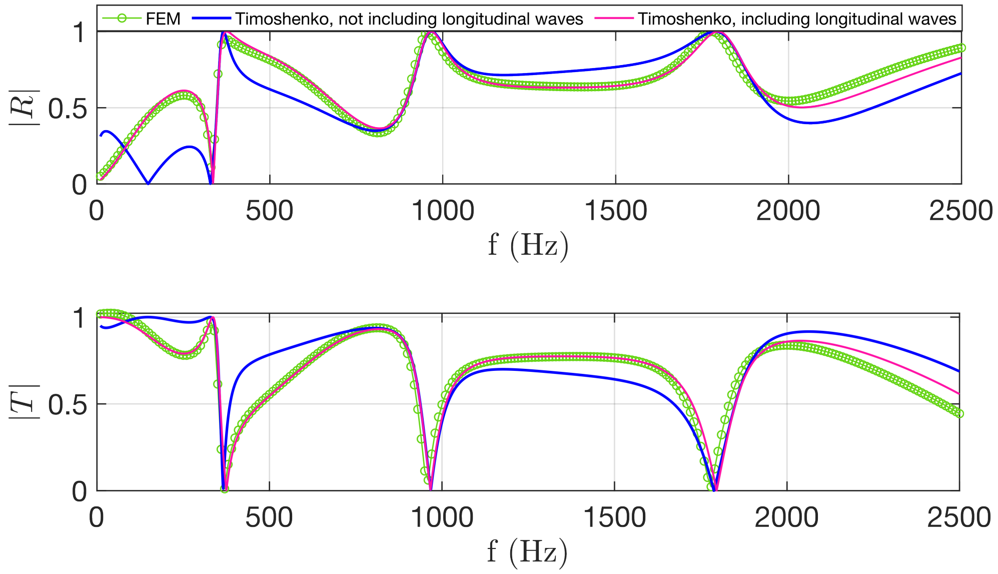

Figure 2. Reflection $|R|$ and Transmission $|T|$ coefficients for the HQ device defined by table 1. The green, magenta and blue curves are respectively corresponding to FEM, Timoshenko + longitudinal waves and Timoshenko model only.

4. Analysis of the zero transmission case

The goal of this section is to analyse the zero transmission conditions. The HQ filter embedded in the infinite host beam is a locally resonant system characterized by trapped modes. These modes are found by solving the homogeneous motion equation of the HQ device embedded in an infinite host beam. The analysis of these trapped modes shows that two groups exist : symmetric and antisymmetric ones, for which the vibrations of the two components are respectively in phase and in antiphase. These modes are complex. Their damping coefficients are mainly controlled by the radiation into the infinite host beam. The antisymmetric modes are generally associated with a lower damping than the symmetric modes. This is related to the fact that the antisymmetric modes are more localized close to the HQ device because less coupled to the host beam. It comes from the destructive or constructive effects induced by wave interaction. This interaction is destructive when the waves radiated from the two components are in antiphase. We show that at a frequency corresponding to zero transmission, the deflection shapes of the components are similar to each other. In this case, the relative phase between the two components is the signature of the antisymetric or symetric nature of a mode (see Fig. 3 and Fig. 4). In Fig. 3, the variations of T reveal several zero transmission frequencies, which correspond to the antisymetric modes for which the phase opposition condition (1) is satisfied. This condition is not fullfilled for the eigenfrequencies of the symmetric modes, also indicated on the figure. It can be verified that this observation is still valid if the length of the HQ filter changes while keeping all other parameters unchanged. In Fig. 3, the length is set $L = 20$cm and the transmission coefficient function is obtained as indicated above. The Fig.4 shows the same results for a doubled length $L = 40$cm.

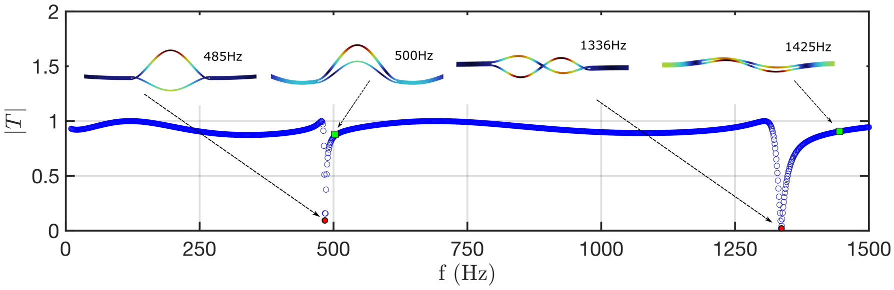

Figure 3. Transmission coefficient $|T|$ for an HQ device defined by $L = 200\text{mm}$, $h_1 = 4\text{mm}$, $h_2 = 3,5\text{mm}$. Modal shapes of symmetric and antisymmetric modes are indicated, showing that the frequencies for which zero transmission is obtained correspond to antisymmetric trapped modes.

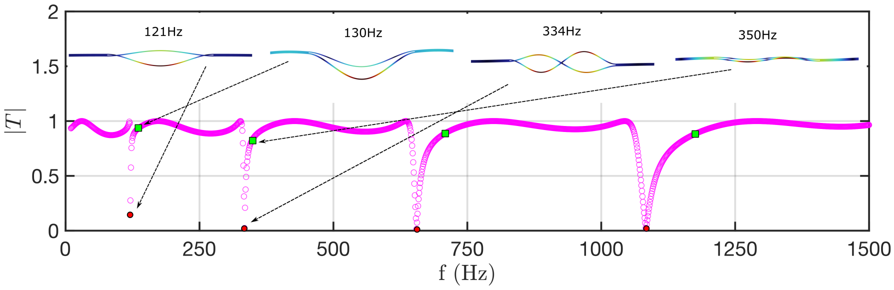

Figure 4. Transmission coefficient $|T|$ for an HQ device defined by $L = 400\text{mm}$, $h_1 = 4\text{mm}$, $h_2 = 3,5\text{mm}$. Modal shapes of symmetric and antisymmetric modes are indicated, showing that the frequencies for which zero transmission is obtained correspond to antisymmetric trapped modes.

5. Conclusion

The adaptation of the HQ concept to beams is tested sucessfully. The simplicity of its implementation in assembly with the correct thickness ratio of the HQ device can provide ideal vibration damping under external loads and bring a new approach to solving problems in vibroacoustics for elastic waves in structures. Analytical and numerical models were developed to describe the HQ effect in beams. It is shown that there exist a discrete set of frequencies at which the transmission coefficient reaches zero value. This is due to HQ induced destructive interferences. Analytical and numerical models are in good agreement with each other. It is also shown that if the longitudinal waves are ignored, we have a discrepancy with the full model, although the zero transmission frequencies are well described. In the future, it is interesting to apply the analysis in the complex plane to describe the behavior of the HQ. Our future work also encompasses the experimental validation of the reported results.

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