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Preliminary study of acoustic protection of Ariane V fairings using layers of porous materials

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ABSTRACT. During lift-off, space launchers are submitted to high level acoustic loads which may damage the payloads. High cost acoustic absorbers have been previously developed by to protect the payload in Ariane V. CNES launched a program in order to reduce the cost by using a layer of porous materials protected by a fabric.

The purpose of this paper is to propose a 1D model of porous layers based on modified BIOT equations. This model has been validated by impedance tube measurements (absorption coefficient) performed by RIETER¹ and the ENTPE.

Based on this model, a parametric study of the material mechanical and acoustic parameters has been carried out with respect of aerospace constraints. The study shows the relevance of the resistivity and the mechanical parameters of the skeleton for the absorption. The effect of the mounting conditions has also been studied experimentally and theoretically. Results reveal the importance of the constraints on the absorption mainly at the low frequency range.

KEYWORDS: BIOT equations, Porous material, 1D model, Absorption.

1. INTRODUCTION

The purpose of this paper is to describe wave propagation in elastic porous layers in order to predict sound absorption inside an impedance tube. The theory used here is based on BIOT theory [1] which has been adapted to acoustic absorbers by Allard & Al [2]. Bolton [3-5] studied transmission through structures lined with elastic porous layers; he described porous materials in terms of displacements of both skeleton and interstitial fluid. Here, we use modified BIOT equations described in terms of skeleton displacement and interstitial fluid pressure. 3 waves propagate inside a laterally infinite porous layer, two compression and one shear wave.

The present work is organised as following. In the first section, we give the solution of the modified BIOT equations propagating inside a laterally infinite porous layer excited by a plane wave under oblique angle. Boundary conditions are explored; the coupling between two porous layers and between a porous layer and a fluid cavity are presented. The case of a septum separating layers (typically used in automotive industry) is studied. In the second section, the case of the novel absorber to be used in Ariane V launcher is studied. The absorber consists of a porous layer covered by a fabric; the latter is simulated as a porous layer as well. A good agreement has been obtained between measurements and simulations. A comparative study of the relevant parameters of the porous layer as well as the effect of the mounting conditions has been carried out.

2. MODIFIED BIOT EQUATIONS

The modified BIOT equations (with $e^{-i\omega t}$ sign convention) written in terms of skeleton displacement and interstitial fluid pressure are

$$\tilde{\rho}_s \omega^2 \underline{U} + \underline{\nabla} \cdot (\underline{\underline{\sigma}}^s - \alpha \phi p \underline{\underline{\delta}}) + \beta \underline{\nabla}(\phi p) = 0 \quad (2.1)$$

$$\underline{\nabla} \cdot \left(\frac{1}{\tilde{\rho}_f \omega^2} \underline{\nabla}(\phi p) - \beta \underline{U} \right) + \frac{\phi p}{R} + \alpha \underline{\nabla} \cdot \underline{U} = 0 \quad (2.2)$$

The equations (2.1) and (2.2) relate respectively the skeleton and interstitial fluid dynamic equilibrium. They look like elasto-dynamic equilibrium equation (2.1) and Helmholtz equation (2.2) coupled by elastic coupling factor α and inertial coupling factor β . The coupling is more complex as the effective mass densities ρ_s and ρ_f are derived from the physical densities, the porosity ϕ , the tortuosity τ and the viscous coupling factor b . Hence, the effective mass densities reflect the inertial coupling between the two phases as well as the viscous coupling which is frequency dependant.

3. WAVE PROPAGATION IN POROUS MEDIA

The problem investigated in this paper involves plane waves propagation inside a finite thickness layer of porous material with infinite lateral dimensions. The explicit variables expressions (pressure, skeleton and fluid displacements, stress...) are given in terms of 3 waves ; 2 compression waves and a shear wave. Each wave is made of a forward and a backward moving waves toward the thickness direction. The six corresponding wave amplitudes are determined by the appropriate boundary conditions.

The skeleton displacement could be split into a rotational and potential displacements $\underline{U} = \underline{U}_l + \underline{U}_r$ with $\nabla \wedge \underline{U}_l = 0$ and $\nabla \cdot \underline{U}_r = 0$. Substituting respectively the rotational and the potential wave form in the modified BIOT equations give wave numbers by (3.1) for the rotational wave and (3.2) for the potential wave.

$$\tilde{\gamma}_r^2 = -\omega \sqrt{\frac{\tilde{\rho}_s}{\mu}} \quad (3.1)$$

$$\underbrace{(\lambda + 2\mu)}_a \tilde{\gamma}_l^4 + \underbrace{\tilde{\rho}_f \omega^2 \left(\frac{\lambda + 2\mu}{R} + \frac{\tilde{\rho}_s}{\tilde{\rho}_f} + (\beta - \alpha)^2 \right)}_b \tilde{\gamma}_l^2 + \underbrace{\frac{\tilde{\rho}_s \tilde{\rho}_f \omega^4}{R}}_c = 0 \quad (3.2)$$

3.1. Boundary conditions

- Coupling fluid layer / porous layer

Coupling a porous and a fluid layers requires 4 conditions. The fluid layer pressure and displacement are noted p^0 and U^0 .

Direct coupling	Coupling through impervious film
$-i\omega(U_z^0 - U_z^2) = -i\omega\phi^2(U_z^{f2} - U_z^2)$	$U_z^0 = U_z^2$
$p^0 = p^2$	$-i\omega\phi^2(U_z^{f2} - U_z^2) = 0$
$-p^0 = \sigma_z^2$	$-p^0 = \sigma_z^2$
$0 = \tau_{xz}^2$	$0 = \tau_{xz}^2$

The direct coupling happens when no facings separate the fluid and the porous layers. The 1st equation is cinematic, it expresses the fluid transfer between the porous layer and the fluid layer. Hence, we write the continuity of the air flow $q = -i\omega\phi(U_n^f - U_n)$ on the interface where ϕ is the surface porosity. In fact, surface porosity is immeasurable, and volume porosity is always used instead for simulations. The 2nd condition expresses the pressure continuity between both layers as the porous material is open. The 3rd and 4th equations are dynamic, they express

the stress continuity between layers. When an impervious weightless film separates the layers, there are two cinematic conditions. The 1st equation expresses skeleton and external fluid normal displacements continuity. The 2nd equation relates air flow nullity as the porous layer is henceforth closed. The dynamic coupling is the same as the direct coupling.

- *Coupling porous layer / porous layer*

Coupling two porous layers requires 6 conditions. We assume here that there is no relative sliding between the porous layers.

Direct coupling	Coupling through impervious film
$U_z^1 = U_z^2$	$U_z^1 = U_z^2$
$U_x^1 = U_x^2$	$U_x^1 = U_x^2$
$\sigma_z^1 = \sigma_z^2$	$\sigma_z^1 = \sigma_z^2$
$\tau_{xz}^1 = \tau_{xz}^2$	$\tau_{xz}^1 = \tau_{xz}^2$
$p^1 = p^2$	$-i\omega\phi^1(U_z^{f1} - U_z^1) = 0$
$-i\omega\phi^1(U_z^{f1} - U_z^1) = -i\omega\phi^2(U_z^{f2} - U_z^2)$	$-i\omega\phi^2(U_z^{f2} - U_z^2) = 0$

We notice here that 4 equations are the same for direct and film coupling. These equations are similar to the coupling between elastic layers. 1st and 2nd equations express cinematic coupling of skeleton displacements. 3rd and 4th equations express dynamic coupling of the total stresses (stress on skeleton and interstitial fluid). The two latter equations differ with the considered configuration. For direct coupling, we have pressure and air flow conservation across interface. For coupling through impervious interface, air flow vanishes for both layers.

4. NORMAL INCIDENCE ABSORPTION COEFFICIENT

We compared measurement and simulations of a 10cm porous layer made of foam. This layer will be integrated in Ariane V fairings as an acoustic protection as a replacement of the high cost fap. Measurements of the absorption coefficient of the naked foam and the foam covered by a fabric have been carried out in a 10cm diameter impedance tube . Results are obtained in the frequency range from 100Hz to 4000Hz. Figure.1 shows a good agreement between measurements and simulations, particularly with the naked foam. The fabric, which aim is the protection of the payload from foam dust, affects highly the absorption coefficient. The absorption coefficient is lowered at the high frequency range (above 500 Hz). Below, fabric enhances the absorption efficiency of the porous complex.

Porous material behaviour is very sensitive to the boundary conditions. In this paper we investigate the sensitivity of the porous material to the lateral and normal boundary conditions. For the normal mounting conditions, two configurations are studied : porous material stuck to the background (S) or laid against the background (L). The former case (S) is simulated by imposing null normal displacement of the porous structure and fluid. The latter (L) is simulated by adding a thin fluid layer between the porous layer and the background (1mm thickness). The main difference between the two configurations is that the frequency of the structure resonance is displaced due to difference in limit conditions. Moreover, the structure resonance is less pronounced with the L configuration. As expected, toward the high frequency range the two configurations tend to converge (Figure 2.1). At the lower frequency range, no clear tendency emerges. For example, with the simulations carried out, the L configuration is better from 150 to 500 Hz. Below, the S configuration ensures better absorption. Lateral boundary conditions have been studied experimentally from 40Hz to 200Hz range. A set of measurement of the foam covered by a fabric has been carried out in a 46 mm diameter impedance tube. Figure 2.2 shows that increasing constraints, at low frequencies (below 250Hz), don't have steady effect. Indeed, with growing frequency, more constraints result first in increasing absorption, then in decreasing it. The combinations of analytical and experimental results stress the importance of boundary conditions on the porous material behaviour mainly at the low frequency range.

A parametric study of the porous materials parameters has been carried out. It shows that the main influencing parameter of the porous material is its resistivity. At high frequency range, a low resistivity enhances absorption. At the low frequency range, no steady effect of the resistivity is observed. Hence, at a given frequency, there's an optimum value of resistivity which gives a maximum of absorption. It is worth noting that the optimum resistivity value depends closely of the mechanical parameters of the porous material and the mounting conditions.

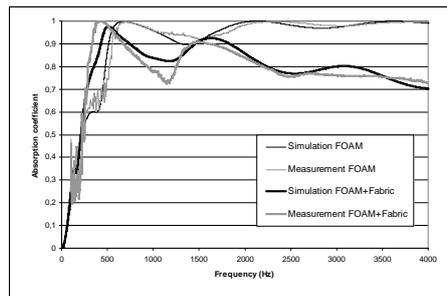


Fig 1. confrontation simulation/measurements (S configuration)

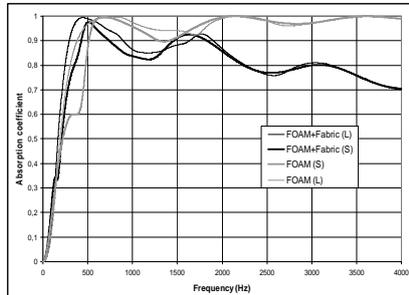


Fig 2.1. Background mounting conditions L&S (simulation)

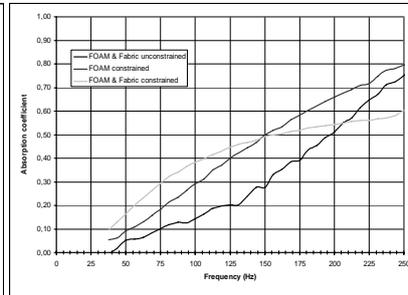


Fig 2.2. Lateral mounting conditions (measurement)

Fig 2. boundary conditions effect on absorption

CONCLUSION

In this paper, the BIOT theory has been used to predict the absorption coefficient of a complex absorber made of a porous foam covered by a high resistif fabric. The comparison of the theory and the measurements for the porous complex shows excellent correlation, particularly with naked foam. Through simulations and measurements, it has been proved that mounting conditions (lateral and normal) are critical with regard to the porous material absorption efficiency. It has also been shown, by parametric studies, that resistivity is the critical acoustic parameter for absorption. At high frequencies, growing resistivity enhances absorption. At low frequencies, a critical value of resistivity gives optimum absorption. Besides, low frequency absorption coefficient is very sensitive to the elastic parameters of the skeleton. Since the model is semi-analytical, an optimisation has been carried out and showed that a modification of the material critical parameters enhances considerably its absorption efficiency (up to 25% at the 63Hz 1/3octave).

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