PERFORATED RESONATORS AND NATURAL FIBERS FOR ACOUSTIC ABSORBING APPLICATIONS

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Abstract. *The general framework of our research is the design of multilayer components of high acoustic performance (absorption and transmission loss). It mainly addresses aeronautic and automotive applications such as trimmed fuselage panels. The use of heavy layers, which directly produce a mass law control, is avoided in our investigations because lightweight structures are desired. In this case, good performance is generally achieved by the use of poro-elastic layers made of glass wool (or plastic foams). However, it must be noticed that this material is not recyclable, which poses environmental problems. As a complementary or alternative solution to the use of glass wool, an original research has been carried out based on micro-resonators. Micro Helmholtz resonators are put side by side to form a layer. The micro perforations provide viscous energy dissipation of the air going back and forth through the layer. A 3D novel Finite Element (FE) formulation has been developed. It solves a linearized form of the Navier-Stokes equation, which governs the phenomenon. The FE formulation is presented and results are compared to analytical models and impedance tube experiments. This type of system can be realized with metallic thin plates. It also shows itself interesting for external covering, where porous materials are not suitable due to environmental and cleaning considerations. The main result obtained is that, in the medium to high frequency range, the analytical models have to be largely tuned to fit the experimental data. At the contrary, the FE micro model of the resonators is more consistent. Therefore, the proposed FE approach seems interesting to adjust analytical models when no tests are available or to create homogenized components of larger scale for meso or macro simulations. Next, we turn our attention to a recent investigation we have initiated: the acoustic analysis and Life Cycle Assessment (LCA) of automobile components made up of renewable materials. In this case, the glass wool or foam layer is substituted by a porous material built from natural fibers such as coconuts fiber, cotton or sisal. The challenging questions of this cross-competency investigation (acoustics and LCA) will conclude the paper.*

Keywords: *Noise reduction, FEM, micro-perforation, natural fibers, LCA.*

1. INTRODUCTION

Our research is concerned with the design of acoustic insulating panels. Such panels are generally multi-layered systems. The standard solution consists of i) the main mechanical structure, ii) covered by poro-elastic acoustic absorbent materials, iii) with a thin air gap cutting the structural vibration from iv) the back covering structure. Transmission and absorption problems are addressed in the field of aeronautic and automotive applications. In the past, we focused our attention to the development of experimental devices and numerical methods. Much work was devoted to poro-elastic material which is the main acoustic component of the system. More recently, we turned our attention to innovative solutions, such as, smart material, double porosity material and repetitive structures. In this paper, two original alternatives to the use of classical poro-elastic materials are presented:

- the use of distributed milli-metric resonators,
- the use of natural fibers based poro-elastic material instead of classical plastic foam or glass wool.

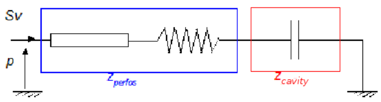
2. MILLI-RESONATORS OF HELMHOLTZ

2.1 Analytical models

The role of Helmholtz resonators or distributed Helmholtz resonators, which consist of a set of acoustic cavities put side by side with a perforated face, is generally well-known. Each single resonator acts as a dynamic mass-spring system, where the mass is relative to the quantity of air going through the resonator orifice and the spring is relative to compressibility of the cavity volume. The dissipative effects can take place in the cavity or in the output orifice. However, for large scale resonators (for instance: characteristic length of 10cm for the cavity and 2 mm for the orifice hole), the natural dissipation is poor and the natural response frequency remains in the low frequency domain (below 800Hz). A common solution to increase the dissipation is putting absorbing material inside the cavity.

A less common solution is the use of small size resonators. In this case, the cavity depth is reduced to a milli-metric size (few millimeters). The natural resonant frequency reaches the medium frequency range (1000, 2000 Hz) while high dissipation phenomena take place in the resonator orifice. The Fig. 1 shows the analytical model we used. In particular, the model is based on two modeling assumptions:

- a pore homogenization technique, as introduced by (Crandall, 1926; Stinson, 1991), considering the orifice as an infinite cylindric tube and solving analytically a linearized equation of Navier-Stokes equation with viscous and thermal effects,
- orifice ending corrections, as introduced by (Sivian, 1935; Ingard, 1953) which is more or less equivalent to an artificial elongation of the length of the pore as considered by (Melling, 1973; Dupont, 2003). The empirical correction of (Fok, 1941), for close holes interactions, is also considered.



$$z = \frac{p}{\phi z_o v} = R + j\omega L + z_{cavity}$$

$$R = \varepsilon \Re(z_{perfos}), \quad L = \Im(z_{perfos})/\omega$$

$$z_{perfos} = \frac{j\omega}{\phi c_o}\left(\frac{e}{F(rk'_S)} + \frac{16r}{3\pi\psi'(\phi)F(rk_S)}\right)$$

$$F(x) = 1 - \frac{2J_1(x)}{xJ_o(x)}, \quad k_S = \sqrt{\frac{-j\omega\rho_o}{\mu}}$$

$$z_{cavity} = -j\cot(k_o D)$$

z : standard impedance of the resonator perforated face side,
$\phi = S_{perfos} / S_{motif}$: porosity,
ψ' : Fok's correction (interactions between holes),
J_i : Bessel's function,
μ : dynamic viscosity ($=1.85e^{-5}$ Pa.s),
k_S' ditto k_S with $\mu' \approx 2\mu$,
c_o, k_o, z_o, ρ_o : celerity, wave number, characteristic impedance and air density (kg/m3),
ε : Dupont's like correction.

Absorption (normal incident plane wave) :

$$\alpha = \frac{W_a}{W_i} = 1 - \left|\frac{z-1}{z+1}\right|^2 = \frac{4R}{(1+R)^2 + (\omega L - \cot k_o D)^2}$$

$$\alpha_{max} = \frac{4R}{(1+R)^2}$$

Note : The maximal absorption is only a function of resistivity R (the dissipative term))

Figure 1. Analitical model for milli-metric Helmholtz resonators

2.2 Finite Element approach

Dynamic equilibrium and behavior

$$-\omega^2 \rho u_i = \sigma_{ij,j}$$

$$\sigma_{ij} = (K - \tfrac{2}{3} j\omega\mu)\varepsilon_{kk}\delta_{ij} + j\omega 2\mu\varepsilon_{ij}$$

$$-p = K\varepsilon_{kk}$$

$$\left.\begin{aligned} K &= 140000\,\text{Pa} \\ \mu &= 1.84.10^{-5}\,\text{Pa.s} \\ \rho &= 1.224\,\text{kg.m}^{-3} \end{aligned}\right\} \longrightarrow$$

At 1 kHz :

$$\lambda = \frac{c}{f} = \frac{2\pi}{\omega}\sqrt{\frac{K}{\rho}} = 340\text{ mm}$$

$$d_\mu = \sqrt{\frac{2\mu}{\rho\omega}} = 0.07\text{mm}$$

Note: Very different scale when considered compression (elastic) nor shearing (viscous) phenomena => possible numerical shear locking problem.

⟶ Choice of a mixed pressure-displacement formulation :

inertia — dissipations — Pressure gradient coupling

$$-\int_V \delta u_i \omega^2 \rho u_i dV + \int_V \delta\varepsilon_{ij}(\tilde{\sigma}_{ij})dV + \int_V \delta u_i p_{,i} dV = \int_S \delta u_i \tilde{\sigma}_{ij} n_j dS$$

compression

$$-\int_V \frac{\delta p p}{K} dV + \int_V \delta p_{,i} u_i dV = \int_S \delta p u_i n_i dS \quad \forall \delta u \text{ et } \delta p$$

$$\tilde{\sigma}_{ij} = -\tfrac{2}{3} j\omega\mu\varepsilon_{kk}\delta_{ij} + 2j\omega\mu\varepsilon_{ij}$$

Figure 2. Finite Element model for milli-metric Helmholtz resonators

A priori, the analytical model is only valid for 1D infinite tubular orifices. For a finite size pores, the problem of computing the damping (resistance) remains. Randeberg (Randeberg, 2000) for the study of slit orifice shapes uses a 2D numerical approach based on a Finite Difference method. From this, we have developed a novel 3D Finite Element formulation. The Fig. 2 summarizes the equations and the variational formulation we use. A mixed pressure-displacement formulation is suggested for solving the Navier-Stokes linearized equation of the problem. The implementation have been carried out using OpenCavok multi-physic FE code, our home-made software. Linear tetrahedron elements with pressure and displacement unknowns are used. Note that the formulation could be coupled with air domains or vibrating structures. The latter could occur because the resonators (owing to light weight consideration) are made of thin sidewalls.

2.3 Experiments and results

A set of experiments have been carried out. The Fig. 3 presents the experimental setup which consists of an impedance tube and two families of samples. The first family is composed of a micro-perforated plate of 2.5 mm thickness with 2mm diameter holes representing 3.5 per cent of the plate surface. The second family is realized with the same plate (2.5mm of thickness) but perforated with 1mm diameter holes covering 2.5 per cent of the total area (note that the covering percentage is the same indicator than the porosity). Next, the samples are placed in the impedance tube considering different positions. The distance of the perforated plate to the rigid ending of the tube represents the resonator cavity. A white noise is produced and the impedance at the perforated plate location is measured. A two microphones technique is used. From the impedance, the absorption curve is deduced.

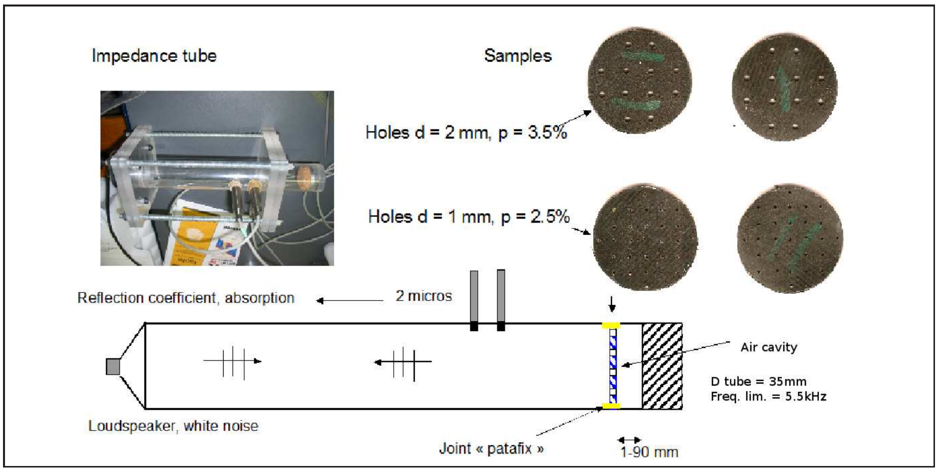


Figure 3. Experiment: Impedance tube and test specimens

The Fig. 4 presents the results obtained for the second family of samples. Five lengths of cavity, A, B, C, D and E are considered from 4.5mm, the larger cavity, to 1.0mm, the smaller cavity. It should be noted than all resonators act in the medium frequency range from 1000 to 1500Hz. The configurations A, B and C produce an important absorption. Next, calculations using the analytical model presented previously is superimposed (blue curves). The results seem satisfactory. However, to obtain them, it was needed to tune the model parameter, R, from a factor 1.3 to 3.0 whereas all the correcting factors had already been taken into account. Therefore, we conclude that the analytical model which does work for large size cavity (5cm for instance) presents weakness for milli-metric size cavities.

To validate the FE model a comparison is done with the analytical model. The depth of the cavity is 1mm while the orifice has a 2mm length and a 1mm diameter. Only the orifice length correction is considered in the analytical model, no supplementary adjustment on the viscosity or on the resistance is introduced. For the numeric model, the cavity is modeled as a volume of 10x10x1mm3. Fig. 5 shows the numerical model where the green part is the cavity, the tube is the resonator orifice and the blue part is an artificial volume for the excitation domain. The numerical and analytical curves, see Fig. 5, show a good agreement.

It is clear that other comparison should be undertaken, in particular, confronting tests and the FE numerical simulations. Current development is concerned with the enhancement of the proposed FE method because a tendency to numerical locking was observed. For the present, the conclusion are the following:

- the analytical model which does work for large size cavity presents weakness for milli-metric size cavities,
- the proposed FE formulation is able to model small size resonators.

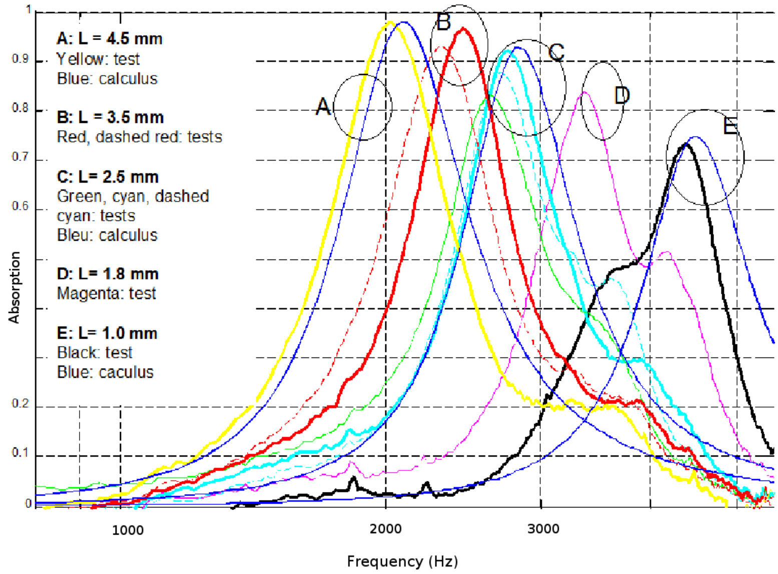


Figure 4. Absorption curves: Analytical calculation and tests comparison

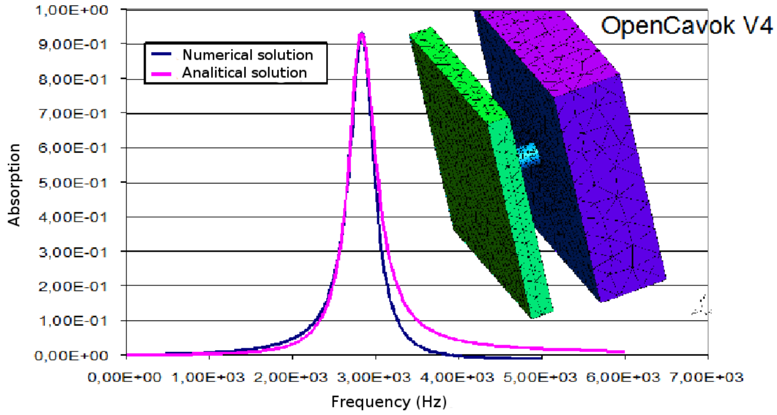


Figure 5. Absorption curves: Finite Element and analytical calculation comparison

3. NATURAL FIBERS COMPONENTS

3.1 Motivation

The industry has to reduce the environmental impacts of its products in order to comply with more stringent regulations and answer its customer's demands. The Directive for End-of Life Vehicles, for instance, demands the reutilization and valorization index of all vehicles in end-of life to be 85% in mass, in average per vehicle and per year in 2006 and in 2015 this index will need to be 95. As explained in the following paragraph, natural fiber materials are attractive and are already used for automotive mechanical parts. In this study, the focus is acoustical performance with the possible replacement of poro-elastic plastic foams and glass-wool layers by natural fiber based materials. These fibers are mainly available in tropical regions. Brazil has potential to produce about 10.000 ton/year of vegetable fibers (Alves *et al.*, 2010) that can be found natively or cultivated, for example: juta, sisal, babaçu (Campos, 2010), coconut (Soeiro, 2004), sugarcane bagasse (Luz *et al.*, 2010), etc.

3.2 Case study

A significant number of vehicle models already feature natural fiber-reinforced polymers because of their major advantages, including lower weight, thermal and acoustic insulation, and carbon dioxide neutrality due to the consumption of CO_2 during growth, Luz *et al.* (2010). For these polymers, processing temperatures are reduced, energy consumption is minimized, cycle times may be reduced by up to 25%, less material is used per unit volume due to the lower specific weight of the natural fibre, shipping costs are lower due to the lower weight and molds last longer due to less wear and due to the less abrasive nature of the natural fibre. Interesting initiative have already been carried out. We may cite the

Poema project which gave birth to the firm Poematec , located in Pará, (Poematec, 2010). This factory uses coconut fibres in order to produce automobile pieces, gardening articles, mattresses and blankets. In our reserach, the real case study consists in two types of acoustic panels for automobiles produced by COPLAC®, an industry located in Itu. These panels, called front body panels, are located between the engine compartment and the passenger compartment. Simple and double layered panels will be considered. The raw material of this product is basically scraps of fabric and ink. So, the natural fiber used here is cotton fiber.

3.3 Preliminary results

As our research is driven by a global objective, the development of a methodology for parts analysis considering jointly the environmental performances and the acoustic behavior, we firstly devoted ourself to the identification of all the key features of the research. The following has been found:

- Analyzing the environmental impacts of parts made up of renewable materials and other materials during their life cycle. This should be carried using the Life Cycle Assessment (LCA) methodology, (Schuhmacher, 2004; Goedkoop *et al.*, 2008), which is covered by ISO 14040 to 14044 standards. The SimaPro® PhD software version with Ecoinvent ® database will be used for the LCA study.

- Introducing to the Uncertainty Theory in the environmental analysis focusing on the input data. Some sources of uncertainties in LCA are: methodology, data quality, lack of site-specific data and data aggregation over different spatial and temporal scales. The major cause is collected data in the inventory phase. Due to this fact, ISO standards encourage practitioners to undertake uncertainty analysis. So, qualitative and quantitative effects of uncertainties in LCA will be taken into account. The software SimaPro® PhD version ables users to addition uncertainties in their analysis using Monte Carlo Method, Rubinstein and Kroese (2008). With thos software, it is possible to calculate uncertainty in inventory results, run comparative uncertainty analyses using advanced process coupled to sampling techniques, and set uncertainty on parameters.

- Studying the acoustic behavior of these parts through simulations and experimental tests. The acoustic natural material will be modeled as a porous material (Allard, 1993). The acoustic analysis will be made through Cavok® and TMTX® codes, (Lamary, 2010). The physical model has to be verified or modified due to the possible heterogeneity of the material. Characterization of the material to input the model parameters will be needed. A set of experiments in acoustics tubes and acoustics transmissibility rooms has to be carried out.

4. CONCLUSION

Two alternatives to the use of classical poro-elastic material were presented.

- Concerning the modeling of milli-resonators of Helmholtz. Analytical models show weakness to reproduce the experiments results without tuning the model parameters. This drawback is not present in the novel 3D formulation we suggested. Therefore, the FE formulation should largely contribute to study such systems. Moreover, numerical modeling apply to complex geometries which open perspective to find optimized solutions.

- Concerning the use of natural fiber based poro-elastic material. A new research is presented where the originality lies in the measurement of the environment impact of the selected solution. Clearly, this question rises of importance every day and will give us constraints in our technical development. A methodology mainly based of Life Cycle Assessment (LCA) tools is adopted.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Allard, J.F., 1993. “Propagation of sound in porous media: Modelling sound absorbing materials”. Elsevier Applied Science.

Alves, C., C.Ferrao, P.M., Silva, A., Reis, L. and de Freitas, M.J.M., 2010. “Ecodesign of automotive components making use of natural jute fiber composites”. Journal of Cleaner Production.

Campos, A., 2010. “Babaçu livre”. <http://www.reporterbrasil.org.br/>.

Crandall, I.B., 1926. “Vibrating systems and sound”. Van Nostrand, Princeton, N.J.

Dupont, T., 2003. “Transparence et absorption acoustiques des structures microperforées”. Ph.D. thesis, Institut national des sciences appliquées de Lyon.

Fok, V., 1941. “Doklady akademii nauk”. SSSR journal.

Goedkoop, M., Schryver, A.D. and Oele, M., 2008. “Introduction to lca with simapro 7”. <support@pre.nl>.

Ingard, U., 1953. “On the theory and design of acoustic resonators”. J. Acoust. Soc. Am.

Lamary, P., 2010. “Study of active and passive noise control of aerospace structures - multi-scale and multi-physic finite element models of acoustic insulation”. Technical report, Unicamp.

Luz, S., Pires, A.C. and Ferrão, P.M., 2010. “Environmental benefits of substituting talc by sugarcane bagasse fibers as reinforcement in polypropylene composites: Ecodesign and lca as strategy for automotive components”. Journal of Resources, Conservation and Recycling.

Melling, T., 1973. “The acoustic impedance of perforates at medium and high sound pressure levels”. Journal of Sound and Vibration.

Poematec, 2010. “Beneficiamento de fibra de coco aglomeradas com látex natural”. <http://www.poematec.com.br/>.

Randeberg, R., 2000. “Perforated panel absorbers with viscous energy dissipation enhanced by orice design”. Ph.D. thesis, Trondheim.

Rubinstein, R.Y. and Kroese, D.P., 2008. “Simulation and the monte carlo method”. John Wiley & Sons.

Schuhmacher, G.S.F.C.M., 2004. “Integrated life-cycle and risk assessment for industrial processes”. Lewis Publishers.

Sivian, L., 1935. “Acoustic impedance of small orifices”. J. Acoust. Soc. Am.

Soeiro, N.S., 2004. “Desenvolvimento de painéis acústicos, confeccionados a partir de fibras de coco, para controle acústico de recintos”. Technical report, Universidade Federal do Pará.

Stinson, M.R., 1991. “The propagation of plane sound waves in narrow and wide circular tubes, and generalization to uniform tubes of arbitrary cross-sectional shapes”. Journal of the Acoustical Society of America.

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