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AIRCRAFT FRIENDLY CABIN ENVIRONMENT ENHANCEMENT ACOUSTIC AND VIBRO-ACOUSTIC NUMERICAL METHODS FOR TRIMMED FUSELAGE MODELS

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Abstract. *In order to limit noise transmission from the exterior to the interior, the fuselage is fitted with acoustical insulations of high performance which reduce noise levels by between 65 and 70 decibels. With regards to calculation methods, no single method exists capable of solving the problem globally. Our study has therefore required the deployment of a strategic solution, encompassing theoretical development, code implementation and realization of experimental devices.*
Most recent work carried out by us has concentrated on the formulation of equations describing poro-elastic media (glass wool and foam). These new formulations, adapted to the numerical processing of the Finite Elements method, represent an important achievement. A revision of formal expression of theory for the so-called (u, U), (u, w) and (u, p) formulations is proposed for a convenient comparison of theses methods. The implementation has been done using our specialized finite element code, CAVOK. We have found the (u, p) formulation more attractive: manipulating the same unknowns that elasto-acoustics and leading for the calculations to less unknowns. For the industrial application, we have concentrated our calculations on plane aircraft fuselage samples, simulating the tests generally carried out in the acoustical chamber. In order to cover the entire range of the Speech Interference Level [355; 5600Hz], we have proposed an approach using 2D models capable of preserving a certain structural complexity. Results are satisfactory, the transition from FE methods to analytical methods, i.e. from low to high frequency, is shown and methods compared to experiments.

Keywords*: insulation, poro-elasticity, panel, transmissibility, finite element.*

1. Introduction

The challenge of today's transportation industry is to provide vehicles that are both comfortable and silent. Such considerations are an established commercial factor and respond, furthermore, to the environmental and life-quality demands of our society. The research that we present plays an integral role in this tendency, and is concerned directly with the simulation and control of noise inside aircraft for passengers comfort. Though notable advances have been achieved in the domain of engine noise, though important research in aerodynamic noise, the aircraft fuselage remains subjected to important fluctuations in pressure from the exterior thus causing it to vibrate. These vibrations, in turn, excite the air of the cabin interior, and reach the passenger's ear. In order to limit noise transmission from the exterior to the interior, the fuselage is fitted with acoustical insulations (fig. 1) of high performance which reduce noise levels by between 65 and 70 decibels. With regards to calculation methods, no single method exists capable of solving the problem globally.

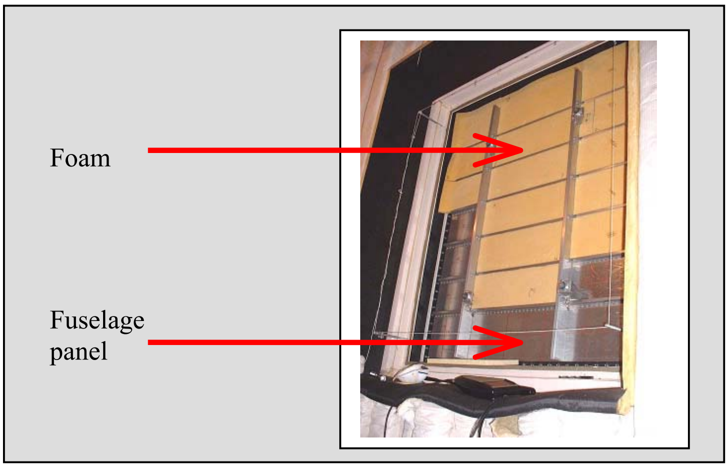

Figure 1. Fuselage panel used for transmissibility tests and numerical simulations

Among the most salient aspects of the problem are: i) The wide range noise band that exists throughout the domain of structural response, obliging us to treat the low frequency, middle frequency and high frequency ranges; ii) The structural complexity of the fuselage and of the acoustical insulation systems, resulting in complex wave propagation, and in particular multi-scale coupling phenomena with regard to the former and stringer structure of the fuselage, the intermediate panels between the former and stringer structures, the acoustical domain of the cabin; iii) The modeling of the insulation systems, in which poro-elastic, glass wool and foam materials play an essential role in noise reduction, but whose dynamic and rheological behavior remains an object of study today.

Towards resolving these problems, most recent work carried out by us has concentrated on the formulation of equations describing poro-elastic media (glass wool and foam). These new formulations, adapted to the numerical processing of the Finite Elements method, represent an important achievement. In order to cover the entire range of frequencies [355; 5,600] of the Speech Interference Level (SIL4), we have proposed an approach using 2D models capable of preserving a certain structural complexity . In addition, we have concentrated our calculations on plane aircraft fuselage samples, as presented figure 1, simulating the tests generally carried out in the acoustical chamber.

Firstly, this paper presents theoretical development for a convenient understanding of the (u, U), (u, w) and (u, p) poro-elastic formulations of Biot's model. Next, the implementation and the development of a specialized finite element code is presented and a validation example shown. Finally, results on the simulation of the fuselage panel in the transmissibility device are given while comparing tests to FE simulations and to an analytical method. For full information, the reader is invited to refer to Tanneau, 2004.

2. Theoritical development

The system under study is a multi-layered system composed of i) the fuselage, ii) absorbing acoustic layers, iii) a layer of air and iv) a back panel which is the panel we can see when being inside the aircraft. For the fuselage and the back-panel, classical equations of elasto-dynamics are used. In the same way, for the acoustic layer, classical equations of acoustics are used. The question is therefore the modeling of the absorbing layers. At present, the more accurate model of continuum mechanics for material as glass-wool, or foam with open cells, is the Biot's model. In this model, the medium is considered as poro-elastic with two phases: one linked to the skeleton of the material, the solid phase, and one linked to the fluid inside the material, the fluid phase, which is, in our case, an acoustic fluid, the air.

Owing to these two phases, they are several way to write the equations, depending mainly on the choice of the unknowns. We first recall the Biot's model before examining the (u, U), (u, w) and (u, p) formulations.

2.1. The Biot model

The rheological poro-elastic model referred as the Biot's model considers the poro-elastic medium as a continuous domain with tow phases: one fluid, linked to the open cell (the pores) and one solid, linked to the frame of the material (the skeleton). For the materials we considered for acoustic insulation, as glass wool or foam, the fluid is the ambient air.

The equilibrium equation is written as a system of two coupled equations expressed in the Fourier domain as follows,

$$\sigma^S_{ij,j} + \omega^2\left(\tilde{\rho}_{11} u_i{}^S + \tilde{\rho}_{12} u_i{}^F\right) = 0 \tag{1}$$

$$\sigma^F_{ij,j} + \omega^2\left(\tilde{\rho}_{12} u_i{}^S + \tilde{\rho}_{22} u_i{}^F\right) = 0 \tag{2}$$

with σ^S and u^S , the stress and the displacement of the solid phase; σ^F and u^F the stress and the displacement in the fluid phase and $\tilde{\rho}_{kk}$ accounting for equivalent complex density taking into account dissipative effects due to the viscous boundary layer between the fluid and the solid. The coefficient $\tilde{\rho}_{12}$ introduces the inertial and viscous coupling between the two phases.

Theses coefficients are linked to the material characteristics considering the expressions:

$$\tilde{\rho}_{11} = \rho_1 + \rho_a + \frac{1}{j\omega}\tilde{b} \tag{3}$$

$$\tilde{\rho}_{12} = -\rho_a - \frac{1}{j\omega}\tilde{b} \tag{4}$$

$$\tilde{\rho}_{22} = \Phi_P \rho_0 + \rho_a + \frac{1}{j\omega}\tilde{b} \tag{5}$$

with,

$$\tilde{b} = \sigma_R {\Phi_P}^2 \sqrt{1 + \frac{4 j \alpha_\infty^2 \eta \rho_0 \omega}{\sigma_R \Lambda^2 \Phi_P^2}} \tag{6}$$

and,

$$\rho_a = \Phi_P \rho_0 (\alpha_\infty - 1) \tag{7}$$

In these expressions appear the acoustic (or fluid) characteristics, with: Φ_P the porosity, σ_R the resistivity (in Ns/m4), α_∞ the tortuosity and Λ the characteristic viscous length (in µm).

We can also notice the density of the homogenized solid phase (the skeleton), $\rho_1 = \rho_S(1-\Phi_P)$, where ρ_S is the density of the material from which the skeleton is made. Considering the fluid as air, the dynamic density, η, is generally taken to 1.84E-5 Pa.s and, ρ_0 , the density, taken as 1.225 Kg.m-3.

The behavior of the medium is described by two coupled constitutive equations:

$$\sigma_{ij}^S = \left(A\varepsilon_{kk}^S + Q\varepsilon_{kk}^F\right)\delta_{ij} + 2\mu\varepsilon_{ij}^S \tag{8}$$

$$\sigma_{ij}^F = \left(R\varepsilon_{kk}^F + Q\varepsilon_{kk}^S\right)\delta_{ij} \tag{9}$$

The complex modulus A , Q , R are linked to the stiffness of the both phases and take into account thermal dissipations. λ and μ are the Lamé coefficients of the skeleton in vacuum. Generally, it is assumed that the modulus of compression of the skeleton in vacuum and of the air are neglectible in regard to the material in which the skeleton is made. It leads to:

$$A = \lambda + \frac{(1-\Phi_P)^2}{\Phi_P} K(\omega) \tag{10}$$

$$Q = (1-\Phi_P) K(\omega) \tag{11}$$

$$R = \Phi_P K(\omega) \tag{12}$$

with,

$$K(\omega) = \frac{\gamma P_0}{\gamma - (\gamma - 1)\dfrac{1}{1 + \dfrac{8\eta}{j\Lambda'^2 N_{P_r} \omega\rho_0}\sqrt{1 + j\rho_0 \dfrac{\omega N_{P_r} \Lambda'^2}{16\eta}}}} \tag{13}$$

where the thermal characteristic length Λ' of the porous material and the thermodynamic proprieties of the air are present with $\gamma = 1.4$ the ratio of the specific heat and $N_{P_r} = 0.71$ the Prandt's number.

2.2. Variational Formulae

Several variational formulae have already been proposed, they mainly differ by the choice of the unknowns.

The (u, U) formulation is based on the choice of u, the frame displacement and U, the fluid displacement, as main unknowns. This formulation developed by Panneton (1996) and used by Dauchez (1999) is therefore directly linked to the local equations (1) and (2) of Biot's theory. Noting u^S , the frame displacement and u^F the fluid displacement, a the weak variational formula is formed following Ritz-Galerkin approach. This one can be directly established adding the two following equations:

$$\int_\Omega \left(\delta \underline{\underline{\varepsilon}}^S : \underline{\underline{\sigma}}^S - \tilde{\rho}_{11}\omega^2 \delta u^S \cdot u^S - \tilde{\rho}_{12}\omega^2 \delta u^S \cdot u^F \right) \, d\Omega = \int_S \delta u^S \cdot \left(\underline{\underline{\sigma}}^S \cdot n \right) \, d\Gamma \tag{14}$$

$$\int_\Omega \left(\delta \underline{\underline{\varepsilon}}^F : \underline{\underline{\sigma}}^F - \tilde{\rho}_{22}\omega^2 \delta u^F \cdot u^F - \tilde{\rho}_{12}\omega^2 \delta u^F \cdot u^S \right) \, d\Omega = \int_S \delta u^F \cdot \left(\underline{\underline{\sigma}}^F \cdot n \right) \, d\Gamma \tag{15}$$

The (u, w) formulation is based on the choice of u, the frame displacement and w the fluid seepage as main unknowns. Already used in sol mechanics by Simon *et al.* (1986), this formulation have been more recently adapted to acoustics by Coyette *et al.* (1995) and Tanneau *et al* (2003).

Noting w = $w^F = \Phi_P\left(u^F - u^S\right)$, adding equations (1) and (2) and using the relations (3), (4) and (5), we obtain a new equilibrium equation as,

$$\sigma_{ij,j} + \omega^2 \rho u_i{}^S + \omega^2 \rho_F w_i{}^F = 0 \quad (16)$$

where σ is the total stress $\sigma = \sigma^S + \sigma^F$ in the porous media and $\rho = (1 - \Phi_P)\rho_S + \Phi_P \rho_S$ is the total density.

A simple rewriting of the equation (2) of the equation of the fluid equilibrium leads to a second equation:

$$\sigma^F_{ij,j} + \omega^2 \Phi_P \rho_F u_i{}^S + \omega^2 \frac{\tilde{\rho}_{22}}{\Phi_P} \rho_F w_i{}^F = 0 \quad (17)$$

The equations (8) and (9) of behavior are combined in order to make appear an equation linking the total stress tensor to the displacement u and w:

$$\sigma_{ij} = \left\{ \left(\lambda + \frac{K(\omega)}{\Phi_P} \right) \varepsilon^S_{kk} + \frac{K(\omega)}{\Phi_P} \varepsilon^W_{kk} \right\} \delta_{ij} + 2\mu \varepsilon^S_{ij} \quad (18)$$

with $\varepsilon^W_{kk} = \Phi_P \left(u^F_{k,k} - u^F_{k,k} \right)$.

For the stress fluid tensor σ^F of equation (9) , we obtain:

$$\sigma^F_{ij,j} = K(\omega)\varepsilon^W_{kk} + K(\omega)\varepsilon^S_{kk} \quad (19)$$

Then, we can notice that:

$$\sigma_{ij} = \lambda \varepsilon^S_{kk} \delta_{ij} + 2\mu \varepsilon^S_{ij} + \frac{1}{\Phi_P} \sigma^F_{ij} = \hat{\sigma}^F_{ij} - p\delta_{ij} \quad (20)$$

With, $\hat{\sigma}^F_{ij} = \lambda \varepsilon^S_{kk} \delta_{ij} + 2\mu \varepsilon^S_{ij}$, the stress in the solid phase without fluid, and p , the pressure in the pore with the deformation of the skeleton.

From this new equations, the weak variational is obtained as the a sum of the following equations:

$$\int_\Omega \left(\delta \underset{=}{\varepsilon}^S : \underset{=}{\hat{\sigma}}^S + \frac{1}{\Phi_P} \delta \underset{=}{\varepsilon}^S : \underset{=}{\sigma}^F - \omega^2 \rho \delta u^S \cdot u^S - \omega^2 \rho_F \delta u^S \cdot w^F \right) \, d\Omega = \int_S \delta u^S \cdot \left(\underset{=}{\sigma}^S \cdot n \right) \, d\Gamma \quad (21)$$

$$\int_\Omega \left(\frac{1}{\Phi_P} \delta \underset{=}{\varepsilon}^W : \underset{=}{\sigma}^F - \omega^2 \frac{\tilde{\rho}_{22}}{\Phi_P} \delta w^F \cdot w^F - \omega^2 \rho_F \delta w^F \cdot u^S \right) \, d\Omega = \int_S - p \delta w^F \cdot n \, d\Gamma \quad (22)$$

This formulation using the total stress rather than the stress in the solid phase has the advantage to isolate the effect of the frequency dependant coefficients to few terms. The application of the boundary conditions will naturally differ from the (u, U) formulation, in particular, the impermeability between two media is, here, directly taken into account while setting w to zero.

The (u, p) formulation is based on the choice of u, the frame displacement and p the pressure in the fluid as main unknowns. As the other formulations, it first appears in the field of geo-mechanics (Zienkiewicz *et al* , 1984, Simon *et al.* , 1986). The proposed approach (Atalla *et al* 1998) is based in a reorganization of equations in the Fourier domain. From the equation (2) of the fluid equilibrium and its divergence, we can express equations using u and p, with,

$$u_i{}^F = \frac{1}{\omega^2 \tilde{\rho}_{22}} \left(\Phi_P p_{,i} - \omega^2 \tilde{\rho}_{12} u_i{}^S \right) \quad (23)$$

$$\varepsilon^F_{kk} = \frac{1}{\omega^2 \tilde{\rho}_{22}} \left(\Phi_P \Delta p - \omega^2 \tilde{\rho}_{12} \varepsilon_{kk}{}^S \right) \quad (24)$$

Leading to,

$$\hat{\sigma}^S_{ij,j} + \omega^2 \tilde{\rho}_e u^S_i + \tilde{\gamma} p_{,i} = 0 \quad (25)$$

and,

$$\Delta p + k^2 p + \tilde{\beta} \varepsilon^S_{kk} = 0 \quad (26)$$

with some new entities:

the solid equivalent density,

$$\tilde{\rho}_e = \tilde{\rho}_{11} - \frac{\tilde{\rho}_{12}^2}{\tilde{\rho}_{22}}$$

a wave number of equivalent fluid,

$$k^2 = \omega^2 \frac{\tilde{\rho}_{22}}{R}$$

and a stress tensor for the uncoupled skeleton,

$$\hat{\sigma}_{ij}^F = \lambda \varepsilon_{kk}^S \delta_{ij} + 2\mu \varepsilon_{ij}^S$$

and also two coefficients,

$$\tilde{\gamma} = \Phi_P \left(\frac{\tilde{\rho}_{12}}{\tilde{\rho}_{22}} - \frac{Q}{R} \right)$$

$$\tilde{\beta} = -\omega^2 \frac{\tilde{\rho}_{22}}{\Phi_P^2} \tilde{\gamma}$$

The coupling between these two equations is fully described by these two coefficients. If we consider, now, the uncoupled equations, setting these two coefficients to zero, we can notice that we obtain for (25) a classical elasto-dynamic equation where the pores act through their equivalent density that take into account some dissipative effects. For (26), the equation becomes exactly the, so-called, fluid equivalent equation given by Allard, 1993.

Using the Ritz-Galerkin method, the weak variational formula is obtained as the sum of the two following equations:

$$\int_\Omega \left(\delta\varepsilon_{ij}^S \hat{\sigma}_{ij}^S - \omega^2 \tilde{\rho}_e \delta u_i^S \cdot u_i^S - \tilde{\gamma} \delta u_i^S \cdot p_{,i} \right) \, d\Omega = \int_S \delta u_i^S \hat{\sigma}_{ij}^S n_j \quad d\Gamma \tag{27}$$

$$\int_\Omega \left(\kappa \delta p_{,i} p_{,i} - \kappa k^2 \delta p p \quad - \tilde{\gamma} \delta p_{,i} u_i^S \cdot \right) \, d\Omega = \int_S \kappa \delta p \left(p_{,i} + \tilde{\beta} u_i \right) n_i \quad d\Gamma \tag{28}$$

with,

$$\kappa = \frac{\Phi_P^2}{\omega^2 \tilde{\rho}_{22}}$$

Using the expressions (10), (11) and (12) of the porous modulus of elasticity, the second member of (28) is simplified as:

$$\int_S \delta p \left((1 - \Phi_P) u_i^S + \Phi_P u_i^S \right) n_i \quad d\Gamma$$

Other formulations can be found in Attala *et al.* , 2003, or more general description of the poro-elasticity with the formulae of Biot and Willis, 1957.

2.3. Coupling

We examine in this section the coupling of the three previous poro-elastic formulations with structural domains and pure acoustic domains, considering, the weak variational formulae,

$$\int_\Omega \left(\delta \underset{=}{\varepsilon} : \underset{=}{\sigma} - \rho\omega^2 \delta u \cdot u^S \right) \, d\Omega = \int_S \delta u \cdot \left(\underset{=}{\sigma} \cdot n \right) \, d\Gamma \tag{29}$$

for the elasto-dynamic equations of the structure, and,

$$\int_\Omega \frac{1}{\omega^2 \rho_a} \left(\delta p_{,i}^a p_{,i}^a \right) - \frac{\omega^2}{c^2} \delta p^a p^a d\Omega \quad = \int_S \delta p^a u_i^a n_i d\Gamma \tag{30}$$

for the Helmholtz equation of acoustics.

The coupling is constructed by adding the variational formulae, where simplifications will occur in the second members of equations linked to surface integral at the coupling interface when specifying conservative of cinematic entities and conservation of normal stresses. Recalling the work of Tanneau, 2004, we summarize the results.

Coupling the (u, U) poro-elastic formulation

with a structure leads to impose:

$$u^S = u$$

if the interface is glued, or

$$u_n^S = u_n$$

if there is a sliding, or

u^S

is set free, if there is a thin layer of air.

$u_n^F = u_n$

with an acoustic fluid leads to the following coupling integrals:

$$\int_S \delta u_i^S \left(\Phi_P - 1\right) p^a n_i d\Gamma - \int_S \delta u_i^F \Phi_P p^a n_i d\Gamma - \int_S \delta p^a \left(\left(1 - \Phi_P\right) u_i^S + \Phi_P u_i^S\right) n_i d\Gamma$$

where, if the boundary is impermeable,

$u_n^S = u_n^F$

Coupling the (u, w) poro-elastic formulation

with a structure leads to impose:

$u^S = u$

if the interface is glued, or

$u_n^S = u_n$

if there is a sliding, or

u^S

is set free, if there is a thin layer of air.

$w_n^F = 0$

with an acoustic fluid leads to the following coupling integrals with:

$$-\int_S \delta u_i^S p^a n_i d\Gamma - \int_S \delta w_i^S p^a n_i d\Gamma - \int_S \delta p^a \left(u_i^S + w_i^F\right) n_i d\Gamma$$

where, if the fluid is impermeable,

$w_n^F = 0$

Coupling the (u, p) poro-elastic formulation

with a structure leads to impose:

$u^S = u$

if the interface is glued, or

$u_n^S = u_n$

if there is a sliding, or

u^S

is set free, if there is a thin layer of air.

Its leads also to the coupling term:

$$-\int_S \delta u_i \; p \; n_i d\Gamma - -\int_S \delta p u_i \; n_i d\Gamma$$

which is the classical term in elasto-acoustic coupling.

with an acoustic fluid leads to the following conditions:

$p = p^a$

If the interface is impermeable, coupling integral terms are needed.

3. Implemenation

The previous formulations were implemented using Cavok software. Much work have been devoted to the enhancement of this code that we present hereafter. Next a validation example is shown.

3.1. Programing

The first lines of the code were written in 1995. This work was undertaken because Object Oriented Languages (OOL), which have been available since this period, opened new perspectives. In particular, OOL allowed us to introduce high level abstraction for Finite Element paradigms.

The originality of this code is to solve differential equations formally. The advanced user can use the FE generator to create new types of FEs. For the proposed problem, we use this feature to investigate Reissner / Mindlin theory for plate bending and transverse shear phenomena, Helmholtz acoustic elements, poro-elastic (u, U), (u, w), and (u, p) finite elements of Biot's rheological model. More comprehensive information concerning the implementation of the method can be found in Lamary *et al,* 2000, 2003 and applications to acoustics in Tanneau *et al* , 2003.

CAVOK software runs as a stand-alone application under Windows™ operating system and, as presented in fig.2, mainly deals with the creation of FEs, the assembly of the Elementary Matrices and the solving of the system. The current size problem is 100,000 DOF which leads to a few minutes CPU time per frequency iteration.

This codes belongs to a new generation of light and powerful tools designed for easy use and for communication with other tools. Large projects are handled following computational strategies where several specific programs interact.

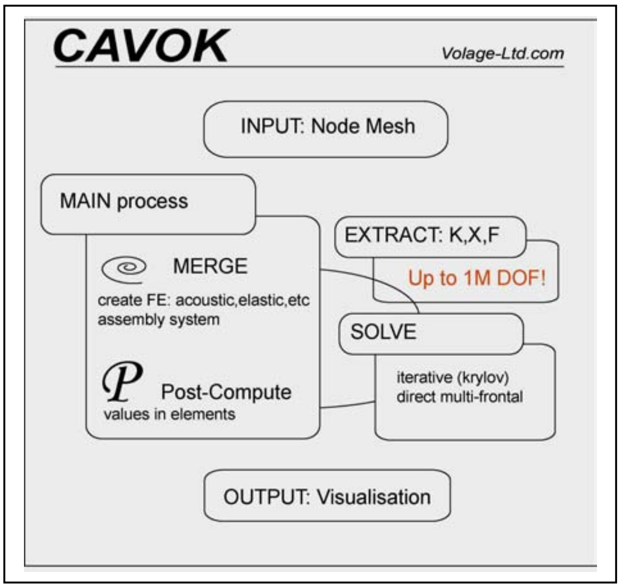

Figure 2. Cavok software

3.2. Validation

This example is extracted from Allard, 1989, corresponding to tests in impedance tube. We compare the results of the three formulation for this mono-dimensional problem. The sample in the tube is of 2cm of thickness with the following poro-elastic characteristics:

Φ_P =0.93, σ_R = 55000 (Ns/m4), α_∞ = 3.2, Λ =30 (µm) , Λ' =320 (µm),

ρ = 30 (Kgm-3), E =504 (KPa), ν = 0.4 and η = 0.1

The finite element model used 10 linear finite elements with a regular spacing. Results of both the 3 methods (fig. 3) are satisfactory. The difference that can be noticed when using the (u, p) formulation on the calculation of the impedance, in figure 3, is due to the fact that the estimation of the fluid speed (needed to compute the surface impedance) is evaluated by calculating the gradient of p. With the linear elements used, it leads to a constant value per element, therefore less accurate than the other methods. This problem does not exist for the solid displacement which is a nodal value in the three methods.

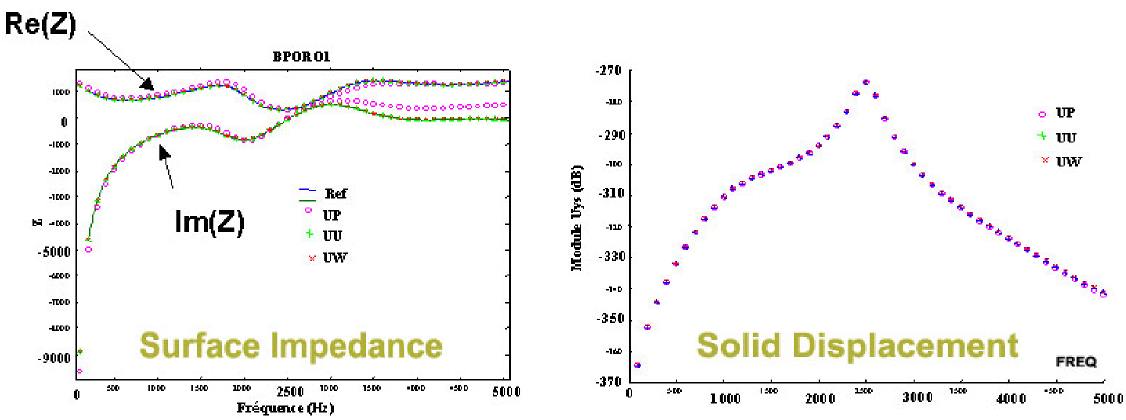

Figure 3. Comparison: Reference, (u, U), (u, w) and (u, p)

4. Results

An aircraft panel of size 1mx1,2m is constructed with no curvature and this flat panel is placed in the transmissibility room as presented figure 1. The standard thickness of the panel is 1.2mm and is made of DURAL. Two configurations are tested :

1. Clamped panel without insulation
2. Clamped panel with 65mm of Green Glass Wool.

Noise is made in the reverberant room, where ideally a white diffuse noise takes place, while the intensity is measured with a probe in the anechoic room. The transmissibility is post-computed, in the frequency domain, as main indicator of the insulation efficiency.

Two numerical methods are considered:

an analytic method, for MF to HF, based on wave propagation in a medium of finite thickness and infinite extension. A Transfer Matrix method is used to link media of different physical nature; in our case, the elastic medium for the fuselage and the poro-elastic medium (modeled with Biot's theory) for the glass wool. Transmissibility is computed for a single incidence of sound or for a diffuse field.

an FE model, for LF to MF frequencies. A 2D model is degenerated from the 3D problem, considering a cross section between stiffeners. The length is set to 508mm while the thickness of the glass wool layer is respected. Q2 elements are created for the plate behavior according to Mindlin's theory. Transverse shear is thus taken into account and a reduced integration technique is used to avoid shear locking phenomena. Q4 elements are introduced for the poro-elastic medium (Biot's theory). A (u, w) formulation is used in (fig. 4) while a (u, p) formulation is presented fig. 5. A single incident acoustic wave is considered in these computations taken at 60° from the normal vector. The plate is clamped and the glass wool is free to move and is permeable except at the interface where only the sliding is authorized.

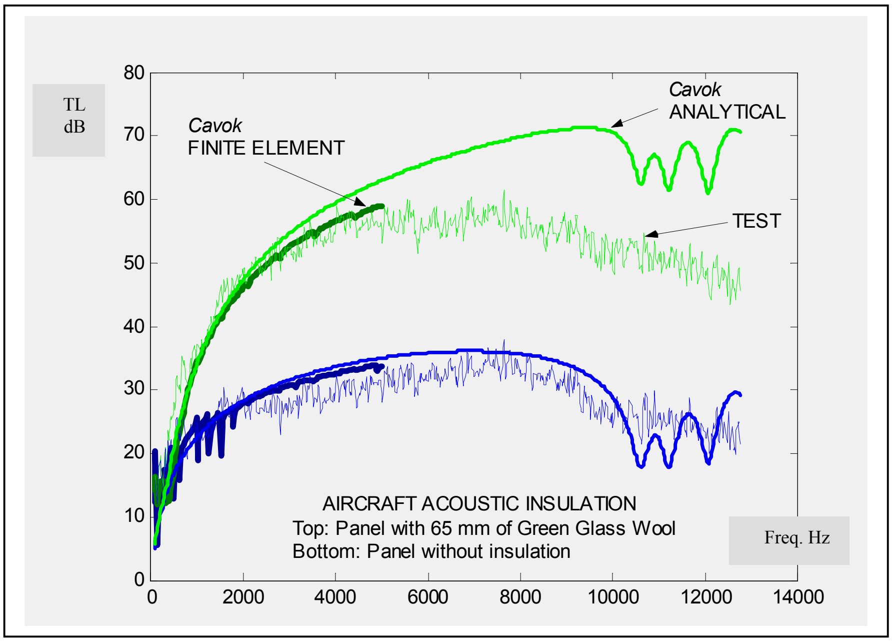

Figure 4. Transmissibility tests and simulations

Figure 4 shows the results obtained. A good agreement is observed in the case of the plate without insulation. The analytical method follows the trend of the test for all the frequencies. The FE method exhibits the first modes of large amplitude of the structure and then joins the analytical method.

In the case of the panel with the glass wool layer, results are also very good but some explanations have to be given. The domain of validity of the acoustic room is [250 to 6000Hz]. In this band, results are satisfactory. However, we can see, that the analytical method tends to over-estimate tests as long as frequency grows.

Figure 5, shows one of the interests of FE computations. The computations allow us to visualize information inside the object. The deep absorption of waves in the glass wool is observed.

5. Conclusion

A revision of formal expression of the poro-elasticity have been proposed, starting with the comprehensive coupled system of local equations of Biot's theory. This system of equations is written using the skeleton displacement and the fluid displacement as main unknowns. It leads to the so-called (u, U) variational formulation. An enhancement of this approach consists to use the fluid seepage, w, instead of the fluid displacement. In this case, the frequency coefficients are more isolated in the final (u, w) variational formulation. Following, the same idea, only one unknown can be used for the behavior of the pores using the pressure, p, (inside the pore) instead of w. We found this last and most recent formulation, called (u, p), the more attractive for acoustics. This formulation manipulates the same degrees of freedom (DOF) than classical elasto-acoustics and can directly degenerates into the "fluid equivalent model". All the formulations give the same results on our validation example. For large size problems, the reduced number of DOF of the (u, p) formulation is also an advantage.

Calculations were applied to the transmissibility of aircraft panels. Owing to the very short wave length in porous materials, we used a 2D models to be able to cover a large frequency range [250 to 6,000Hz]. The FE method is compared to tests and also to analytical calculations. The general trends of the calculations is to over-estimate the transmissibility. For complex configurations, panels with stiffeners, junctions between the fuselage and the back-panel, the FE calculation is fully used. The simulations of tests shows itself of most practical benefit for engineers.

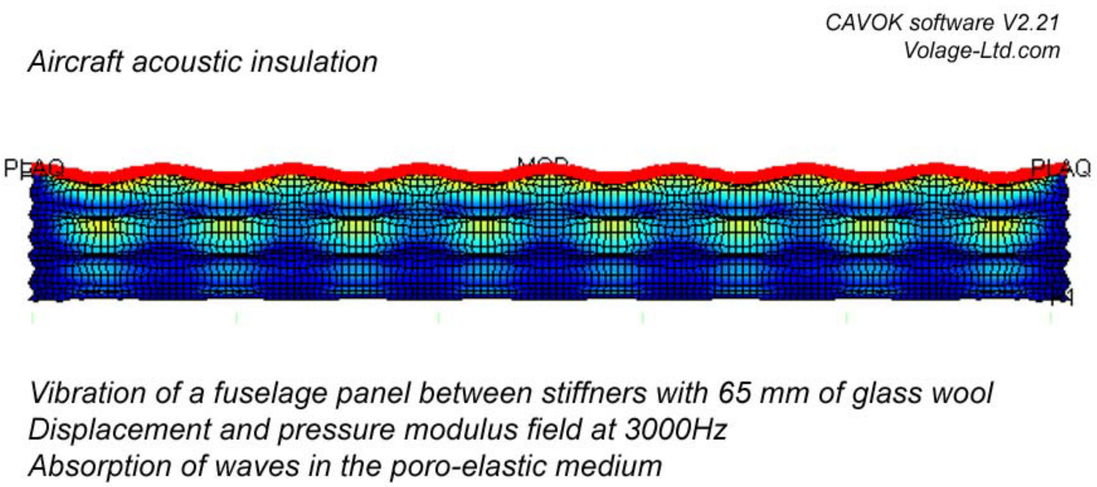

Figure 5. FE analysis.

For the most part, industrial actors, and in particular those with whom we have collaborated, carried out tests on plane samples to design and determine the sizing of insulating systems. But most recently, these industrial actors have expressed the need to know also the influence of curvature and stiffeners. In the continuity of the presented work which has been mainly made at the ISMEP of Paris, these new topics are now part of current research at the Vibro-acoustics Laboratory of UNICAMP.

6. Acknowledgements

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7. References

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