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Characterisation of porous materials viscoelastic properties involving the vibroacoustical behaviour of coated panels

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Porous materials are widely used for noise control. Often attached to a structure subjected to vibration, the porous layer contributes to diminish vibration by increasing structural damping and also reduce noise level in cavities by sound absorption. For optimal design, it is often necessary to know the viscoelastic properties of these materials in the frequency range relevant to their application. At these frequencies and for most of porous materials the viscoelastic properties can not be determined by standard methods because of the strong coupling with air. The method proposed is based on measurements representative of industrial use (car, aircraft, train): acoustic radiation of vibrating coated panel and transmission loss of coated panel. The use of an inverse method based on analytical models to determine the viscoelastic properties insure a good simulation of the porous material behaviour in the required context.

1 Introduction

Porous materials such as polymer foams and fibrous materials are used for acoustical comfort design in transport applications (car, aircraft, train) because of lightness, efficient acoustical absorption and structural damping improvement. Simulation of their performances requires the knowledge of acoustical characteristics such as porosity, air flow resistivity but also viscoelastic properties of the solid phase: Young's modulus E and structural loss factor η which are frequency dependent. Several methods based on measurements on porous samples [2, 6] exist to characterize these mechanical properties. The use of samples allows in most cases to neglect the coupling with external fluid in the inverse model but requires numerous measurements to set the usual strong inhomogeneity. Moreover, because of the non-linear and anisotropic behaviour of porous material, the mechanical properties obtained by applying a deformation can not be used for another type of deformation. A method which solicits the material in a context close to its actual use seems to be more adapted. Thus, two methods based on the vibration of a porous plate [8] and a coated beam [9] have been studied. However both neglect the coupling with external fluid, in spite of the broad size of the porous layer, and may give an erroneous estimation of the viscoelastic properties.

The innovative contribution of the work proposed in this paper is to provide representative results of the actual applications, i.e., in the frequency range (200 Hz - 4000 Hz) where porous layer has a significant influence and without neglecting the coupling with external fluid. This insure a good simulation of the porous material behaviour in the required context.

Two methods are confronted: the first, based on transmission loss measurement of large size coated panel and a second based on radiation efficiency measurement of medium size coated panel. For both configurations, mechanical behaviour of the porous layer has a significant influence on the structure vibroacoustic response. An inverse method based on analytical models is used to characterize viscoelastic properties of porous materials. Finally, viscoelastic properties obtained with both configurations are compared.

2 Transmission loss of large size panel

The transmission loss (TL) of a structure is a measure of its sound insulation. It is defined as the ratio of the acoustic power incident on the structure and the acoustic power transmitted through the structure. Large size panel are used to bring the disturbing modes below the studied frequency bandwidth 200 Hz - 4000 Hz. An infinite lateral size analytical model based on sound propagation of plane waves in stratified media using transfer matrices [5] is used for the characterization inverse method. The structure studied is considered as a layered media composed of a foam layer bonded onto a layer of aluminium of thickness 1.2 mm and density 2625 kg m^{-3} . The main parameters which describe the foam layer are given Table 1. In the model, sound propagation in porous layer is modelled using Biot-Allard theory [4] to take into account the motion of the skeleton and the thin aluminium plate is modelled as a plate subjected only to bending vibrations.

Thickness (mm)	18.9
Air flow resistivity (N s m^{-4})	57 000
Porosity	0.97
Viscous length (μm)	24.6
Thermal length (μm)	73.8
Skeleton density (kg m^{-3})	46

Table 1: Parameters of the porous material

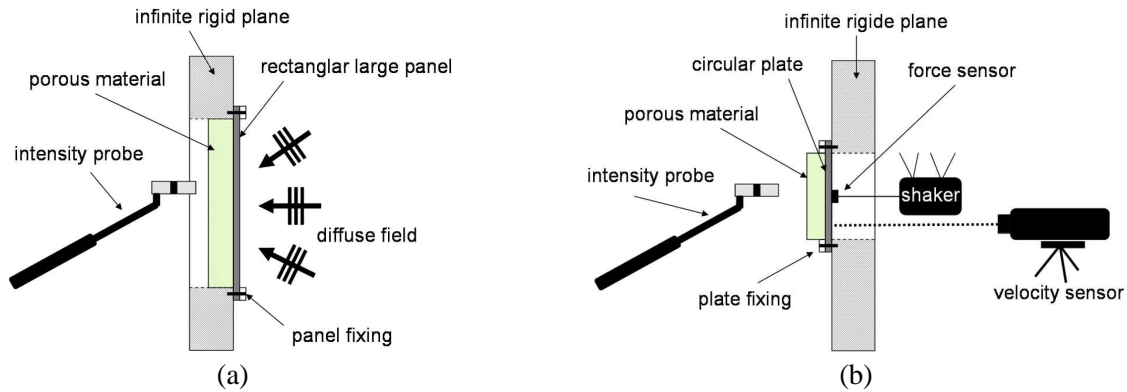


Figure 1: (a) Transmission Loss measurement set-up. (b) Radiation efficiency measurement set-up.

Measurement of the TL is performed using the intensity method (see Fig. 1 (a)). The tested structure is placed in an aperture of 0.85 m by 0.75 m between a reverberation room and a semi-anechoic room. In the reverberation room, a diffuse sound field is generated to excite the structure. In this diffuse sound field, the acoustic power incident on the structure is determined from the average of pressure measurements carried out at six different locations in the room. The transmitted power is determined from intensity measurement using a sound intensity probe in the adjacent semi-anechoic room. Figure 2 presents the experimental and simulated transmission loss of the rectangular aluminium panel covered or not by a polyurethane foam layer.

In the low frequency range and within the presence of the porous layer, the increase of the TL is due to the added mass effect. Around frequency f_1 (see Fig. 2), a local decrease of the TL can be observed: it is due to the first resonance frequency in the thickness of the porous layer. The model is thus fitted acting on the viscoelastic parameters at this frequency. Note that using constant viscoelastic parameters versus frequency gives good results on the whole frequency range, because, in this context, their influence is mainly limited to the f_1 region. The fitted parameters, given Tab. 2, are considered as reference because the transparency experimental method is standardized and mastered.

3 Radiation efficiency of medium size panel

By reducing the size of the studied panel, the experimental set-up can be considerably simplified (no need of a reverberation room) but on the other hand modal behaviour of the structure has to be accounted in the frequency range under interest. The radiation efficiency is used to characterize the acoustical power radiated by the vibrating structure. It is defined as the ratio of the acoustic power radiated and the vibratory power.

3.1 Experimental set-up

Measurement of the radiation efficiency of a plate with or without covering porous layer has been performed. The experimental configuration is an aluminium circular plate ($\text{Ø}29$ cm) of thickness 1 mm and density 2615 kg m^{-3} , clamped in a rigid baffle. The shape of the plate is chosen circular to simplify the analytical model (see 3.2). The center of the back face is connected to a shaker to excite only axisymmetric modes (see Fig. 1 (b)). Vibratory power of the plate is determined from the quadratic mean of normal velocities measured at 8 points by a laser vibrometer. The front face that can be covered by a porous layer is radiating in an anechoic chamber. Acoustic radiated power is determined from the average of intensity measurements carried out on a quarter of

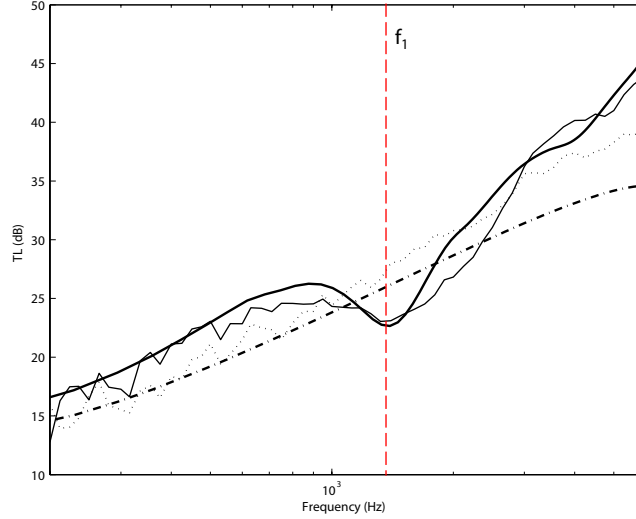


Figure 2: Transmission Loss (TL) of 1 m² Aluminium panel: Experiment, (...) panel, (–) coated panel ; Theory, (-.) panel, (-) coated panel

plate surface using an intensity probe. This probe is made of two 1/2 inch microphones spaced by 12 mm. To provide more informations on poroelastic layer behaviour, normal velocity on the porous surface is measured using a laser vibrometer.

3.2 Analytical model

In the proposed model, the acoustical and vibratory behaviours are considered decoupled and the analyses are performed separately. The vibratory analysis is based on a dynamic study of the two-layer system from mechanical properties of an equivalent plate. In this case, the coupling between porous skeleton and air are neglected and the porous layer can be considered as a viscoelastic layer corresponding to the skeleton in vacuum [7]. From an acoustic point of view, the effect of the porous's layer on the radiation efficiency of the plate is taken into account by applying an impedance to the equivalent plate. This impedance, called "transfert impedance", is derived by considering the material as locally reacting and using a one-dimensional model based on Biot-Allard theory [4]. It is defined as [10]:

$$Z_T = \frac{p}{v_0 - v}, \quad (1)$$

where v_0 is the velocity at the interface porous-plate, p and v are respectively the pressure and the velocity of air at the interface porous-air.

For harmonic motion at frequency ω , the total acoustic power radiated from the plate can be obtained by integrating the farfield acoustic pressure p over a hemisphere of radius r . Considering a plate of surface S , vibrating in a infinite rigid baffle and characterized by the transfert impedance Z_T , the complex acoustic pressure can be written in terms of the plate surface velocity V using Rayleigh integral [1, 10]:

$$p(r) = j k \rho c \frac{2Z_T}{Z_T + \rho c} \iint_S V \frac{e^{-jk|r-r_0|}}{4\pi|r-r_0|} dS, \quad (2)$$

with ρ , the density of air, c the sound velocity in air, $k = \omega/c$ the acoustic wave number and r_0 the point source location on the plate. The normal velocity V is derived from the modal response of the plate excited at its center by an harmonic punctual force. To avoid an expensive analytical model in computing times, the shape of plate is chosen circular and the hypothesis is made that only axisymmetric modes contribute to acoustic radiation. It is coherent with experimental set-up which includes an excitation at the center of the plate.

Figure 3.(a) presents the total radiation efficiency of the plate covered or not with the foam layer (Tab.1) of arbitrary viscoelastic properties: $E = 200$ kPa and $\eta = 0.15$. Three zones can be distinguished. In the low frequency range, the porous has no or little effect on radiation efficiency. An increase of the acoustic radiation is observed in the mid frequency range due to " $\lambda/4$ " skeleton resonance in the thickness of the layer. Above these frequencies, radiation efficiency decreases, due to structural, viscous and thermal dissipation in

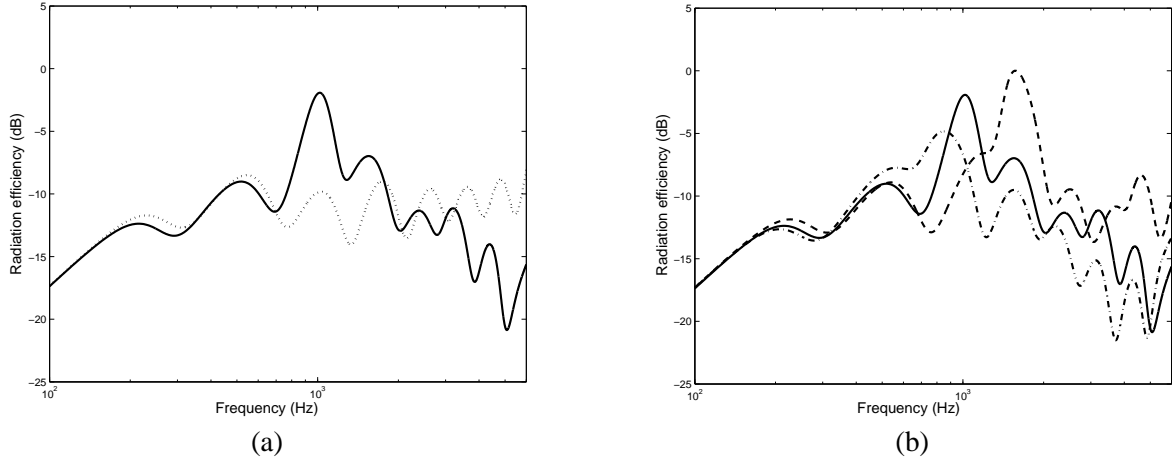


Figure 3: Total radiation efficiency of an aluminium clamped circular plate fixed in a rigid baffle: (a) (...) Bare plate, (-) Coated plate with porous Young's Modulus $E = 200$ kPa. (b) (-) Coated plate with porous Young's Modulus E , (-.) Coated plate with porous Young's Modulus $E/2$, (- -) Coated plate with porous Young's Modulus $E * 2$.

the porous layer. On Figure 3.(b), it appears clearly that the Young's modulus has an influence on the frequency and amplitude of the acoustic radiation increase. Simulation will be fitted on experimental data at the maximum of the peak acting on viscoelastic properties.

3.3 Results and discussion

Figure 4.(a) presents the measurement of the radiation efficiency of the vibrating plate covered or not by the porous layer. For frequencies ranging between 300 Hz and 800 Hz (grayed zone), intensity measurements are strongly perturbed by non-axisymmetric modes and thus, the "Pressure-Intensity Index δ_{PI} " defined by Fahy [3] is not satisfied. Eigen-frequencies of axisymmetric modes are represented by circles and squares respectively for the bare plate response and the coated plate response. A light shift of these axisymmetric modes resonances is noticed within the presence of the porous layer due to an added mass effect (see for exemple the fourth axisymmetric mode: point *B* and *C*). At 1200 Hz and 2000 Hz (see point *A* and *D*), an increase of the acoustical radiation is observed, which amplitude and frequency depend on viscoelastic properties of the porous layer. A significant decrease of the total radiation efficiency appears between these two peaks.

First, the model is fitted on the frequency of the first peak (see points *A* and *A'* Fig. 4.(b)), acting on the Young's modulus E . Then, structural loss factor η is adjusted so that the relative increase matches the experimental data (+ 7 dB). The fitted viscoelastic properties are given in Tab. 2.

Fig. 5 presents the mean square velocity on the surface of the porous over the mean square velocity of the plate. Experimentally two velocity increases due to skeleton resonance appear at 1200 Hz and 2000 Hz, corresponding to the radiation efficiency increases (Fig. 4.(a) point *A* and *D*). The simulated curve derived from the acoustical analysis using the one-dimensional model of propagation in the porous layer clearly indicates that the first radiation peak appears at the first " $\lambda/4$ " resonance frequency in the thickness of the porous layer.

After the first resonance, one can notice two significant differences between model and experience (see Fig. 4): the experimental radiation efficiency decreases after the radiation peak and another radiation peak is observed at " $\lambda/2$ ". These differences are due to strong assumptions made in the model construction. Experimentally, a coupling is observed between the modes of the plate and the modes of the porous layer which is not taken into account in the vibratory model. Moreover non-axisymmetric modes have a non negligible influence on the structure acoustical radiation. However, from an acoustical point of view, the basic model allows us to simulate accurately the acoustical behaviour of the structure until the first porous resonance included and also in the high frequency range: a realistic simulation of the global radiation decrease due to dissipation in the porous thickness is performed.

Viscoelastic properties derived with both methods are coherent. Compared with transmission loss method, the radiation method underestimates the viscoelastic properties. This can be due to the strong assumption made

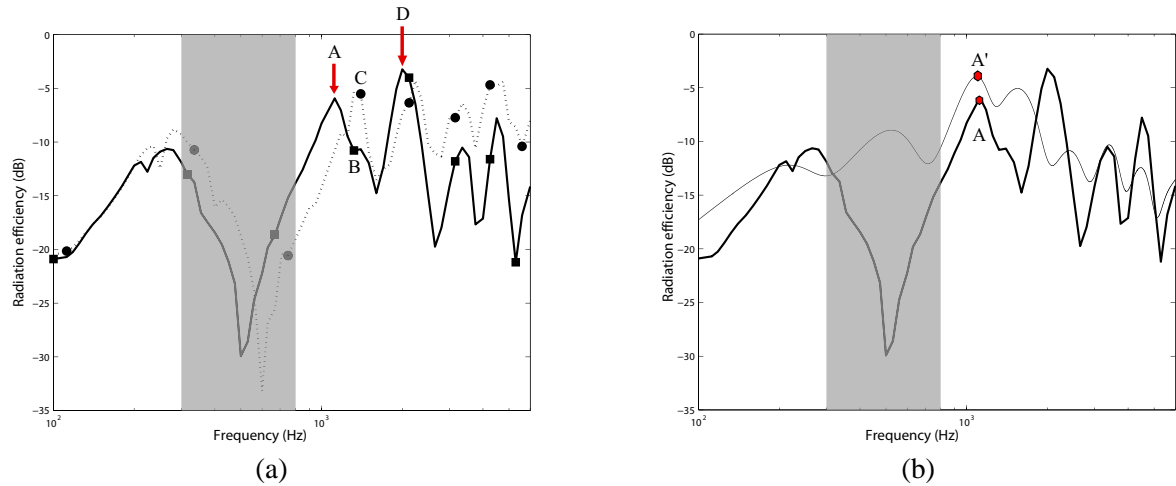


Figure 4: Total radiation efficiency of an aluminium clamped circular plate fixed in a rigid baffle; **(a)** Experiment: (...) Bare plate, (-) Coated plate with foam layer. Eigen-frequencies of axisymmetric modes are located by: (circle) bare plate, (square) coated plate. **(b)** Radiation of the coated plate: (-) Experiment; (—) Simulation.

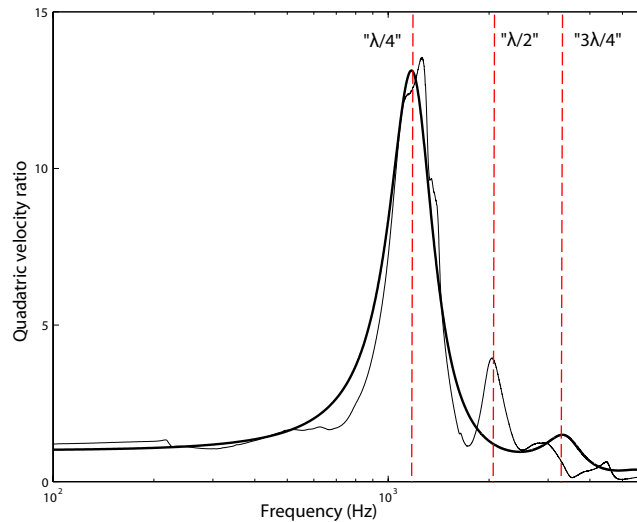


Figure 5: Mean quadratic velocity ratio: (—) Experiment, (---) Theory

	Young's Modulus (Pa)	Loss factor
Transmission Loss method	300 000	0.27
Radiation method	260 000	0.22

Table 2: Viscoelastic parameters fitted

in the model construction which no account for the modal coupling between the plate and the porous layer.

4 Conclusion

Methods to characterize viscoelastic properties of porous materials based on coated plate vibroacoustic behaviour have been presented. These methods are based on inverse characterisation technics using analytical models. Viscoelastic properties are derived in the useful frequency range taking into account the coupling with external fluid for a vibration loading relevant to their industrial application. First, inverse method is applied to

transmission loss measurement of large size coated panels using Transfert Matrix Modelling analytical model. The fitted viscoelastic parameters are taken as referencies because the experimental set-up is standardized and mastered. To access more easily to experimental data, the experimental set-up is simplified by reducing the size of the studied panels and by making use of a mechanical excitation (no need of a reverberant room). The new method uses radiation efficiency measurements and an analytical model is built for the inverse characterization. In the model, the acoustical and vibratory behaviours are considered decoupled. The use of an impedance, derived from a one-dimensional model using Biot-Allard theory, applied to an equivalent plate allows to simulate accurately the acoustical influence of the porous layer. The model is fitted on experimental data at the first " $\lambda/4$ " resonance in the thickness of the porous layer acting on the viscoelastic properties of the layer. Results with both methods are coherent but the second method seems to underestimate the viscoelastic properties and has to be improved to account for the strong coupling of both subsystems in the " $\lambda/4$ " region.

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