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Optimization of the acoustic performance of Polyimide foams

Olivier Doutres[a)]
Noureddine Atalla[b)]
GAUS, Department of mechanical engineering
Université de Sherbrooke (Qc)
Canada, J1K 2R1

Rebecca Wulliman[c)]
Shari Ferguson[d)]
Steve Bailey[e)]
Evonik Foams
1560 Highway 371 South,
Magnolia, AR 71753, USA

Due to their low weight, high fire resistance and good mechanical strength, SOLIMIDE® Polyimide foams are good candidates for sound packages in aerospace sound transmission applications. However, their high resistance to airflow limits the sound absorption efficiency inside a double wall structure and thus the sound transmission loss of the structure. The paper discusses two concepts to improve the transmission efficiency of such materials for double wall applications: (i) improving its sound absorption behavior by removing mechanically or chemically the cell membranes and thus decreasing both the flow resistance and tortuosity, (ii) coupling the Polyimide foams to screens (porous or impervious) to improve the transmission loss in targeted frequency bands.

1 INTRODUCTION

Polyimide foams were originally developed to meet the extreme requirements of the NASA space program. SOLIMIDE Polyimide Foams are known for their unique combination of superior fire resistance, low smoke and virtually no toxic gas emission, wide operating temperature range and extremely low weight. This combination of properties has led to SOLIMIDE Polyimide Foams' specification and use in naval and commercial marine, aircraft / aerospace, building / construction, rail transportation, appliances, electronics / instrumentation, cryogenic, and high temperature industrial applications. The particular microstructure of Polyimide foams is constituted of large cells connected to each other by thin membranes. For acoustic applications, these membranes provide (i) the visco-thermal couplings between the frame and the interstitial fluid (here air) which induce acoustic attenuation but at the same time, (ii) a very high tortuosity and airflow resistance and (ii) a strong coupling between the movement

[a)] Email: olivier.doutres@usherbrooke.ca
[b)] Email: noureddine.atalla@usherbrooke.ca
[c)] Email: rebecca.wulliman@evonik.com
[d)] Email: shari.ferguson@evonik.com
[e)] Email: steve.bailey@evonik.com

of air and frame. Used as the sound package in aircraft double wall structure, the high resistance to airflow of the material may limit its sound absorption efficiency in the mid frequency range and thus lead to a decrease of the sound transmission loss of a double wall structure. The paper discusses two concepts to improve the transmission efficiency of such materials for double wall applications: (i) improving its sound absorption behavior by removing mechanically or chemically the cell membranes and thus decreasing both the flow resistance and tortuosity, (ii) coupling the Polyimide foams to screens (porous or impervious) to improve the transmission loss in targeted frequency bands. The non-acoustic properties of the different types of Polyimide foam (treated and untreated) are measured using both direct and inverse techniques. A model based on transfer matrices is then used to optimize a multilayer sound package from different combinations of layers. It is shown that the two proposed concepts allow a great improvement of the SOLIMIDE Polyimide foam's acoustical behavior compared to the untreated monolayer configuration, and thus increase considerably the transmission loss of the double wall structure.

2 FOAM CHARACTERIZATION

In this work, Polyimide foams are modeled using the classical Transfer Matrix Method (TMM) associated to the main three classical porous models[1]: (i) the elastic model which accounts for frame motion, viscous and thermal dissipation mechanisms, (ii) the rigid equivalent fluid model derived from the elastic model considering that the displacement of the frame is zero and (ii) the limp equivalent fluid model derived from the elastic model considering that the frame has no bulk stiffness (this model accounts for the frame motion). The main non-acoustic parameters required in the elastic model are: porosity ϕ, static airflow resistivity σ, tortuosity α_∞, viscous characteristic length Λ, thermal characteristic length Λ', bulk density ρ_1, Young's modulus E, Poisson's ratio ν and structural loss factor η. The last three parameters involved in frame deformation are not required in the limp equivalent fluid model. The last four parameters involved in frame inertia and deformation are not required in the rigid equivalent fluid model.

The bulk density ρ_1, the porosity ϕ and the airflow resistivity σ are determined from direct measurements[2,3]. Airflow resistivity of each sample is measured for various static airflow (between 95 and 165 ccm/min) and its real value is considered as the asymptotic value for an airflow equal to 0 ccm/min. Tortuosity of low resistive materials is determined by acoustical techniques as an ultrasonic measurement of transmitted waves[4]. This latter method being restricted to low resistive materials, the tortuosity α_∞ of highly resistive foams is estimated from the measurement of acoustic wave reflected by a slab of porous material at oblique incidence[5]. The two characteristic lengths (Λ, Λ') are determined using the indirect characterization method proposed by Panneton and Olny[5,7]. This requires the measurement of the equivalent dynamic bulk modulus $K_{eq}=K/\phi$ and equivalent dynamic density $\rho_{eq}=\rho/\phi$ of the tested material performed here using the 3-microphone impedance tube method proposed by Salissou and Panneton[8]. The indirect method associated to the 3-microphone impedance tube method has been recently detailed by the authors in ref.[9]. The tube used for the measurements has a 44.5 mm inner diameter and the loudspeaker at one end generates a broadband random signal in the frequency band 200-4000 Hz. The determination of the two characteristic lengths (Λ, Λ') is considered satisfactory when both the measured equivalent dynamic bulk modulus and equivalent dynamic density of the materials are correctly predicted. Mechanical parameters were determined at very low frequencies using a quasi-static method[10,11].

The acoustic behaviour of the foams is investigated by means of the absorption coefficient α and the normal incidence sound transmission loss $nSTL$. The absorption coefficient is measured in an impedance tube according to the standard ISO-10534-2 [12]. The normal incidence sound transmission loss is measured using the 3-microphone method recently proposed by Salissou[13] (also presented in ref.[9] in the case of symmetric samples).

3 MICROSTRUCTURE OPTIMIZATION

3.1 Untreated Polyimide

Fig. 1 presents two pictures of the Polyimide microstructure. Picture of Fig. 1 (a) is obtained using a scanning electron microscope (SEM) and the one presented in Fig. 1(b) is a 2D slice from 3D structure captured by x-ray tomography. It is observed that Polyimide foams are constituted of large cells connected to each other by thin membranes (~15 μm thick). Even if Polyimide foam appears to be closed-cell type (as shown in Fig. 1(b)), the thin membranes are not connected all together or easily ruptured which makes Polyimide foams highly porous foams but with low cell-interconnectivity. Non-acoustic properties of the untreated Polyimide are given in Table 1. Porosity of this untreated Polyimide is 95%. The low interconnectivity between cells induces large airflow resistivity (σ=400 000 N.s.m^{-1}) and tortuosity (α_∞=3) and thus a poor sound absorption behavior as shown in fig. 2 (a). Indeed, the absorption coefficient is close to 0.4 between 1 Hz and 3 kHz. The pick appearing around 2.6 kHz is due to a frame resonance and its frequency largely depends on sample mounting conditions. Both rigid and elastic models correctly estimate the measured sound absorption coefficient. Limp model is not valid in this case since the stiffness influence of the frame cannot be neglected.

A way to improve the acoustic efficiency of Polyimide foams is to destroy or remove the membranes closing the cells so as to help the acoustic wave to penetrate the material. Several methods based on different physical process have been developed to reticulate closed-cell foams: e.g., hydraulic, electrical, thermal, mechanical, chemical, methods based upon gas explosion.... Due to the high fire resistance of SOLIMIDE Polyimide Foams, the reticulation methods based on the membrane’s destruction by heat cannot be easily controlled (i.e., thermal, gas explosion, electric). Thus, only the mechanical and chemical reticulation methods are tested and described here after.

3.2 Mechanically reticulated Polyimide

The mechanical reticulation process applied to the SOLIMIDE Polyimide foams is based on a specific crushing process of the porous frame. Typical non-acoustic parameters of a mechanically reticulated Polyimide foam are given in table 1. Fig. 2(b) shows that the absorption behavior is clearly improved by this reticulation method: the sound absorption coefficient reaches 0.9 at 2 kHz. However it decreases above 2 kHz to reach 0.6 at 4 kHz. Both limp and elastic models depict correctly the sound absorption behavior. In this case the rigid model is not valid, meaning that the frame inertia has a strong influence on acoustic performance. This is due to the fact that both the frame stiffness and the airflow resistivity have been considerably decreased by the reticulation process (see Tab. 1). The sound absorption dip predicted by the elastic model at the $\lambda/4$ frame resonance (~1 kHz) seems overestimated compared to measurements. In fact, it can be attributed to the tube measurements for which this dip is damped due to viscous dissipation phenomena around the sample edges; this phenomenon is important at the frame resonance frequency because the frame deformation and thus the frame/fluid coupling are important. Note that it also explains why the absorption peak predicted by the elastic model in the case of the untreated Polyimide is not as large compared to measurements (see Fig. 2(a)).

3.3 Chemically reticulated Polyimide

This reticulation process is simply based on the membranes destruction when the material is in contact with a specific chemical solution. Typical non-acoustic parameters of a chemically reticulated Polyimide foam are given in table 1. Fig. 2(c) shows that the absorption behavior is clearly improved by this reticulation method: the sound absorption coefficient reaches 0.6 at 2 kHz and 0.8 at 4 kHz. In this case, the three models give similar predictions meaning that the material acts mainly as a rigid layer. This can be attributed to the fact that stiffness, airflow resistivity and tortuosity are all greatly reduced.
While the process effectively produces reticulated foams, there are numerous disadvantages. The precise orientation of reticulation is difficult to control by this process (i.e. resulting in a lack of homogeneity). Further, there are numerous steps in this process resulting in considerable cost.

3.4 Numerical comparison with the reference fiberglass material

Fig. 2(d) presents the comparison between the elastic simulations of the sound absorption coefficient for the three Polyimide foams and a reference fiberglass typically used as sound package in aircraft double wall structures. All samples are 1 inch thick. It is shown that the reticulation process allows a great improvement of the sound absorption of the Polyimide in specific frequency bands: medium frequencies in the case of the mechanical reticulation and high frequencies for the chemical one. In their optimum frequency bands, each reticulated Polyimide foam reaches the fiberglass sound absorption efficiency.

4 MULTILAYER OPTIMIZATION

This section presents a Polyimide multilayer sound package optimized for aircraft double wall insulation. The reference structure consists of two 1 mm thick, aluminum flat panels (m_{s1}= m_{s2}=2.742 kg/m^2) separated by 116 mm (~4.5 in.), with a 89 mm (3.5 in) thick layer of fiberglass material placed close to the first panel. The objective is to replace the fiberglass with a Polyimide multilayer and reach similar (or even better) double wall sound transmission loss performance. The polyimide multilayer is made of Polyimide foam layers of various thicknesses, mechanical and acoustical properties. First, the different layers are described and characterized. Then, a Polyimide multilayer is proposed and the normal incidence sound transmission loss of the double wall structure filled by this multilayer is estimated from classical impedance tube measurements as proposed recently in references[14,15,16]. Note that a detailed description of this impedance tube method, with numerical validations and experimental results for the reference double wall structure including the 3.5 in. fiberglass, are presented in another NOISE-CON 2011 paper and thus will not be reminded here (see sec. 2 and 3 of ref. [16]). It is important to note that this impedance tube method is the step preceding classical TL measurements.

4.1 Layers characterization

Because of its good acoustic performances and the low cost associated to the reticulation process, the mechanically reticulated Polyimide foam described in sec. 3.3 is used as base material. For conciseness this material is named here PolyMR. Its non-acoustic properties are given in Table 1 (second column). Simulations and measurement of the sound absorption and normal incidence sound transmission loss are given in Figs. 3(a) and (d).

Two thin Polyimide layers shown in Fig. 4 are also investigated: a 1/8 inch thick layer of untreated Polyimide foam, named PolyU, and a 2.2 mm thick compressed Polyimide layer named PolyC. The first layer is simply cut from an untreated Polyimide bun slightly denser (ρ_1=8.5 kg.m^{-3}) and less resistive (σ=210 000 N.s.m^{-1}) compared to the untreated Polyimide presented in sec. 3. It is modeled as a homogeneous isotropic porous material. The second layer is obtained by compressing a 1 inch thick untreated Polyimide; resulting in a dense impervious screen (ρ_1=64 kg.m^{-3}, d=2,2 mm). This layer is modeled here as an impervious heavy layer. Figs. 3 (b), (c), (e) and (f) show that the two screens can be correctly modeled using TMM except at some local frequencies where large peaks and dips indicate bending vibration modes. The model does not take into account these bending vibrations but still allows a good estimation of the mean behavior. Compared to the thin untreated Polyimide (PolyU), the compressed Polyimide (PolyC) shows poor absorption behavior but a considerable sound transmission loss.

These two screens are now coupled to mechanically reticulated Polyimide (PolyMR) samples in order to improve their acoustic performance. Two bi-layers are investigated; a 1 inch thick PolyMR sample covered either by a PolyC layer (see Figs. 5(a) and (d)) or by a PolyU layer (see Figs. 5(b) and (e)). It is shown in Figs. 5 (a), (b), (d) and (e) that the TMM simulations are in good agreement with measurements even for complex Polyimide bi-layers samples. No adhesive are used between the layers because it has been found in reference[16] that it can affect the microstructure of the porous layers and then considerably modify their acoustic behavior. Effects of PolyU and PolyC screens on the acoustic behaviors of the mechanically reticulated Polyimide are investigated numerically in Figs. 5 (c) and (f): the PolyC layer decreases considerably its absorption behavior while it enhances its sound transmission loss; the PolyU layer increases its absorption at low frequencies and slightly increases its sound transmission loss without adding mass.

4.2 Multilayer and experimental validation

By combining the different layers previously presented, an optimum Polyimide multilayer is proposed and shown in Fig. 6(b). This multilayer combines 2×1/8” untreated Polyimide layers, 3×1” mechanically reticulated Polyimide layers and 2×2.2 mm compressed Polyimide layers. The normal incidence sound transmission loss of the double panel structure filled by this optimum multilayer is simulated with TMM and determined experimentally from impedance tube measurements using the method described in references[15,16].

The double wall structure consists of two 1 mm thick, aluminum flat panels (m_{s1}= m_{s2}=2.742 kg/m^2) separated by 116 mm (~4.5 in.), with an 89 mm (3.5 in) thick sound package placed close to the first panel (2mm). A numerical analysis using TMM is first performed to investigate the effect of various double wall sound packages: multilayer A made of 3.5 inch thick fiberglass with a surface density of 0.49 kg.m^{-2} (the reference material), multilayer B made of the optimum Polyimide multilayer with a surface density of 0.73 kg.m^{-2}, and multilayer C made up of 3.5 inch thick mechanically reticulated Polyimide with a surface density of 0.46 kg.m^{-2}. Fig. 7 shows the normal incidence sound transmission loss of the three double panel structures and of the empty structure. Compared to the reference fiberglass (multilayer A), the multilayer C only made with PolyMR shows a constant transmission loss decrease around 6dB on the whole frequency range. On the contrary, the proposed Polyimide multilayer B shows an enhancement between 2dB and 10dB for frequencies above 1.5 kHz. This trend, mainly due to an added mass effect, is confirmed experimentally by the impedance tube measurements (see Fig. 7, solid black curve). Up to 1.5 kHz the fiberglass shows the higher performance. In this frequency band, the transmission loss measurement determined from the impedance tube method is not valid since frame effects are predominant[14,15].

5 CONCLUSIONS

In this paper, methods to optimize the acoustic behavior of Polyimide foams for aircraft sound insulation applications have been presented. The first method is based on the modification of the Polyimide microstructure. Both mechanical and chemical reticulation processes are applied to the foam to remove or destroy membranes closing the cells, thus decreasing its resistivity, tortuosity and stiffness. Both reticulation processes enhance the sound absorption behavior of the material. A complete characterization of the non-acoustic properties of the treated and untreated Polyimide foams is carried out and lead to good numerical predictions of the material behavior using TMM with classical limp frame and elastic models.

The second method couples thin porous screens and “heavy” layers made from Polyimide material with thick mechanically reticulated Polyimide samples in order to enhance its acoustic performance. It is shown that a compressed Polyimide material can be used as an impervious “light” heavy layer; the absorption of the bi-layer is decreased but its transmission loss greatly improved due to added mass effect. Thin Polyimide layers (i.e., 1/8” thick untreated Polyimide) are also used as “microperforated” screens. As non-woven screens, they provide a sound absorption improvement at low to mid frequencies and a light transmission loss increase. Once again, the complete characterization of the non-acoustic properties of theses Polyimide screens provides simulations in good agreement with impedance tube measurements. A 3.5 inch thick specific combination of these different Polyimide layers is then proposed as a sound package for aircraft double wall sound insulation. Compared to a typical aircraft’s grade fiberglass, the proposed multilayer allows a normal incidence sound transmission loss increase between 2dB and 10 dB for frequencies above 1.5 kHz. This numerical estimation is validated from impedance tube measurements using a straightforward method developed by the authors.

Future works will be to optimize the Polyimide multilayer to improve the sound transmission loss of the double wall structure at low frequencies (i.e., between 500 Hz and 1500 Hz) without adding too much mass. This is done by improving the reticulation process and developing optimized multilayers.

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Table 1 Properties of the material samples

Material properties	Polyimide not treated	Polyimide mechanically reticulated	Polyimide chemically reticulated	Fiberglass
Porosity	0.95	0.99	0.99	0.99
Density (kg/m^3)	5.4	4.8	4.7	5.5
Airflow resistivity (Ns/m^4)	400 000	26 000	17 600	14 000
Tortuosity	3	2.2	1.3	1
Viscous length (μm)	300	100	100	70
Thermal length (μm)	300	240	250	107
Young's modulus (Pa)	282 000	150 000	3 855	3 000
Poisson's ratio	0.45	0.45	0.45	0
Structural damping	0.06	0.03	0.04	0.01

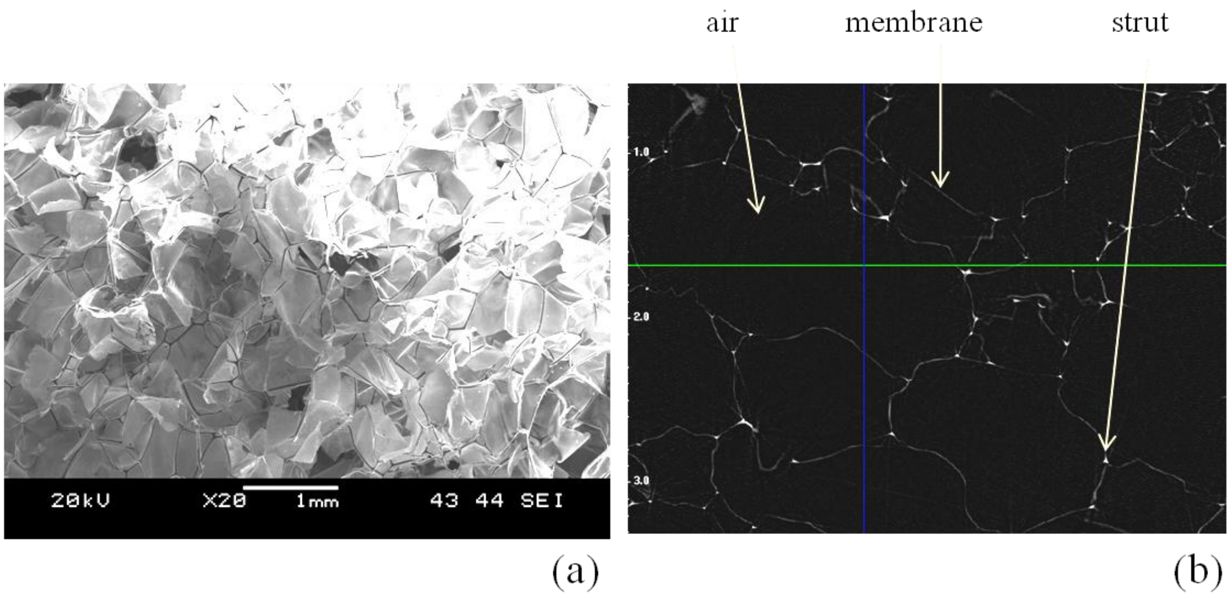

Fig. 1 - Images of Polyimide microstructure from (a) SEM (b) X-ray tomography (2D cut)

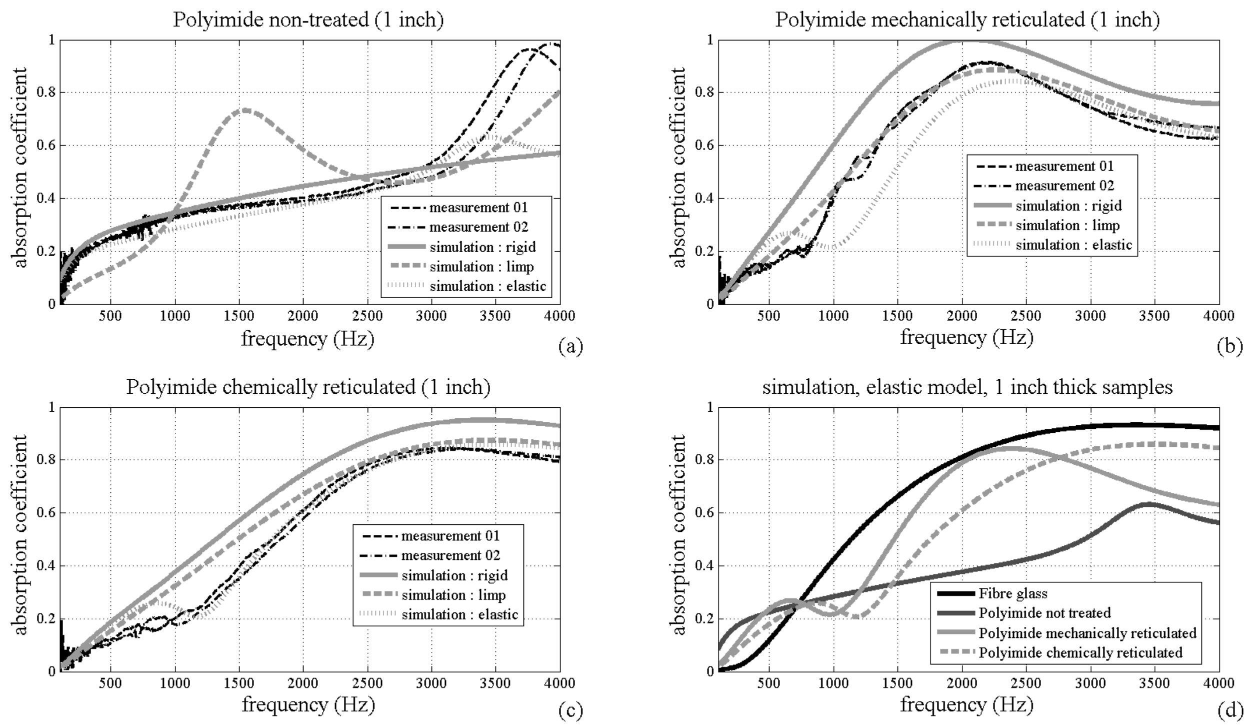

Fig. 2 - Sound absorption of Polyimide materials (a) not treated, (b) mechanically reticulated [MR], (c) chemically reticulated [CR], (d) comparison of different simulations using the elastic model.

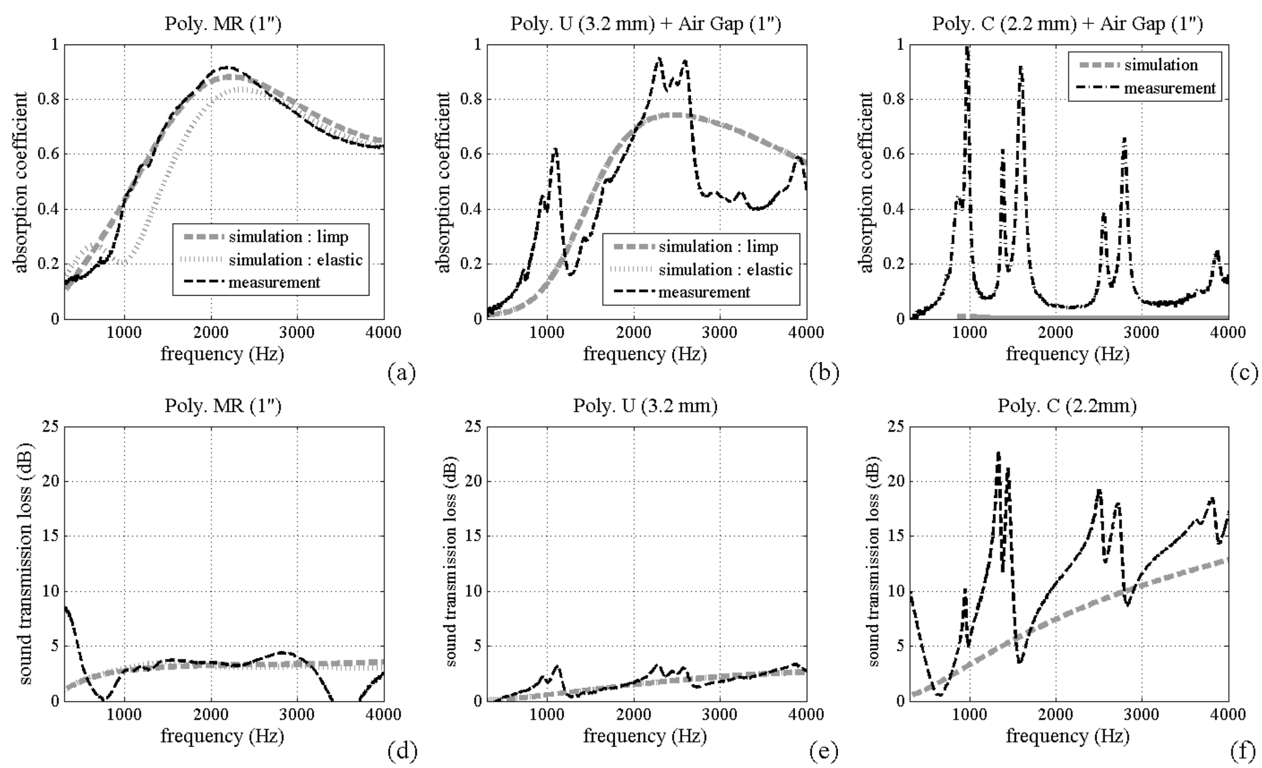

Fig. 3 - Mechanically reticulated Polyimide MR (a) absorption coefficient (d) sound transmission loss; Untreated Polyimide 1/8" thick layer (b) absorption coefficient (e) sound

transmission loss; Compressed Polyimide 2.2mm thick layer (c) absorption coefficient (f) sound transmission loss.

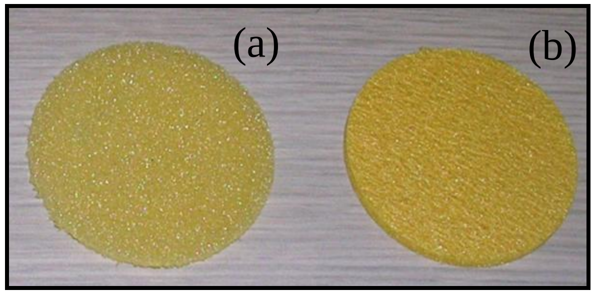

Fig. 4 - (a) Untreated 1/8"thick Polyimide layer called PolyU, (b) Compressed Polyimide 2.2 mm thick layer called PolyC.

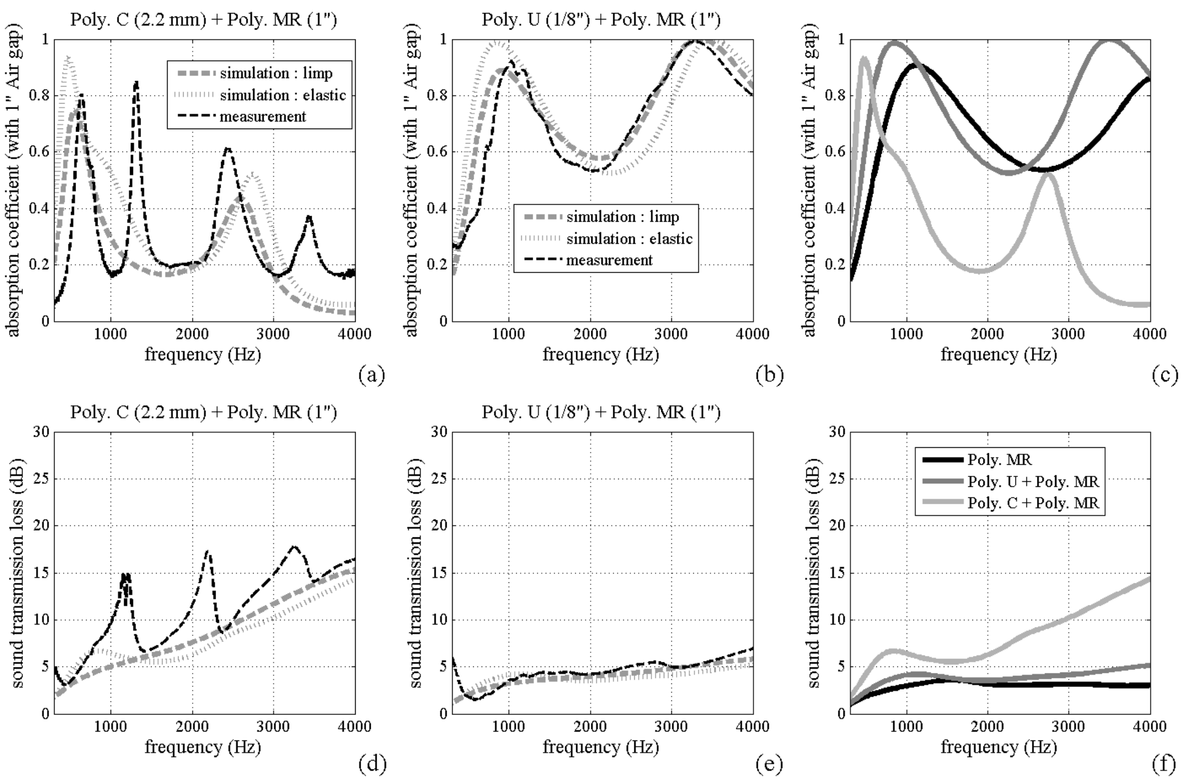

Fig. 5 - Acoustic behavior of Polyimide bi-layers; "Polyimide U / Polyimide MR" (a) absorption coefficient (d) sound transmission loss; "Polyimide C / Polyimide MR" (b) absorption coefficient (e) sound transmission loss; comparison of different simulations using the elastic model (c) absorption coefficient (f) sound transmission loss.

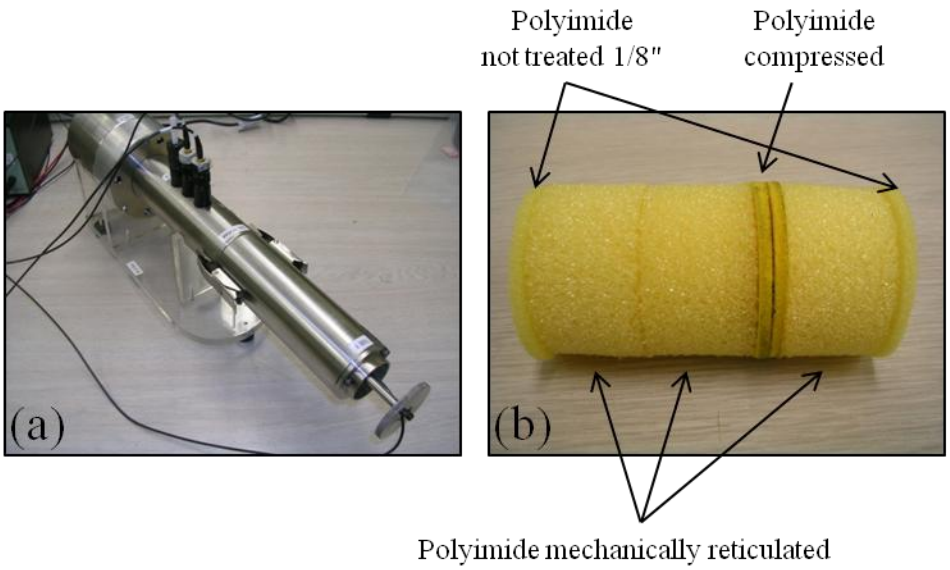

Fig. 6 - (a) 3-microphones impedance tube, (b) Polyimide multilayer B

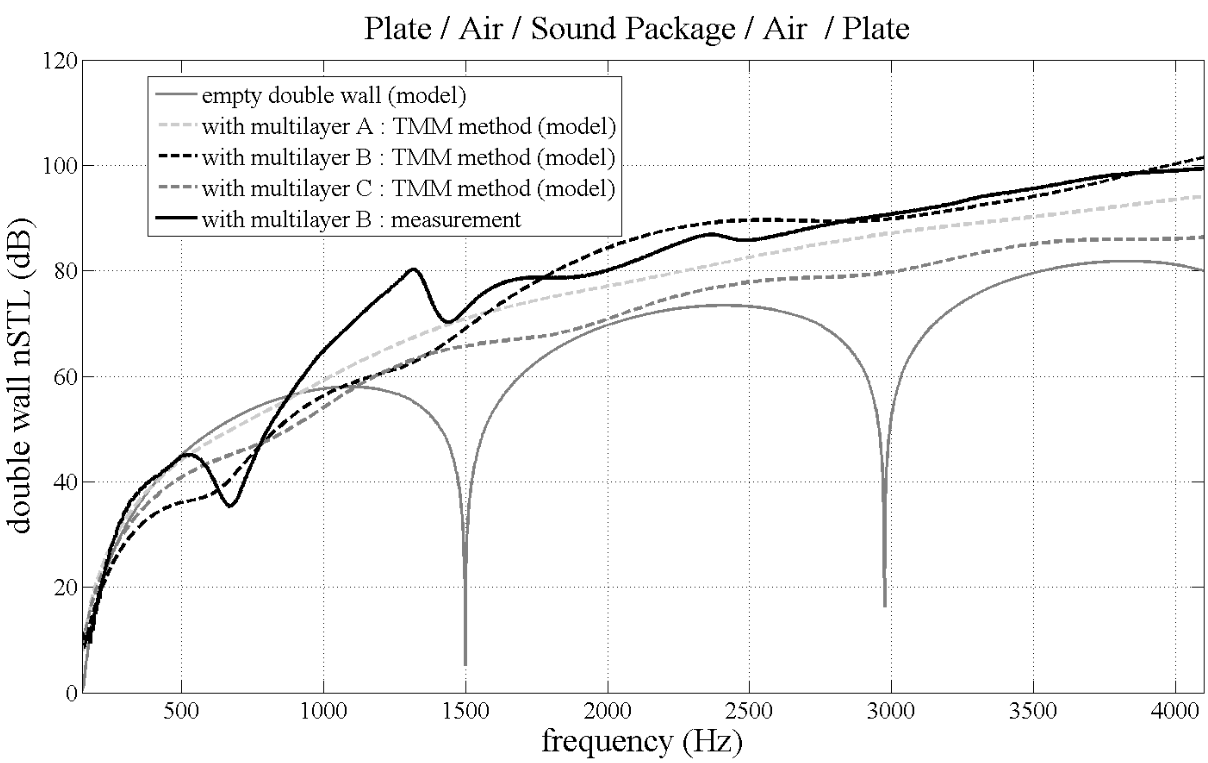

Fig. 7 - Normal incidence sound transmission loss of the double wall structure: empty, filled with multilayer A, B or C.