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A practical impedance tube method to estimate the normal incidence sound transmission loss of double wall structure.

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The objective of this paper is to propose a practical impedance tube method to optimize the sound transmission loss of double wall structure by concentrating on the sound package placed inside the structure. In a previous work, the authors derived an expression that breaks down the transmission loss of a double wall structure containing a sound absorbing blanket separated from the panels by air layers in terms of three main contributions; (i) sound transmission loss of the panels, (ii) sound transmission loss of the blanket and (iii) sound absorption due to multiple reflections inside the cavity. The sound transmission loss contributions of the blanket can thus be estimated from three acoustic measurements using impedance tube techniques: two reflection coefficients at the front face and the rear face of the blanket placed in specific positions characteristic of its position inside the double wall structure and its sound transmission coefficient. The method is first validated in the case of an aeronautic-type double wall structure filled with a 3.5 inch fiberglass. Next, it is applied to a multilayer sound package with a particular focus on the interlayer-interface conditions.

1 INTRODUCTION

Measurement of the sound transmission loss of double wall (DWL) structures with an inner sound package generally requires an important setup consisting of two coupled rooms[1], e.g. a reverberant and an anechoic one, and large samples. The setup could be simplified and the size of the tested structure considerably reduced by measuring its transmission loss in an impedance tube. However, such measurement is difficult for highly insulating systems with thin walls: (i) required sliding boundary condition is difficult to realize[2,3] (i.e., bonded plate leads to undesired resonances or air-gaps around its circumference leads to leaks), (ii) the sound transmission loss of the double wall system can be high and use of classical impedance tube methods can show a lack of accuracy due to the very low pressure level downstream the structure. This paper presents a method to estimate the transmission loss of the double wall configuration from classical impedance tube measurements of the sound package only. This method is based on an expression that breaks down the normal incidence airborne sound transmission loss of a double wall structure, without mechanical links, in terms of three main contributions[4] (i) sound transmission loss of the panels, (ii) sound transmission loss of the blanket and (iii) sound absorption due to multiple reflections inside the cavity. The transmission loss contributions of the blanket can thus

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be estimated from three impedance tube measurements[5]: two reflection coefficients of the blanket placed in specific configurations related to its position inside the double wall structure and its sound transmission loss. The above mentioned experimental difficulties involved in transmission loss impedance tube measurements of thin and highly insulating DWL systems are avoided. Testing the influence of various sound packages in a given double panel structure thus becomes quick and much less expensive compared to classical tests.
In this paper the method and an experimental validation in the case of a double wall structure filled in with a 3.5 inch thick fiberglass are first presented. Note that detailed numerical validations have been presented in reference[4]. Next, the value of the proposed method is demonstrated by investigating experimentally the effect of a multilayer sound package made up of a combination of melamine foam and screens. In this case, a particular attention is given to the interlayer-interface conditions.

2 METHOD

A schematic view of the structure is shown in Fig. 1(a). This structure is a partition consisting of two thin homogeneous panels, separated by an air-gap containing an acoustically absorbing multilayer blanket, and with no mechanical links between the two panels. The air layer between the first panel and the front face of the porous multilayer has a thickness D_1 and is referred to here by the upstream cavity. The air layer between the rear face of the porous layer and the second panel has a thickness D_2 and is referred to by the downstream cavity. The porous multilayer thickness is denoted by d.
The authors have recently shown[4] that the use of a wave decomposition of the acoustic field allows one to break down the normal incidence sound transmission loss into three main parts,

$$TL = (TL_{p1} + TL_{p2}) + TL_m + (TL_u + TL_d) \quad \text{dB.} \tag{1}$$

TL_{p1} and TL_{p2} account for the sound transmission loss of the first and second panel. For normal incidence, they are simply derived from their surface mass density m_{sj} (j=1,2) as

$$TL_{pj} = -20\log\left(\left|\frac{2Z_0}{2Z_0 + j\omega m_{sj}}\right|\right) \tag{2}$$

with Z_0 the characteristic impedance of the fluid and ω the angular frequency. TL_u and TL_d, account for the multiple wave reflections in the upstream and downstream cavities inside the double wall structure, respectively. They are given by

$$TL_u = -20\log\left(\frac{1}{\left|1 - r_1 r_{p1} e^{-2jk_0 D_1}\right|}\right) \tag{3}$$

and

$$TL_d = -20\log\left(\frac{1}{\left|1 - r_2 r_{p2} e^{-2jk_0 D_2}\right|}\right) \quad (4)$$

Here, k_0 is the wave number in the fluid. r_1 is the reflection coefficient at the front face of the blanket backed by an air gap of thickness equal to the thickness of the downstream cavity and the second panel. The second panel can be replaced by a rigid and immobile termination in the calculation of r_1, leading to a discrepancy in the estimation of the mechanical behavior of the double wall structure in the low frequency range around the Double Wall Resonance (DWR) frequency[4]. r_2 is the reflection coefficient at the rear face of the blanket when backed by an infinite air layer. TL_m, accounts for the sound transmission loss of the sound absorbing blanket.

The two reflection coefficients, r_1 and r_2, are measured in an impedance tube according to the standard ISO-10534-2 [6]. A schematic view of the impedance tube setups to measure r_2 and r_1 are shown in Figs. 1(b) and (c) respectively. The normal incidence sound transmission loss of the sound absorbing blanket TL_m is measured using the 3-microphone method recently proposed by Salissou [7] (see Fig. 1(d)).

Finally, r_{p1} and r_{p2} used in Eqs. (3) and (4) are the reflection coefficients of the first and second panels respectively and are also derived knowing the surface mass density of each panel as

$$r_{pj} = \frac{j\omega m_{sj}}{2Z_0 + j\omega m_{sj}} \quad (5)$$

The plates behavior (i.e., TL_{p1}, TL_{p2} , r_{p1} and r_{p2}) can be easily modeled knowing their surface densities only using Eqs. (2) and (5), or using the classical Transfer Matrix Method (TMM).

It is worth mentioning that the blanket transmission loss contributions determined under normal incidence excitation (due to impedance tube measurements) are considered to be sufficiently representative of the material behavior to be used as criteria for real double wall structure optimization. This assumption represents the main practical limitation of the proposed method.

3 VALIDATION ON A FIBERGLASS LAYER

First, the validity of the proposed experimental method is checked by comparison with a full TMM solution in the case of an aeronautic-type double wall configuration. The 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. Specifically, the upstream cavity D_1 is set to 2 mm and the downstream cavity D_2 to 25.4 mm (1.0 in.). The TMM solution requires a proper fiberglass modeling[8]. Since the porous layer is not directly bonded on the vibrating panel in this case, it is considered acoustically limp[8], i.e. the frame can move and its inertia effect is taken into account. The fiberglass parameters are given in Table 1.

Figs. 2 (a)-(c) present TMM simulations and impedance tube measurements of the absorption coefficient related to r_1, r_2 ($\alpha_i=1-|r_i|^2$, i=1, 2) and the sound transmission loss of the foam TL_m. As shown in Figs. 2 (a)-(c), there is a good agreement between measurements and simulations. The underestimation of TL_m in the high frequency range is attributed to the sample mounting conditions. When set in the impedance tube, part of the 3.5 in. limp fibrous sample is subjected to frame compression which induces a higher airflow resistivity and thus a higher sound transmission loss than the one predicted by TMM.

The measured reflection coefficients and sound transmission loss are then used in Eqs. (3) and (4) to determine the sound transmission loss contributions TL_u and TL_d and finally Eq. (1) is used to estimate the normal incidence sound transmission loss of the double wall structure. Fig. 2(d) presents the comparison between the TL of the double wall structure estimated from the proposed method (solid black line), the TMM simulation (dashed grey line) and the TL simulation of the empty structure (solid grey line). Note that the simulation of the empty structure is also determined from Eq. (1). It is shown that the proposed experimental determination of double wall structure transmission loss gives the same result compared to the reference TMM model. The reflection coefficient r_1 being measured in an impedance tube, the second panel is replaced by the rigid termination of the tube. Note that, as known, the effect of fiberglass starts mainly at the first resonance of the cavity (see Fig. 2(d)); $f=c_0/2(D_1+D_2+d)$~1500 Hz, with c_0 is the speed of sound in air. It attenuates the dips of insulation controlled by the cavity resonances around 1.5 kHz and 3 kHz and improves the insulation at high frequencies.

4 APPLICATION ON A MULTILAYER SOUND PACKAGE

As mentioned in reference[5], the prediction of the multilayer blanket behavior (i.e, TL_u, TL_d, TL_m) using the classical TMM is not straightforward since the non-acoustic properties of each layer constituting the blanket have to be known (i.e. requires independent measurement of their Biot properties) together with the details of the interlayer-interface conditions. The latter are not always known, in real life applications, making modeling of the multilayer with the TMM inaccurate. The alternative proposed by this method is thus to determine the transmission loss contributions of the sound absorbing blanket from three impedance tube measurements of the blanket acoustic properties (i.e. r_1, r_2 and TL_m). It is used in reference[5] to demonstrate (i) the effect of frame compression of a 2 inch fiberglass in an aeronautic-type double wall structure and (ii) the effect of double porosity with or without porous inclusions in a building-type double wall structure. It is worth stressing that great care is needed during tube measurements to ensure that the measured behavior is representative of the large scale sound package behavior (especially the alleviation of mounting conditions). It follows that the frequency bands where frame effects are predominant (e.g., frame resonances, spring mass resonances,…) have to be discarded from the analysis because tube measurements are extremely influenced by the sample mounting conditions at these frequencies.

The work presented in this section focuses on the effect of interlayer-interface conditions. The double wall structure is filled with a porous multilayer constituted by a non-woven screen in between two melamine 1-inch thick samples. The main goal is to investigate how TMM interlayer-interface conditions (i.e., continuity of stress and velocity between layers, see ref. [8] p°257) match real interlayer-interface conditions of a multilayer set in an impedance tube.

4.1 Effect of interlayer-interface conditions

The effect of interlayer-interface conditions is investigated from TMM simulations and tube measurements in the case of the bi-layer composed by 1-inch thick melamine sample covered by a thin non-woven screen (0.35 mm thick). The two materials are modeled using the limp frame model and their non-acoustic parameters are given in Table 1. Non-woven are highly porous and highly resistive materials. They are mainly used as bi-permeable concepts[9] in automotive applications and allow improvement of the absorption at low and mid frequencies without losing too much at high frequencies. The acoustic indicators are the normal incidence sound transmission loss TL_m and the absorption coefficient when the porous layer is backed by a 1-inch air cavity ($\alpha=1-|r_1|^2$). The experimental setup is described in Fig. 3(a). Plastic rings are used here to maintain the multilayer at the desired position and minimize the leaks around the sample. Figs. 4 (a), (b), (d) and (e) show that the two monolayers can be correctly modeled using TMM and the equivalent limp frame model except at some local frequencies due to boundary condition impact and frame resonances. In the case of the thin non-woven screen, the numerous peaks and deeps appearing at low frequencies are due to bending vibration modes[10]. The model does not take into account these bending vibrations but still allows a good estimation of the mean behavior.

Acoustic performances of the bi-layer “Non-Woven/Melamine” are now investigated with the three interlayer-interface conditions shown in Fig. 3(b): (i) without adhesive, (ii) with a mesh of adhesive points (each 4.5mm) and (iii) with the whole surface covered by adhesive. The adhesive used in the experiment is a glue applied with a spray-can. Figs. 4 (c) and (f) show that the first two interlayer-interface conditions, i.e., without glue (triangles) and mesh of glue points (circles), provide an acoustic behavior in good agreement with TMM simulations (solid grey curve). The interlayer-interface condition involving adhesive on the whole surface (squares), shows lower absorption in the mid and high frequency range but a significant improvement of the sound transmission loss (+5 dB above 2 kHz). These two phenomena are due to the non-woven microstructure modification with the presence of glue leading to different non-acoustic properties: important increase of the density (×4), airflow resistivity (×2), tortuosity and decrease of the porosity. Modified parameters of the non-woven screen covered by the glue are estimated and given in Table 1. Simulations of the performances of the bi-layer with glue are also presented with dashed grey line in Figs. 4 (c) and (f). TMM simulations using these modified parameters still allow a good prediction of the multilayer behavior including the effect of glue (mainly an added mass effect). This stresses the importance of correctly characterizing the interface conditions in TMM simulations (or with any other method for this matter). Conversely, the importance of transposing carefully predictions based on ideal multilayered materials to real life ones.

4.2 Normal incidence sound transmission loss

The proposed method is now applied to a three-layer blanket made up of a non-woven screen in between two 1-inch thick melamine layers. According to previous conclusions, no glue is used between the layers. The double wall structure considered here consists of two 1 mm thick, aluminum panels separated by 116 mm (4.5 in. as in sec. 3) partially filled with the multilayer (see Figure 1). The upstream cavity D_1 is 38.1 mm thick (1.5 in.) and the downstream cavity D_2 is 25.4 mm thick (1 in.).

Figs. 5 (a)-(c) present TMM simulations and impedance tube measurements of the absorption coefficient related to r_1, r_2 and the sound transmission loss of the foam TL_m. As shown in Figs. 5 (a)-(c), there is a good agreement between measurements and simulations except around 950 Hz due to a frame resonance. As suggested by the presented method, the measured reflection coefficients and sound transmission loss are now used in Eqs. (3) and (4) to determine the sound transmission loss contributions TL_u and TL_d and finally Eq. (1) is used to estimate the normal incidence sound transmission loss of the double wall structure. Results are presented in Fig. 5(d). It is shown that the method correctly estimates the normal incidence sound transmission loss of the complex multilayer. The frame related damped resonance appearing in Figs. 5 (a)-(c) also appears in the experimental estimation of the transmission loss (Fig. 5(d)); the frequency band around 950 Hz should be discarded.

5 CONCLUSIONS

This paper presented a simple experimental method to estimate the normal incidence sound transmission loss contributions of complex sound packages filling a double wall structure from three impedance tube measurements of the sound package alone. It is based on a model recently proposed by the authors[4,5] which allows one to derive the sound transmission loss of the structure from the estimation of the absorption and transmission loss contributions of the sound package inside the structure. The proposed method requires three impedance tube measurements: two reflection coefficients at the front and rear face of the blanket placed in specific positions characteristic of its position inside the double wall structure and its transmission loss coefficient. The method is first validated experimentally in the case of a double wall structure filled with a fiberglass material. Next, it is used to highlight experimentally the effects of interlayer-interface conditions. It is shown, in impedance tube conditions, that the interlayer-interface conditions considered in TMM model correspond experimentally to the case where the layers are simply put together with little or none adhesive. Adding too much adhesive affects the behavior of the porous layers since it adds considerable mass and closes the pores at a microscopic scale. In the case of the used non-woven screen, the glue added to the layer transforms the highly porous screen into an impervious heavy layer.

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Table 1 Properties of the material samples

Material properties	Fiberglass	Melamine	Non-Woven screen	Non-Woven screen with glue
porosity	0.99	0.99	0.95	0.6
Density (kg/m^3)	5.5	8.5	200	800
Airflow resistivity (Ns/m^4)	14 000	11 000	2 875 000	6 000 000
Tortuosity	1	1.01	1.2	1.6
Viscous length (μm)	70	80	30	30
Thermal length (μm)	107	150	60	60

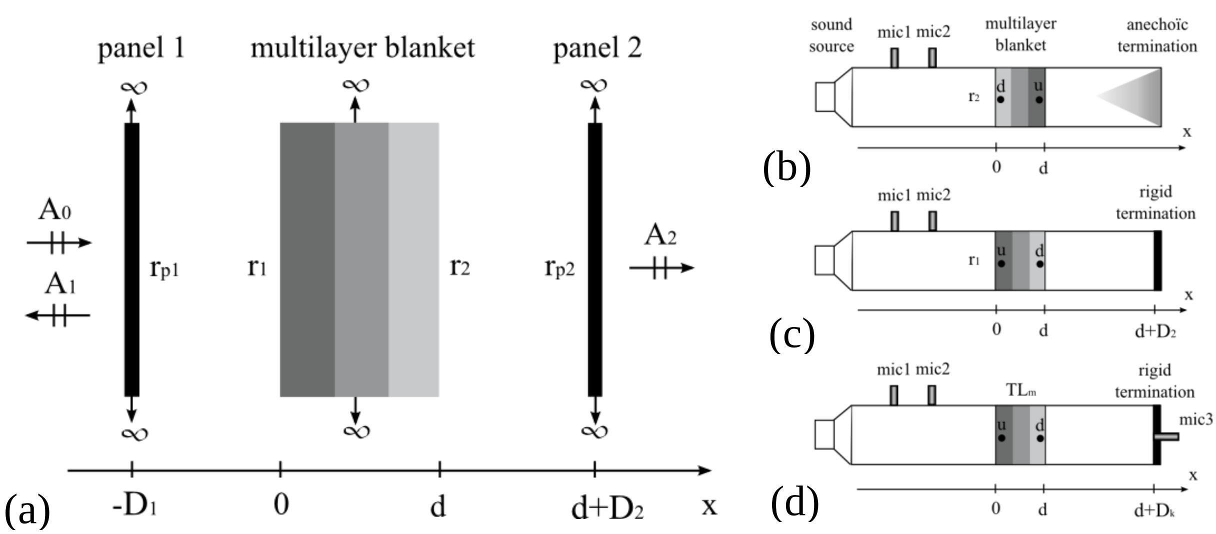

Fig. 1 - (a) Schematic view of the double wall structure[4]; Schematic view of the three impedance tube setups[5]: (b) measurement of r_2, (c) measurement of r_1, (d) measurement of TL_m.

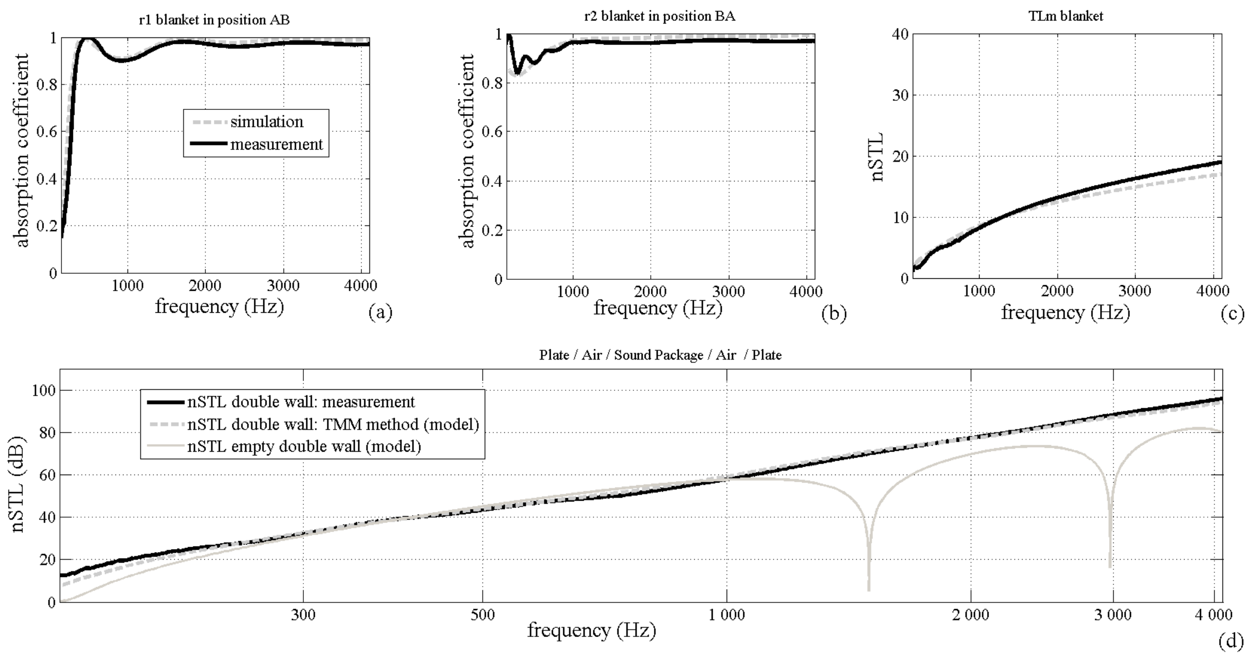

Fig. 2 - 3.5 inch fiberglass: (a) absorption coefficient related to r_1 *with* D_2*=25 mm (b) absorption coefficient related to* r_2 *(c) sound transmission loss* TL_m, (d) *Normal incidence sound transmission loss of the empty double wall structure or filled in with the fiberglass.*

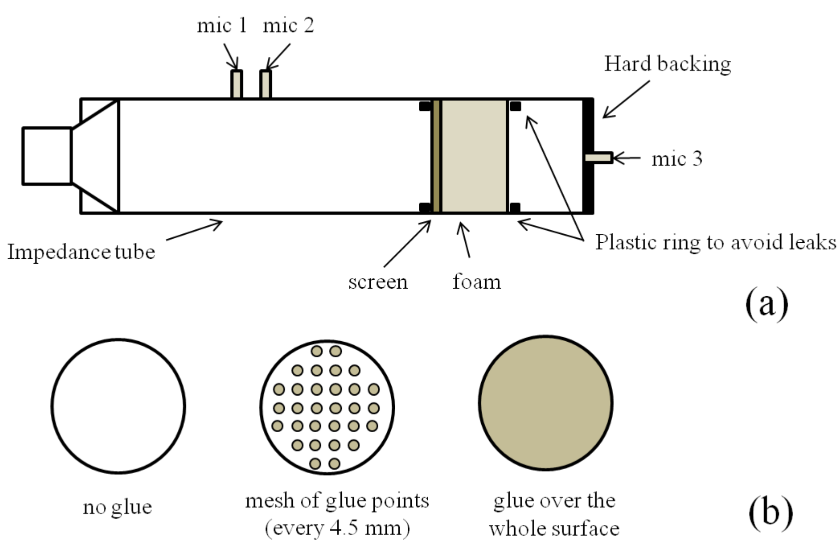

Fig. 3 - Schematic view of the (a) *impedance tube setup for multilayer measurements: (b) three interlayer-interface condition.*

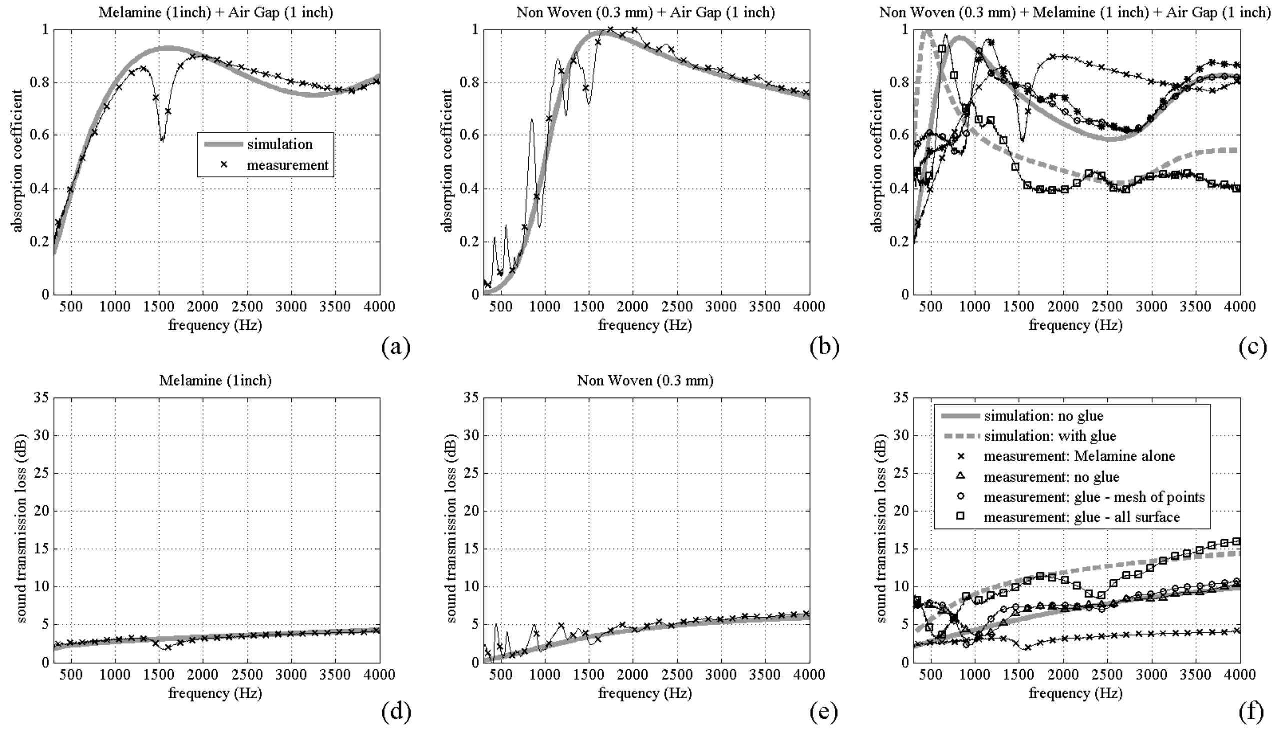

Fig. 4 - Melamine (a) absorption coefficient (d) sound transmission loss TL_m; Non-Woven (b) absorption coefficient (e) sound transmission loss TL_m; Bi-layer "Now-Woven/Melamine" (c) absorption coefficient (f) sound transmission loss TL_m.

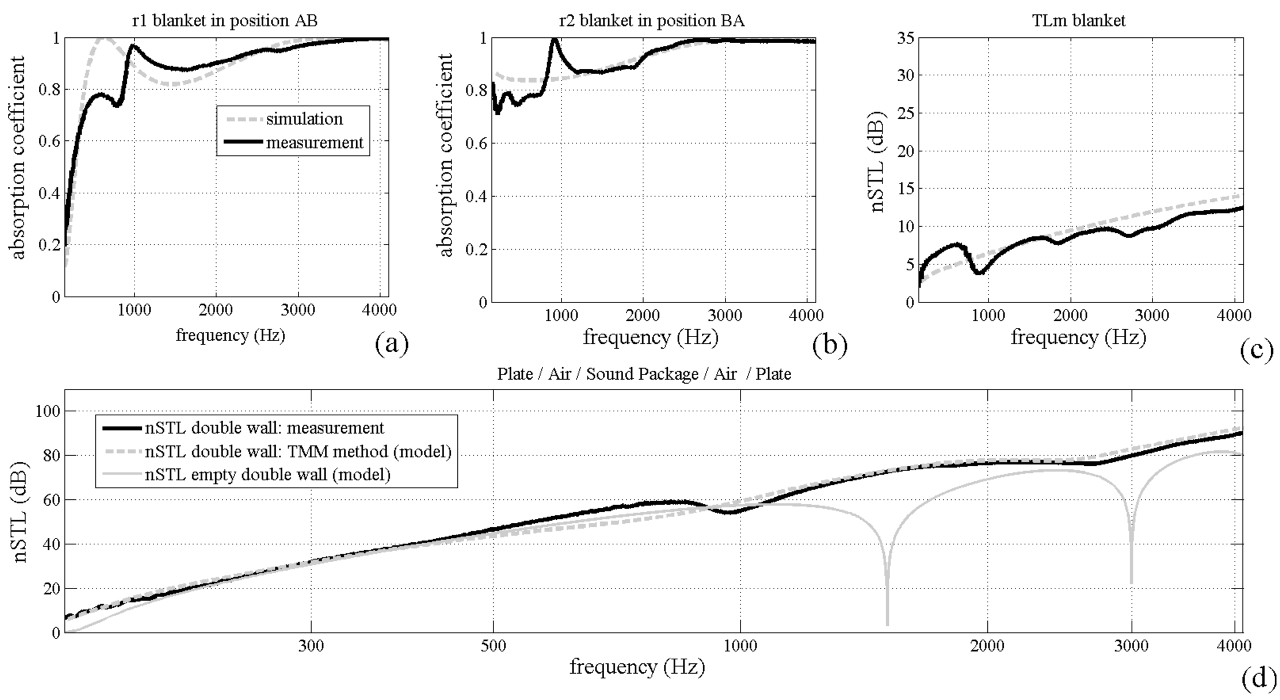

Fig. 5 - multilayer sound package: (a) absorption coefficient related to r_1 *with* D_2*=25 mm (b) absorption coefficient related to* r_2 *(c) sound transmission loss TL_m*, (d) *Normal incidence sound transmission loss of the empty double wall structure or filled in with the multilayer.*