Improvement of Low Frequency Sound Absorption of Acoustical Materials

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Abstract

The acoustic materials are porous in nature and they have inherent problem of low sound absorption in the low frequency range, say up to 500 Hz. This low frequency range is widely prevalent in automotive structures and power plants. It becomes a challenge for the NVH designer to find out appropriate solutions with a combination of materials to attenuate the noise at these low frequencies. Some of the techniques, which are employed for this typical problem, are increasing the thickness or density of the porous materials, air gap, use of membrane sound absorbers with impervious films, etc. This paper presents a methodology for prediction of sound absorption of multilayer systems using computer simulation based on existing three models and their validation. It is concluded that existing models are not accurate enough to use at low frequencies.

1. Introduction

Acoustic porous materials are widely used for noise control applications at many places in automotive as well as in building acoustics. In automotives, low frequency noise is more predominant. The acoustic materials used for noise control at these places lack the capacity to reduce this low frequency noise, generally below 500 Hz. To solve this problem, some of used are air gaps and Impervious Films (IFs). Air gaps give good sound absorption at lower frequencies even though they require larger depths as shown in Fig. 1 [1]. IFs achieve this by shifting the peak absorption from high to low frequencies. In addition, they act as protective cover; however it come at a cost.

This paper uses three widely used models for predicting the bulk acoustic properties of foams, fibrous materials and IFs. A code has been developed to compute the sound absorption coefficient of multilayers using the above models by calculating the transfer matrix for each layer of porous material and normal surface impedance of the multilayer systems. The codes were validated with two microphone impedance tube for foam, fibrous materials, air gaps and IFs and their combinations. Based on the validations, the suitability of these models for low frequency absorption coefficients are reviewed.

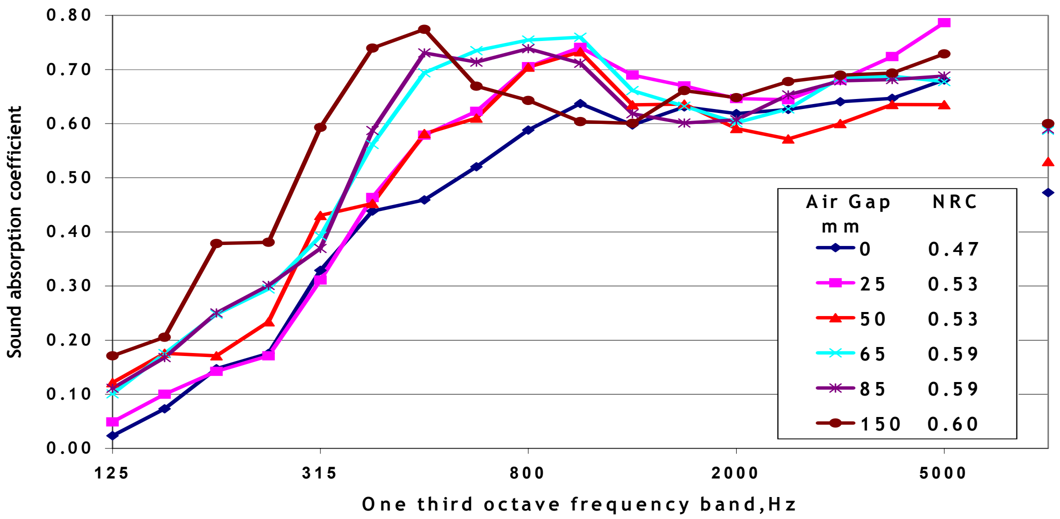

Fig 1: Effect of Air gap on random incidence sound absorption coefficient for Foam, 25mm thick and density 70 kg/m^3

2. Models for bulk acoustic properties

2.1 Model for Foams

The empirical model for foam and fibrous materials used is Allard-Champoux [2]. This model is based on dynamic permeability and tortuosity in porous media and includes the characteristic length to describe the high frequency behaviour of the dynamic density and complex compressibility of air in porous materials.

The dynamic density $\rho(\omega)$ and complex compressibility $K(\omega)$ are given by equations (1) and (2).

$$\rho(\omega) = \rho_0 \alpha_\infty \left[1 + \frac{\sigma\phi}{j\omega\rho_0\alpha_\infty} \sqrt{\frac{4j\alpha_\infty{}^2\eta\omega}{\sigma^2\Lambda^2\phi^2}} \right] \text{........................ (1)}$$

$$K(\omega) = \gamma P_0 \left[\frac{\gamma - (\gamma - 1)}{1 + \dfrac{8\eta}{j\Lambda' N_{pr}\omega\rho_0} \sqrt{1 + j\rho_0 \dfrac{\omega N_{pr}\Lambda'}{16\eta}}} \right]^{-1} \text{.............. (2)}$$

where ϕ is porosity, σ is flow resistivity, α_∞ is tortuosity, Λ is viscous characteristic length, Λ' is thermal characteristic length, ρ_0 is density of fluid, P_0 is atmospheric pressure, γ is specific heat ratio N_{pr} is Prandtl number, η is coefficient of viscosity of air and ω is circular frequency.

The characteristic impedance $Z(\omega)$ and propagation constant $\Gamma(\omega)$ are predicted using equation (3) and (4).

$$Z(\omega) = \sqrt{\rho(\omega)K(\omega)} \text{.................................... (3)}$$

$$\Gamma(\omega) = j\omega[\rho(\omega)/K(\omega)] \text{................................ (4)}$$

2.2 Model for Fibrous Materials

For fibrous materials, the empirical model of Delany & Bazley [3] is used. These are based on power laws obtained from fitting the curves for experimental data. This model requires only one parameter viz. flow resistivity, which is easily measurable. This works very well over a limited frequency range [4]. The characteristic impedance $Z(\omega)$and propagation constant $\Gamma(\omega)$are predicted using equations, (5) and (6).

$$Z(\omega)=\rho_0 c\left[1+0.0571(\rho_0 f/\sigma)^{-0.754}-j0.087(\rho_0 f/\sigma)^{-0.732}\right] \ldots\ldots\ldots\ldots\ldots \text{(5)}$$

$$\Gamma(\omega)={}^{j\omega}\!/_{c}\left[1+0.0978(\rho_0 f/\sigma)^{-0.700}-j0.189(\rho_0 f/\sigma)^{-0.595}\right] \ldots\ldots\ldots\ldots \text{(6)}$$

where f is frequency in *Hz*, σ flow resistivity in *rayls/m* and c is speed of sound in *m/s*.

2.3 Model for Impervious films (IF) with Porous Absorbers

In case of impervious films, Bies & Hansen model is used to find the normalized impedance [5]

$$Z_f = j\,2\pi\,\rho_0 c f\,\sigma' \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

where f is frequency of incident sound and σ' is mass per unit area.

3. Transfer Matrix Method for single and multilayer porous materials

3.1 A simple Transfer Matrix Method (TMM) [6-9] is used to model the design configurations. The general representation for a Transfer matrix of a single layer acoustic system (Fig.2) is

$$\begin{bmatrix} P_r \\ V_r \end{bmatrix} = \begin{bmatrix} T_1 \end{bmatrix} \begin{bmatrix} P_{r+1} \\ V_{r+1} \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

Where P_r is sound pressure and V_r is sound velocity and T_{11}, T_{12} T_{21} & T_{22} are four pole parameters or transfer matrix elements.

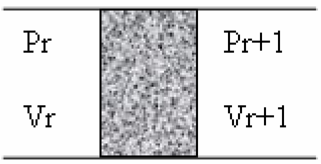

Fig.2

3.2 For foam and fibrous materials of thickness, l, the transfer matrix is given as

$$T_1 = \begin{bmatrix} \cos(\Gamma(\omega).l) & {}^{j}\!/_{Z(\omega)}.\sin(\Gamma(\omega).l) \\ j\,Z(\omega).\sin(\Gamma(\omega).l) & \cos(\Gamma(\omega).l) \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

where $Z(\omega)$ and $\Gamma(\omega)$ are characteristic impedance and propagation constant respectively.

3.3 For an air gap of depth , d , the transfer matrix is given by

$$T_2 = \begin{bmatrix} \cos(k_0 d) & {}^{j}/_{\rho_0 c}.\sin(k_0 d) \\ j\rho_0 c.\sin(k_0 d) & \cos(k_0 d) \end{bmatrix} \quad (10)$$

where ρ_0 is density of air and c is velocity of sound and $k_0 = \omega / c$.

3.4 Similarly for IFs, the transfer matrix is represented as

$$T_3 = \begin{bmatrix} 1 & Z_f \\ 0 & 1 \end{bmatrix} \quad (11)$$

where Z_f is normalized impedance of the IF.

3.5 For multilayer configuration, the overall Transfer Matrix , T , is obtained by multiplying the above matrices for required configuration.

$$[T] = [T_1][T_2].......[T_n] \quad (12)$$

The total impedance Z_s is given by

$$Z_s = \frac{P_r}{V_r} = jZ(\omega)\coth\left[\Gamma(\omega).d\right] \quad (13)$$

The normal incidence sound absorption α for an absorbing material with rigid backing is given by

$$\alpha = 1 - \left| \frac{Z_s - \rho_0 c}{Z_s + \rho_0 c} \right|^2 \quad (14)$$

4. Work Carried Out

4.1 Experimental Set up

The measurements were conducted by two microphone impedance tube method in accordance with ISO 10534-2 [10]. The lower and upper limiting frequencies for this tube is 125 Hz and 2000 Hz. The experimental setup is shown in Fig. 3.

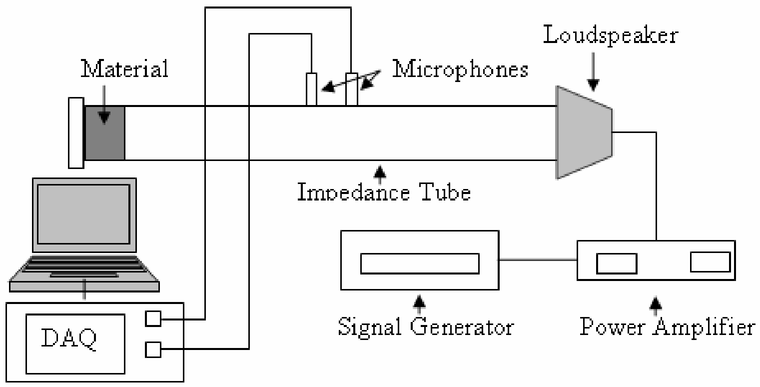

Fig. 3 Schematic of Experimental Setup for Normal Incidence Sound absorption coefficient

4.2 Material Combination

The following material combinations were tried out:

1. Foam with density of 32 kg/m^3 , l = 0.025 m, σ =4500 $rayls/m$, ϕ =0.97
2. Combination of 1 + air gap of 25 mm
3. Combination of 1 + IF with surface density of 0.055 kg/m^2, thickness =50 μ m, facing the source
4. Glass wool with density of 48 kg/m^3, l = 0.025 m , σ =6500 $rayls/m$, ϕ =0.98
5. Combination of 4 +air gap of 25 mm
6. Combination of 4 + IF with surface density of 0.055 kg/m^2, thickness =50 μ m, facing the source

The porosity, ϕ, and flow resistivity, σ, were experimentally determined according to ISO 4590 and 9053 respectively. The following properties were assumed α_∞ =1, Λ =125 μm, Λ' =150 μm, c =340 m/s, N_{pr} =0.707, ρ_0 =1.29 kg/m^3, P_0 =101320 N/m^2, η =1.84e-5 $kg\,m^{-1}s^{-1}$ and γ =1.4. All the configurations were tested with a rigid backing of steel plate of 25 mm thick in the impedance tube and the measured results were compared with predicted ones.

5. Results

5.1 Foam (Combination -1), Foam with Air gap (Combination-2) and Foam with IF (Combination-3)

Figure 4(a) compares the experimental and simulated results for the three combinations of foam viz. only foam, foam with air gap and foam with IF.

The simulated results compare well with the experimental ones upto 1100 Hz for foam alone and foam with air gap. For foam with IF the measured one is much higher than predicted at almost all frequencies when looked closely upto 500 Hz, (of our interest), as seen from Figure 4(b), the prediction for foam alone and foam with air gap is reasonably matching between 250 Hz and 500 Hz. For foam with film there is no matching at all.

Table I compares the average SAC (arithmetic average of values at 125 Hz, 200 Hz, 300 Hz, 400 Hz and 500 Hz) of computed and measured values. Here again, there is a reasonable match for foam alone and air gap while substantial difference is present for foam with IF.

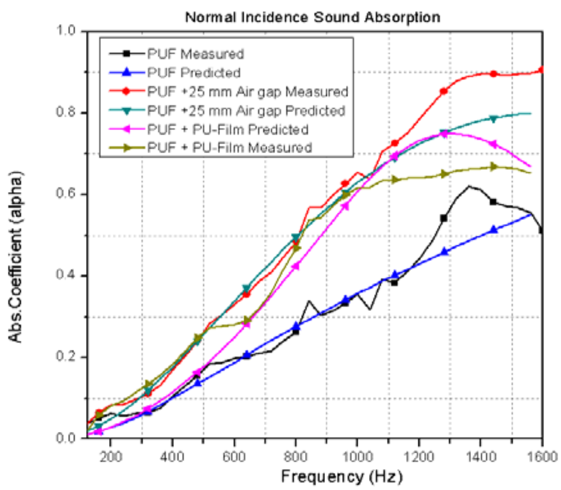

Fig. 4(a) Comparison of SAC for Foam

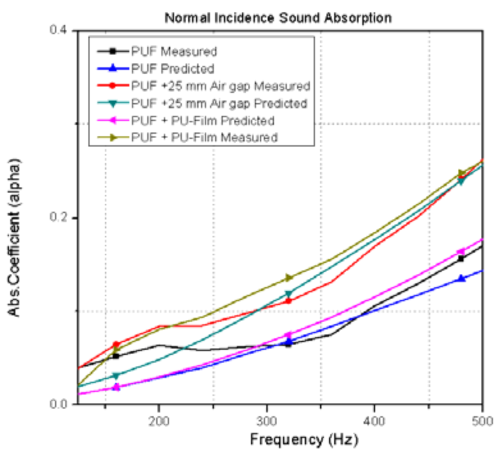

Fig. 4(b) Insight upto 500 Hz

Table I. Average SAC of Foam with Configurations

Material	Configuration	Avg. SAC Pre.	Avg. SAC Mea.
Foam	Nil	0.09	0.07
	25 mm Air gap	0.13	0.14
	PU-Film	0.10	0.14

5.2 Glass wool (Combination -4), Glass wool with Air gap (Combination-5) and Glass wool with IF (Combination-6)

Figure 5(a) compares the experimental and simulated results for the three combinations of glass wool viz.only glass wool, glass wool with air gap and glass wool with IF.

The simulated results compare well with the experimental ones upto around 1100 Hz for glass wool alone and air gap. For IF the measured one is much higher than predicted almost at all frequencies. When looked closely upto 500 Hz, (of our interest), as seen from Figure 5(b), none of the prediction is matching with experimental values. This is also confirmed by Table II which compares the average SAC (arithmetic average of values of 125 Hz, 200 Hz, 300 Hz, 400 Hz and 500 Hz) of computed and measured values.

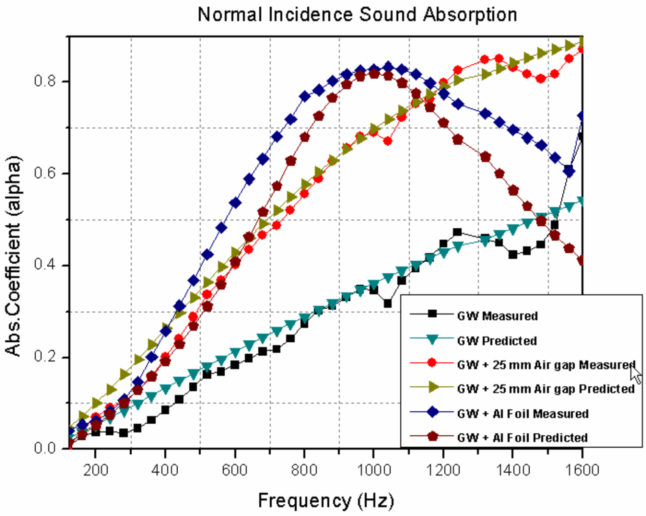

Fig. 5(a) Comparison of SAC for Glass wool

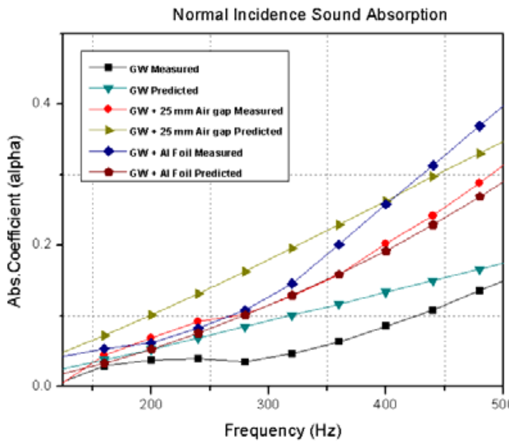

Fig. 5(b) Insight upto 500 Hz

Table II. Average SAC of Glass wool with Configurations

Material	Configuration	Avg. SAC Pre.	Avg. SAC Mea.
Glass wool	Nil	0.07	0.10
	25 mm Air gap	0.15	0.19
	AL Foil	0.14	0.19

6. Discussions

6.1 Foam

It is found that the predicted results are not matching at low frequencies. The problem may be due to the model used for prediction as well as the accuracy of the number of properties assumed. Also another possible reason for the mismatch could be Transfer Matrix Method itself does not work well at low frequencies but good at mid and high frequencies [11]. This could be the reason why the there is a reasonable match for frequencies above 500 Hz. In case of foam with IF, the model used for IF may not be accurate and need substantial improvement in the formulation over the complete frequency range.

6.2 Fibrous Material

It is observed that the predicted results are not matching for glass wool and air gap at low frequencies. The problem may be due to empirical model used for prediction. Also another possible reason for the mismatch could be Transfer Matrix Method itself does not work well at low frequencies but good at mid and high frequencies. In case of glass wool with IF, the problem may be cumulative of both the inaccuracies in the fibrous model as well as IF.

7. Conclusions

A method for predicting normal incidence sound absorption coefficient for multi layers with various configurations was presented. This technique provides prediction of low frequency noise absorption with multi layers using foam and fibrous materials along with air gap, and impervious films. The prediction used three different models available in literature. The experimental validation on six different combinations uses a two microphone impedance tube according to ISO 10534-2. For foam and foam with air gap, the prediction was reasonably good at higher frequencies while this was not so at low frequencies. The possible reasons could be the accuracy of the models used for prediction, that of the number of properties assumed and the transfer matrix method itself. In the case of fibrous materials, the case is still worse. It is concluded that existing models are not accurate enough to use at low frequencies and there is a need to develop more accurate models.

7. Acknowledgement

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