Journal of Acoustical Society of India : Vol. 38, No. 2, 2011 (pp. 53-58)

Simulation and Validation of Sound Absorption Coefficient Measured in a Reverberation Room

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[Received: 16.12.2010; Revised: 25.02.2010; Accepted: 24.03.2011]

ABSTRACT

Poro-elastic materials play a vital role in passive noise control. These materials are used in the form of sound absorbers in various applications like in automotives, gensets and building acoustics. These materials are tested in reverberation room as per ISO 354 or ASTM 423 standards for random incidence sound absorption coefficient (RISAC) which gives true value in diffuse field as compared to impedance tube method as per ISO 10534 for normal incidence sound absorption coefficient (NISAC). As per international standards, the measurement in reverberation room requires large sample sizes, specialized facility and testing time. To save time and cost required for the measurement in reverberation chamber, OEM's are tending towards prediction of acoustic behaviour of noise control materials using mathematical models which requires macroscopic parameters of porous materials like flow resistivity, porosity etc. These parameters can be measured using direct experimental methods or they can be inverted from measured sound absorption coefficient from impedance tube using inversion methods. This paper discusses theoretical background of the numerical simulation of RISAC measured in a reverberation room and also the effect of sample size and angle of incidence on RISAC. These simulated results are validated with experimental results.

1. INTRODUCTION

Sound absorbing poroelastic materials consists of continuous solid elastic material interconnecting pores generally referred as frame with interstitial fluid (i.e. air) inside them. These poroelastic materials dissipate acoustical energy into heat as a result of interaction of their solid and fluid phases. In particular, they convert the acoustical energy into heat by thermal means (irreversible heat flow from interstitial fluid to fibres or pores forming the frame), by means of viscous means (associated with oscillatory shearing of the fluid in the vicinity of the frame surface) as well as through structural means (irreversible losses associated with flexure of the fibres or pores comprising the frame). The acoustic performance of these materials is evaluated in terms of sound absorption and sound transmission loss measured in impedance tube as per ISO 10534-2 and Reverberation suite as per ISO 354 [1, 2]. In impedance tube, sound absorption is measured experimentally using small samples with plane wave excitation. But in practical, materials of different sizes and shapes are used in noise control applications and acoustic field in diffuse field (i.e. sound waves come from various physical phenomenons like reflection, refraction and scattering). So sound absorption measured in impedance tubes can not give actual idea of sound absorption in reverberant field. Hence sound absorption of poroelastic materials is measured in Reverberation room in diffused field. In this paper, first theory behind poroelastic materials is discussed in detail with complete material characterization. At the end, experimental results are validated using mathematical modelling using Johnson-Champoux-Allard model.

2. POROELASTIC MATERIALS AND MODELLING

In this section, Johnson-Champoux-Allard (JCA) [3] model is discussed which uses all five macroscopic physical parameters viz. flow resistivity, porosity, tortuosity and the characteristics lengths to predict the performance of a porous absorber. In this model the frame of this material assumed to be acoustically rigid (motionless) over a wide range of frequencies. In this case, the porous material can be replaced on a macroscopic scale by an equivalent fluid of effective dynamic density and effective bulk modulus. The motionless frame condition can occur either because of high density or elasticity modulus, or because of particular boundary conditions imposed during the test. The characteristic impedance and the complex wave number of the porous specimen are related to the effective properties of the porous medium as follows

$$z_c = \sqrt{\rho_c K_c} \tag{1}$$

$$k_c = j\omega\left[\rho_c / K_c\right] \tag{2}$$

The dynamic density and complex bulk modulus for Johnson Model are given by following equations.

$$\rho_c = \rho_0 \alpha_\infty \left[1 + \frac{\sigma\varphi}{j\omega\rho_0\alpha_\infty}\sqrt{\frac{4j\alpha_\infty{}^2\eta\omega}{\sigma^2\Lambda^2\varphi^2}}\right] \tag{3}$$

$$K_c = \kappa P_0 \left[\kappa - (\kappa-1) \Big/ 1 + \frac{8\eta}{j\Lambda' N_{pr}\omega\rho_0}\sqrt{1 + j\rho_0\frac{\omega N_{pr}\Lambda'}{16\eta}}\right]^{-1} \tag{4}$$

2.1 Transfer Matrix Approach

In this section, transfer matrix method (TMM) used to predict acoustic behaviour of sound package materials is explained [4]. The general representation for a Transfer matrix of a single layer acoustic system is

$$\begin{bmatrix} P_n \\ V_n \end{bmatrix} = \left[T\right] \begin{bmatrix} P_{n+1} \\ V_{n+1} \end{bmatrix} \tag{5}$$

Where P_n is sound pressure and V_n is sound velocity and T_{11}, T_{12}, T_{21} & T_{22} are four pole parameters or transfer matrix elements. For foam and fibrous materials of thickness d, the transfer matrix is given as

$$T = \begin{bmatrix} \cos(k_c.d) & j/z_c.\sin(k_c.d) \\ j z_c.\sin(k_c.d) & \cos(k_c.d) \end{bmatrix} \tag{6}$$

where, Z_e and K_c are characteristic impedance and complex wave number respectively. The total impedance Z_s is given by

$$Z_s = j z_c \coth\left(k_c.d\right) \tag{7}$$

When the pressure amplitudes for the incident and reflected sound waves on the surface are A and B respectively, the complex amplitudes of the pressure and particle velocity on the surface of the acoustic system can be expressed in terms of P_{n+1} and V_{n+1} for the right end matrix, as follows

$$A+B = P_1 = T_{11} P_{n+1} + T_{12} V_{n+1} \tag{8}$$

$$(A-B)/ \rho_0 C_0 = V_1 = T_{21} P_{n+1} + T_{22} V_{n+1} \tag{9}$$

Since the particle velocity $V_{n+1} = 0$ on a rigid wall, the pressure reflection coefficient $R=A/B$ can be expressed by the transfer matrix elements as

$$R = \frac{T_{11} \cos\theta - \rho_0 c_0 T_{21}}{T_{11} \cos\theta + \rho_0 c_0 T_{21}} \tag{10}$$

The random incidence sound absorption coefficient and transmission loss can be evaluated by considering random incidence and integrating over angles 0° to 90° using Paris's formula as follows.

$$\alpha_{random} = \int_{\theta_{min}}^{\theta_{max}} \alpha(\theta).\cos\theta.\sin\theta \, d\theta \tag{11}$$

where θ is the limiting angle varying between θ_{min} and θ_{max}. Generally the limiting angle is in between 70° to 85°. In theory, the area of the sound absorber is assumed to be infinite, but this is not the case. As mentioned in ISO 354, finite area of the absorber is used for measurement. Thomson has shown that finite size of a sample has large effect on sound absorption of the sample [5]. Then the corrected formula for finite size of the sample is given as

$$\alpha_f = \frac{4\,\mathrm{Re}(Z_s)}{\pi} \int_0^{\pi/2} \int_0^{2\pi} \frac{\sin\varphi}{\left|Z_s + Z_f\right|^2} d\varphi d\theta \tag{12}$$

where, Z is the normalized surface impedance and is the field impedance and related to radiation impedance.

3. EXPERIMENTAL TECHNIQUES

In this section, experimental techniques used to measure intrinsic physical parameters and acoustic parameters are discussed. The performance of sound absorbing materials can be predicted with prior measurement of five intrinsic physical parameters like porosity, flow resistivity, tortuosity, viscous and thermal characteristic lengths and three mechanical parameters like Young's modulus, Poisson ratio and loss factor. The experimental measurement of these parameters requires specialized test rigs like; porosity is measured using an air porosity meter based on Boyle's law [6]. Flow resistivity is measured using flow resistivity test rig based on ASTM C522 standard [7]. Tortuosity and characteristic lengths are inverted using optimization technique based on Genetic Algorithm [8]. This technique requires prior measurement of sound absorption coefficient with surface impedance using two microphone impedance tube, porosity and flow resistivity to fit a mathematical model. The global solution of this optimization problem gave tortuosity and characteristic lengths. In this study only five physical intrinsic parameters were considered for simulation as mechanical parameters does not affect acoustic behaviour of sound absorbing materials. In this study, four samples like PU foam-26 kg/m^3, PET felt-24 kg/m^3, Cellular rubber-140kg/m^3 and Polyester felt-32kg/m^3 were chosen and their random incidence sound absorption coefficient was measured in Reverberation chamber as per ISO 354. In this room an Omni-directional source was placed to create diffused field inside the reverberation room as shown in Fig. 1. A large sample of size 6 m^2 is used to measure random incidence sound absorption coefficient. The method is based on the calculation of two reverberation times T_1 and T_2 with and without the sample. The equivalent sound absorption area A_1 of the empty reverberation room and with sample of area A_2 is calculated as

$$A_1 = \frac{55.3V}{c_0 T_1} - 4Vm_1 \quad A_2 = \frac{55.3V}{c_0 T_2} - 4Vm_2 \tag{13}$$

where, V is the volume of the empty reverberation room in cubic meters, C_o is the speed of sound in meters per second, T_1 is the reverberation time in seconds of the empty reverberation room, T_2 is the reverberation time in seconds of the reverberation room with specimen placed inside the room and is the power attenuation coefficient in reciprocal meters calculated according to ISO 9613-1 using climatic conditions as given

$$m \quad \frac{\alpha}{10\log(e)} \tag{14}$$

The sound absorption coefficient α_s of a plane absorber can be calculated as follows

$$\alpha_s = (A_2 - A_1)/S \tag{15}$$

where, S is the surface area of the test specimen.

4. RESULTS AND DISCUSSION

The physical intrinsic properties measured using specialized test rigs of tested samples are given in table 1. These parameters are used for simulation. Figure 2, shows the effect of incidence angles on sound absorption coefficient for PU foam samples. As the angle of incidence increases the sound absorption of materials decreases as sound waves becomes more and more parallel to the sample under test. Sound absorption at 0° gives absorption at normal incidence after that it becomes maximum, when the angle between incident wave and sample surface is grazing (i.e. 75°-85°). The prediction formula equation (12) considers integration over all the angles of incidence. Figures 3 and 4 show comparison of experimental sound absorption with simulation using physical parameters for Polyester felt of different densities, which shows good correlation between experimental and simulated results. Similarly figure 5 shows comparison of experimental and simulated results for cellular rubber.

Table 1. Measured physical parameters of sound absorbing materials

Material Samples	Porosity [-]	Flow Resistivity [Ns/m4]	Tortuosity [-]	VCL [μm]	TCL [μm]
PU foam	0.99	4276	1.25	112	273
PET Felt	0.99	6634	1.06	147	203
Cellular Rubber	0.84	150333	3.97	29	29
Polyester Felt	0.95	4335	1.01	125	180

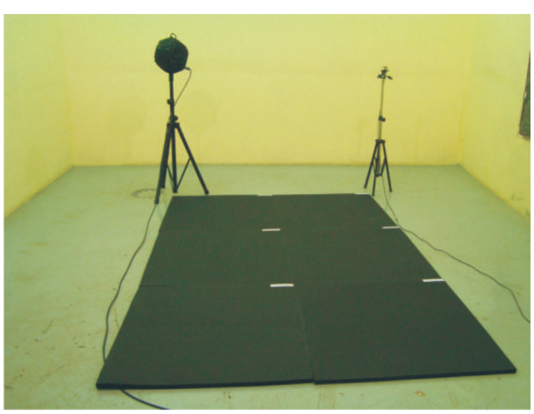

Fig. 1. Reverberation Room with Sample

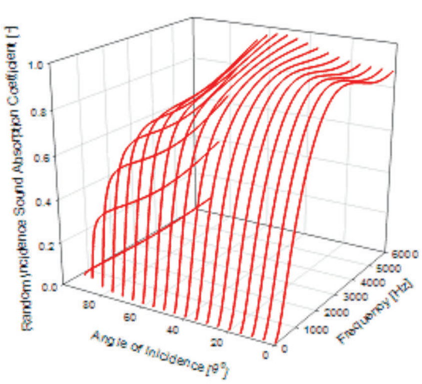

Fig. 2. Effect of Angle of incidence on sound absorption of PU foam

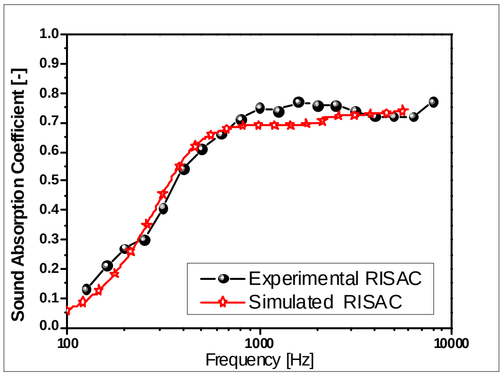

Fig. 3. Comparison of random in incidence sound absorption coefficient with simulation for PET felt

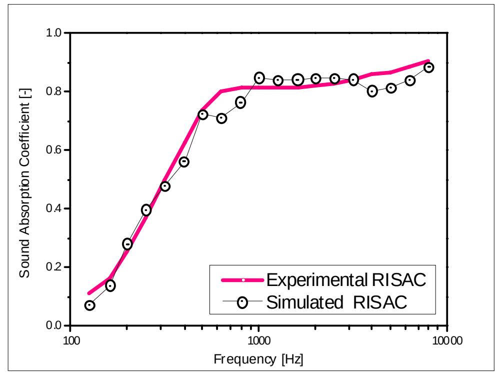

Fig. 4. Comparison of random in incidence sound absorption coefficient with simulation for polyester felt

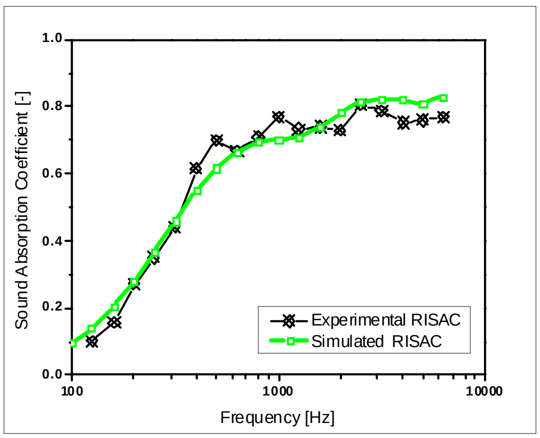

Fig. 5. Comparison of random in incidence sound absorption coefficient with simulation for cellular rubber

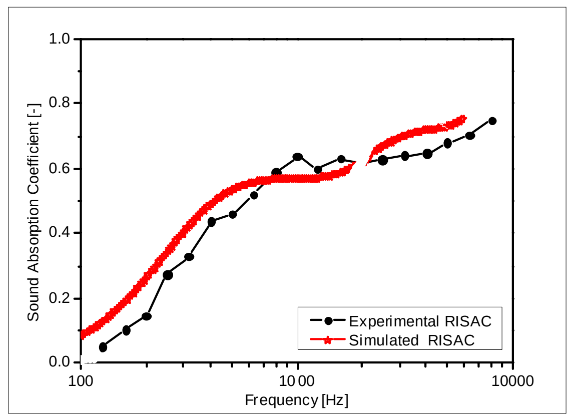

Fig. 6. Comparison of random in incidence sound absorption coefficient with simulation for PU foam

Figure 6 shows comparison of experimental sound absorption with simulation for PU foam. In this comparison, there is slight deviation at low frequency. This might be due to anisotropic and inhomogeneous nature of PU foam.

5. CONCLUSION

This paper presents a detailed discussion on modelling of sound absorbing materials relating its intrinsic physical parameters with random incidence sound absorption coefficient. It also validates the experimental results with simulation using JCA model. It presents experimental methods for measurement of physical parameters using specialized test rigs. From this validation, it is clear that intrinsic physical parameters can easily be used to predict random incidence sound absorption coefficient. It is observed that, the correlation between experimental and simulated results is good when sound absorbing materials are homogenous and isotropic.

6. ACKNOWLEDGMENT

The authors are thankful to Director, ARAI for his permission and support to complete this work. The authors are also thankful to NVH Dept. for their help during the work.

7. REFERENCES

[1] ISO 13534-2- Normal incidence measurement of sound absorption coefficient using impedance tube- Transfer function method

[2] ISO 354: 2003. Acoustics - Measurement of sound absorption in a reverberation room.

[3] J. F. ALLARD and Y. CHAMPOUX, 1992. New empirical equations for sound propagation in rigid frame fibrous materials, *J. of Acoust. Soc. of Am.*, **91**(6), 3346-3353.

[4] B.H. SONGand S.J. BOLTON, 2000. A transfer matrix approach for estimating the characteristic impedance and wave numbers of limp and rigid porous materials, *J. of Acoust. Soc. of Am.*, **107**, 1131-1151.

[5] S.I. THOMSON, 1980. On the absorption coefficient, *Acustica*, **44**, 265-273.

[6] Y. CHAMPOUX, M.R. STINSON and G.A. DAIGLE, 1991. Air-based system for the measurement of porosity, *J. of Acoust. Soc. of Am.*, **89**, 910-916.

[7] ASTM-C522, 1991. Acoustics-Materials for acoustical applications-Determination of airflow resistance.

[8] P. SHRAVAGE, K.V. DE'SA and S. RAJU, 2008.