VOL. 10, NO. 8, MAY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

REVIEW OF ACOUSTIC CHARACTERISTICS OF MATERIALS USING IMPEDANCE TUBE

Niresh J.[1], Neelakrishnan S.[1], Subharani S.[2], Kannaian T.[3] and Prabhakaran R.[1]
[1]Department of Automobile Engineering, PSG College of Technology, Coimbatore, India
[2]Department of Electronics and Communication Engineering, PSG College of Technology, Coimbatore, India
[3]Department of Electronics, PSG College of Arts and Science, Coimbatore, India
E-Mail: nireshcbe@gmail.com

ABSTRACT

With the unprecedented growth of automobiles in emerging economies, it is essential to ensure a qualitative competition among automotive manufacturers. The benchmarking of each product requires precise testing equipment for qualitative parametric valuation and marketing. Automotive noise control is one such area, and is important in preventing the noise as it is not desirable inside the vehicle. Noise control materials are used in passive noise control and are sensitized to different noise sources. These materials need to be characterized for noise control characteristics. This paper elaborately discusses various methods available for measuring the acoustic characteristics of materials.

Keywords: acoustic characteristics, impedance tube, absorption coefficient, ASTM E-1050, reflection coefficient.

1. INTRODUCTION

Cabin noise control in automobiles is mainly achieved with the help of acoustic materials. These characteristics are studied using ASTM E-1050 and ISO-10534. The sound absorption coefficient of the material is the measured characteristic. However, one of the main challenges in the application of acoustic materials is that the frequencies range from 200 Hz to 6.4 kHz and one single material is not available that covers the entire frequency range. Hence characterization of these materials plays an important part in their selection and appropriate application. Selecting a best method for analyzing the material's acoustic properties would be useful for industrial applications. These methods provide material acoustic properties like characteristic impedance, random incidence absorption coefficient and propagation constant. The methods shall be applicable to both single layer and multi layer composite materials. A material's acoustic properties can be found in terms of its bulk properties. These properties include complex characteristic impedance, complex propagation constant, and random incidence absorption coefficient. The properties can be determined either theoretically using the empirical prediction based on regression analysis or experimentally using impedance tube. Various methods are available for measuring the acoustic properties of the materials. These methods include standing wave ratio method by Seybert A F and Ross D (1977) [1], transfer function method Ideo et al., [2], two cavity method and two load method and reverberation method ASTM C423-02a [3]. The reverberation method is mostly used, but it requires large setup environment and sample but the other methods require small set up along with small samples. These methods differ in their accuracy of measurement and speed. This paper discusses all the above mentioned methods in detail and discusses their efficiency. The work of this paper is intended to provide the fundamental knowledge behind each method and also aid in the selection of the best method for specific applications. The following sections detail the requirement of noise control, materials used, measurement of sound.

2. NOISE CONTROL IN AUTOMOBILES

While the demand for vehicles has increased manifold, innovation in automotive technologies has taken a huge leap leading to competitions one of the factors that influence selection of an automobile is noise (especially noise). It is seen that the noise produced in vehicles varies from vehicle to vehicle and require the noise control materials with selective acoustic properties for different frequency range of interest. These materials mainly absorb noise produced by various elements such as engine, tire, rotating mechanical components and the outside environment. Each element produces noise in different frequency ranges with different decibel values. Further, in order to comply with regulations constraining the level of noise to certain range of dB value, the use of noise control materials in vehicles is necessitated. Noise control is essential as it not only increases the comfort of those travelling; it also makes long distance travelling less tiring. Automotive companies employ various noise control materials at various locations in the vehicle. A car typically uses materials like Polyester, Polypropylene, and Nylon, Composites of carbon and aramid fibers for noise suppression. The materials are placed in interior fitments, safety facilities, tire reinforcement, and carpets. They are also used for thermal insulation.

3. THEORY AND MEASUREMENT OF SOUND ABSORPTION

Sound is a mechanical wave that transmits through a medium. A medium can be a solid, liquid or gas. The sound propagation in a standing wave duct is assumed as stationary plane waves with zero mean flow speed propagating in air. The complex acoustic pressure p(x,t) and the particle velocity v(x,t) of the medium are,

$$p(x,t) = Ae^{j(\omega t-kx)} + Be^{j(\omega t+kx)} \quad (1)$$

$$v(x,t) = \frac{1}{z_0}\left[Ae^{j(\omega t-kx)} - Be^{j(\omega t+kx)}\right] \quad (2)$$

where A and B are amplitudes of incident and reflected wave respectively, ω is the angular frequency, k is the wave number , and zo is the characteristic impedance of the air at 20 oC, the ρ and c respectively are the air density and speed of sound in air. The absorption of sound results from the dissipation of acoustic energy into heat. The sound is converted into heat through frictional losses, momentum losses and temperature fluctuations. Generally the sound wave is a longitudinal wave carried by the air molecules. The frictional losses occur when the air molecules carrying the sound wave vibrate inside the material with frequency of the sound. The momentum losses occur when there is a change in the flow direction of sound waves, together with the expansion and contraction phenomenon of flow through irregular pores. Similarly, the temperature fluctuation is caused owing to the exciting of the sound; air molecules in the pores undergo periodic compression and relaxation. A number of measurement techniques can be used to quantify the sound absorbing behavior of porous materials. In general one is interested in one of the following properties: sound absorption coefficient (α) Reflection coefficient (R), or surface impedance (Z). Some of the sound absorption coefficients measuring techniques are Reverberant field methods, Impedance tube methods, Scale model measurement. In the Impedance tube measurement it was noted that a very strong signal to noise ratio must be achieved. The reverberation method of finding the acoustical properties of sound absorption requires large samples and setup when compared to the impedance tube. Based on the survey of the various methods employed for measuring the sound absorption characteristics, it is seen that the impedance tube is the most popular. Hence the various impedance tube variations used are discussed in the following sections. The following sections detail the various variations of impedance tube.

4. NEED FOR IMPEDANCE TUBE MEASUREMENTS

4.1 Introduction to impedance tube

The impedance tube was originally invented to find the velocity of sound in gases. The tube later was used to demonstrate the Standing waves of sound. The tube is made by rigid, transparent or opaque materials to confine the sound within the tube along one direction towards the direction of propagation. Thus the impedance tube simplifies the three dimensional wave equations into one dimensional wave equation. The reverberation method of finding the acoustical properties of sound absorption requires large samples and setup when compared to the impedance tube. The transparent tube was used for standing wave demonstration and not used for experimental determination of normal incidence absorption coefficient where the rigid impedance tube is used. The design specifications of the tube are given by ASTM standards [3, 4, 5]. Figure-1, the impedance tube design with a loud speaker at one end and sample holder with rigid termination at other end. The microphones are placed between the loud speaker and the sample. The loud speaker is driven by the signal source and the one dimensional wave carries the sound energy towards the sample.

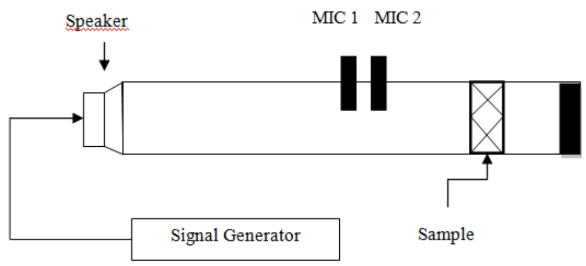

Figure-1. General set up of Impedance tube.

The material placed at the other end absorbs the sound energy based on the absorption coefficient of the material. The remaining sound energy is reflected back to form the standing wave pattern.

4.2 Parameters determination

The impedance tube is used to measure the complex acoustical properties like normal incidence absorption coefficient, complex surface impedance, propagation constant and effective bulk modulus. The random incidence absorption coefficient is measured either directly from reflection coefficient or from the characteristic impedance. The tube also helps in determining the non acoustical properties such as flow resistivity, porosity, tortuosity, viscous characteristic length, and thermal characteristic length which are used to determine effective density and bulk modulus of fibrous materials. Kino and Ueno [6] found that flat and triangle fibers provide some improvement in non acoustical properties of porous materials. The studies are useful in determining the methods for improving the absorption characteristics of noise control materials without adding the weight where the automobile and aeronautical industries are weight sensitive.

5. TYPES OF IMPEDANCE TUBE MEASUREMENTS

5.1 Standing wave ratio method

The standing wave ratio method is the oldest and simplest method and more accurate than the transfer function method. The standing wave ratio method is a direct method in which the complex acoustical properties are measured from the standing wave ratio. Figure-2 shows the setup for the standing wave ratio method.

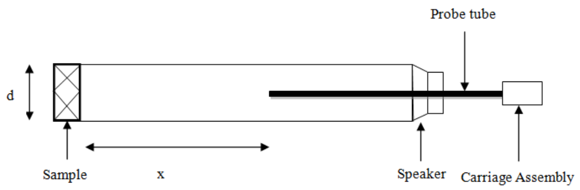

Figure-2. Setup for standing wave ratio method.

In a cylindrical tube, when an incident wave train encounters a boundary with impedance between hard and soft, part of incident wave is reflected and another part is absorbed. The hard boundary layer produces inversion in the boundary layer. In standing wave ratio method the sample is attached with the probe containing microphone. The standing wave produced inside the tube contains number of nodes and anti-nodes. The probe is moved to measure the distance of the first node from the sample node. This method relies on the fact that there are only plane incident and reflected waves propagating along the tube axis in the test section of the tube (the section where standing pattern is explored). The incident plane sinusoidal sound wave is generated by loudspeaker placed at one end of the tube. The other end of the tube is terminated with the test sample backed with a reflective end.

By moving the probe along the length of the tube the standing wave ratio is also measured.

$$\frac{B}{A} = \frac{S-1}{S+1} \tag{3}$$

where the A and B are amplitudes of incidence and reflected waves and S is the standing wave ratio.The phase angle is also calculated by,

$$\theta = 2k(L\text{-}X_1) - \pi \tag{4}$$

where L is the length of the tube and x_1 is the distance of the first node from the end. The absorption coefficient can be calculated from the standing wave ratio.

5.2 Standing wave ratio method using frequency response

It is based on the transfer function of two fixed microphones which are located at two different positions in the tube wall. The standing wave pattern is built up from a broadband stationary noise signal. With the measured transfer function, incident and reflected waves are separated mathematically. This leads to the reflection coefficient of the sample for the same frequency band as the broadband signal. Figure-3 shows the schematic diagram of the method. The sample is placed at the end supported by rigid termination. The two microphones placed at two locations measure the auto spectral densities S_{11}, S_{22} and also measure the cross spectral density $S_{12} = X_{12}+jY_{12}$. The auto-spectra S_{AA} and S_{BB} of the incident and reflected sound waves in the upstream,

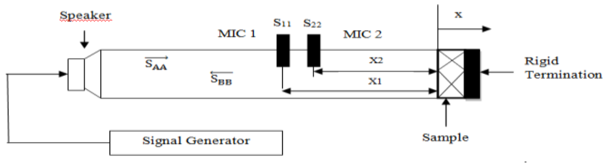

Figure-3. Setup for two microphone standing wave ratio method.

$$\begin{bmatrix} S_{AA} \\ S_{BB} \\ X_{AB} \\ Y_{AB} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 2cos2kx_1 & 2sin2kx_1 \\ 1 & 1 & 2cos2kx_2 & 2sin2kx_2 \\ coskn & coskn & 2coskm & 2sinkm \\ -sinkn & sinkn & 0 & 0 \end{bmatrix}^T \begin{bmatrix} S_{11} \\ S_{22} \\ X_{12} \\ Y_{12} \end{bmatrix} \tag{5}$$

where , $S_{AB} = X_{AB}+jY_{AB}$ is the cross spectrum between the incident and reflected waves, x_1 and x_2 are the distances between the front surface of the sample and the microphone 1 and 2 respectively and $m = x_1+ x_2$, $n = x_1- x_2$ .The absorption coefficient is calculated from

$$A = 1- \frac{S_{BB}}{S_{AA}} \tag{6}$$

where $S_{AA}= X_{AA}+jY_{AA}$, $S_{BB}= X_{BB}+jY_{BB}$

The normalized acoustic impedance on the front surface of the material is

$$Z = \frac{S_{AA}-S_{BB}-2jY_{AB}}{S_{AA}+S_{BB}-2X_{AB}} \tag{7}$$

The standing wave method is well developed and it produces the accurate result because of direct measurement but this method is slower and it takes at least 30 minutes to provide15 frequency points where as transfer function method takes less than 5minutes to provide 128 frequency points.

5.3 Transfer function method for absorption coefficient

The transfer function method is the most widely used method for measuring the normal incidence absorption coefficient of the noise control materials. The method is comparatively faster than the standing wave ratio method. This method is called as transfer function method because it determines the normal incidence absorption coefficient of the noise control materials by the measurement of transfer function between the microphones. The method was earlier used with two microphones but now used with three microphones. This method is basic for the two cavity method, two load methods and the transfer matrix method.

The two microphone transfer function method be implemented using ASTM E-1050 [5]. Figure-4 describes about the set up for the transfer function method. This

VOL. 10, NO. 8, MAY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

method requires a dual channel spectrum analyzer to measure the power spectral densities S_{11}, S_{22} and cross spectral density S_{12} at the two microphone locations. The signal source should be able to produce noise signal with uniform spectral density.

The microphones need to be phase matched to get accurate result. The measurements are made in narrow constant bandwidth linearly spaced bands using Fast Fourier Transform techniques the transfer function method is calculated from the auto and cross spectral densities measured by Kino N and Ueno T (2007).

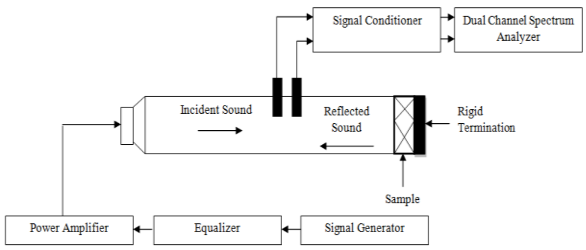

Figure-4. Setup for two microphone transfer function method.

$$\overline{H} = \frac{S_{12}}{S_{11}} \tag{8}$$

The complex reflection coefficient can be measured as,

$$R = \frac{H - e^{-jks}}{e^{jks} - H} e^{j2k\,(l+s)} \tag{9}$$

The normal incidence absorption coefficient can be calculated from the reflection coefficient as follows:

$$\alpha = 1 - |R|^2 \tag{10}$$

The normal specific acoustic impedance ratio can be calculated as

$$z/\rho c = \frac{(1+R)}{(1-R)} \tag{11}$$

The transfer function method can be used for low and high frequencies and this method works well for high frequencies than the low frequencies. The other acoustical parameters can also be measured from the transfer function method.

5.4 Two cavity method

This method is best suited for the materials with symmetry and reciprocity properties for measuring the propagation constant and characteristic impedance of single layer noise control materials. This method can be used for wider range of frequencies and can provide best results for low flow resistance materials. This method is described in Figure-5.

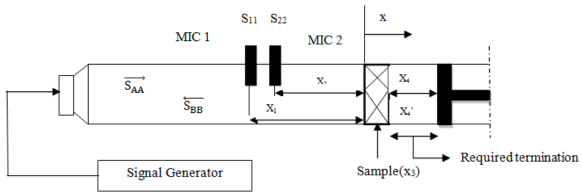

Figure.5. Setup for two cavity method.

The experiment is carried out with cavities of different depths between the sample and the movable piston. Yaniv, 2009 [7] proposed a two cavity method in which the two cavities are selected as sample backed by a rigid wall and one quarter wavelength of air cavity between the sample and the rigid wall surface of the movable piston. But, the method has evolved with two cavities of non-zero depth values. The depth of the cavity between the sample and surface of the piston is varied by changing the position of the movable piston. The sound pressure is measured in the upstream section of the impedance tube is captured with two microphones. The characteristic impedance of the sample is calculated as,

$$Z_c = \pm\sqrt{\frac{Z_1 Z_1'(Z_2 - Z_2') - Z_2\, Z_2'(Z_1 - Z_1')}{(Z_2 - Z_2') - (Z_1 - Z_1')}} \tag{12}$$

The sign in the equation is chosen so that the real part of impedance is positive. From eq (12), Z_1 or Z_1' is acoustic impedance of the sample with thickness t3, with air layer of depth t4 or t_4', which is made between the sample and the movable piston as seen from the front surface of the sample. Z_2 or Z_2' are the acoustic impedance of the impedance tube with the air cavity depth of t4 or t_4'. The Z1 and Z2 can be calculated from the Equation (13).

$$Z_1 = jZ_0 \frac{-H\sin t_2 + \sin kt_1}{H\cos kt_2 + \cos kt_1} \tag{13}$$

$$Z2 = -jZ0\cot(kt4) \tag{14}$$

where H is the transfer function between the microphones 1 and 2 and k is the wave number. The complex propagation constant is also calculated as,

$$\gamma = \alpha + j\beta = \frac{1}{2t_3} \ln\left(\frac{Z_1 + Z_c}{Z_1 - Z_c} \cdot \frac{Z_2 - Z_c}{Z_2 + Z_c}\right) \tag{15}$$

where, γ is the complex propagation constant and α, β refers the attenuation constant and phase constant respectively. Finally, the complex acoustic impedance of the sample is calculated from the surface impedance of the sample in test,

ARPN Journal of Engineering and Applied Sciences

$$\alpha = 1-\left|\frac{Z_1 - Z_0}{Z_1 + Z_0}\right|^2 \quad (16)$$

The results obtained from the two source method can be validated through Delany-Bazely 1969 [8] semi empirical formulae. This method is best suited for frequencies above 1 kHz. The errors that occur in the measurement is explained by Delany and Bazley's effective frequency interval,

$$0.01 \leq f\rho/R \leq 1.0 \quad (17)$$

where R is the flow resistivity and ρ is the density of the air. The two cavity method can measure the normal incidence absorption coefficient of the samples having the flow resistance R lies in between ρf2 and 100ρf1. The transfer matrix for the homogenous and isotropic material is calculated as,

$$[T] = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cos k_m t_3 & j z_c \sin k_m t_3 \\ j \sin k_m t_3 / Z_c & \cos k_m t_3 \end{bmatrix} \quad (18)$$

where k_m is the wave number in the acoustic material $k_m = \gamma / j$. The normal incidence absorption coefficient can be calculated from this transfer matrix. The normal incidence absorption coefficient α is,

$$\alpha = 1-\left|\frac{T_{11} - Z_{uc}T_{21}}{T_{11} + Z_{uc}T_{21}}\right| \quad (19)$$

If a multi layered material is used than the transfer matrix can be derived for each layer and the total transfer matrix can be calculated by multiplying the transfer matrix of each layer. The total transfer matrix is,

$$[T] = [T_1][T_2] \ldots \ldots \ldots [T_n] \quad (20)$$

5.5 Two load method

The two load method uses two loads for measuring the normal incidence acoustic absorption coefficient. The loads are anechoic and rigid terminations. The method can be done in two ways either testing in single time using four microphones called four microphone two load method or testing two times with two microphones called two microphone two load methods. Both the methods theoretically produce the same results. In impedance tube with circular cross section the sound pressure and normal particle velocities of the material is calculated as,

$$\begin{bmatrix} p_u \\ v_u \end{bmatrix} = [T] \begin{bmatrix} p_d \\ v_d \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p_d \\ v_d \end{bmatrix} \quad (21)$$

where the values with subscript u refer particle pressure and velocities in the upstream of the duct and similarly the values with subscript d refers the downstream values. If the plane wave across the acoustic materials is isentropic plane sound wave propagation, the amplitudes of complex pressures of positively and negatively travelling, p_u^+, p_u^- in the upstream of the cylindrical impedance tube and p_d^+, p_d^- for the downstream can be related using the pressure transfer matrix,

$$\begin{bmatrix} p_u^+ \\ p_u^- \end{bmatrix} = [t] \begin{bmatrix} p_d^+ \\ p_d^- \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} p_d^+ \\ p_d^- \end{bmatrix} \quad (22)$$

The elements in the transfer matrix are calculated further. They represent the material used for testing.

$$\begin{bmatrix} T_{11} \\ T_{12} \\ T_{21} \\ T_{22} \end{bmatrix} = 2 \begin{bmatrix} 1 & Z_{dc}^{-1} & Z_{uc} & Z_{uc}/Z_{dc} \\ 1 & -Z_{dc}^{-1} & Z_{uc} & -Z_{uc}/Z_{dc} \\ 1 & Z_{dc}^{-1} & -Z_{uc} & -Z_{uc}/Z_{dc} \\ 1 & -Z_{dc}^{-1} & -Z_{uc} & Z_{uc}/Z_{dc} \end{bmatrix}^{-1} \begin{bmatrix} t_{11} \\ t_{12} \\ t_{21} \\ t_{22} \end{bmatrix} \quad (23)$$

where, characteristic impedance z with subscripts describe for upstream and downstream section for standing wave. To calculate the elements of the matrix the incident transmission coefficient T_{in}, reflected transmission coefficient T_{re} and reflection coefficient R as,

$$T_{in} = \frac{p_u^+}{p_d^+}, T_{re} = \frac{p_u^-}{p_d^-}, R = \frac{p_d}{p_d^+} \quad (24)$$

The absorption coefficient can be calculated from reflection coefficient. The measurement is carried out for the two terminations and the elements are calculated as,

$$t_{11} = \frac{R_b T_{ina} - R_a T_{inb}}{R_b - R_a} \; t_{12} = \frac{T_{inb} - T_{ina}}{R_b - R_a}, \quad (25.1)$$

$$t_{21} = R_a R_b \frac{T_{rea} - T_{reb}}{R_b - R_a} \; t_{22} = \frac{R_b T_{reb} - R_a T_{rea}}{R_b - R_a}, \quad (25.2)$$

From these values the transfer matrix can be calculated.

5.6 Reverberation method

The reverberation method is used to find the random incidence sound absorption coefficient. The reverberation chamber method is performed as a comparison measurement between the reverberation times of an empty chamber and with the absorptive material in place. In this method reverberation time and decay rate of the reverberation room is measured. The reverberation time is defined as the time for the sound to die dawn to a level of 60 dB. Two standards describe about the set up and procedure for reverberation room measurements, namely ASTM C-423 02a [3] and ISO 354:2003. The absorption coefficient is calculated using the Sabine formula as follows,

$$A = 0.921 \frac{V.d}{c} \quad (26)$$

The ASTM C-423 method requires a measurement of the absorption of the empty room and the absorption of the room with the sample in the room,

$$A = A_2 - A_1 \quad (27)$$

ARPN Journal of Engineering and Applied Sciences

The increase in the absorption is divided by the area of the sample to create the absorption coefficient,

$$\alpha = \frac{A_2 - A_1}{S} + \alpha_1 \quad (28)$$

where α is the absorption coefficient of the test specimen in sabins/ft^2, S area of the test specimen, m^2 or ft^2, α_1 absorption coefficient of the surface closed by the specimen. The absorption coefficient, α_1, of the room surface covered by the specimen should be added when it is significant. However, the absorption coefficients of hard surface, such as the floor of a reverberation chamber, are so small that they may be neglected and no adjustment should be made for such a floor.

where A is the absorption of the specimen in m^2, A_1 is the absorption of the empty reverberation chamber in m^2 or Sabins and A_2 is the absorption of the reverberation room after the specimen has been installed.

where A is sound absorption in m^2, V is the volume of the reverberation room in m^3, c is speed of sound and d is decay rate dB/s. the random incidence absorption coefficient can be calculated from the following Sabine's formula as well,

$$RT_{60} = \frac{0.161.V}{A} \quad (29)$$

If the absorbent materials are close to the source then the Sabine's formula no longer be used. The reverberation method may produce the test results of random incidence absorption coefficient that may exceed unit converse to the physics of absorption which means the sound source is internally generating. Specifically, when the test materials are highly absorptive the random incidence absorption coefficient will exceed the unity. The reasons are attributed to three main problems. They are edge diffraction, non-diffuseness and Sabine formulation. The diffraction from the edges at low frequencies causes the reflected wave to no longer be planar, so the edge diffraction produces edge effect where more absorption occurs at edges than the centre. In order to conduct the reverberation experiment the sound field should be established as diffuse field. An ideal diffuse state produces same result regardless of measurement configurations. But the non-diffuseness affects the result. If Sabine formula is applied a statistical approach is assumed to define the sound field in the room. Therefore it can be assumed that the time and space distribution of sound pressure level is even across the room, which is typically not the case in real situations. But this problem is addressed by adding the panels that should be kept moving to have a room that changes continuously. The panels should be added up to when the change in absorption coefficient is negligible. The Sabine formulation should not be applied when the mean absorption is greater than 0.4. According to ISO 354:2003, the minimum volume of the room is 150 m^3 and generally 200m^3 is preferred. The length of the longest straight line which fits in the boundary of the room should satisfy,

$$l_{max} < V^{\frac{1}{3}} \quad (30)$$

No two dimensions of the room should be equal or in the ratio of small whole numbers. The room is designed so that the reverberant sound field closely approximates a diffuse sound field both in the steady state when the sound source is on and during the decay after the sound source has stopped. Failure to establish the diffuse state would produce significant effects on accuracy. Eyring observed that the establishment of diffuse state among sound waves should be given most care to give rise to the use of weighted arithmetic mean of the coefficients of absorption and a value of mean free path between reflections. The sample size should be between 10 m^2 to 12 m^2. The signal level in the room should exceed at least the ambient noise by 10 dB. The microphones should be placed away from the dominant nodes or anti-nodes of smallest resonance. Each microphone should be placed at least 1.5 m away from each microphone. The sample should be flat and should be placed above the surface and at least 1.5 m form the surface of the wall and the sides of the sample should not be parallel to the wall. The samples as per ISO 354: 2003 should have length to width ratio of 1:0.7 to 1:1. The temperature and humidity have to be monitored and controlled as this will affect the result significantly. Relative humidity in the chamber should be at least 30% and at most 90 %. The temperature in the room should be at least 15^{o}C. The dodecahedron type loud speakers are used.

5.7 Hybrid multi layer prediction method

The methods described above are suited to single layer porous materials for the measurement of acoustical properties but for multi layered materials the flow resistivity for each layer differs greatly. Thus the multi layered materials are treated by combining the two cavity method and two load method. Wang *et al*., 2008 [9] calls this method as hybrid multi layer prediction method. Wang in his paper reported to have tested number of multi layered materials for absorption coefficient. He calculated the absorption coefficients of all the multi layered materials using the two cavity method and the transmission loss of all the materials are measures using the two load method. he observed that for prediction of multilayered materials, according to the transfer matrix theory two cavity method and two load method are best suited. Further in any application by incorporating the hybrid prediction function with the impedance tube, it is possible to test any kind of material sample regardless of layers present in the material, thickness.

6. IMPEDANCE TUBE DESIGN ANALYSIS

The design specifications of the impedance tube significantly affect the accuracy of the result. These include the diameter of the tube, the distance of the microphones from the samples and the distance between the microphones. The tube should be long so that the plane waves are fully developed before reaching the

VOL. 10, NO. 8, MAY 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

microphones and the test specimen. The length (L) and the diameter of the tube is related as follows:

$$L > 3\,d \quad (31)$$

The relation between the diameter of the impedance tube and the frequency range of the tube is given as follows:

$$d < K\,c/f_u \quad (32)$$

where d = diameter of the tube, m; c= speed of sound in the tube, m/s; K=0.586

Thus the diameter of the tube is inversely proportional to the frequency. Larger tubes can measure for low frequencies and smaller tubes can measure for high frequencies. The frequency range of the tube is limited by upper f_u and lower frequencies f_l.

$$f_l < f < f_u \quad (33)$$

If the frequency limit is exceeded than, the wave becomes a non-plane wave and cross modes occur at high frequencies when the acoustical wavelength approaches the sectional dimension of the tube. The number of microphones also affects the accuracy. But the same number of microphones will not perform better for all frequencies. Ralph and Walter 2002 [10] find that, for materials with low flow resistivity the four microphone method performs better than the three microphone method. They also concluded in their paper that three microphone methods should not be used for low frequency measurement of low flow resistivity materials. Since plane waves may not be fully developed at some locations, it is necessary to place microphones at different locations. The size of the microphones depends on the range of the frequencies involved. For low frequencies high sensitive microphones are used where as for high frequencies low sensitive microphones are used. The sensitivity and the diameter of the microphone are inversely related. Thus the desired microphone size can be chosen based on the frequency range. A larger spacing between the microphones enhances the accuracy of the measurement, but the microphone spacing must be less than the shortest half wave length of interest.

$$0.01*(c/f_l) < s << c/2f_u \quad (34)$$

where, s is spacing between the microphones. The recommended value for the maximum microphone spacing s be of 0.8*(c/2fu). The signal source should produce noise signal with uniform spectral density. The noise level in the tube should be at least greater than the outside noise by 10 dB. The distance between the microphones should be smaller than the distance between the microphones and the sample. The distance between the nearest microphone and the sample should be greater than at least one half of the tube diameter. The microphones should be flush mounted and the depth of the microphone should be zero so that the diaphragm of the microphone should align with the wall of the tube. The microphones should be well calibrated for phase and gain. To calibrate, the transfer function between the microphones are measured as,

$$\hat{H}_{12}(f) = \widehat{S_{12}}(f)/\widehat{S_{11}}(f) \quad (35)$$

where $\hat{S}_{11}$(f) is smoothed estimate of auto spectral density of microphone 1 and $\hat{S}_{12}$(f) is smoothed estimate of cross spectral density between microphones 1 and 2. The spectral responses are calibrated as

$$\hat{S}_{11}(f) = [\hat{S}_{11}(f)]_u \quad (36)$$

$$\hat{S}_{22}(f) = [\hat{S}_{11}(f)]_u/|\hat{H}_{12}(f)|^2 \quad (37)$$

$$\hat{S}_{12}(f) = [\hat{S}_{12}(f)]_u/\hat{H}_{12}(f) \quad (38)$$

where, the subscript u refers the uncorrected values of spectral densities.

The design can be further extended by incorporating different setup combinations. Among them are implementing the methods using the LABVIEW measurement suite.

7. VALIDATION OF RESULTS BASED ON THEORETICAL COMPUTATIONS

The results predicted from the above methods can be compared using the theoretical models developed by Delany and Bazley [8]. From large number of measurements on porous materials with porosities close to 1, Delany and Bazely have proposed empirical expressions for the values of the complex wave number k and characteristic impedance z_c for such materials. It is the simplest model requiring one parameter the flow resistivity for calculation. It is an empirical model originating from regression analysis of the acoustic properties and the static air flow resistivity σ of the fibrous absorbers with a high porosity. The characteristic impedance Z_c and wave number k are given by,

$$Z_c = \rho_0 c_0 [1 + 9.08\left(10^3 \frac{f}{\sigma}\right)^{-0.75} + i\,11.9\left(10^3 \frac{f}{\sigma}\right)^{-0.73}] \quad (39)$$

$$k = \frac{\omega}{c_0}\left[1 + 10.08\left(10^3 \frac{f}{\sigma}\right)^{-0.70} - i\,10.3\left(10^3 \frac{f}{\sigma}\right)^{-0.59}\right] \quad (40)$$

where, ρ_0 is the density of air and c_0 is the speed of sound in air. These equations are considered valid for 0.01 < f/σ < 1. Miki 1990 [11] altered the real and imaginary parts with new coefficients. An improved formula is suggested by Miki, called Miki model,

$$Z_c = 1 + 5.50\left(10^3 \frac{f}{\sigma}\right)^{-0.632} + i\,8.43\left(10^3 \frac{f}{\sigma}\right)^{-0.632} \quad (41)$$

$$k' = 1 + 10.08\left(10^3 \frac{f}{\sigma}\right)^{-0.70} + i\,11.41\left(10^3 \frac{f}{\sigma}\right)^{-0.618} \quad (42)$$

Here the characteristic impedance and wave number are normalized. The Delany model did not consider bulk modulus of elasticity but the Biot Allard model considers the bulk modulus. Scott R A 1946 [12] finds that estimation of characteristic impedance and wave number is severely affected by magnitude and phase of the pressure transfer functions and other factors including the sample length, tube length, tube radius and microphone position produce negligible error.

8. CONCLUSIONS

The various methods in practice for measuring the acoustical properties of noise control materials of both single layer and multi layered type using the Impedance tube have been presented. Seven methods have been discussed. These methods are used to measure acoustical properties of noise control material not only used for materials used for sound absorption for automobiles but also used for room acoustics like an auditorium. The experimental results can be compared with those obtained from theoretical models developed by Delany-Bazely, Miki and Biot-Allard. The theoretical models are selected depending on the degree of accuracy needed. This paper enables researchers to select the optimum test method based on accuracy, time requirements, efficacy and cost. Out of all the methods. The standing wave ratio method is the oldest and proven for its accuracy and it is the best method as all types of materials can be tested. It can also be used with two, three, four microphones for measurement of absorption coefficient and transmission loss. Two cavity methods can be used only for the materials with symmetry, reciprocity and low flow resistivity. The hybrid multi layered prediction method is a new method for predicting the acoustical properties of multi layered materials. There are certain constraints in applying these methods, as the same material may not produce same results with all the test methods but will confine to the acceptable range of error.

All methods must ensure that the impedance tube is calibrated for accuracy with null mismatch when interfacing the electronic components as otherwise the accuracy of the results will be severely affected.

REFERENCES

[1] Seybert A. F, Ross D. F. 1977. Experimental Determination of Acoustic Properties Using a Two-Microphone Random-Excitation Technique. J. Acoust. Soc. Am. 1362-1370.

[2] Ideo Utsuno, Tohitmitsu Tanaka, Takeshi Fujikawa. 1989 Transfer function method for measuring characteristic impedance and propagation constant of porous materials. J. Acoust. Soc. Am, August.

[3] ASTM C423-02a, 1990. Standard method for sound absorption and sound absorption coefficients by the reverberation room method. American Society for Testing and Materials; Philadelphia,

[4] ASTM C384-90a. 1990. Standard method for impedance and absorption of acoustical materials by the impedance tube method. American Society for Testing and Materials; Philadelphia.

[5] ASTM standard E1050-98, 1998. Standard Test Method for Impedance and Absorption of Acoustical Material Using a Tube. Two Microphones and a Digital Frequency Analysis System.

[6] Kino N, Ueno T. 2007. Investigation of sample size effects in impedance tube measurements. Applied Acoustics. 1485-1493.

[7] Yaniv S.L. 2009. Impedance Tube Measurement of Propagation Constant and Characteristic Impedance of Porous Acoustical Material. J. Acoust. Soc. Am, 3049-3056.

[8] Delany M.E, Bazley E.S. 1969. Acoustical properties of fibrous absorbent materials. Journal of Applied Acoustics, August.

[9] Wang Y.S, He H, Geng A.L. 2008. Comparison and application of the experimental methods for multi-layer prediction of acoustical properties of noise control materials in standing wave-duct systems. Journal of Applied Acoustics; 847-857.

[10] Ralph T.Muhlesisen, C.Walter beamer IV, 2002. Comparison of errors in three and four microphone methods in the measurement of the acoustic properties of porous materials. J. Acoust. Soc. Am. 112-117.

[11] Yasushi Miki. 1990. Acoustical properties of porous material - Modification of Delany - Bazley models. Journal of Acoustic society of Japan. 19-24.

[12] Scott R.A. 1946. The Propagation of Sound between Walls of Porous Material. Proc. Phys. Soc. 358-368.