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# TEST METHOD TO DETERMINE THE ACOUSTIC PROPERTIES OF BUILDING MATERIALS BY USING FOUR MICROPHONE IMPEDANCE TUBE

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***Abstract**: The paper discusses a simple and low-cost method to design four microphone impedance tube of measuring the acoustic properties of building materials. The acoustic properties of the material are defined by the reflection coefficient, absorption coefficient, and transmission coefficient. The experimental setup follows the ASTM-E2611 standard of four microphone impedance tube with two load boundary conditions to measure these coefficients. The setup consists of four microphones around a brass tube with the speaker at one end and termination at the other. Raw data from the four microphones is obtained through a Virtual Instrument (VI) program developed in LabView. The novelty in the design is the tapered connection between the two pipes connected via the sample holder. The mathematical equation involved in estimating acoustical properties is solved in MATLAB 2019a. The reflection and absorption coefficient data of ephony fibbrette of 15 mm thickness are compared with the data provided by an accredited laboratory. The experimental results of the in-house designed impedance tube are in good agreement with the lab results. This material is used in the auditorium, theatres for hearing comfort. Further, two new samples of ephony fibbrette along with wood fibre cement and damper has been analysed. It has been found that adding a layer of wood fibre results in an increase in the absorption coefficient whereas the addition of the damper results in an increase in the reflection coefficient.*

***Keywords:** Impedance tube, Reflection coefficient, Absorption coefficient, Noise Control, Building Material*

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## 1.INTRODUCTION

Noise pollution is one of the invisible adversaries that cause permanent hearing loss and mental illness in people[1,2]. For the human ear, a healthy or adequate noise level is 68 decibels (dB) or less [3]. To keep the noise level up to an adequate limit, various noise insulation materials such as sound-absorbing panels, porous material, and various metamaterials are designed [4–7]. The sound attenuating potential of these materials should be known when choosing a suitable material for a particular case. The sound attenuation potential of these materials is determined by calculating the different coefficients such as absorption coefficient reflection coefficient and transmission coefficient. There are different methods to measure these coefficients [8]. The conventional approach is to use a reverberation space in combination with an anechoic room[9]. However, this approach is time-consuming and needs a lot of costly equipment. To address these shortcomings, a theory known as the transfer matrix is developed[10]. Following that, different criteria for constructing the impedance tube are established in order to approximate the acoustic properties whereas ASTME and ISO standards are the most used[11–13].

Bolton et al. used four microphones to calculate the pressure at four different positions in a standing wave tube in order to approximate the acoustic properties of sealant [14]. Dean et al. studied for the evaluation of impedance over different flow conditions [15]. Melling et al. described the acoustic impedance and insertion loss in acoustic metamaterials at high sound pressure levels[16]. Fukuda et al. reported a theoretical formula for attenuation based on the theory of electric transmission lines [17]. Jason et al. designed a standing wave apparatus for estimating acoustic properties of materials [18]. The transfer matrix methodology has been used for a long time and has sparked a lot of interest in assessing the acoustical properties of materials[19]. This approach is employed with two termination conditions i.e., rigid and anechoic. When only one condition is utilized, it is referred to as a one-load method; when both conditions are applied, it is referred to as a two-load method. Transfer matrix method has also been used in the fluid also where it is known as the four-pole method [20]. For the transient measurement, To et al. employed a four-pole parameter technique [21].

The impedance tube is a very essential and powerful instrument for determining the acoustic characteristics of a material. However, the simplest version of these tubes costs is around ten thousand USD and comes with a plug-and-play option. These tubes do not provide a clear picture of how an impedance tube works. In this article, we have designed four microphone impedance tube of brass to gain a better perspective and also to have a low-cost design alternative. The article is broken down into five sections. In the second part, the theory underlying the four microphone impedance tubes is discussed. Theoretical analysis of the application of transfer matrix in the computation of various acoustic parameters is described in this section. The third section is related to the fabrication of experimental setup and experimentation. The techniques used to estimate the acoustical coefficient are described here. Several experiments are performed on the ephony fibrette to validate the experimental setup and their findings. Comparisons of the experimental results with the results from the accredited laboratory are reported in the fourth section. Two more samples of different configurations are also analyzed in this section. Finally, a conclusion based on the results and discussion is prepared to summarise the article.

## 2. THEORETICAL ANALYSIS AND DESIGN PRINCIPLES

The designs of the four microphone impedance tube is based on the transfer matrix formulation. Acoustic pressure is used to express the transfer matrix. In an impedance tube, acoustic pressure is considered to vary in the direction of the tube. This acoustic pressure is defined in terms of forward and backward traveling wave. ASTME standard E2611-19 is used in the formulation. Fig. 1 depicts a schematic diagram of four microphone impedance tubes.

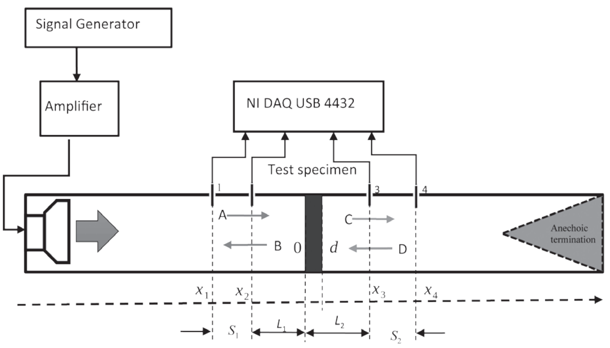



*Fig. 1: Schematic of the measurement setup*

The sound field in the four-microphone impedance tube is analyzed by assuming one-dimensional acoustic wave propagation. Sound field pressure in the upstream and downstream sections of the impedance tube is assumed as the superposition of the wave moving in the positive and negative x-direction. It is possible to write the pressure field in terms of complex amplitude i.e. ***A*** to ***D*** at four microphone positions.

$$\left.\begin{aligned} P_1 &= Ae^{-jkx_1} + Be^{jkx_1} \\ P_2 &= Ae^{-jkx_2} + Be^{jkx_2} \\ P_3 &= Ce^{-jkx_3} + De^{jkx_3} \\ P_4 &= Ce^{-jkx_4} + De^{jkx_4} \end{aligned}\right\} \qquad (1)$$

Here

***k*** represents the wavenumber whereas

***x*** is the location of the ***i<sup></sup>***$^{th}$ microphone. The above equation yields four equations to estimate the value of ***A*** to ***D***

$$A = j\frac{P_1 e^{jkx_2} - P_2 e^{jkx_1}}{2\sin k(x_1 - x_2)}$$

$$B = j\frac{P_2 e^{-jkx_1} - P_2 e^{-jkx_2}}{2\sin k(x_1 - x_2)}$$

$$C = j\frac{P_3 e^{jkx_4} - P_4 e^{jkx_3}}{2\sin k(x_3 - x_4)}$$

$$D = j\frac{P_2 e^{-jkx_3} - P_2 e^{-jkx_4}}{2\sin k(x_3 - x_4)}$$

The above equations can be further simplified in terms of transfer functions as

$$\left.\begin{aligned} A &= j\frac{H_{1,ref}e^{-jkL_1} - H_{2,ref}e^{-jk(L_1+S_1)}}{2\sin kS_1} \\ B &= j\frac{H_{2,ref}e^{+jk(L_1+S_1)} - H_{1,ref}e^{+jkL_1}}{2\sin kS_1} \\ C &= j\frac{H_{3,ref}e^{+jk(L_2+S_2)} - H_{4,ref}e^{+jkL_2}}{2\sin kS_2} \\ D &= j\frac{H_{4,ref}e^{-jkL_2} - H_{3,ref}e^{-jk(L_2+S_2)}}{2\sin kS_2} \end{aligned}\right\} \qquad (2)$$

Here,

$\boldsymbol{H_{i\,ref}}$ refers to the transfer function between the th microphone and the reference microphone.

***H*** is computed by taking the ratio of the complex sound pressure at the ***i***$^{th}$ microphone to that of the reference microphone. We have chosen the microphone 1 as the reference microphone.

Thus, a transfer matrix is formulated to relate the properties of the sound pressure and velocity on the two faces of samples extending from ***x=0*** to ***x=d***. These coefficients ***A*** to ***D*** are used for the transfer matrix estimation using rigid and anechoic termination conditions. In our formulation '***a***' represents the rigid termination where '***b***' represents the anechoic termination condition. Transfer matrix with termination '***a***'

$$\begin{pmatrix} P_a \\ U_a \end{pmatrix}_{x=0} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} P_a \\ U_a \end{pmatrix}_{x=d} \qquad (3)$$

Transfer matrix with termination '***b***'

$$\begin{pmatrix} P_b \\ U_b \end{pmatrix}_{x=0} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} P_b \\ U_b \end{pmatrix}_{x=d} \qquad (4)$$

The pressures and particle velocities at the front and back surface of the test sample are expressed as

$$\left.\begin{aligned} P_0 &= A + B \\ U_0 &= (A - B)/\rho c \\ P_d &= Ce^{-jkd} + De^{+jkd} \\ U_d &= (Ce^{-jkd} - De^{+jkd})/\rho c \end{aligned}\right\} \qquad (5)$$

Here

***ρ(rho)*** and ***c*** are the density and speed of sound of the medium respectively. The transfer matrix in equations (4) and (5) can also be rewritten as

$$\begin{pmatrix} P_a & P_b \\ V_a & V_b \end{pmatrix}_{x=0} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} P_a & P_b \\ V_a & V_b \end{pmatrix}_{x=d} \qquad (6)$$

Inverting the above expressions yields the final transfer matrix as

$$T = \begin{pmatrix} \frac{P_{0a}U_{db}-P_{0b}U_{da}}{P_{da}U_{db}-P_{db}U_{da}} & \frac{P_{0b}U_{da}-P_{0a}U_{db}}{P_{da}U_{db}-P_{db}U_{da}} \\ \frac{U_{0a}U_{db}-U_{0b}U_{da}}{P_{da}U_{db}-P_{db}U_{da}} & \frac{P_{da}U_{0b}-P_{db}U_{0a}}{P_{da}U_{db}-P_{db}U_{da}} \end{pmatrix}$$

This can be expressed as

$$T = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \tag{7}$$

**2.1 Measurement of acoustic properties:**

Acoustic qualities of a material subjected to sound waves at normal incidence, such as absorptivity, reflectivity, and transmissivity, can be estimated by estimating the reflection coefficient, absorption coefficient, and transmission coefficients. These coefficients are determined using transfer matrix as follows.

*a. Reflection coefficient (R) and Transmission coefficient (T):*

All normal incident waves are expected to be absorbed when a sample of thickness ***d*** is backed by an anechoic termination. As a result, in the downstream portion, ***D*** is believed to be zero. Thus, pressure at the front and back surface of the sample can be written as

$$P_0 = 1 + R$$

$$U_0 = \frac{1-R}{\rho\, c}$$

$$P_d = Te^{-jkd}$$

$$U_d = \frac{Te^{-jkd}}{\rho\, c}$$

Here

***R*** depicts the plane wave Reflection coefficient such as ***R =B/A*** and

***T*** represents the Transmission coefficient given by ***T=C/A***. The values are substituted in Eq. (3) and (6) and finally, we get, Reflection coefficient as

$$R = \frac{A_{11} + \frac{A_{12}}{\rho\, c} - \rho c A_{21} - A_{22}}{A_{11} + \frac{A_{12}}{\rho\, c} + \rho c A_{21} + A_{22}} \tag{8}$$

Also, when the sample is positioned against the rigid backing then $U_d=0$ and thus,

$$R = \frac{A_{11} - \rho c A_{21}}{A_{11} + \rho c A_{21}} \tag{9}$$

Transmission coefficient (***T***):

$$T = \frac{2e^{jkd}}{A_{11} + (A_{12}/\rho c) + A_{21}\rho c + A_{22}} \tag{10}$$

**2.2. Absorption coefficient:**

The absorption coefficient is calculated by using the reflection coefficient. It is given by:

$$\alpha = 1 - \left|R^2\right| \tag{11}$$

## 3. FABRICATION AND EXPERIMENTATION

**3.1. Impedance tube:**

The impedance tube is a hollow cylinder having a sound source on one end and a termination on the other. Microphones are installed at predetermined intervals around the tube. The data collected by the microphones is then processed by the data acquisition system (DAQ). The impedance tube structure is critical in measuring acoustical properties and determining the upper and lower frequency limitation.

**3.1.1. Tube:**

The impedance tube's cross-section should be uniform from one end to the other. Minor flaws in the tube can cause reflections, which cause significant experimental errors. The tube might be round or rectangular in shape, but it must be uniform. In this case, we utilized a brass circular tube with a diameter of 5 cm and a length of 87 cm. The tube is divided into three sections: the first, known as the upstream part, the second, known as the downstream portion, and the third, known as the sample holder. Threads are made on the upstream part for easy fitting over the conical part of the sound source. Similarly, the same threads are created in the downstream portion to enable the option of adjusting the termination condition based on the results of the experiments. An internal taper of 70 is made on both sections to fit the sample holder between the upstream and downstream sections. A schematic diagram of the impedance tube is shown in Fig. 3. The measurable frequency range in the tube depends upon the diameter (***d***) of the tube and spacing between the microphones. The upper limit of the frequency is determined by equation (12). Beyond this upper-frequency limit the 1D wave propagation approximation does not hold true:

$$f_u = 0.586\,\frac{C}{d} \tag{12}$$

**3.1.2. Sample holder:**

The sample holder is constructed of the same material as the tube and has a consistent cross-section. The specimen should be airtightly fastened in the sample holder. To fit the sample holder with the upstream and downstream portions airtight, the sealant is being utilized. Teflon tape is used in our setup to form an airtight seal. Both sides of the sample holder have an exterior tapering of a 70 angle with a length of 5 cm. The sample holder is 20cm long in total. The diagram of the sample holder is shown in Fig. 3.

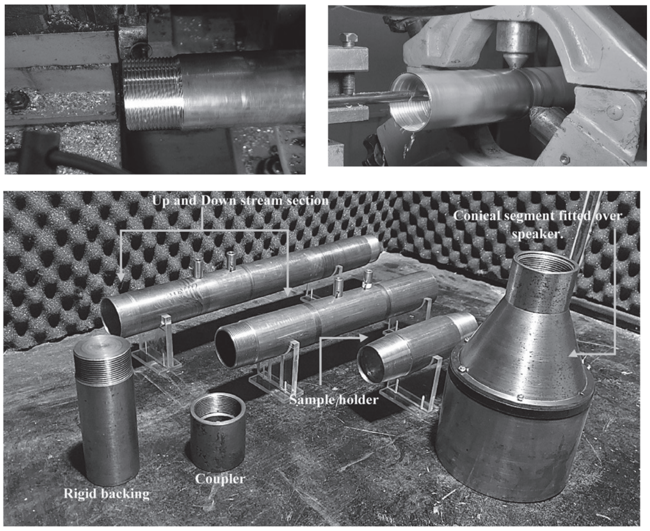



*Fig. 2: Fabrication and fabricated Parts of the four microphone Impedance tube*

### 3.2. Microphone:

Four pressure-based quarter-inch PCB microphones are used to acquire the data at the front and rear sides of the specimen. The distance between the microphones is set at 6.5 cm. The detectable lower limit of the frequency in the tube is determined by the distance between the microphones. The wavelength associated with the lowest frequency limit is 100 times the distance between microphones. The microphone closest to the sound source should always be placed at a distance more than twice the diameter of the tube. The measuring end of the microphone should always be parallel to the interior surface of the tube while fitting around a tube. Small deflections result in significant experimental errors.

### 3.3. Experiment:

The sound pressure is measured in four microphone impedance tube tests to determine the acoustic characteristics of the materials. The complex pressure ratio measured at four microphones is used to compute the transfer function. These transfer functions are then entered into a transfer matrix, which calculates the different acoustic characteristics of the materials.

The sample is airtightly fitted in the tool holder before being assembled with upstream and downstream sections. The sample is placed at the equidistance from microphones 2 and 3. The microphone sensors are inserted into the sensor holder and connected to the impedance tube through threads on its surface. The white noise is produced by a signal generator and amplified by a 30W power amplifier with a frequency range of 20 Hz to 5kHz. The amplified waves are delivered from one end via a speaker, and these sound waves are believed to be a planner. Sound pressure is measured before and after the sample interaction with the sound wave through microphone sensors. Eight sets of measurements are obtained with anechoic and rigid termination conditions. These microphone sensors are connected to the NI data acquisition system (NI-USB-4432). Fig. 2 shows the experimental apparatus in its assembled form. The data obtained is further processed in MATLAB to estimate the transfer function and then the acoustical properties of the materials.

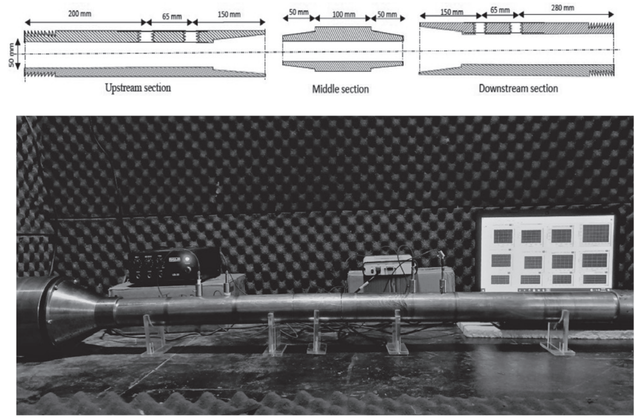



*Fig.3: Four microphone impedance tube design and assembly*

Before the actual experiment, the microphone sensors are calibrated, and a correction factor is determined by swapping the microphones. In the first reading, sound pressure is taken at positions 1, 2, 3, and 4, and then in the second reading, microphone 1 and 2 are swapped. The correction factor is measured by taking the ratio of the transfer function in the original condition to the transfer function evaluated when microphones are swapped. This eliminates the possibility of amplitude and phase mismatch errors in transfer function measurements.

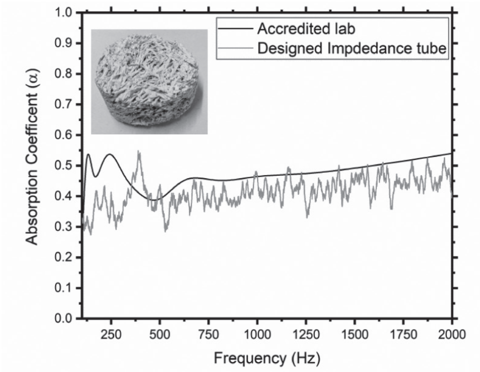
## 4. RESULT AND DISCUSSION

The developed experimental setup is validated by analyzing the sample with the known value of the absorption and reflection coefficient . The sample is fitted airtightly within the holder. Teflon tape is wrapped outside over the tapered part of the tool holder to prevent any sound leakage. Experiments are conducted in an acoustic enclosure to reduce external noise.

### 4.1. Validation:

A 15 mm ephony fibrette of diameter 50 mm is used to check the accuracy of the four-microphone impedance tube setup. These type of materials are commonly used in auditoriums, theatres to have good hearing comfort. Experiments are conducted using two load boundary condition method. Eight data sets are obtained from the experiments are processed in MATLAB R2019a. The material is tested within the frequency range of 50 Hz to 2000 Hz. The transfer function formulation is used to evaluate the acoustical properties of the material. The value of the transfer function is plugged in equation (2) to estimate the transfer matrix. Elements of the transfer matrix is used in equation (8) and (11) to compute the reflection and absorption coefficient. The evaluated absorption coefficient and reflection coefficient are compared with the standard value of the absorption and reflection coefficients of the material tested at Acoustic laboratory at research department, All India Radio and Doordarshan Delhi. The average absorption coefficient calculated for the experiment is approximately 0.42, whereas the absorption coefficient for the same material of the same thickness according to the standard data is 0.45, which is quite comparable. Fig 4(a) shows the frequency vs absorption plot for experimental and standard results of the material. The reflection coefficient for the same standard specimen is given around 0.7 whereas the reflection coefficient estimated is by the experiment is around 0.8. The reflection plot given Fig. 4(b) for standard and experimental data shows a good correlation.

*(a)*




*(b)*

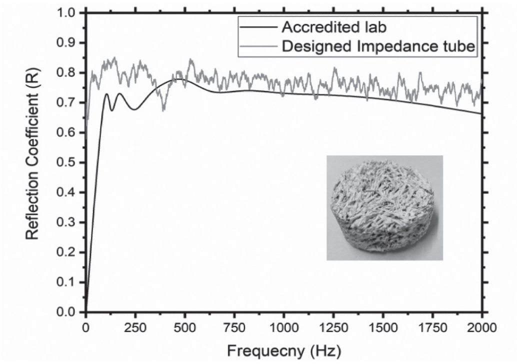
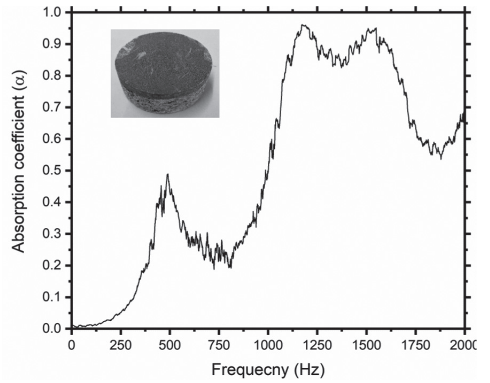


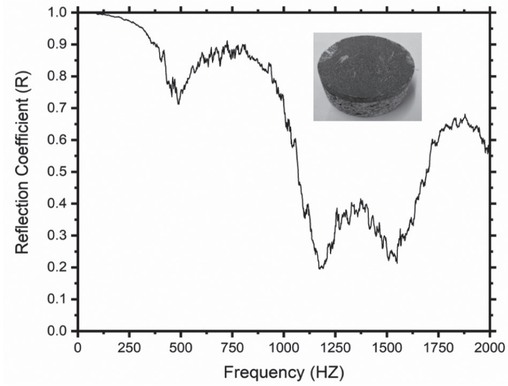

*Fig. 4: (a) Absorption coefficient vs Frequency (b) Reflection coefficient vs Frequency*

**4.2. Ephony fibrette backed with wood fibre cement:**

A sample of the ephony fibertte backed with wood fibre cement is prepared and acoustical properties are tested in the developed four microphone impedance tube setup. Wood fibre cement of 5 mm thickness is fixed at one end of the 25 mm ephony fibrette. The material is tested by placing it in such a way that the wood fibre cement part is facing the termination end. The material is tested within the frequency limit of 50 Hz – 2000Hz. The effect of the wood fibre cement results in increased absorption within the material at the mid-frequency range 800 Hz -1750 Hz. Also, an increase in the reflection coefficient can be seen in the low frequency 200 Hz to 500 Hz. The estimated reflection coefficient and absorption coefficient plotted against frequency is shown in Fig. 5b. Octave band represents the audible frequencies. Tab. 1 shows the value of reflection coefficient, absorption coefficient at various octave frequencies.




*(a)*




*(b)*

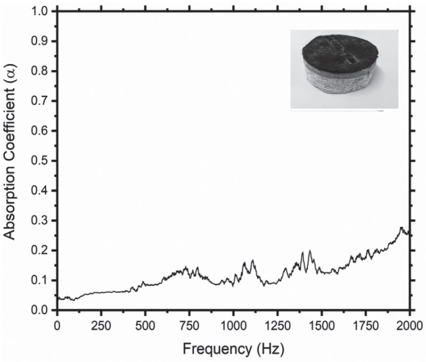
*Fig.5: (a) Absorption coefficient vs Freuency (b) Reflection coefficient vs Frequency*

| Frequency (Hz) | Absorption Coefficient (α) | Reflection Coefficient (R) |
|---|---|---|
| 63 | 0.0084 | 0.9981 |
| 80 | 0.011 | 0.9983 |
| 100 | 0.012 | 0.994 |
| 125 | 0.011 | 0.995 |
| 160 | 0.02 | 0.0989 |
| 200 | 0.028 | 0.985 |
| 250 | 0.05 | 0.974 |
| 315 | 0.094 | 0.951 |
| 400 | 0.271 | 0.852 |
| 500 | 0.431 | 0.752 |
| 630 | 0.27 | 0.846 |
| 800 | 0.193 | 0.899 |
| 1000 | 0.4942 | 0.706 |
| 1250 | 0.88468 | 0.327 |
| 1600 | 0.897 | 0.31 |
| 2000 | 0.688 | 0.556 |

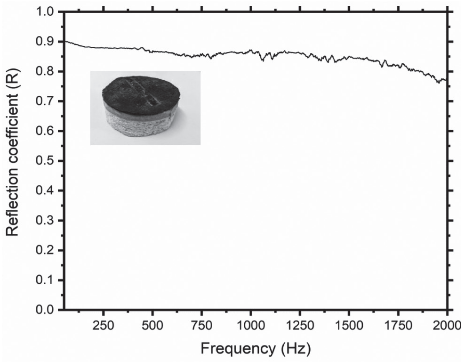
*Table 1.Data for the Reflection coefficient, absorption coefficient at octave band frequencies*

**4.3. Ephony fibrette backed with wood fibre cement and 2mm damper sheet :**

A sample of ephony fibrette backed with wood fibre cement is further modified and a 2 mm hard damper sheet is placed on the backside of it. This material is tested by placing the damper part facing the source end. The material is tested in the frequency limit of 50 Hz to 2000 Hz. Placing the damper results in an increased reflection coefficient. The average reflection coefficient is around 0.85. The resulting damper wall behaves as a reflective surface. The effect of the wood fibre can be observed from the absorption graph. As the frequency approaches the mid-frequency region there is an increase in the absorption coefficient. Fig. 6b shows the plot for the absorption coefficient and reflection coefficient. Tab. 2 shows the value of reflection coefficient, absorption coefficient at various octave frequencies.




*(a)*




*(b)*

*Fig. 6 (a) Absorption coefficient vs Frequency (b) Reflection coefficient vs Frequency*

| Frequency (Hz) | Absorption Coefficient (α) | Reflection Coefficient (R) |
|---|---|---|
| 63 | 0.0259 | 0.8997 |
| 80 | 0.03658 | 0.8963 |
| 100 | 0.04981 | 0.89303 |
| 125 | 0.0501 | 0.88725 |
| 160 | 0.05635 | 0.88178 |
| 200 | 0.06 | 0.88097 |
| 250 | 0.06095 | 0.8789 |
| 315 | 0.608 | 0.8781 |
| 400 | 0.0706 | 0.877 |
| 500 | 0.091 | 0.868 |
| 630 | 0.1109 | 0.855 |
| 800 | 0.125 | 0.8443 |
| 1000 | 0.0908 | 0.867 |
| 1250 | 0.09447 | 0.86125 |
| 1600 | 0.13847 | 0.838 |
| 2000 | 0.26 | 0.769 |

*Tab. 2. Data for the Reflection coefficient, absorption coefficient at octave band frequencies*

## 5. CONCLUSION

Noise control and measurement is a growing area these days, and excessive noise environmental pollution necessitates the selection of materials based on acoustic characterization. We have come up with a design of the four-microphone impedance tube made up of brass. The working frequency range of the setup is 50 Hz – 2000 Hz. The accuracy of the tube is confirmed by testing a standard specimen of given acoustical properties. The same acoustical properties i.e., absorption coefficient and reflection coefficient are estimated with a designed setup. The two properties are compared and found a good correlation between experimental data and standard data provided by an accredited laboratory. Two new samples are also made by adding wood fibre cement and a damper of 2 mm thickness. The acoustical properties of the two samples are also estimated. The sample with wood fibre cement shows both reflective and absorptive behavior whereas the sample with a 2 mm thick damper majorly shows the reflective behavior. The proposed setup is extremely beneficial for the rapid testing of new building materials. The proposed novel design can be utilized to create a low-cost and accurate impedance tube.

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