inter.noise
HAMBURG 2016

Acoustical characterization of bulk natural fibrous material using flow resistivity

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ABSTRACT

This paper provides an easy and simple way to estimate the normal specific sound absorbing properties of natural fibrous materials. These materials are considered to be bulk reacting. Using the empirical relationship between the characteristic impedance and complex wave number with the flow resistivity of the material, the normal specific sound absorbing material of two natural materials jute and coconut coir are estimated. Further using the four microphone impedance tube method, the characteristic impedance and complex wave number of these materials are also measured. The measured values are then used to validate the normal specific sound absorption coefficient of the bulk sound absorbers, jute felt and coconut coir. Certain calibration checks are also made in the four microphone impedance tube using the two-load method by determining the characteristic impedance and complex wave number of air in an empty rigid closed tube. Then again using the measured parameters of characteristic impedance the input impedance of a closed tube of finite length is estimated. This method establishes the fact that with the knowledge of the flow resistivity of a fibrous natural material, only the empirical relationship can be used to predict the sound absorption coefficient of bulk natural fibrous materials.

Keywords: Sound absorbing coefficient, impedance, jute, coir
I-INCE Classification of Subjects Number(s): 72.7

1. INTRODUCTION

In recent years, worldwide there is a quest for designing and developing environmentally friendly products. Noise control engineering professionals are no less away from this quest. In search of eco-friendly materials, naturally occurring fibrous materials from plants are being explored and applied for noise control instead of traditional glass fibre materials (1). Noise control materials have two most important properties one being the sound absorption coefficient and the other being the transmission loss (2). These properties of the materials can be measured in the laboratory as per established international standards. However, these acoustical properties of fibrous materials are also influenced by their physical properties like bulk density, porosity, fiber diameter, flow resistivity etc. Empirical relationship between the characteristic impedance, complex wave number of the fibrous materials with their flow resistivity has been established by Delany and Bazley in 1970, which is widely used by everyone around the world even today (3). Delany and Bazley mostly considered glass fibre type of materials in their empirical relations.

In this paper the use of the existing empirical relationship for natural fibrous material like jute and coconut coir in order to determine their bulk sound absorbing properties is made. However, when sound absorbing materials are considered as locally reacting the surface impedance of these materials is considered. If the thickness of the material used is significant then the bulk properties is preferred (4,5). From the estimated bulk properties of characteristic impedance of the fibrous natural material the normal specific sound absorption coefficient for a hard backing is calculated. In order to use the empirical relationship only the material's flow resistivity value needs to be known. Researchers have reported the flow resistivity values of jute felt and coconut coir, which have been used in the present

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study (6,7).

Next, in order to validate the estimated normal specific sound absorption coefficient of the material, the four microphone method, impedance tube using the two-load method has been used to measure the characteristic impedance of the fibrous natural material. For validation of the measurements, the measured characteristic impedance of the fibrous material was used to predict the normal specific sound absorbing coefficient of the fibrous material for a different length, which was again compared with that from the Delany and Bazley empirical relationships and measurements in the impedance tube. Further in the four microphone impedance tube method the characteristic impedance of air with no material in the tube was also measured. The measured characteristic impedance of air was then used to predict the input impedance of a closed tube of a certain length which is as per theory.

In the following sections a brief description of the experimental, empirical and prediction methods are described.

2. EMPIRICAL RELATIONS

For the sake of completeness the empirical equation of Delany and Bazley used in the present study to predict the characteristic impedance, Z_c and complex wave number, $k^{'}$ of the natural fibrous material is given in Equations (1) and (2), respectively.

$$Z_c = \rho c\left[1+0.586\left(\frac{f}{\sigma}\right)^{-0.75} - j0.768\left(\frac{f}{\sigma}\right)^{-0.73}\right] \quad (1)$$

$$k' = \frac{\omega}{c}\left[1+0.0857\left(\frac{f}{\sigma}\right)^{-0.70} - j0.1749\left(\frac{f}{\sigma}\right)^{-0.59}\right] \quad (2)$$

Where ρ is the density of the ambient air, c is the speed of sound in ambient air, σ is the flow resistivity and f is the frequency. All the quantities given in Equation (1) and (2) are in SI units. The above equations are used for fibrous materials which satisfy the relationship $0.01 < \frac{f}{\sigma} < 1.00$.

For a bulk sound absorbing material of thickness d, the surface impedance of the material is given as per Equation (3)

$$Z_{in} = -jZ_c \cot(k'a \quad (3)$$

Then, from the relationships given in Equations (4) between the complex reflection co-efficient, R and the surface impedance of the material, the normal specific sound absorption co-efficient, α can be calculated using Equation (5).

$$Z_{in} = \rho c\frac{1+R}{1-R} \quad (4)$$

$$\alpha = 1-|R|^2 \quad (5)$$

3. EXPERIMENTAL DETAILS

3.1 Impedance Tube

The characteristic impedance of the fibrous material has been measured using the four microphone, two-load transfer matrix method as per the ASTM E 2611-09 standard (8). A schematic diagram of the experimental setup used is shown in Figure. 1. The setup consists of a circular tubes of diameters 100 mm and 29 mm, which give a working frequency range of 50 Hz to 1600 Hz and 500 Hz to 6400 Hz, respectively. In the results reported in the present study only the small tube of 29 mm diameter has been used, though the large tube could have been used to measure from the lower frequencies of 50 Hz.

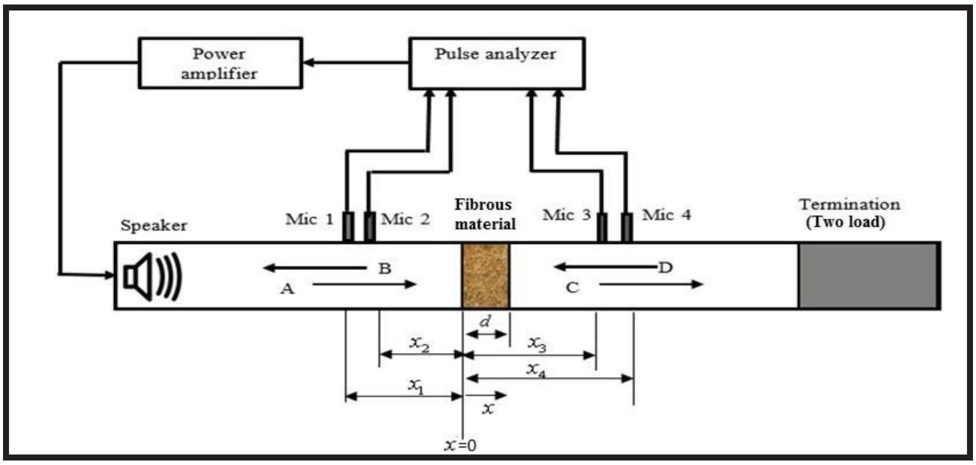

Figure 1–Schematic diagram showing the four microphone locations.

A photographic view of the impedance tube setup (B&K 4206T along with PULSE analyzer) with the 29 mm diameter is shown in Figure 2. In Figure 2, the larger tube can also be seen at the far end.

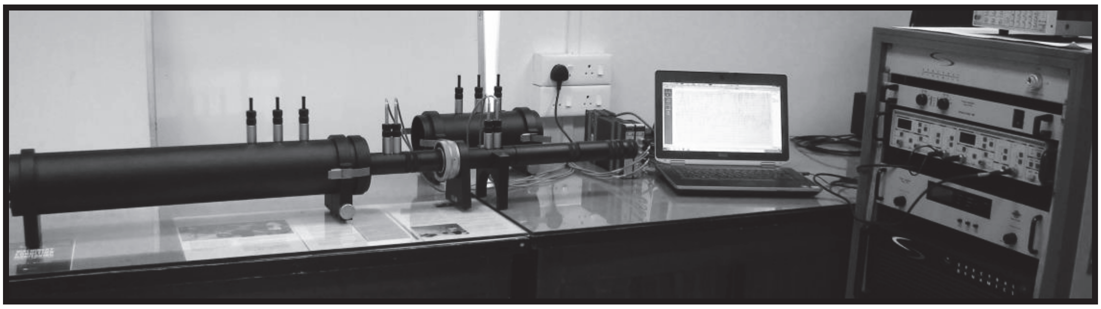

Figure 2-View of the impedance tube in the laboratory

3.2 Measurement of Characteristic Impedance

In Figure 1, a fibrous sample of thickness *d* is located between microphone 2 and microphone 3. The sound pressure at each microphone can be described by Eqs. (1) to (4). In the present tube the distance between microphone 2 and 3 is fixed at 200 mm.

$$P_1 = (Ae^{-jkx_1} + Be^{jkx_1})e^{j\omega t} \tag{6}$$

$$P_2 = (Ae^{-jkx_2} + Be^{jkx_2})e^{j\omega t} \tag{7}$$

$$P_3 = (\mathrm{C}e^{-jkx_3} + De^{jkx_3})e^{j\omega t} \tag{8}$$

$$P_4 = (\mathrm{C}e^{-jkx_4} + De^{jkx_4})e^{j\omega t} \tag{9}$$

where *k* is the wave number and *A*, *B*, *C* and *D* are the complex wave amplitudes of the four plane waves as shown in figure. The complex wave amplitudes *A* to *D* can be easily determined from Eqs. (10) to (13):

$$A = \frac{jP_1e^{jkx_2} - P_2e^{jkx_1}}{2\sin k(x_1 - x_2)} \tag{10}$$

$$B = \frac{jP_2 e^{-jkx_1} - P_1 e^{-jkx_2}}{2\sin k(x_1 - x_2)} \tag{11}$$

$$C = \frac{jP_3 e^{jkx_4} - P_4 e^{jkx_3}}{2\sin k(x_3 - x_4)} \tag{12}$$

$$D = \frac{jP_4 e^{-jkx_3} - P_3 e^{-jkx_4}}{2\sin k(x_3 - x_4)} \tag{13}$$

The sound pressure and particle velocity at the front and back surfaces of the sample can then be defined in terms of a transfer matrix by using the two-load method:[8] i.e.,

$$\begin{bmatrix} P_{(a)} & P_{(b)} \\ V_{(a)} & V_{(b)} \end{bmatrix}_{x=0} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P_{(a)} & P_{(b)} \\ V_{(a)} & V_{(b)} \end{bmatrix}_{x=d} . \tag{14}$$

To solve the 2x2 transfer matrix, it is necessary to perform tests using two different terminations (acoustical load) represented by indices *a* and *b* in Equation (14). In our experiments the two terminations were provided by acoustical loads of two closed tubes of different lengths, instead of anechoic termination. The acoustic pressure and particle velocity at the front and back of the sample can be described as given in Equation (15).

$$P\big|_{x=0} = A + B \qquad P\big|_{x=d} = Ce^{-jkd} + De^{jkd}$$

$$V\big|_{x=0} = \frac{A - B}{\rho \mathrm{c}} \qquad V\big|_{x=d} = \frac{(Ce^{-jkd} + De^{jkd})}{\rho \mathrm{c}} . \tag{15}$$

Once these values for the two end conditions are substituted into Equation (14), it is possible to solve for the four transfer matrix elements, T_{11}, T_{12}, T_{21}, T_{22}.

Now the measured complex wave number and the characteristic impedance can be calculated using Equations (16) and (17), respectively.

$$k'_{meas} = \frac{1}{d} \cos_{-1} T_{11} \tag{16}$$

$$Z_{c\,meas} = \sqrt{\frac{T_{12}}{T_{21}}} \tag{17}$$

3.3 Measurement of sound absorption coefficient

Using the measured values of the characteristic impedance and the complex wave number, the normal specific sound absorption coefficient of a bulk fibrous absorber of any thickness, d can be calculated using Equations (3), (4) and (5).

Further using the experimental setup, the reflection coefficient, R can then be calculated using Equation (18) for rigid backing case and then Equation (5) is used to calculate the normal specific sound absorption coefficient, α.

$$R = \frac{T_{11} - \rho c T_{21}}{T_{11} + \rho c T_{21}} \tag{18}$$

Thus in the present study we have found the sound absorption coefficient of fibrous natural materials by three approaches, for clarity are briefed as follows:

(i) Sound absorption estimation by obtaining characteristic impedance and complex wave number from Equations (1) to (5), for material of any thickness d. This henceforth will be referred as *calculated sound absorption coefficient*.

(ii) Sound absorption estimation by measurements using Equations (18) and (5). This will henceforth be known as *measured sound absorption coefficient*.

(iii) Sound absorption by using measured characteristics impedance and complex wave number given in Equation (16) and (17), and then using Equations (3), (4) and (5), for any thickness d. This henceforth will be known as *predicted sound absorption coefficient*.

4. FIBROUS NATURAL MATERIAL

In our present study we have considered two naturally occurring fibrous material jute and coconut coir. The jute material used in the present study was used in a felt form. The photographs of the two materials are shown in Figure 3. The left one is jute material. The flow resistivity of the materials used in the estimations of the characteristic impedance are those that has been reported in the literature. Table 1.provides a description of the materials. Test samples were made from these materials in cylindrical form with an outer diameter of 29 mm and in lengths of 25 mm and 50 mm.

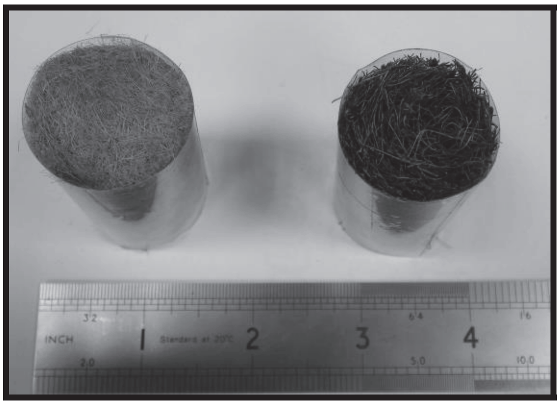

Figure 3-View of the natural fibrous samples (left-jute, right-coir)

Table 1.Material parameters used for the fibrous materials

Material	Bulk density (kg/m^3)	Flow Resistivity(N-s/m^4)
Jute felt	100.00	26000.00
Coconut Coir	130.00	2600.00

5. RESULTS AND DISCUSSIONS

5.1 Measurements in tube without any fibrous sample

Using the four microphone method, two load method in the impedance tube, without any sample, the characteristic impedance of air at room temperature of 21^0C was measured. The real and imaginary part of the characteristic impedance of air are shown in Figure 4. The real part of the characteristic impedance is around 415 Kg/m^2-s, at all frequencies. Incidentally, knowing the density of air, the speed of sound in air can also be estimated, (9). In this case it turns out to be 345 m/s. The imaginary part of the characteristic impedance is negligible, as is evident from Figure 4.

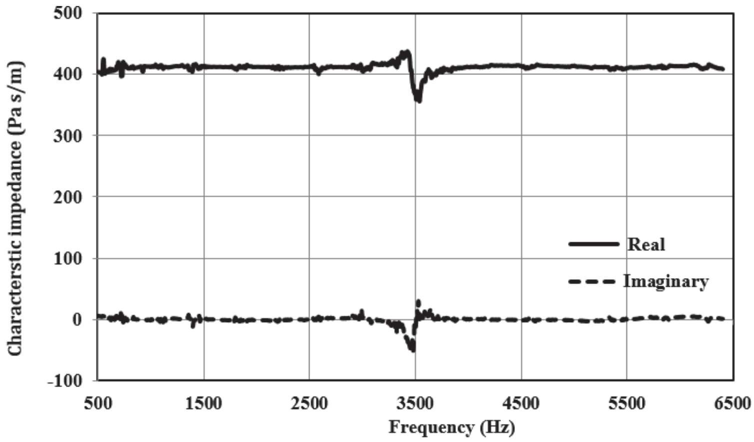

Figure 4-Measured characteristic impedance of air

Thus, by measuring Z_c and k' from the measurements using the four microphone, two-load method, using Equation (3) the input impedance of a 100 mm closed tube with air as a fluid is estimated. The imaginary part of the impedance is shown in Figure 5. This coincides with the theoretical input impedance of a closed tube of length d, as given in Equation (19).

$$\frac{Z_{in}}{\rho c} = -j\cot(k'd) \tag{19}$$

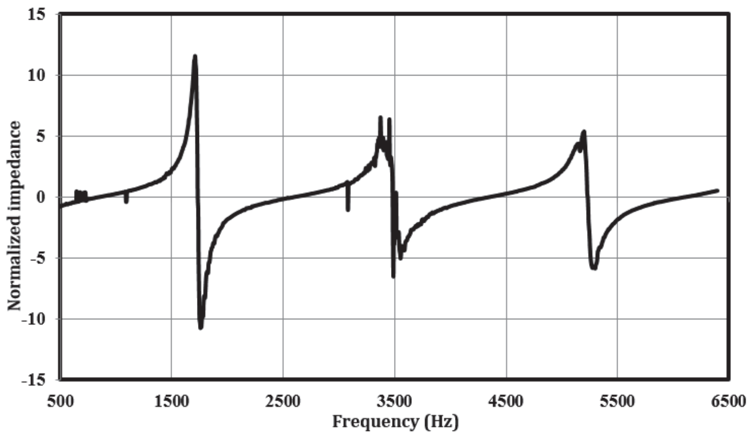

Figure 5-Estimated input impedance of a closed tube of 100mm length using the measured characteristic impedance of air

5.2 Measurements with fibrous samples

At first the characteristic impedance of the fibrous materials for two different sample thickness of 25 mm and 50 mm, was measured. As is expected the characteristic impedance of these bulk absorbing natural fibrous materials should be independent of the length. Figure 6 and 7, show the measured real and imaginary part of the characteristics impedance of jute felt and coir.

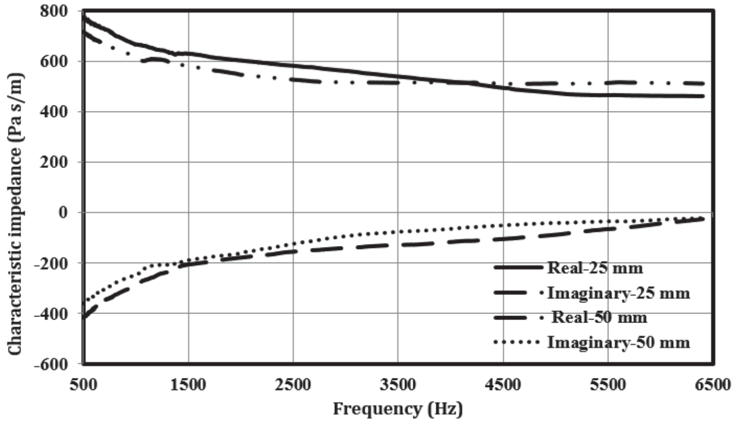

Figure 6-Measured characteristic impedance of jute felt sample of two different thicknesses

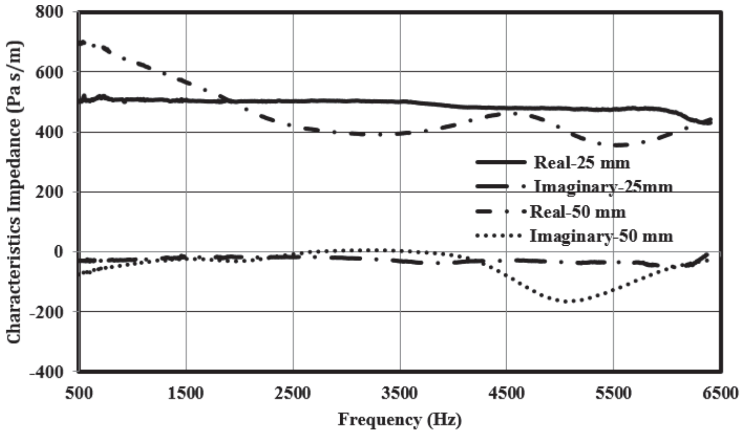

Figure 7-Measured characteristic impedance of coconut coir sample of two different thicknesses

As has been stated earlier in section 3.3, the sound absorption coefficient of the natural fibrous samples have been measured by three different approaches. The measured, predicted and calculated sound absorption co-efficient for the two natural fibrous materials, are shown in Figures 8 and 9, for jute felt and coconut coir, respectively. The samples were of length 50 mm.

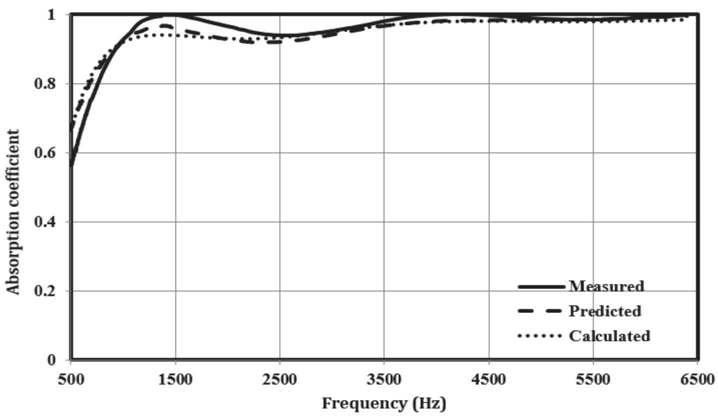

Figure 8-Sound absorbing coefficient for 50 mm sample length of jute felt.

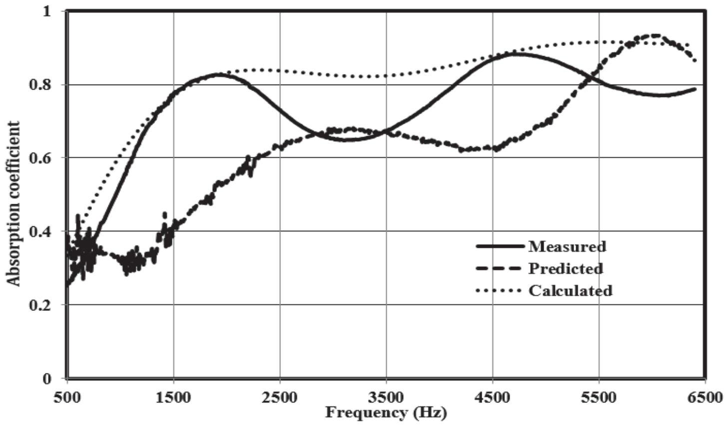

Figure 9-Sound absorbing coefficient for 50 mm sample length of coconut coir.

From the sound absorption co-efficient plots obtained by three different approaches, it is seen that there is a close matching for the case of jute felt, where the flow resistivity is high. In the case of coir the flow resistivity is about 10 times low. With increase in the flow resistivity there is an increase in the sound absorption by the fibrous natural material. The results in Figures 8 and 9, establish the fact that for natural fibrous materials, even the empirical relationship given by Delany and Bazley can be used for estimation of sound absorption, provided the flow resistivity of the material. This further establishes the fact that for fibrous material, for a quick estimate one need not measure the sound absorbing coefficients by the impedance tube, instead of with a simple apparatus measure the flow resistivity of the sample, and use the empirical relations.

6. CONCLUSIONS

In this paper it has been experimentally validated that the characteristic impedance can be measured and used to predict the sound absorbing co-efficient of fibrous material for any sample length, by considering them as sound absorbers. Further the empirical relationships established by Delany and Bazley can also be used for fibrous **natural** material, to predict their characteristic impedance, complex wave number and the sound absorbing coefficient. Knowledge of flow resistivity of a fibrous natural material is good enough to accurately estimate its sound absorbing coefficient. The four microphone impedance tube can be used to measure the speed of sound in air. The approaches presented in this work can be used for other naturally occurring fibrous materials as well.

ACKNOWLEDGEMENTS

The first author would like to acknowledge Department of Science and Technology, Government of India for providing the DST-Inspire fellowship. The authors would like to acknowledge Indian Institute of Technology Kharagpur for providing the experimental facilities used in this work.

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