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INVERSE ESTIMATION OF SOUND ABSORPTION COEFFICIENT OF NATURAL JUTE MATERIAL BASED ON PARTICLE SWARM OPTIMIZATION ALGORITHM

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Now a days use of natural materials have significantly increased in different fields of engineering mainly because of their environmental friendliness. In acoustics and noise control domain, natural material are also being effectively used. In this study, the acoustical characterization of three different types of natural *jute* felt material is performed by measurements in the laboratory and particle swarm optimization (PSO) based inverse acoustical characterization method. There are many empirical models available in literature which describes the acoustical behavior of a specific material accurately. In this work, measured values of air flow resistivity are used in Delany-Bazley model and Dunn-Davern model for sound absorption prediction of the natural material, *jute*. It is observed that, normal sound absorption coefficient values predicted using these two models deviate significantly from the experimental values throughout the frequency range of interest. Therefore, the inverse prediction of the eight regression coefficients in Dunn and Davern model using PSO method is conducted, and new regression coefficients for jute material are found. Results of predicted sound absorption using inverted coefficients for three types of jute felts are found to be better compared to prediction results from the original Delany and Bazley model and Dunn and Davern model, particularly in the low-frequency region.

Keywords: sound absorption coefficient, jute, particle sound optimization

1. Introduction

In recent times concern about noise is increasing in areas like transportation vehicles, buildings, work places, etc. Reverberation inside these places is controlled by using sound absorbing materials. Traditionally, synthetic materials like polymeric foams, glasswool, rockwool *etc.* for sound absorption have been used. Because of the various disadvantages associated with these materials like high cost, not environment friendly, have potential health effects, trend is now growing towards the use of natural materials for sound absorption [1]. Whereas, natural materials are of low cost and biodegradable. Natural jute material is abundantly available in India and it contributes to about 60% of the total production of jute across the world. The prospective application of jute material for sound absorbing and sound blocking, has been experimentally demonstrated by researchers [2-3]. Jute material has significant environmental advantage since it can withstand high amount of moisture and in fact jute is hydrophilic to water, and thus can be used in building acoustics.

For using jute as an acoustical material, knowledge of its acoustical properties is crucial. With the knowledge of acoustical properties, its acoustical performance can be simulated using various numerical methods like finite and boundary element. Many empirical models are available in literature which is used for prediction of acoustical performance of fibrous materials. Delany and Bazley model [4], and Dunn and Davern model [5] are empirically developed models for glass wool material and reticulated foam material respectively. These models are simple to use and are based on only measured value of air flow resistivity of acoustical materials. Furthermore, these models are used in the standard EN 12354-6:2003 [6] related to building acoustics.

Delany and Bazley have obtained eight coefficients of their model by measuring values of the characteristic impedance and the propagation coefficient for fibrous material with porosity close to one. They normalized the values of these parameters as a function of frequency and flow resistance. The eight coefficient values of regression constants were obtained by plotting normalized real and imaginary parts of the characteristic impedance and propagation constant. The measured flow resistances of test samples were used for normalization procedure. Later on, Dunn and Davern used the same equations for the characteristic impedance and the propagation coefficient as in Delany and Bazley model, but obtained new values of eight coefficients for foam material. Hence, using new regression coefficients sound absorption of foam material can be well predicted.

When Delany and Bazley model, and Dunn and Davern model are used for sound absorption prediction of jute material, significant amount of mismatch can be seen with experimental sound absorption throughout the frequency range of interest. This mismatch is large particularly in the low frequency region. The performance of these models is governed by values of the eight regression coefficients which are fitted for a particular material. Therefore when these models are used to predict sound absorption of jute material, results deviate significantly from the measured data.

2. Material

Jute material is mainly extracted in the form of raw jute fibers from jute plants. These raw jute fibers are treated further as per the Indian standard [10] for the production of jute felts. Three types of jute materials used in this study are classified as Type 1 felt, Type 2 felt, and Type 3 felt based on the thickness of the single layer and surface density of the felt. The photograph of jute felts is shown in Fig. 1 and the classification is listed in Table 1. The optical microscope images of the three types of jute felt are shown in Fig. 2, where the fiber diameter is indicated.

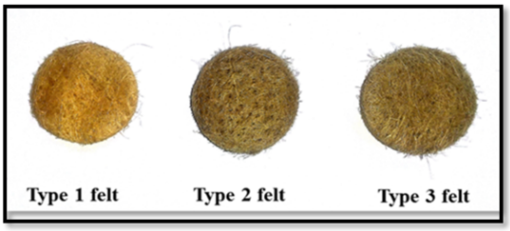
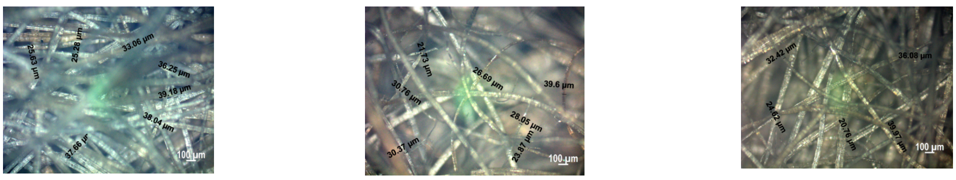


Figure 1: Photograph of the three types of jute felt used in the study

Table1: Categorization of jute felts

Felt type	Thickness	Surface density (gm/m^2)
Type 1	4 mm	400
Type 2	8 mm	1000
Type 3	10 mm	1200



(a) **(b)** **(c)**

Figure 2: Optical microscope images for the three types of jute felt used in the study (a) Type 1, (b) Type 2, and (c) Type 3 felt

3. Sound absorption prediction of jute material

Sound absorption coefficient of jute material is predicted from the empirical based impedance prediction models like Delany and Bazley model, and Dunn and Davern model [4-5].

3.1 Delany and Bazley model

According to the Delany and Bazley model, the empirical expressions for the characteristic impedance z and the propagation constant k is given as

$$z = \rho_{air} c \left[1 + c_1 \left(\frac{\rho_{air} f}{\sigma} \right)^{-c_2} - jc_3 \left(\frac{\rho_{air} f}{\sigma} \right)^{-c_4} \right] \quad (1)$$

$$k = \omega / c \left[1 + c_5 \left(\frac{\rho_{air} f}{\sigma} \right)^{-c_6} - jc_7 \left(\frac{\rho_{air} f}{\sigma} \right)^{-c_8} \right] \quad (2)$$

for

$$0.01 < \frac{f}{\sigma} < 1.00 \quad (3)$$

where σ is the flow resistivity, f is the frequency of sound waves in Hz, ρ_{air} is the density of air in kg/m^3, $c_1 - c_8$ are the regression coefficients

3.2 Dunn and Davern model

Dunn and Davern used the equations in the same form as given by Delany and Bazley. Delany and Bazley model was developed for fibrous material whereas Dunn and Davern utilized it for modelling the acoustic behaviour of recycled foam material.

3.3 Calculation of sound absorption coefficient

The normal incidence sound absorption coefficient, α is calculated by

$$\alpha = 1 - |R|^2 \quad (4)$$

where

$$R = \frac{Z_s - \rho_{air} c}{Z_s + \rho_{air} c} \quad (5)$$

$$Z_s = -jz \cot(kL) \quad (6)$$

where L is the thickness of fibrous material layer, c is the speed of sound in air, R is the complex reflection coefficient, $j = \sqrt{-1}$ complex number.

4. Measurement of flow resistivity

The air flow resistivity is an important non-acoustical parameter of fibrous materials. It determines resistance to the air flow through the porous material. Flow resistivity of jute material is measured using indigenously developed experimental setup as per the ISO 9053 standard [9]. The flow resistivity is calculated by Eq. (7) as

$$\sigma = \frac{\Delta P}{VL} \quad (7)$$

where ΔP is pressure difference across the sample thickness, V is air flow velocity, L is the sample thickness.

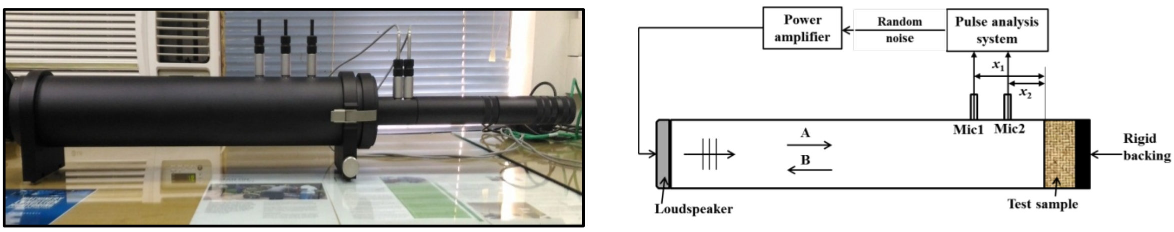
The measured values of flow resistivity for Type 1, Type 2, and Type 3 felt are listed in Table 2

Table 2: Bulk density and measured flow resistivity of jute felts

Material	Measurement	
	Bulk density ρ_1 (kg/m^3)	Flow resistivity σ (Ns/m^4)
Type 1 felt	76.13	33190
Type 2 felt	116.4	25342
Type 3 felt	148.3	28852

5. Measurement of the sound absorption of jute felts

The normal incidence sound absorption coefficient of jute felt is measured by using B&K 4206 impedance tube as shown in Fig 3(a). The schematic of the measurement system is as shown in Fig.3 (b). The samples are prepared with diameters of 29 mm and 100 mm. The frequency range of interest for measurement is from 50 Hz to 6400 Hz.



(a) **(b)**

Figure 3: Sound absorption coefficient measurement (a) Experimental setup, (b) schematic diagram

6. Inverse estimation of eight coefficients using the particle swarm optimization method

In this study, eight coefficients of Dunn and Davern model are estimated using inverse acoustical characterization method based on the particle swarm optimization technique. In this method, error between the predicted and experimentally measured sound absorption coefficient is minimized and values of the eight coefficients are adjusted so that there is matching between experimental and predicted sound absorption coefficient. The objective function used for this inverse problem is given by [6].

$$E(\alpha)^{\text{NRMSE}} = \left(\sqrt{\frac{1}{n} \Sigma_{i=1}^{n} \left(d_i^{\text{expt}} - d_i^{\text{model}} \right)^2} \Big/ \left(d_{\max}^{\text{expt}} - d_{\min}^{\text{expt}} \right) \right) \tag{8}$$

where n is the total number of data points, d^{expt} is the experimental sound absorption coefficient data, d^{model} is the calculated sound absorption coefficient data from the Dunn and Davern model and Delany and Bazley model used in this study. $\text{E}(\alpha)^{\text{NRMSE}}$ is the normalized root mean square error given in percentage.

PSO algorithm works according to the social behaviour of birds [7]. Birds while moving in flock in search of their food exchange information about their position, velocity, and fitness. In PSO algorithm, the words bird and particle are used interchangeably. Individual particle has information about its position vector in the solution range and the associated velocity vector. The velocity vector of each particle is given as

$$v_{k+1}^{i} = wv_{k}^{i} + c_1 r_1 \frac{\left(p_k^i - x_k^i\right)}{\Delta t} + c_2 r_2 \frac{\left(p_k^G - x_k^i\right)}{\Delta t} \qquad (9)$$

where w is an inertia weight, p is the best particle position and r is a random number between 0 and 1.

All particles change the position at a particular time which is set in the algorithm. Then the velocity vector is used to calculate new location of a particle for the next time step. The position vector of each particle is given as

$$x_{k+1}^{i} = x_k^i + v_{k+1}^i \Delta t \qquad (10)$$

where $x = [c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8]^{\mathrm{T}}$ is the vector consisting of coefficients to be inverted in the Delany and Bazley model, and Dunn-Davern model, v_{k+1}^i is the corresponding velocity updated vector and Δt is the time step value generally set as unity.

6.1 Inverse estimation of eight coefficients for Type 1, Type 2 and Type 3 felt using the PSO

Normal incidence sound absorption coefficient for Type 1, Type 2 and Type 3 felt were obtained by measurements using the impedance tube, Dunn-Davern model with new coefficient values for jute material obtained from the PSO (indicated as inverted Dunn and Davern model in Table 3) are displayed in Fig. 4. Also, a comparison of predicted sound absorption coefficient using original Delany-Bazley model, and Dunn-Davern model with experimental data is shown in Fig. 4. In original Delany-Bazley model, and Dunn-Davern model, values of coefficients $c_1 - c_8$ are same as suggested by these authors and are listed in Table 3. New values of coefficients $c_1 - c_8$ obtained from an inverse method using PSO for Type 1, Type 2 and Type 3 felt are also given in Table 3.

Table 3: Coefficients for different models

Model	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
Delany - Bazley model	0.057	0.754	0.087	0.732	0.189	0.595	0.098	0.700
Dunn and Davern model	0.114	0.369	0.099	0.758	0.168	0.715	0.136	0.491
Inverted Dunn and Davern model for Type 1 felt	0.277	0.331	0.109	0.170	0.256	0.263	0.004	0.225
Inverted Dunn and Davern model for Type 2 felt	0.658	0.155	0.075	0.396	0.510	0.135	0.013	0.929
Inverted Dunn and Davern model for Type 3 felt	0.750	0.027	0.029	0.784	0.416	0.266	0.086	0.362

Sound absorption prediction results obtained for three types of jute felts using inversely estimated coefficient values are represented by the legend PSO in Fig 4. It shows excellent match with experimental sound absorption in the overall frequency range. Hence, this perfect matching of sound absorption data confirms accurate inverse estimation of coefficient values using PSO method. Therefore, by using same equations as given by Dunn and Davern model but with new coefficients values, accurate estimation of sound absorption of jute felt can be done.

The convergence pattern of eight coefficient values for Type 1, Type 2, and Type 3 felt is represented in Fig. 5, Fig. 6, and Fig. 7 respectively.

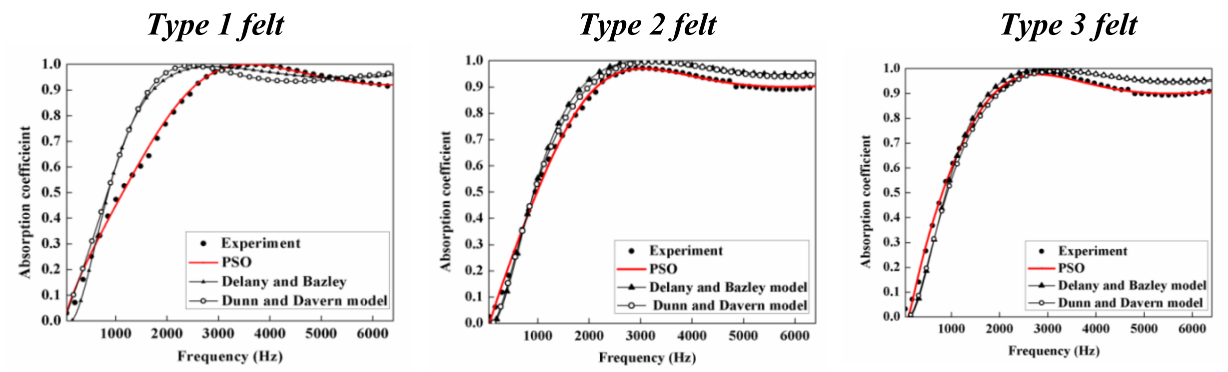


Figure 4: Comparison of normal incidence sound absorption coefficient of Type 1, Type 2, and Type 3 felt obtained from different approaches

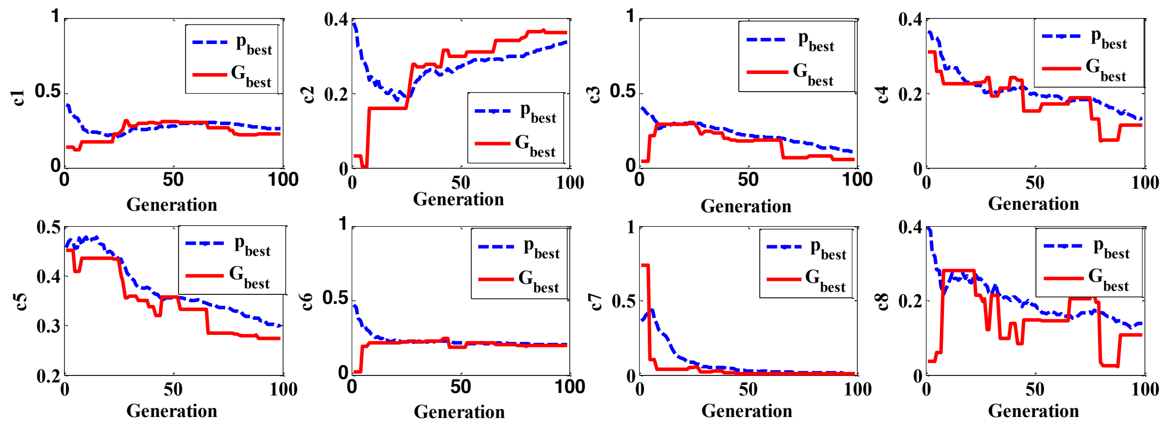


Figure 5: Convergence pattern for estimation of eight coefficients for Type 1 felt using PSO inversion method.

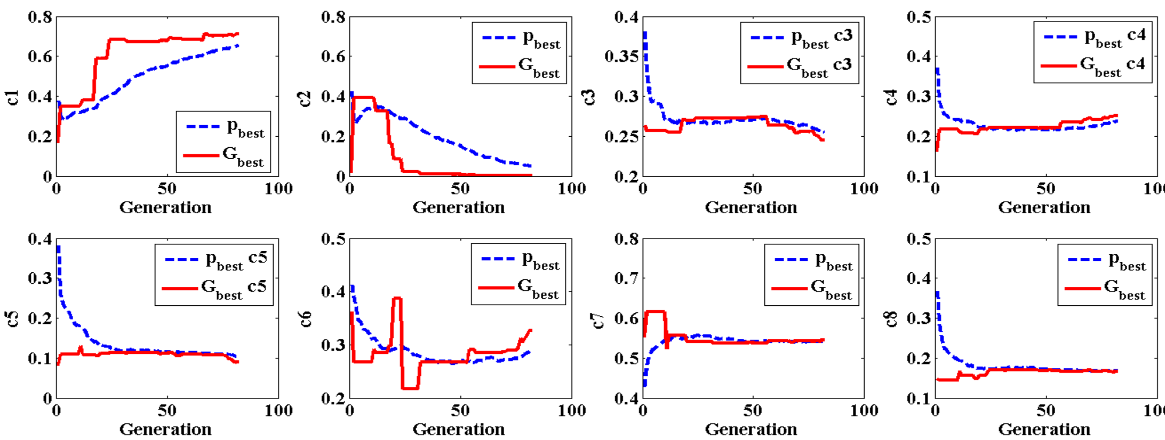


Figure 6: Convergence pattern for estimation of eight coefficients for Type 2 felt using PSO inversion method.

During the iteration process in the PSO, the initialized number of particles spreads over the defined solution range for each individual parameter. The calculated error of each particle relative to the experimental data is given by p_{best} while G_{best} gives the least of collective errors of all particles together relative to the experimental data. In each iteration new p_{best} and G_{best} values are calculated. Each time the algorithm keeps the new p_{best} values but the selection of G_{best} is dependent on the comparison with previous G_{best} value and newly calculated G_{best} value. The G_{best} value which gives minimum error with the experimental data during all performed iterations is only considered and used for further computations. All p_{best} values follow G_{best} values during each iteration and moves in the direction of global solution. The matching of these two values over generations indicated the best possible solution for the coefficients determination.

If the G_{best} value is found in early generation and not changing further, then the solution converges within less number of generations. So the number of generations actually required for convergence depends on the G_{best} value. It is totally problem dependent and may vary for each case. For the problem mentioned in this paper, the convergence is achieved for all types of jute felts in the range of 50 – 100 generations. The exact number of generations only depends on the degree of error between the predicted and measured data.

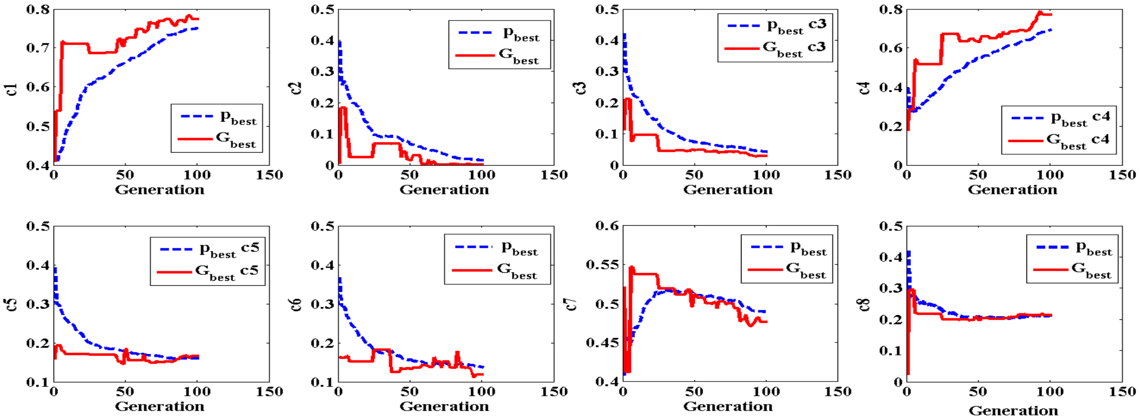


Figure 7: Convergence pattern for estimation of eight coefficients for Type 3 felt using PSO inversion method.

Non-physical behaviour of the new model for jute material is tested. This new model is based on the same equations as given by Delany and Bazley model but uses inversely estimated coefficients for jute material. Kirby [8] reported that Delany and Bazley model gives negative values for the real part of the equivalent density when the factor $X = \rho_0 f/c$ is plotted against the equivalent density. Display of negative values of the equivalent complex density indicates the nonphysical behaviour of the model in the low-frequency range.

When it is assumed that the porous material is treated as an equivalent fluid, then its basic properties can be represented in terms of equivalent density and the speed of sound. Any changes that are made to modify the Delany and Bazley model can be evaluated to check its nonphysical behaviour by checking of values of the equivalent fluid density. In terms of Delany and Bazley model, the equivalent fluid density is given as

$$\hat{\rho} = -\left\{c_1 X^{-c_2} + i\left[1 + c_3 X^{-c_4}\right]\right\}\left\{c_7 X^{-c_8} + i\left[1 + c_5 X^{-c_6}\right]\right\} \tag{13}$$

where $\hat{\rho} = \rho/\rho_{air}$ and $X = \rho_o f/c$. $c_1 - c_8$ are inverted coefficients from PSO for three types of felt. To check the nonphysical behaviour of this new model for jute material, the real part of the complex equivalent density is plotted against the factor X . Results for three types of felts are indicated in Figure 8.

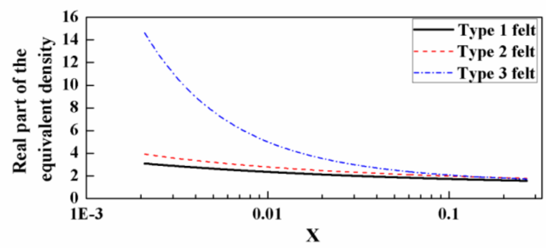


Figure 8: Real part of the equivalent density of three types of felts

For all three types of jute felts the values of the equivalent density is positive in the frequency range of interest.

7. Conclusions

In this study, the PSO method is used for inverse estimation the eight coefficients values of Dunn and Davern model for jute material. The measured flow resistivity for three types of jute felts is used in this model for the inverse prediction of eight coefficients. Results of sound absorption prediction using inversely estimated eight coefficient values are validated against experimental sound absorption data for three types of felt and good matching of both data is found throughout the frequency range of interest. The misfit between predicted and experimental data is rectified using inversely estimated eight coefficients. Moreover, the nonphysical behaviour of the new model for jute material is also studied in this paper and found working satisfactorily. Therefore, the inverse estimation method using PSO method gives correct prediction of the eight coefficients for jute material.

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