Improving Sound Absorption coefficient and analysis of polyurethane foam reinforced with wood powder

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Abstract:
When it comes to acoustic insulation Polyurethane foam plays a very vital role for various sound absorption applications. The interest of this paper is to spot out the best combination of bio-based porous materials to obtain the best acoustic property. Here the porous materials used are polyurethane foam, pine wood with air gap. The sound absorption depends on the material properties such as Flow resistivity, porosity, tortuosity, thermal characteristic length and physical characteristic length, the different combinations of materials with air gap are being tested for sound absorption coefficient using impendence tube method using COMSOL. The results are being compared with numerical values obtained using impendence tube that helps us to present the best combination which provides the maximum sound absorption.

Keywords: Polyurethane foam, pine wood, impedance tube, COMSOL, sound absorption analysis.

1. Introduction:
One of the major problems in the industry is the accumulation of the wastes and the other major problem is the noise pollution being increased drastically which is a major concern for the human health. Thus, an environment friendly material and efficient enough with the sound absorption property has to be developed [1].

The fluid phase and the solid phase combine together to form a porous material [2]. A better absorbing porous material is obtained when the fluid phase percentage is higher than the solid phase. At lower frequencies better acoustic damping is obtained, thus it is obtained by increasing the water content and decreasing the cell diameter [3]. By adding a highly active catalyst an improved cellular structure would be obtained which will improve the sound absorption of the flexible foam.

Polyurethane foam is formed by the combination of di-isocyanate (NCO) and polyol (OH) [4]. The different of polyurethane foams can be obtained when they are mixed in different proportions. Flexible foam is obtained when the NCO group is higher than the OH group and when the OH group is more in ratio then a foam with increased sound absorption coefficient is obtained [5]. To increase the absorption of the incident pressure waves, natural fibres are added, which in term increases the voids in the foam [6].

Currently the main area of research is acoustics and experiments are being conducted widely around the globe. Wood powder [7-9] which is used as one of the porous materials is one the most easily and abundantly available. These are unburned by-products that can be obtained cheaply. This has man other advantages as they are renewable and abundant, don’t cause damage to the health of living beings and are also nonabrasive. The most important of all is that wood has a very good sound absorbing property [10-14] which would enhance the sound absorption in this experiment.

Thus, the above experiment was carried out for various combinations of porous materials; i.e. wood powder and Polyurethane using COMSOL. The best combination was chosen and the sound absorption experiment was conducted for that combination. The same combination was used in COMSOL Multiphysics for the numerical prediction [15-16].

2. Experimental Setup:
2.1. Materials
In various fields Polyurethane foam is used as a generally for the noise control applications. Since the foam has effect on the human health the usage of the foam is limited. A new study has been made to improve the effective...
use of the foam. Thus, Wood Powder also known as Saw Dust has been used. Wood Powder helps in the improvement in the sound absorption effectively. Wood Powder contains of vast number of voids and is a natural porous material which helps in the investigation of sound absorption coefficient. The Wood Powder is mixed with the matrix and a thickness of 30 mm has been used. Bio-based Polyurethane foam is used for obtaining the composite matrix material needed for this experiment. Polyol and isocyanate methylene diphenyl diisocyanate together form the bio-based polyurethane foam.

![Fig. 1 Material Description in COMSOL](image)

### 2.2. Measurements of Acoustic Properties

Sound absorption coefficient of the foam is measured using the ASTM E1050-12. The frequency ranges between 220 – 4500 Hz. Circular cross sections of diameter 33mm and 96mm are used form the sample. Samples of different combinations are being used for the test. Random signals are being generated from the source. The power amplifier is connected to a DAQ at one end and to the other end a speaker of 16ohm is connected. Two 1/2” MicrotechGefell microphone is connected to the M+P Vibpilot DAQ. The M+P Vibpilot DAQ spectrum analyser, time domain is extracted from the bandwidth of 6400Hz with a frequency resolution of 0.5Hz.

![Fig. 2 Impendence tube setup](image)

### 3. Numerical Model:

Here we will look into two formulations by which we can study and predict the acoustic behaviour. It is known as the displacement-pressure \((u^s, P)\), which has 6 variables for 3D: 3 for the solid phase and the other 3 for the fluidic phase. The combined variable is used by the 4-space variable. When the poroelastic material is subjected to a single acoustic wave of angular frequency \(\omega\), then the formulation be as such for:

For solid phase:

\[
N\nabla^2 u^s + (P - N) \nabla \nabla \cdot u^s + Q \nabla \cdot (\nabla \cdot u^s) + \omega^2 (\overline{\rho}_1 \overline{u}^s + \overline{\rho}_{12} \overline{u}^f) = 0
\]  

(1)

For fluid phase
\[(\nabla u^s) - R \nabla (\nabla u^f) + \omega (\bar{\rho}_{11} u^s + \bar{\rho}_{22} u^f) = 0 \quad (2)\]

Here, \(u^s\) and \(u^f\) is used to represent the displacement vector in structured and saturated fluid.

Whereas, \(\bar{\rho}_{11}, \bar{\rho}_{12}, \bar{\rho}_{22}\) are obtained from the factor of mass coupling.

\[
\bar{\rho}_{11} = \rho_{11} - j \frac{b}{\omega}, \quad (3)
\]
\[
\bar{\rho}_{12} = \rho_{12} - j \frac{b}{\omega}, \quad (4)
\]
\[
\bar{\rho}_{22} = \rho_{22} - j \frac{b}{\omega}, \quad (5)
\]

Here,

- \(b\) is the viscous coupling factor
- Mass coupling factor is obtained by:
\[
\rho_{12} = \rho_{1} - \rho_{22} \quad (6)
\]
\[
\rho_{12} = -\Phi \rho_0 (a\omega - 1) \quad (7)
\]
\[
\rho_{22} = -\Phi \rho_0 - \rho_{12} \quad (8)
\]

Viscous coupling parameter:

\[
b = \sigma \phi^2 \left[ \sqrt{1 + \frac{\Lambda \eta \rho_{air} \omega \rho_T}{\sigma^2 \phi^2}} \right] \quad (9)
\]

Where,

- \(\phi\) is the porosity

For fluidic region dynamic tortuosity is given by:

\[
\rho_{eff} = \frac{\rho_{air}}{\phi} \left[ 1 + \frac{\sigma \phi}{\Lambda \eta \rho_{air}} \sqrt{1 + \frac{\Lambda \eta \rho_{air} \omega \rho_T}{\sigma^2 \phi^2}} \right] \quad (10)
\]
\[
K_{eff} = \frac{\gamma \rho_{air}}{\phi} \left[ 1 + \frac{\sigma \phi}{\Lambda \eta \rho_{air}} \frac{\Lambda \eta \rho_{air} \omega \rho_T}{\sigma^2 \phi^2} \right] \quad (11)
\]

Here,

- \(\Lambda\) is viscous characteristic length
- \(\Lambda'\) is thermal characteristic length
- \(\sigma\) is the flow resistivity
- \(\rho_{air} = 1.21 \text{ kg/m}^3\)
- \(\gamma = 1.14\) is the specific heat ratio of air at standard temperature
- \(P_o = 101320 \text{ N/m}^2\)
- \(\eta = 1.84 \times 10^{-5} \text{ Ns/m}^2\) (for air)
- \(Pr = 0.702\) (for air)

Characteristics impedance:

\[(Z_p) = \sqrt{p_{eff} \times K_{eff}} \quad (12)\]

Wave number:
\[ (k) = \omega \sqrt{\frac{\rho \text{eff}}{K \text{eff}}} \]  

Normalized surface impedance is obtained by:

\[ Z_{\text{sneq}} = \frac{Z_{\phi}}{\phi} \cot(k*L) * Z_{\text{air}} \]  

Where L is the thickness of the porous material

Compute sound reflection:

\[ R = \frac{Z_{\text{sneq}} - 1}{Z_{\text{sneq}} + 1} \]  

Absorption Coefficient:

\[ (\alpha) = 1 - |R|^2 \]  

3.1. Numerical prediction of COMSOL

The acoustical behavior of the samples is obtained by simulating them using the finite element approach. High physical parameters are necessary to simulate the porous materials since it a combination of fluid and solid phases. There are different models for determining the acoustics properties of the materials; and of those JCA model is being used in this paper. This model is used to predict the important factors such as the material porosity, airflow resistivity, tortuosity, thermal characteristic length and viscous characteristic length. This model is used to express the equations in equations (10) and (11).

3.2. Model Definition

In the system that is modeled, the incident sound frequencies hit the layer of the porous material at angle of 0 degrees and it has a wave vector k. In this, the model mentioned has a height of 600mm and consists of a width of 100mm. The height of each porous layer; i.e. Polyurethane and Wood is 30mm. The model of the incident field was made in such a way that a background pressure is applied to air domain. The boundary condition for the model is that an air pressure is applied to the boundary model. Sound hard boundary is applied to the top and bottom of the model so that there is no leakage of the pressure outside of the model. Another boundary called the poroelastic material is applied to the porous domain. In these five domain parameters are applied to porous materials. One of the advantages that COMSOL Multiphysics carries is that two or more phases can be coupled in this software. A free triangular mesh is used in this analysis. The mesh is of the size 0.21 times of the wavelength. Finally, the important parameter; i.e. sound absorption coefficient can be evaluated. The absorption results can be seen in the figure 4(a) and 4(b).
4. Results and discussion:
Using the impedance tube, we out find out the sound absorption coefficient for the different combination of 30mm thick wood powder and the foam along with air and using COMSOL Multiphysics with the help of the JCA model the same is predicted.

4.1. Effect of wood on porous materials
Sound absorption coefficient results for different combinations of wood and foam is shown in figure 5. From the result it can be observed that with the presence of wood the sound absorption is enhanced and particularly for the lower frequency it is more effective and leads to added benefits. Without combining the porous materials, it was observed that the sound absorption was in average but when the combinations of the porous materials were used the lower frequencies were effectively absorbed. Meanwhile, the combinations were altered it acted as a resonator and it showed a good result of sound absorption in lower frequencies and the oscillating tends to happen at higher frequencies.
After plotting the results for the different combinations such as Air-Polyurethane-Wood, Polyurethane-Air-Wood, Polyurethane-Wood-Air, it was found out that Polyurethane-Wood-Air combination showed better sound absorption compared to the other two. Another set of combinations were also made by keeping the first material constant and reciprocating the last two materials and in such case also Wood-Polyurethane-Air combination showed better sound absorption. It can be seen that when air as a material was positioned before the porous materials it affected the sound absorption by reducing it but when the porous materials were positioned ahead of air as a material, we could see that the sound absorption was better. Thus, it can be clearly stated that air has a significant role in the sound absorption.

![Absorption Coefficient](image)

**Fig. 5 Absorption Coefficient for Different combinations**

### 4.2. Validation using Minitab

The predicted sound absorption for different combinations using the COMSOL Multiphysics are been validated using Minitab. The sound absorption is being plotted with respect to the frequency as shown in figure 6. The demonstrated validation shows that the predicted values as the inputs make good agreement for the different combinations of the porous material and air medium. For the case of Polyurethane-Wood-Air it was found sound absorption was the maximum as per the experimentation though it does not go in agreement with the prediction made in Minitab. But it was also found that of the different combinations, Polyurethane-Wood-Air had the shown up with strong correlation values whereas Wood-Air-Polyurethane and Air-Polyurethane-Wood had an intermediate correlation values clearly stating that Polyurethane-Wood-Air is the most appropriate combination to go with for obtaining the maximum sound absorption as shown in figure 7. In other cases, though it might have a good predicted value the combination is not strong enough which might reduce the effectiveness of the absorption.

![Scatterplot](image)

**Fig. 6 Validation of Absorption Coefficient for Different combinations**
Fig. 7 Correlation factors for different combinations

\[ \mu = \frac{\sum xy - \sum x \sum y}{\sqrt{\left(\frac{\sum x^2 - (\sum x)^2}{n}\right) \left(\frac{\sum y^2 - (\sum y)^2}{n}\right)}} \]

Here \( \mu \) is the correlation factor

0.25 \leq \mu < 0.75 it would be an intermediate correlation

0.75 \leq \mu < 1 it would be a strong correlation

Fig. 8 Contour plots for Frequency vs Porous material with respect to the height

5. Conclusion
To conclude, this study was been focused to develop a new combination among the porous materials which is bio-based and which is eco-friendly as well. The samples were developed using the wood powder and polyurethane foams along with air medium when used for experimentation as well as for simulation. Different possible combinations were made by shuffling the arrangements of the fibres and air. The samples were then tested using the impedance tube. Using the COMSOL Multiphysics, sound absorption predicted by numerical method is being compared with that of the experimental results. The comparison results were in good but the prediction and it was to be in match with the correlation factors the combination that has been chosen is being said as a correct combination.
Furthermost, the results states that:

1. The inclusion of the wood powder as a porous material increases the sound absorption coefficient even at the lower frequencies.
2. As observed from the physical it can be seen that the flow resistivity increases due to the inclusion of the wood powder.
3. Due to the formation of the different combinations of the porous materials and analysing the results, based on the different applications the combinations can be altered and can be used.
4. Better sound absorption can be obtained by using a powder fibre material.

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