MODELLING OF ACOUSTIC WAVE PROPAGATION THROUGH THE NATURAL FIBER COMPOSITES

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Abstract
The theoretical explanation of the absorption phenomena of various porous materials was stated by many authors by proposing various models. The purpose of almost all the models was to estimate the materials acoustical parameters such as, characteristic impedance, surface acoustic impedance and wave propagation constant. The absorption behavior of any porous material can be capably derived from a viewpoint of materials physical realizability and their effect on acoustic absorption. In addition, a successful establishment of link between modified physical parameters and acoustical parameters of the material could play a significant role to promote its absorption mechanism. This study presented the review of various experimental and methodical methods which had been implemented to understand the absorption phenomena of various synthetic and natural fibers, relevance to the acoustics. The intension of this review was mainly for a potential exploration of an analytical method by over viewing various analytical and experimental studies on fibrous sound absorbing materials for acoustic absorption purpose. The study discussed the theoretical outcomes of Delany-Bazley and Biot-Allard models. The study also discussed the opportunities to improve the value of acoustic absorption coefficient at low frequency (below 1000 Hz) range through experimental and analytical studies, considering various physical properties of fibrous material and their reinforced composites.

Keywords: Acoustic absorption, Delany-Bazley and Biot-Allard model.

1. Introduction
The recent development of the acoustic performance of various porous absorbers is due to the routine investigation of their acoustic characteristics by many researchers. This investigation is motivated by the growing concern of environmental problem and human health issue. There are many conventional
acoustic materials which are offered to use in indoor and outdoor applications for acoustic absorption purpose. Due to the ascending price and threat to environment of using conventional acoustic materials, some researchers have proposed to use natural and biomass waste materials as alternatives of conventional fibrous and foam absorbers. The study discusses the acoustic characteristics of those proposed natural fibrous and biomass materials as acoustic materials and their potential to replace the conventional acoustic materials. There are few studies have developed about the significant benefit and the physical mechanism associated with the use of fibrous acoustic materials together with a biomass material for acoustic absorption purpose. Expanding the understanding of the physical mechanism of these composite materials and refining of the fibers physical properties are expected to enhance the low frequency absorption. This review is an opportunity to provide the details that may help to overcome the shortcomings in acquiring enhanced acoustic absorption performance especially at low frequency region.

In practical there are various sound absorptive materials for noise control engineering. All widely used sound absorptive materials are porous, where sound absorption takes place as sound waves pass through them. The porous sound absorptive materials are usually contemplated as an assembly of capillary tubes. They are solid materials and composed of the channels, cavities or interstices which make them to allow the sound waves to pass through them. According to the microscopic structure of porous sound absorptive materials they can be categorized as granular, cellular and fibrous[1]. This study focuses only on the acoustic absorption of fibrous composite materials at normal incidence of sound wave.

In recent years, natural fiber reinforced resin/polymer composites have earned a lot of attention due to its light weight, abundance in nature, cost efficiency, biodegradability and eco-friendly nature. These materials are cheaper and environmentally superior to glass fiber reinforced composites [2]. Moreover they have the potential to be used as porous absorber and low health risk during the processing and handling [3]. Consequently, natural substances such as coir fiber [4], tea leaf fiber [5], bamboo fiber [6], date palm fiber [7, 8], rice straw [9, 10], rice husk [11], oil palm fiber [12], jute fiber [13], Arrenga Pennata fiber [14], kenaf fiber [15], kapok [16], grass and corn fiber [17] have already been reported as promising and efficient alternatives of synthetic fibers.

However, due to high flammability, low interfacial adhesion, poor moisture resistant and low anti-fungus quality of natural fiber composites, these materials are still not quite popular as sound absorption materials compared to the synthetic based composites. As a matter of fact, researchers are trying to tune the fibers quality through chemical treatment prior to natural fiber reinforced composites production, to overcome their shortcomings.

In porous material the most important mechanism of sound absorption is viscosity. The thickness of viscous boundary layer is defined by the tangential velocity of an incident wave from zero at the wall to the free stream value far away from the wall. This viscous boundary layer effect plays a great role in sound absorption mechanism in porous media. Since air is a viscous fluid, the viscous loses occur in the boundary layer of air adjacent to pore walls. In general, these air layers are of sub-millimeter size at audible frequencies. The thermal conduction from air to absorbers materials takes place simultaneously with viscous effects. Owing to sound pressure, the incident sound wave propagates
through interconnected pores of porous materials and dissipated via friction of air molecules with pore walls.

With the frequency of exciting sound wave, the oscillation of air molecules in the interstices of the porous material results frictional losses. In case of fibrous materials, at the exciting state of sound, the fibres of the fibrous materials vibrates and loss their internal energy as a result of vibration. Frictional losses occur when the fibres are rubbing with each other. The speed of sound is proportional to all above mentioned losses and the sound energy converted into heat energy. The sound absorption performance of a material is determined by the five governing parameters such as porosity, tortuosity, flow resistivity, viscous and thermal characteristics lengths. Amongst them the effectiveness of porosity, tortuosity and two characteristics lengths were found at high frequency region, while for low frequency, porosity, air flow resistivity and thermal permeability are the key parameters to characterize the sound absorption phenomena of poroelastic materials. Hence it is obvious the factor that has significant role in complete range of frequency is porosity [18]. However, the capability of material thickness, bulk density and fiber size is also undeniable in reducing the sound at low frequency band [19, 20].

2. Experimental Overview of Acoustic Absorption

The significant effects of chemical treatment [21] and incorporation of additional filler or matrix (e.g. rice husk) in fiber reinforced composite [22] have been observed to be provided on fibers physical and acoustical properties. It was found that the alkaline treatment (mercerization) of fresh natural fibers results in the reduction of fiber diameter, which is the key factor to improve low frequency sound absorption. The incorporation of natural substance (e.g. rice husk) improves stiffness, increases the bulk density and flow resistivity of the composite material, which have significant effect in enhancing low frequency acoustic absorption. In addition, chemical concentration and fiber-matrix composition ratio may also be the vital factors to improve low frequency sound absorption [11].

Fiber diameter has a significant role in enhancing the sound absorption performance at low frequency region. The value of sound absorption coefficient in this region is inversely proportional to the fiber diameter. The volume density occupied by fibers with thicker diameters requires more fibers with thinner diameters. Therefore, the surface area of the material through where the incident sound wave propagates is inversely proportional to the fiber diameter at constant volume density and thickness of the material. A huge surface area leads to an increased viscous friction, hence energy losses by means of more frictions of surface area with air molecules [23]. Moreover, the addition of more fibers cause more tortuous passages and make the propagation path longer within the absorbent and higher the air flow resistance. Furthermore the movement of thin fiber is easier than thick fiber in sound wave which causes vibration in air, as well as enhance the absorption by means of more viscous losses due to air vibration [24]. The significant enhancement in low frequency absorption was found due to the reduction of coir fiber diameter in the numerical simulation [20], for different fiber size at constant thickness (50mm) of the sample material.

Asmatulu et al. [25] reported the potential of electro-spinning nanofibers for acoustic absorption purpose. The significant enhancement of low frequency
acoustic absorption was for fiber diameter 200 nm to 7 µm. The reason of this performance was stated for higher surface area, attributed by thinner fibers and their interaction with more air molecules.

Flow resistivity of a material has a significant contribution in better acoustic absorption purpose. The incorporation of a raw biomass material such as rice husk at its optimum weight composition will increase the flow resistivity by filling the pores of the surface area of material. It has been reported that dried rice husk together with polyurethane binder showed significant value of sound absorption coefficient at low frequency region compare to wood shaved materials. The absorption peak was found at frequency 250 Hz for 25% rice husk-polyurethane composite with a value of 0.889 [11].

Rahman et al. [26] investigated the potential of date palm fiber (DPF) and corn fiber (C.F) for green acoustic absorption materials. In this study the influence of bulk density, fiber density and thickness of the materials was taken into account for the enhancement of sound absorption coefficient at low frequency range. It was observed that the sound absorption coefficient at lower frequency range shifted to peak value with increasing materials bulk density (due to extra matrix material) and layer thickness as well. A comparison on acoustic absorption was made between DPF and C.F in the study. Date palm fiber showed better acoustic absorption coefficient performance than coir fiber at both low and high frequencies. This performance is due to the thinner fiber diameter (123 µm) of DPF than the diameter of (252 µm) C.F. For 40mm thickness of DPF, the value of sound absorption coefficient is 0.98 at 1381.25 Hz -1506.25 Hz and 0.99 at 4521.88 Hz - 4906.25 Hz. The study concluded that material with smaller fiber diameters, lower fiber density, increased bulk density and thickness shows good acoustic absorption.

In 2011, Fouladi et al. [27], studied the acoustical characteristics of coir fiber as a porous material. Based on Delany-Bazley and Biot Allard analytical approach, the value of sound absorption coefficients were investigated for fresh and industrial coir fiber mixed with latex binder. It was found that Allard model showed a better resonance prediction of coir fiber porous material than Delany-Bazley model. In this study, at 45 mm sample of coir fiber thickness, the value of sound absorption coefficient was found 0.8 at frequency 578 Hz. In addition, the study suggested to add further materials to improve some physical properties such as stiffness, flammability, anti-fungus etc. which may help to enhance the sound absorption properties of the material.

The observation indeed helps to conclude that fiber diameter and flow resistivity of the material is the important parameters to enhance the sound absorption at low frequency region. In most studies related to natural fibers, the simultaneous improvement of the longevity together with acoustic absorption quality of the fiber was overlooked. In terms of moisture absorption capability, fresh fiber shows better sound absorption performance at low frequency region compare to the industrially prepared fiber mixed with binder. However, it was suggested to use improved industrially treated fiber in real world application due to better stiffness, less moisture and larger life expectancy by [4]. In recent years, it has been investigated that the pre-treatment of natural fiber improves fibers fitness, resistance to moisture absorption and fiber-matrix adhesion. A commonly used pre-treatment method is alkali treatment of natural fiber, or it is known as
mercerization. The alkali treatment has significant effect in producing high quality fibers. It helps to reduce fiber diameter and moisture absorption [28].

One of the main concerns of the paper is about the development of fibers anti-fungus and moisture resistive qualities in the context of pretreatment such as, mercerization. At the same time the study is a careful observation about the effective role of reduced fiber diameter, for enhancement of low frequency acoustic absorption, after fiber chemical treatment.

3. Analytical Overview of Acoustic Absorption

In the case acoustic wave propagation through the porous media at normal incidence, air is considered as propagating media, which is a viscous, polyatomic and compressible medium. The acoustical properties of porous material are characterised by the characteristics acoustic impedance \( Z_f \) and propagation constant \( \gamma_f \).

The complex expressions of \( Z_f \) and \( \gamma_f \) are estimated as follows,

\[
Z_f = R + jX
\]

\[
\gamma_f = \alpha + j\beta
\]

where,

- \( R \) = Real component
- \( X \) = Imaginary component
- \( \alpha \) = Attenuation constant in nepers/m
- \( \beta \) = Phase constant = \frac{\text{angular frequency}}{\text{speed of sound}} = \frac{\omega}{c} \text{ rad/m}

In order to estimate the characteristic impedance \( Z_f \) and wave propagation constant \( \gamma_f \), Delany and Bazley [29] have developed an empirical formula of a homogenous and isotropic fibrous materials and normalized them into a dimensionless group. Since this method depends only on the flow resistivity parameter of the material, their model is considered to be a simple model and easy for fast approximation. This model can be used for large frequency range and availability of the flow resistivity of the material. However, the implementation of the model is restricted to a certain range of flow resistivity \( (\sigma) \), which is \( 10 \leq f / \sigma \leq 1000 \) and porosity close to 1, where, \( f \) is the frequency in Hz and \( \sigma \) is the flow resistivity in MKS raylm\(^{-1}\).

So, \( \frac{\rho_0 f}{\sigma} \) is a normalized dimensionless parameter whose validity range is restricted to \( 0.01 \leq \frac{\rho_0 f}{\sigma} \leq 1.0 \).
In terms of Eqs. (1) and (2), the empirical relation for characteristic impedance \( Z_f \) and propagation constant \( \gamma_f \) can be expressed by the flow resistivity \( \sigma \) [30, 31] as:

\[
Z_f = \frac{\rho_0 c_0}{\sigma} \left[ 1 + a \left( \frac{\rho_0 f}{\sigma} \right)^a \right] - j \left[ 1 + c \left( \frac{\rho_0 f}{\sigma} \right)^c \right] \]  

(3)

\[
\gamma_f = \frac{\omega}{c_0} \left[ \frac{\rho_0 f}{\sigma} \right]^p - j \left[ 1 + r \left( \frac{\rho_0 f}{\sigma} \right)^r \right] \]  

(4)

where,

\( \rho_0 = \) Air density;
\( c_0 = \) Speed of sound in air;
\( f = \) Sound wave frequency;
\( \sigma = \) Flow resistivity;
\( a, c, p \) and \( r = \) Coefficient of \( \frac{\rho_0 f}{\sigma} \);
\( b, d, q \) and \( s = \) Degrees of \( \frac{\rho_0 f}{\sigma} \);

Miki [32] reported that according to Delany-Bazley model, the real part of surface impedance tends to negative values at low frequencies at some extent, when computed. Miki [32] modified the Delany-Bazley model to obtain a real positive value at wider frequency range and generalized with the models with respect to porosity, tortuosity and the pore shape factor ratio. Later Delany-Bazley model was corrected by Mechel and Ver as a function of a dimensional parameter, density by the quotient, between frequency and resistivity.

Beranek and Vér [33] indicated that the Mechel-Ver model is more accurate and improved adjustment than the Delany-Bazley method at low frequency region.

Delany-Bazley, Miki and Mechel-Ver models are well-known empirical model as conventional prediction methods. They have same formula structure as stated in Eq. (3) and Eq. (4). The only difference among them is in the values of coefficients and degrees in the formulae, which are stated in Table 1 for Delany-Bazley, Miki and Mechel-Ver models.

A theoretical explanation was developed by Biot [34] for the saturated porous material. Biot’s theory is the identification of three types of waves for continuous material, which are two compression waves and one shear wave. Porosity \( \phi \), flow resistivity \( \sigma \), tortuosity, viscous and thermal characteristics lengths - all these parameters appear in the Biot’s general model.

An elaborated description of Biot's model was developed by Allard [35] with improved explanation of sound propagation in porous materials. In this model, the frame (fiber) is considered as elastic cylindrical fiber, which deals with the study of frame - fluid interaction. Therefore, both frame (fiber) and fluid (air) are in
motions. The acoustic losses occur due to heat conduction and for this, compressibility of the medium is an important factor.

Table 1. Coefficient and degrees of $\frac{\rho_0 f}{\sigma}$ in Delany-Bazley [29], Miki [32] and Mechel-Ver models [33].

<table>
<thead>
<tr>
<th>Coefficients &amp; Degrees</th>
<th>Delany-Bazley Model</th>
<th>Miki Model</th>
<th>Mechel-Ver Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>0.0169</td>
<td>0.160</td>
<td>0.396</td>
</tr>
<tr>
<td>$q$</td>
<td>−0.595</td>
<td>−0.618</td>
<td>0.458</td>
</tr>
<tr>
<td>$r$</td>
<td>0.0858</td>
<td>0.109</td>
<td>0.135</td>
</tr>
<tr>
<td>$s$</td>
<td>−0.700</td>
<td>−0.632</td>
<td>0.646</td>
</tr>
<tr>
<td>$a$</td>
<td>0.0497</td>
<td>0.0699</td>
<td>0.0668</td>
</tr>
<tr>
<td>$b$</td>
<td>−0.754</td>
<td>−0.632</td>
<td>0.707</td>
</tr>
<tr>
<td>$c$</td>
<td>0.0758</td>
<td>0.017</td>
<td>0.196</td>
</tr>
<tr>
<td>$d$</td>
<td>−0.632</td>
<td>−0.632</td>
<td>0.549</td>
</tr>
</tbody>
</table>

In Biot-Allard model compressibility of the medium was taken into account and the acoustical properties of the fibrous material were calculated based on two compression waves which are frame borne and air-borne waves. The technique is useful to assess bulk modulus of air in porous material by means of characteristic dimensions. Based on previous studies the comparison between Delany-Bazley and Biot-Allard model are reported in Table 2.

Table 2. Comparison between Delany-Bazley and Biot-Allard model.

<table>
<thead>
<tr>
<th>Delany-Bazley Model</th>
<th>Biot-Allard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derived from empirical equation.</td>
<td>Based on wave transmission equation.</td>
</tr>
<tr>
<td>It is a simplified model.</td>
<td>It is a complicated model compared to the empirical one.</td>
</tr>
<tr>
<td>Based on only one parameter flow resistivity.</td>
<td>Based on five parameters; porosity, tortuosity, flow resistivity, viscous characteristic length and thermal characteristic length.</td>
</tr>
<tr>
<td>Frame elasticity is not included in this technique.</td>
<td>Frame elasticity is included in this technique.</td>
</tr>
<tr>
<td>It is a fast and general approximation technique for overall broadband trend acoustical behavior.</td>
<td>It is a good and clear approximation technique for overall broadband trend acoustical behavior.</td>
</tr>
<tr>
<td>The frame resonance information is absent in overall absorption pattern.</td>
<td>The frame resonance information is well predicted in overall absorption pattern.</td>
</tr>
</tbody>
</table>

4. Conclusions

The current paper introduces a review of previous research to study the low frequency acoustic absorption on the basis of various experimental analyses.
From various experimental observations it is concluded that, the following key factors play a great role in enhancing low frequency acoustic absorption of a fibrous material.

- Thinner fiber diameter
- Higher surface area
- Higher flow resistivity

It also presents the review of previous research on the application of Delany-Bazley, Miki, Mechel-Ver and Biot-Allard model to study the phenomena of acoustic absorption and for the formulation of low frequency acoustic absorption. As indicated in Table 2, it was found that frame resonance is clearly predictable by Biot-Allard model in overall absorption pattern. The elasticity of frame is included as one of the parameter in Biot-Allard formulation, which prevents strong frame resonance at some frequency band due to high flow resistivity of the material. Further study is needed for deeper understanding of the phenomena of acoustic absorption enhancement through analytical and experimental investigation.

References


