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SOUND INSULATION PERFORMANCE OF KENAF FIBRE AS A NOISE CONTROL TREATMENT IN CAR USING STATISTICAL ENERGY ANALYSIS

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ABSTRACT

Low noise level in car cabin has always become an important target for automotive manufacturers. If low exterior noise is bounded by environmental regulation, low interior noise is subjected to customer's satisfaction, which thus offers a competitive advantage in the automotive industry. Common noise control treatment in car cabin is by applying sound absorbing materials attached to various vehicle components such as floor, roof and door panel. In this paper, the study is presented to discuss the performance of natural fibres as the noise control treatment materials. A three-dimensional plate attached with natural fibres namely kenaf, coir, oil palm and ijuk was simulated using VA-One and the sound transmission loss calculated based on the statistical energy analysis method is presented. The performances are then compared to that of felt materials, usually used in the current commercial vehicles. Parametric simulation was then conducted to study the effect of various designed parameters of the natural materials such as the thickness and flow resistivity. The methodology is presented and the results are discussed.

Keyword: *Transmission loss; statistical energy analysis (SEA); kenaf; parameters; natural fibre.*

1. INTRODUCTION

Towards green technology, natural fibres have been extensively studied as substitute materials to the existing synthetic materials which can be harmful to the environment in a long period. Natural fibres are gaining popularity, not only because of their non-toxic nature, but also their performances, such as structural integrity, thermal conductivity and sound absorption (Asdrubali *et al*., 2012).

One of the natural fibres which has been extensively studied is extracted from kenaf, where this plant has been cultivated in many countries including Malaysia. The fibres come from its stem, which consist of long bast fibres and short fine fibres. These fibres are used from engineering composite to pack materials (Khalil *et al.,* 2010). Tan *et al*., (2016) found that coir, kenaf, and kapok fibre could be used as the acoustical panels for the reduction of noise. Recently, Ying *et al.* (2016, 2018) showed that kenaf fibre also has excellent performance as sound absorber materials. Figure 1 shows the kenaf fibres compressed in the form of mat.

The objective of this paper is to study the sound transmission loss (TL) of the kenaf fibre to observe its feasibility as the noise control treatment (NCT) material in cars. The TL is calculated using Statistical Energy Analysis (SEA) technique in VA-One software. A three-dimensional SEA model of a rectangular plate is created together with a layer having material properties of kenaf fibres attached to the plate. The results of TL by varying the parameters of the kenaf layer are discussed in this paper.

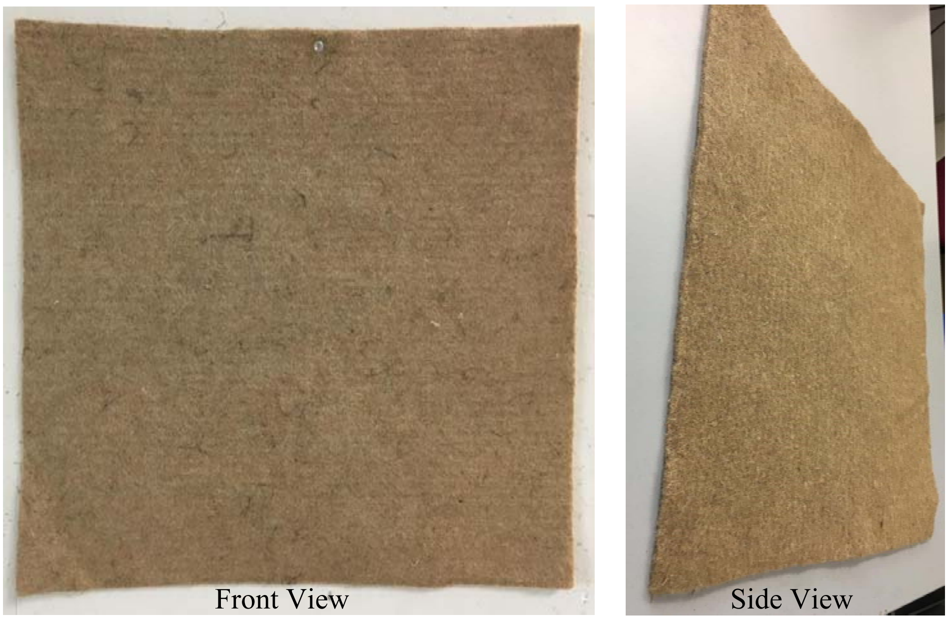

Figure 1: Kenaf fibre in the form of mat.

Figure 2 shows the common noise propagation from the source room to the receiver room. The noise transmitted to the receiver room can be either directly through air or can be through the vibration of structures, which produces noise radiation. The former is called airborne noise and the latter is called structure-borne noise. If the vibration of the partition of the room (which causes noise radiation to the receiver room) is due to the excitation of sound from the source room, the noise is called indirect airborne noise.

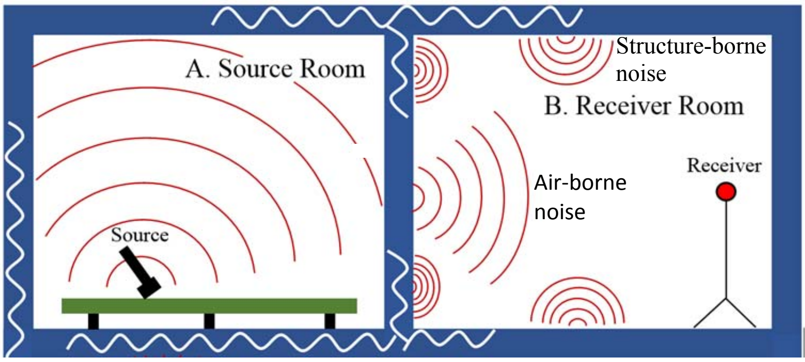

Figure 2: Sound transmission paths between a source and receiver room.

Sound transmitted through of a partition is categorised as the indirect airborne noise. Figure 3 shows the illustration of sound transmission through a partition. The sound waves produced in the source room strikes the partition where the sound energy is partially absorbed by the partition (due to damping), some energy is transmitted into the receiver room and the rest is reflected back into the source room. The sound transmission loss (TL) can be defined as the decrease of sound energy when it is transmitted.

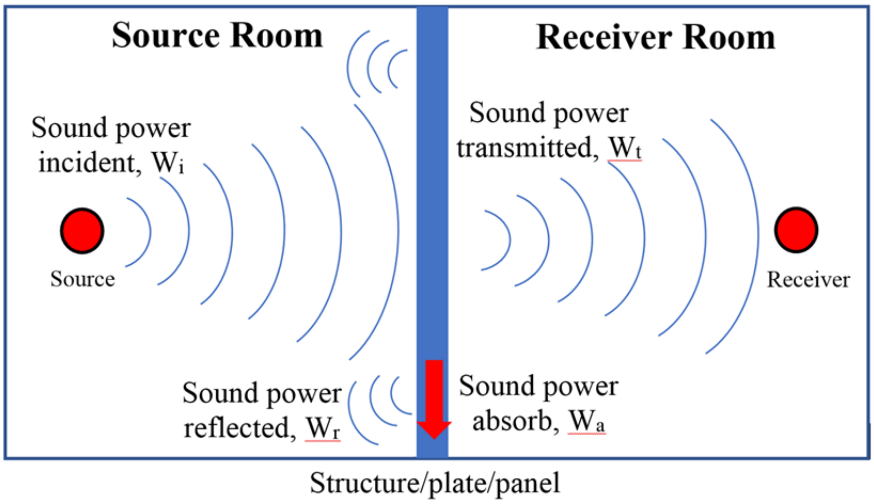

Figure 3: Basic concept of sound transmission through a partition.

Sound transmission loss (TL) is given by

$$TL = 10 \log \frac{W_i}{W_t} \tag{1}$$

where W_i denoted as the incident sound power and W_t denoted as the transmitted sound power. The incident sound power assuming the source room forms a diffuse field is given by,

$$W_i = \frac{\bar{P}^2}{4\rho c}\,(S) \tag{2}$$

where $\bar{p}^2$ is the mean sound pressure, ρ is the density of air (1.21 kg/m3) and c is the speed of sound in the air (343 m/s) and S is the surface area excited by the sound.

Theoretically, the TL of a partition can be divided into four regions as shown in Figure 4. The first region is the stiffness-controlled region at very low frequencies, where it is the stiffness of the panel which determines the level of TL. The second region is resonance-controlled region at low to medium frequencies. In this region, the response is identified by the static stiffness of the panel. Resonance can also occur depending on the internal damping in the panel which decreases the TL. The third region is the mass-controlled region, where the response is governed by the mass of the panel and the curve follows a typical 6 dB/octave slope. By doubling the mass of the panel, the TL increases by 6 dB. The fourth region is the coincidence region at high frequencies the acoustic wavelength is the same as the structural wavelength.

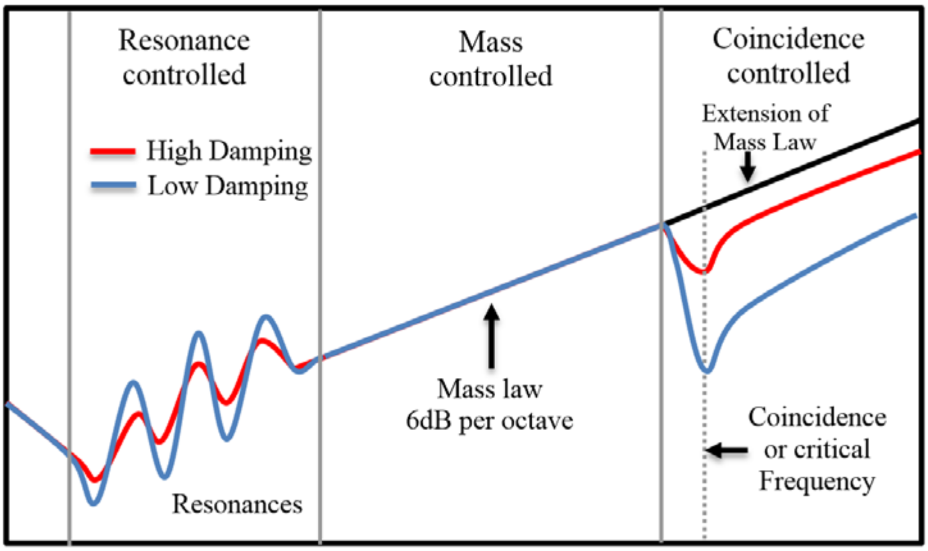

Figure 4: Theoretical TL for an isotropic plate.

2. METHODOLOGY

2.1 Model of SEA Plate

The Statistical Energy Analysis (SEA) was first introduced in 1959 and has been extensively used to predict the transmission of acoustic and vibration of complex structures, especially in a motor vehicle. The method breaches the structures into sub-systems consisting of plates, beams and cavity, and each of this subsystem acts as an energy reservoir. The SEA assumes that each subsystem must store energy with sufficient modal energy density so that statistical average at high frequencies is valid (Lyon, 1975). The subsystem must be dominated by the reverberant field and the direct field is neglected (Putra *et al*., 2015). To fulfil this requirement, the SEA is only valid when the propagating acoustics or vibration wavelength is much smaller than the dimension of the structure. Recently, a hybrid FE-SEA was proposed to accommodate the presence of low modal density structures and thus covers the analysis from low-to-high frequencies (Shorter & Langley, 2005).

In this study, a three-dimensional model of a rectangular plate is constructed in VA-One with an aluminium plate of dimensions 10 cm x 10 cm and thickness of 5 mm. The SEA cavities (dimensions of 10 cm x 10 cm x 10 cm) are applied to both side of the plate as the storage for the sound energy, representing source and the receiver subsystems. The diagram is shown in Figure 5.

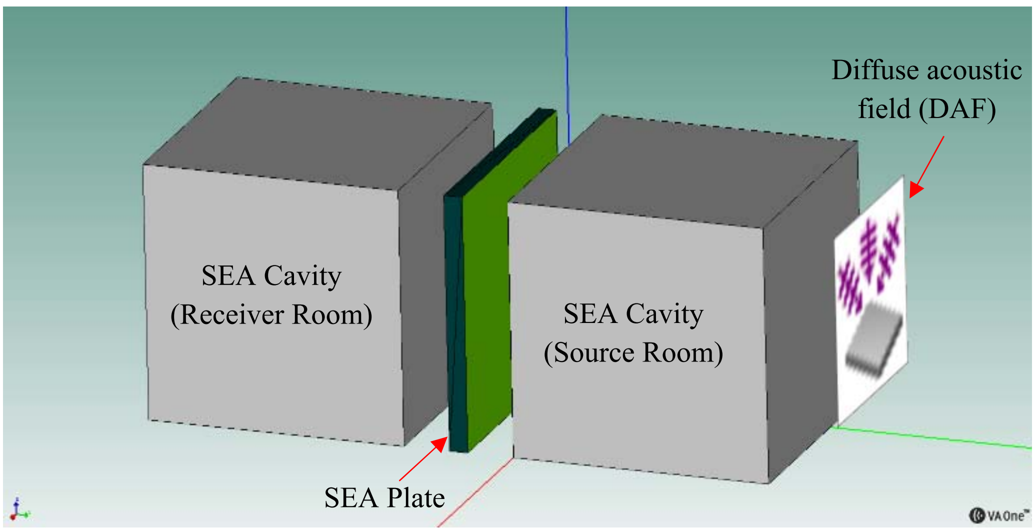

Figure 5: The SEA model of sound transmission loss of a rectangular plate.

The plate facing the source cavity is excited with a diffuse acoustic field (DAF) of 1 Pa sound pressure (as in Eq. (2)), which represents a diffuse acoustic pressure load acting over the surface area of a subsystem. The maximum solving frequency is set to 6 kHz. Coupling linkages between the SEA plate and SEA cavities (i.e. the contact area) are set with SEA area junction to represent the area of acoustic energy transmission between SEA plate and a SEA acoustic cavity.

2.2 Application of Natural Fibre to SEA Plate

Noise Control Treatment (NCT) material is defined as a single or multi-layered material attached to the surfaces of the SEA plate to absorb or to block the incoming sound energy. In this simulation, the natural fibre is applied to the receiver side of the SEA plate as shown in Figure 6. This simulates the NCT of a car body, where felt materials are applied in the inner side of the car body panels as the interior sound absorber and also to reduce the noise transmission from the exterior.

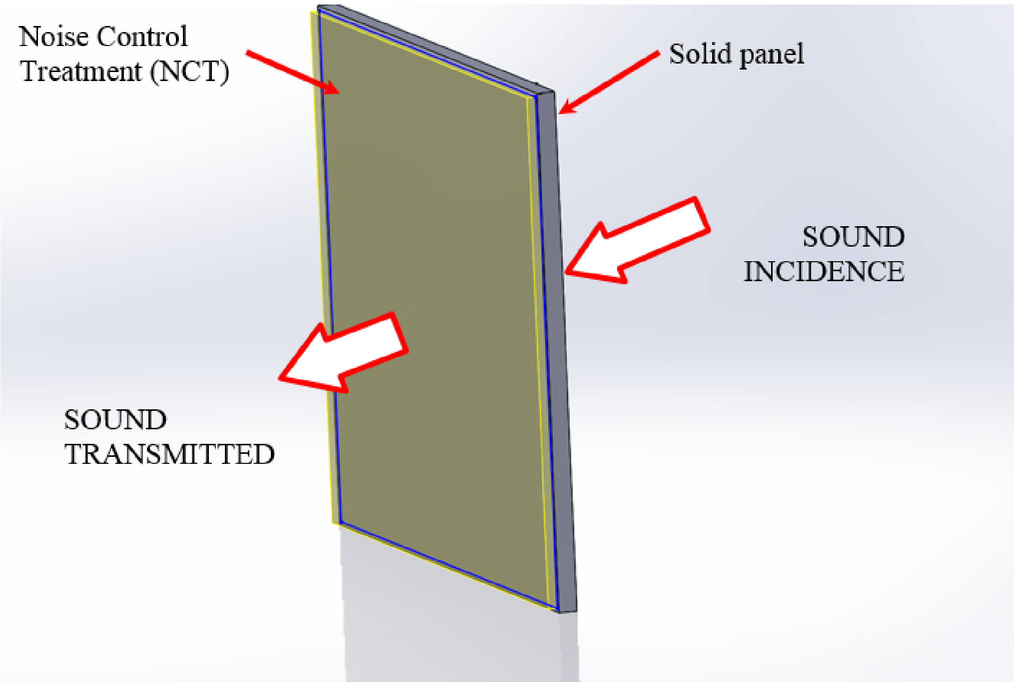

Figure 6: NCT attached to the SEA plate.

The NCT materials can provide substantial local subsystem damping when they are applied on a panel. They can affect: (i) the mass and stiffness (or reactive impedance) of the panel and (ii) the energy flows that occur between panel and any adjacent acoustic cavity subsystem.

This study is to simulate the performance of sound insulation of the kenaf fibre. Before the discussion is focused on the kenaf, performances of other natural fibres are presented. Table 1 lists the properties of the natural fibres, namely kenaf, coir, oil palm and ijuk extracted from existing studies. This includes the felt used as the baseline for the TL. The density can be seen to be different for each material.

Table 1: Material properties of natural fibres.

Item	Unit	Felt	Kenaf	Oil palm mesocarp	Ijuk	Coir
Density, ρ	kg/m^3	50	40	247	300	821
Flow Resistivity, σ	N.s/m^4	40000	6215	37415	11383	1359
Porosity, Ø	-	0.92	0.99	0.85	0.85	0.89
Tortuosity, α	-	1.50	1.05	1.09	1.09	1.06
Viscous Characteristic Length, ʌ	ɱm	56	68	97.81	70	133.5
Thermal Characteristic Length, ʌ'	ɱm	122	177	195.62	180	266.9
Reference	-	VA One (2015)	Shravage (2009)	Latif *et al.* (2016)	Sambu *et al.* (2016)	Jailani *et al.* (2010)

2.3 Simulation of Natural Kenaf Fibre as NCT Material in Car Interior

Transmission of noise from the engine, tyre and other exterior noise into the car cabin directly depends on the treatment applied to the car body as illustrated in Figure 7. This includes the acoustic trim materials and also the damping layer to the body panel. In the market, most car manufacturers use synthetic fibres, known as felt as the NCT as well as for the interior design of a car cabin.

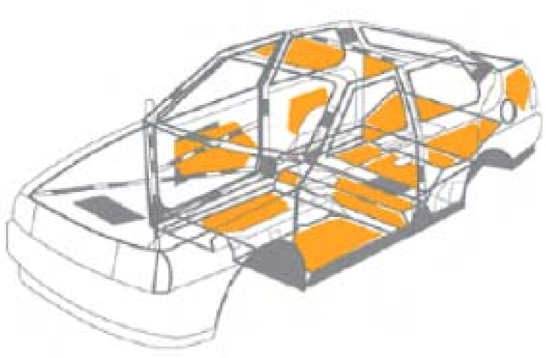

Figure 7: Locations of damping treatment in a car body (Furukava *et al.*, 2009).

In this study, a simulation is performed where kenaf fibre is used as the NCT material in a car. Figure 8 shows the 3D model of the car designed in the VA One software. The car body is divided into plates/shells representing the floor, dash, roof, windows, doors and firewall. The properties are listed in Table 2. The interior was subdivided into acoustic spaces where they are classified into front cavity and rear cavity.

The material properties of Kenaf and Felt can be seen in Table 1. In the simulation, Kenaf was replaced in the position of Felt to study the sound absorption of both materials and placed in floor, roof, firewall, door and window's frame.

Sound excitation using diffuse acoustic field (DAF) is applied on the outer surface of the firewall to represent the noise from the engine, on the floor to represent the noise from tires and on the side door and windscreen to represent the wind noise. The sound pressure level (SPL) in the front cavity and rear cavity is calculated. The results are compared for the case where no NCT is applied (white body)

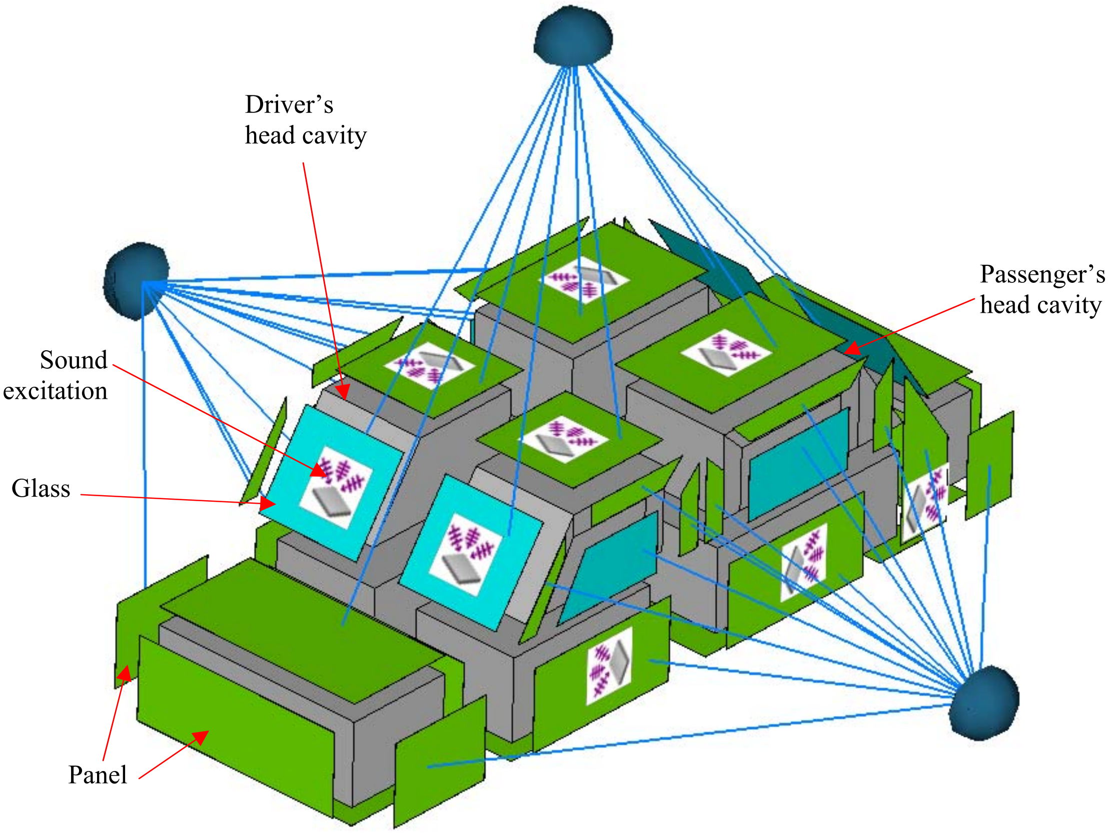

Figure 8: The 3D car model of SEA subsystems in VA One (shrink mode).

Table 2: Properties of car panels in VA One.

Structure	Material	Thickness (mm)
Roof panel	Steel	1
Floor panel	Steel	1
Door panel	Steel	1
Pillars	Steel	1
Glass panel	Glass	1.5

3. RESULTS AND DISCUSSION

3.1 The Simulated Transmission Loss of SEA Plate

Figure 10 shows the TL of the SEA panel obtained for five different fibres as listed in Table 1. All fibre layers are simulated with the same thickness of 5 mm. It can be seen that the TL of the plate increases when NCT materials are applied to the plate. The felt material can be seen to have superior insulation performance. Here, only the oil palm fibres have similar TL with that of the felt material. From Table 1, although both materials have different density, they have similar flow resistivity and are the greatest among other fibres. The direct relationship between the density of the fibrous material and its flow resistivity is given by

$$R = A\rho B \tag{3}$$

where ρ denoted as mass density of the material (mass per unit of volume) and A and B are the coefficients which depend on the type of the fibres.

Figure 10 shows the coincidence frequency of the panel can be seen to be at 1.6 kHz, which is the critical frequency of the 5 mm aluminium panel (see again Figure 4). The effect of different fibres can be observed to mostly affect at above the coincidence frequency, with almost no significant difference at the mass-controlled region below 1.6 kHz. This due to the weight of the fibres which is much smaller compared to weight of the aluminium panel. The effect of porosity and flow resistivity are discussed in the next sections and the focus is only for the kenaf fibres to observe the potential of this material for the future NCT in automotive.

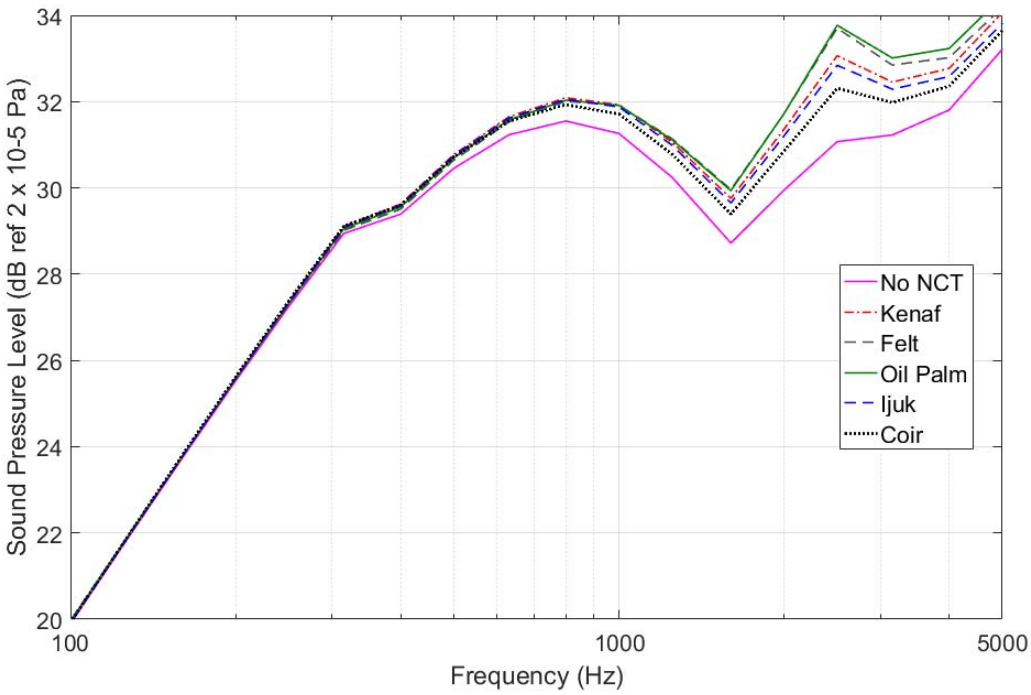

Figure 10: Results of TL of the SEA plate with noise control treatment of various fibres (based on data in Table 1 and with 5 mm thick).

3.2 Parametric Study of Kenaf fibres as NCT

Based on the designed model, the felt material used in automotive is set as the baseline performance and the sound insulation performance of the proposed natural kenaf material is compared against that of the felt. This study includes the NCT thickness, flow resistivity, porosity and tortuosity. Shravage *et al*., (2010) shows that flow resistivity, porosity and tortuosity are one of the most important parameters of acoustic behaviour of the porous material compare to elastic parameters which does not affected the acoustic behaviour of the poroelastic materials.

3.2.1 Effect of Thickness

The average thickness of the felt in automotive used was roughly 5.0 mm. To study the thickness effect on the STL of the plate, the analysis was performed using three different thickness of the kenaf fibres; 5.0 mm, 7.0 mm and 9.0 mm. In Figure 11, it can be seen that with additional of 2 mm fibre thickness (total thickness of 7 mm), the TL of the kenaf fibres can have the same performance to that of the felt for the frequency range from 100 Hz to 5 kHz.

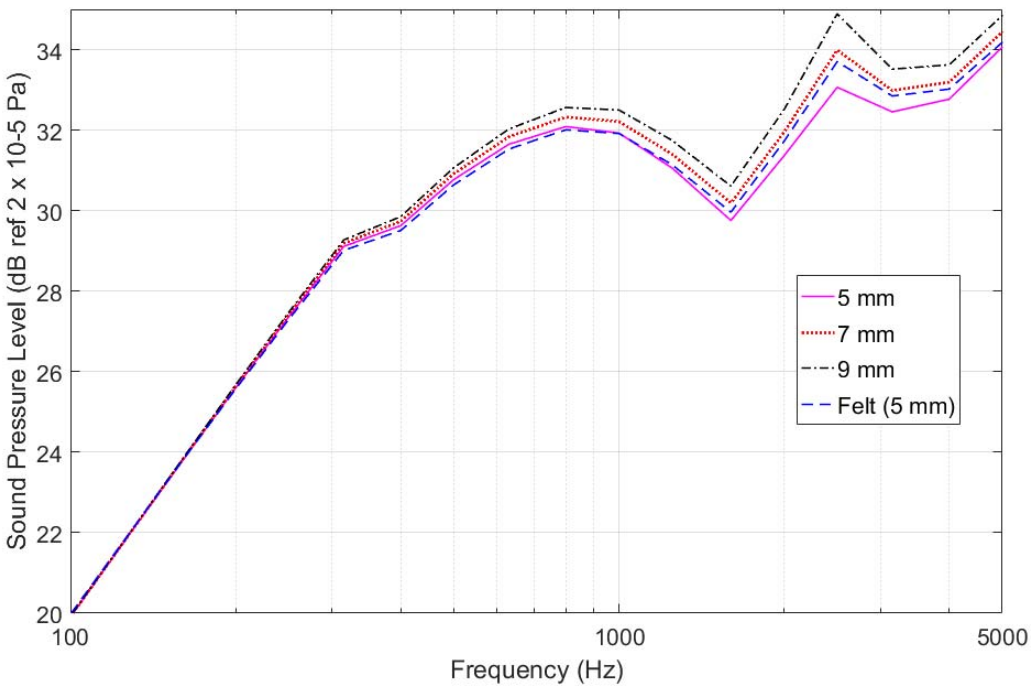

Figure 11: Effect of thicknesses on sound transmission loss.

The data use the same density of fibres, i.e. 40 kg/m^3, which means by increasing the thickness, more fibres are added to maintain the density. In this way, increasing the thickness means increasing the mass, and thus improvement at mass law region can thus be observed below 1.6 kHz.

Tan *et al*., (2016) also showed in their study that the most effective way to enhance the transmission loss of fibrous panel is by increasing the mass of the fibres.

3.2.2 Effect of Flow Resistivity

The flow resistivity can be defined as the viscous resistance to the steady flow of air in the acoustic material. Shravage *et al*., (2010) studied about the effect of flow resistivity on absorption and transmission loss of the poroelastic materials. Their study shows that by increasing the flow resistivity up to a certain value, significant increase in sound absorption coefficient is obtained in the mid-frequency range and as well as in the TL.

In this study, flow resistivity of the material is varied from 6,215 to 40,000 N.s/m^4, while other parameters are kept constant. From Figure 12, it can be observed that by increasing the flow resistivity, the improvement is only effective above the coincidence frequency (above 1.6 kHz), while almost no improvement at the mass law region . The lower frequency can easily pass the through the fibre (the incoming acoustic wavelength is larger than the thickness of the panel), while the higher frequencies have greater resistance inside the fibre.

As the flow resistivity is proportional to the density of the fibres (Eq. (3)), the results above 1.6 kHz is consistent with those in Figure 11. The negligible effect obtained below 1.6 kHz is because the panel thickness is kept constant at 5 mm.

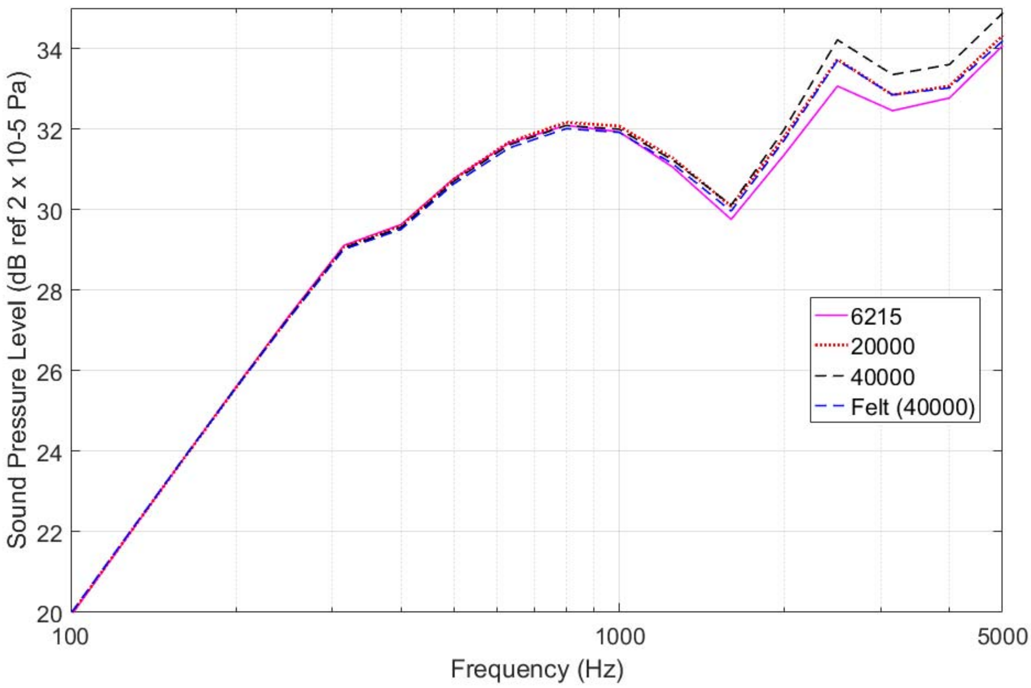

Figure 12: Effect of flow resistivity of kenaf fibres on sound transmission loss.

3.2.3 Effect of Porosity

The porosity refers to the degree of pores in the panel. As also observed by Shravage *et al*., (2010), the porosity has more influence on the TL at mid to high frequencies. The TL increases with increase in porosity.

Porous materials generally have porosity near 0.7-0.9. Here the porosity is varied from 0.5 to 0.9. From Figure 13, the TL improves as the porosity increases. The greater the porosity, the easier the sound penetrates the panel.

Note that the simulation assumes the panel to have a constant bulk density, i.e. constant ratio between the mass of the fibres to the total volume of the panel (including the air in the porous). In practice, increasing the porosity while maintaining the thickness of the panel can reduce the mass of the panel. Meanwhile, increasing the density of the fibres to maintain the mass can reduce the porosity as the fibres become more compact in the panel (Putra *et al.,* 2013).

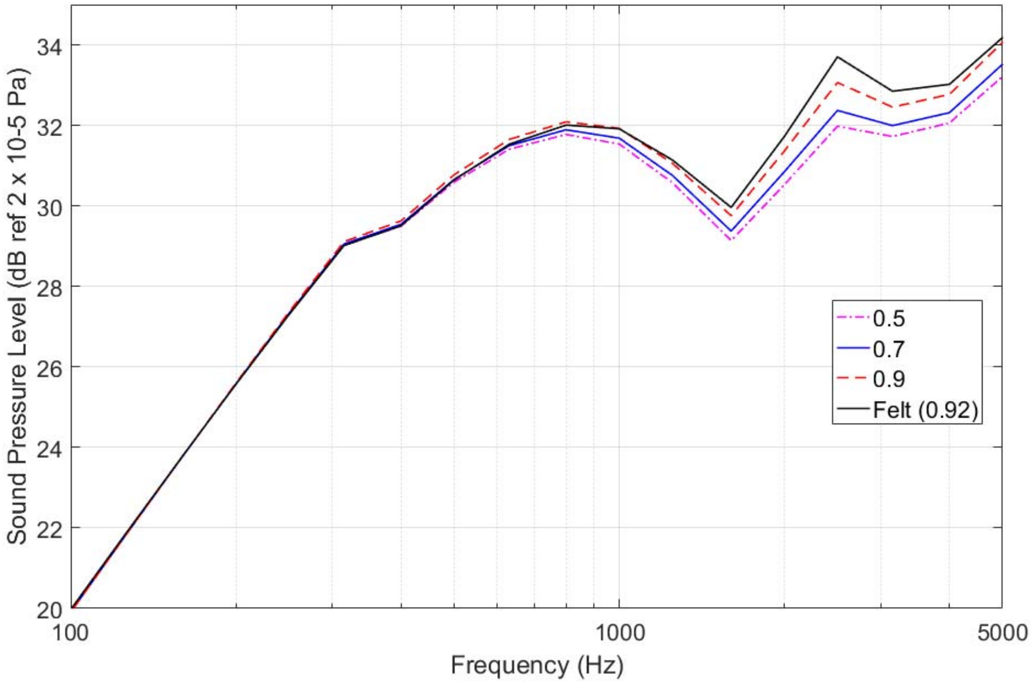

Figure 13: Effect of porosity on sound transmission loss.

3.2.4 Effect of Tortuosity

Tortuosity defines the curliness or complexity of pores of the material, which means the more complex the material path, the more time the sound wave is in contact with the fibres and the more energy dissipation obtained.

In this study, tortuosity of 0.8, 1 and 1.5 are used. In Figure 14, it is shown that the smaller the value of this parameter, the greater the TL. The simulation shown by Shravage *et al*. (2010) indicates the fluctuation of TL as the function of tortuosity values due to resonance and anti-resonance phenomena. The choice of 0.8-1.5 values here may be in the range of where the TL decreases as the tortuosity increases.

The difference of TL compared to the TL of felt is however is not significant as in Figure 14. The TL difference is almost negligible below 2 kHz, and only differs by less than 1 dB above 2 kHz.

3.3 Effectiveness of Kenaf Fibre as NCT

In this simulation, the performance of the kenaf and felt layer as the sound insulator is compared in terms of the sound energy built up in the car cabin due to the input of sound excitation from the exterior. Besides the sound energy is reduced due to insulation, it is also damped due to the sound absorption from the layer. The absorption coefficient for the felt is obtained from the study of Ricciardi & Lenti (2010) and for the kenaf is from Lim *et al.* (2015).

Figures 15 and 16 show the built-up sound pressure level (SPL) at the driver's and passenger's cavities, respectively. It can be seen that the performance of kenaf layer is almost similar to that of the felt layer, except at around 400 Hz - 1 kHz where the felt outperforms the kenaf by roughly 5 dB in average. This is due to the absorption coefficient of the felt is greater than the kenaf fibre for the frequency above 400 Hz.

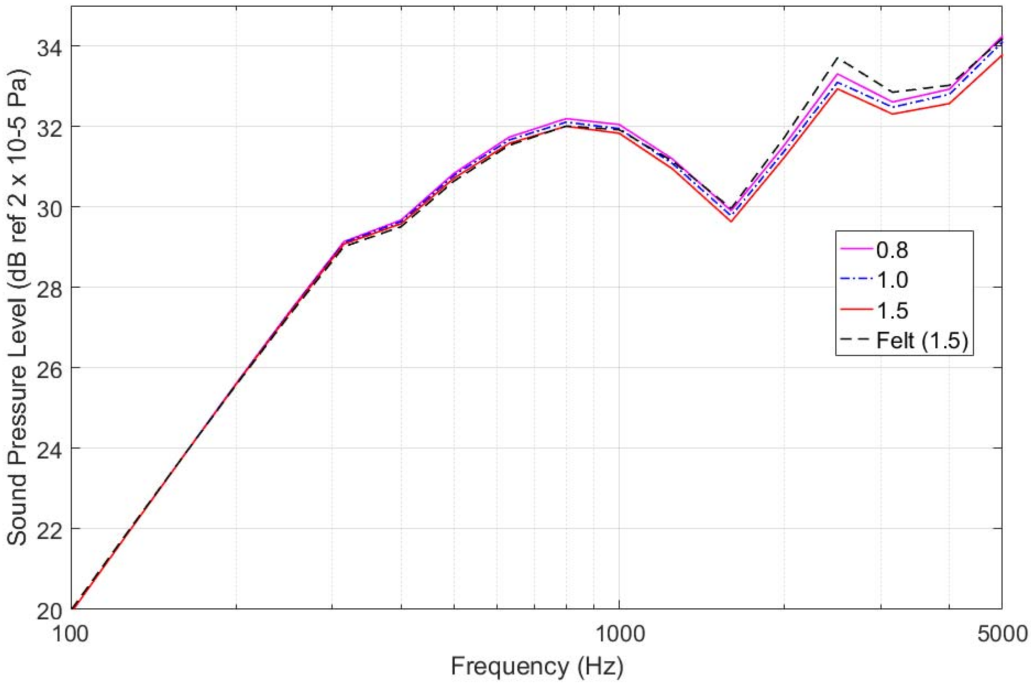

Figure 14: Effect of tortuosity on sound transmission loss.

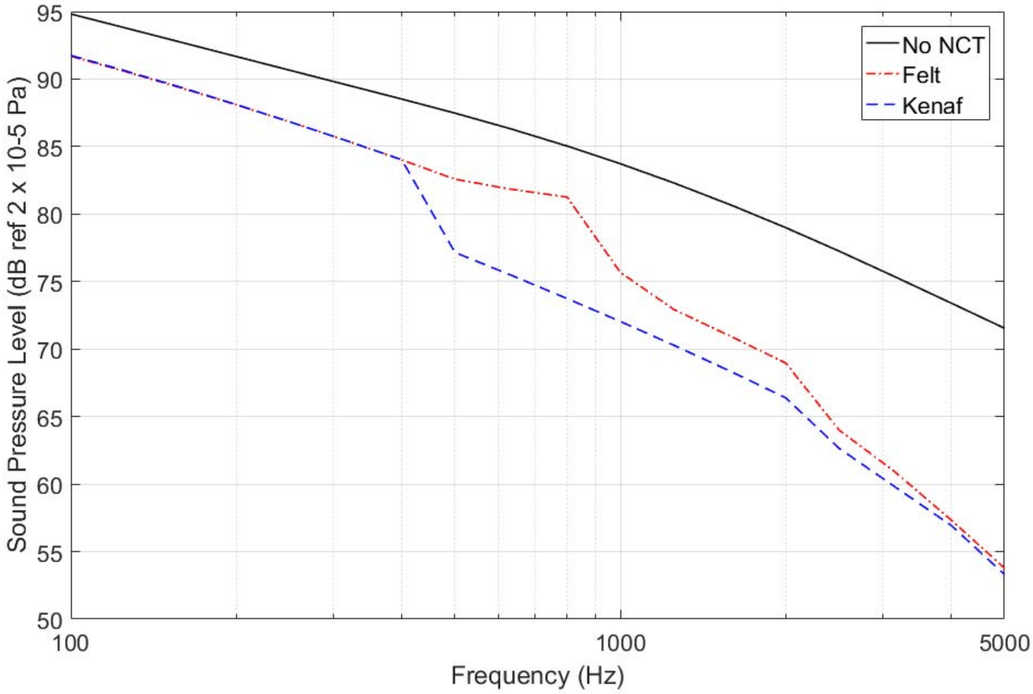

Figure 15: Effect of NCT on front driver cavity.

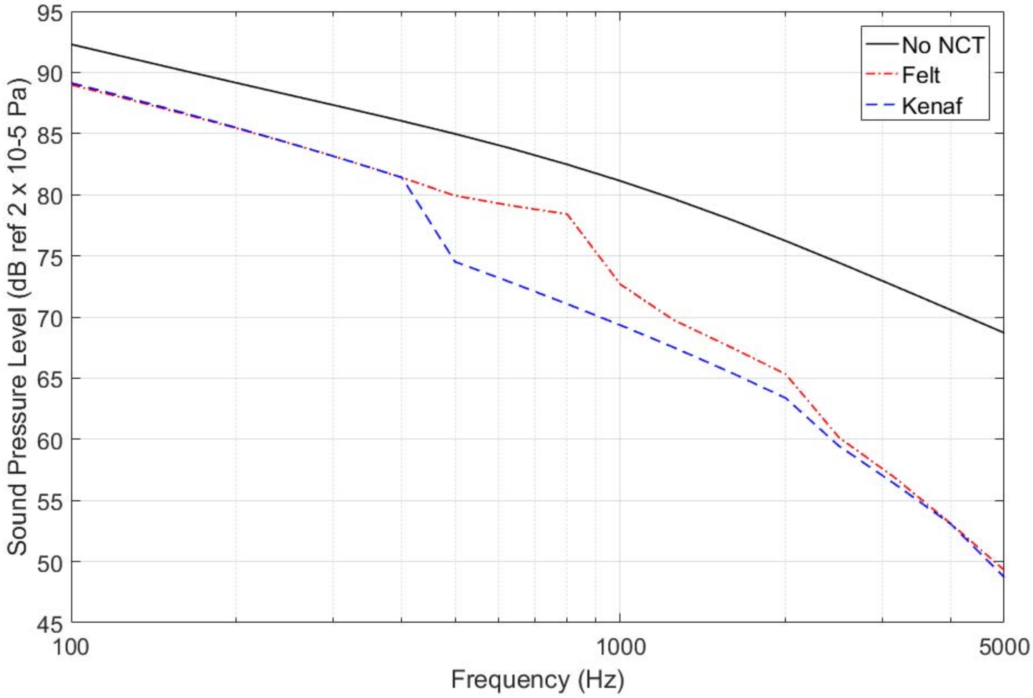

Figure 16: Effect of NCT on rear passenger cavity.

Note that the simulation is modelled with the NCT layer directly attached to the car body panel. In practice, the inner car body consists of other layers of additional steel panel or plastic-like materials before it is finished with felt layer, and thus the built-up SPL should be much lower than those shown in Figure 15 and 16.

The sound excitation in the simulation also assumes diffuse acoustic field with the sound energy level almost constant across the frequency. For the experiment with the input of real engine noise, the engine order of 2X (where X is the frequency related to the engine speed) will be the dominant peak frequency in the SPL spectrum. The transition of the airborne and structure borne sound transmission at frequency 300-500 Hz will also be evidence showing the effectiveness of partition (including NCT materials) to effectively block the airborne noise above this transition frequency (Putra *et al*. 2012).

4. CONCLUSION

The performance of kenaf fibres used as the noise control treatment in a car has been discussed in this paper. The results show that the natural kenaf fibres have a comparable performance with the commercial felt materials. For the same layer thickness, the felt still have greater sound transmission loss, but the difference is only within 1-2 dB with that of the kenaf fibres. The kenaf fibres can outperform the felt by controlling the acoustical parameters of the fibres, particularly by increasing the density of the fibres. This paper presents the initial stage of results for the performance of kenaf fibres as the noise control treatment in a motor vehicle towards utilising green material. The next study can be extended to present the data on the experiment and the treatment of the fibres to have the same quality as of the commercial felt, especially in terms of fire retardancy.

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