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Effect of tufting technique on sound insulation of multi-layer glass woven fabrics

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Abstract

A new idea to influence the sound insulation property of multi-layered woven fabric by the embedded tufting yarns is presented in this paper. The effect of layer number, layer orientation, tufting density and tufting pattern is investigated respectively, in the basis of sound transmission loss (STL) analysis measured by an impedance tube. The experimental results show that the sound insulation can be enhanced by increasing the number of layers or maintaining the same lay-up orientations. Moreover, the effect of tufting yarns on sound insulation is more sensitive in the low-middle frequency range and relatively more complicated. The obtained results can be applied in the part design, the preform engineering, and the positioning of tufting process.

1. Introduction

With the development of modern technology, noise control has obtained much attention for improving living conditions. Noise can be an important issue to our human health, as it may lead to hearing loss, psychological harms and sleep disturbance [1, 2]. The materials with high density, such as steel, can insulate the sound effectively, but these metal materials reflect most of sound back to environment, causing sound pollution again [3]. At the same time, the heavy weight of these rigid materials makes them hard to be applied effectively in the automotive industries for sound insulation purpose. On the contrary, textile materials have gained much attention, as they not only have a great potential to sound absorption, but also present a low density.

The acoustic properties of textile materials strongly depend on the fabric internal structure, where small air spaces can improve the sound absorption properties [4]. Woven fabric containing a large number of small holes (less than 1 mm) between the two orthogonally interwoven yarns (warp and weft) [5] can be seen as a porous material, but its porosity is relatively weak compared to the non-woven fabric. However, several studies have illustrated that the woven fabric also can be applied as a sound absorber in some actual products, such as hanging curtains [6], porous woven hose [7], and upstream resistive layer [8]. In addition, many researches have done extensive analysis on the relationship between sound absorption properties and various fiber-related parameters, including film coverage, surface treatment, formation processes and physical structure, for fibrous and porous textiles [9–14]. It can be concluded that the fabric porosity and fabric density always have a significant effect on the sound absorption properties. Therefore, in order to improve the sound absorption performance of woven fabric, a common approach is accepted by arranging multiple layers of woven fabrics in particular forms. Due to the multilayered structure, more air spaces are introduced between layers to increase the porosity of the entire fabrics. Several academic studies have been applied on the sound absorption for multilayered woven fabrics. Prasetyo et al [15] studied that high and low flow resistance have different impact on sound absorption properties for a double-layered woven fabric. Parham et al [16] reported that the acoustic characteristics of woven fabric are correlated with fabric structural parameters and air permeability. The effect of...
Fabric thickness was analyzed by comparing the three and six layered test samples. In this work, we investigated complementally the effect of lay-up orientations of multilayered woven fabrics on sound absorption property.

On the other hand, in the mesoscale, the tows in the woven fabrics can be modified and interlaced freely according to the practical requirement. Kang et al. [17] found that the different weaving patterns and yarn fineness in the fabric have a significant influence on the air permeability linearly in relation to the sound absorption coefficient. Therefore, a new idea of whether the additional inserted tufting yarn can modify the sound insulation property has come into the mind. Tufting process [18, 19], regarded as a relatively novel technique, has become a commercially available approach for the production of through-thickness reinforcements (TTR) [20–22], which can impede effectively the slippage between layers and enhance the impact damage resistance. Traditional stitching process [23–26] has a double-thread feed system and needs to interlace the two threads to each other. On the contrary, the tufting process with single-thread feed system can much reduce the damage to the reinforced fabric caused by the sewing effect. Many published papers have focused on the tufting technique, especially concerning the general introduction of tufting process [26], the comparisons of tufting to other textile techniques [21, 27, 28], the formability behavior or forming defects of tufted fabrics [18, 19, 29] and the basic mechanical performance of tufted composites [21, 30]. However, to the author’s opinion, no paper has been devoted to the investigation of the sound insulation properties of the inserted tufting yarns in a multilayer structure.

As a result, the objective of this paper is to investigate the influence of both the stacking structure of multilayered woven fabrics and the through-thickness tufting yarns on the sound insulation performance. In particular, the effects of layer numbers, lay-up orientations, tufting density and tufting pattern are mainly discussed. The knowledge of this study can effectively improve the sound insulation performance as much as possible while ensuring the impact resistance of a tufted product.

2. Materials and methods

2.1. Materials

In the present work, a commercial E-glass plain woven fabric owning an areal density of 157 ± 5 g m−2 and a thickness of 0.3 mm is investigated. A 67 tex twisted carbon thread (TENAX®) is tufted into the fabrics via a hollow needle of 2 mm diameter using a programmable tufting machine. Figure 1 illustrates schematically the features of a test sample, the 3D structure of sample in (a), the photo of sample in (b), the schematic plan view of sample in (c) and the dimension of sample in (d). It can be seen that (figure 1(a)) the inserted tufting threads stretch on the front surface of fabric and form a loop at each tufting node on the opposite side. Due to the size restrictions of the measurement device of sound insulation, all the test samples are deliberately cut into circles with a diameter of 30 mm. In the schematic plan view of sample, the yellow dots represent the position of tufting nodes and the black solid line refers to the tufting yarns on the surface.

In order to investigate the influence of both the fabrics and the tufting yarns, four different groups are tested and table 1 illustrates the details of these test samples. The effects of the layer number, lay-up orientation, tufting density and tufting pattern on the sound insulation are discussed respectively. At the level of fabric effects (Group 1 and 2), the tufting yarns are also used to binder the multiple layers, so as to facilitate the subsequent
Table 1. Main properties of the test samples.

| Group 1: Effect of the number of layers |
|---------------------------------------|
| Pattern                              |
| Sample name | Layer 1 | Layer 2 | Layer 4 |
| Number of layers | 1 | 2 | 4 |
| Tufting points       | 4 | 4 | 4 |

| Group 2: Effect of lay-up orientation |
|---------------------------------------|
| Pattern                              |
| Sample name | Orientation 0 | Orientation 45 | Orientation 22.5 |
| Number of layers | 4 (0/0/0/0) | 4 (0/45/90/135) | 4 (0/22.5/45/67.5) |
| Tufting points       | 4 | 4 | 4 |

| Group 3: Effect of the amount of tufts |
|---------------------------------------|
| Pattern                              |
| Sample name | Radiation 18 | Radiation 27 | Radiation 36 |
| Number of layers | 2 | 2 | 2 |
| Tufting points       | 18 | 27 | 36 |

| Group 4: Effect of tufting pattern |
|-----------------------------------|
| Pattern                           |
| Sample name | Radiation 36 | Short radiation |
| Number of layers | 2 | 2 |
| Tufting points       | 36 | 36 |

| Pattern |
|---------|
| Sample name | Wheel | Ring |
| Number of layers | 2 | 2 |
| Tufting points       | 36 | 36 |
sound insulation measurement process. The same tufting patterns (a square path coupled with four tufting nodes) are applied on the samples in Group 1 and 2 to eliminate the interference from the inserted tufting yarns. Furthermore, except for Group 2, the fabric layers of the samples in the other groups are always stacked with an identical orientation. Each type of sample has been tested 3–5 times to ensure the accuracy of the experimental results. The coefficient of variation ($C_v$) is used and calculated for each sample at different frequencies to evaluate the extent of variability in relation to the mean of the population. According to the following statistical equations (1) and (2), all the $C_v$ values are distributed in a range of 1.6%–8.4%, lower than 10%, whose variability is considered to be weak.

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_i - \mu)^2} \quad (1)$$

$$C_v = \frac{\sigma}{\mu} \quad (2)$$

where $\sigma$ is the standard deviation; $N$ is the number of population; $\mu$ is the mean value of population; $C_v$ is the coefficient of variation.

### 2.2. Tufting process

The tufting technique is a relatively novel approach in the manufacture of the through-thickness composites. Compared to the traditional dual-thread stitching technique, tufting process with a tension-free system can much reduce damage to the fabric caused by the sewing effect [26, 31]. The access of tufting needle from one side of the fabric also contributes to a higher efficiency and simpler operations. As shown in figure 2, a hollow needle carrying the tufting yarn penetrates through the fabric into the underlying foam. The inserted tufting yarn is then retained inside the foam and form a loop on the opposite side due to the friction effect, when the needle retracts. In addition, it is important to well consider the properties of tufting thread and the needle eye shape to avoid the frequent thread breakage. In this study, an experimental tufting device developed by GEMTEX laboratory was used for the tufting process. The presser foot device applies a constant pressure on the fabric prior to the insertion of tufting needle and is released only after the full retraction of needle. The tufting routines can be programmed in the computer for achieving an automated manufacturing process.

### 2.3. Sound insulation measurement

In this paper, sound transmission loss (STL) was measured by an impedance tube (AWA88551) conforming to the GB/T 18696.2-2002 standard. The schematic of this device is illustrated in figure 3. The diameter of the impedance tube is 29 mm. Four microphones are placed on both sides of the test samples to record the transmitted and reflected sound pressures respectively. The STL is then calculated in dB according to a transfer matrix relating the forward and backward traveling acoustic waves [32, 33]. The test range of sound frequency used in this study is set from 500 to 6300 Hz. The experiments are always carried out in a constant environment with a temperature of 23 °C and a humidity of 40%.

### 3. Results and discussion

#### 3.1. Effect of number of layers on sound insulation

Three test samples are analyzed in order to determine the effect of the number of fabric layers on acoustical properties. A sound insulation comparison between the samples with various numbers of layers has been shown...
In Figure 4(a), as sound transmission loss (dB) versus frequency (Hz). It can be observed that the sample containing more layers presents a better sound insulation property over the entire frequency range. Considering the mass law [34], which is the most important physical property for the airborne sound transmission loss and can be applied to most materials in certain frequency ranges, a material with a larger areal density, kg/m², would have a higher STL. Therefore, the four-layer sample owning the largest areal density compared to the others leads to the best sound insulation property. In addition, as illustrated in Figure 4(b), the four-layer sample can generate a higher amount of acoustic reflections due to the multi-layer structure. At the same time, the increased thickness results in a more sound absorption achieved by transferring the sound energy into the vibration of the fabrics, which may also yield potentially more frictional heats.

During the overall frequency range, the STL of the four-layer sample is approximately 2.5 times to the one-layer sample (10.25 dB and 4.11 dB at 6.3 kHz respectively). This ratio value drops to 1.3 times in the comparison between the two-layer and one-layer samples (5.35 dB and 4.11 dB at 6.3 kHz). That is to say, the increase rate of STL is less than the increase rate of the number of fabric layers to some extent. It can be explained that the sound transmission in fibrous materials depends on many parameters such as the diameter of fibers, density of material, frequency, the viscosity of air and so on [35], contributing to a complex logarithmic relationship between the STL and the sound transmission coefficient. As a result, doubling the number of layers cannot lead to a doubled STL.

Furthermore, as shown in Figure 4(a), the curves of STL for each test sample have the similar tendency, where the STL amplitude fluctuates slightly at first, then decreases and at last increases along with the frequency. However, the mass law theoretically predicts that the STL of a material would successively grow with the increasing sound frequency. The experimental results suggest that the mass law could be effectively broken using such kind of woven fabrics in the low-middle frequency range. This behavior is also observed in several other studies for multi-layer structure [10, 36]. It can be considered that owing to the resonance and stiffness of
material structure, the STL curves would undergo some unexpected fluctuations. In particularly, when the fabrics have the same vibration direction as the sound wave transmission, the STL will be reduced significantly. Thus, only when the frequency is higher than the range of the so-called stiffness control region [37], the STL curve can go back to mass control region and satisfy the mass law. This critical frequency is defined as the location of the minimum STL value, i.e. 4000 Hz in this case.

3.2. Effect of lay-up orientation on sound insulation
The lay-up orientation is also an important parameter for materials with a multi-layer structure. In this section, the effect of the layer orientations on the sound insulation has been further investigated. All the test samples are made up by four fabric layers with 0°, 22.5° and 45° relative orientations respectively. The comparison results of STL between these samples, as a function of frequency, have been shown in figure 5. Again, the curves of STL for the three test samples fluctuate and decrease at first due to the resonance and stiffness of fabrics. After the frequency of 4000 Hz, the curves turn to increase, as the STL starts to be predominately controlled by the mass law.

For the influence of lay-up orientation, the STL of the sample with 0° relative orientation is considerably higher than the other two. The lowest value of STL is observed in the case with 22.5° relative orientation, but it is quite close to the one with 45° relative orientation. The possible reason is contributed to the different sound transmission paths in each sample. The woven fabrics composed of two initially orthogonal sets of yarns (warp and weft) make the sound propagate mainly along the fiber directions in the materials. As shown in table 2, the overall sound transmission paths in the absorbing materials are significantly different. For the sample with 0° relative orientation, the sound waves are concentrated in the two orthogonal directions. The superimposed effect from each ply much enhances the vibration of the whole fabrics. Thus, more energy is dissipated in the fabrics during the sound transmission, so as to improve the sound insulation performance. On the contrary, due to the increase of the sound transmission paths, the sound wave tends to be more randomly distributed in the fabrics. The vibration of the fabrics becomes relatively weak, leading to a considerable decrease of the sound insulation property. Moreover, in the case of Orientation 22.5°, although it has 8 different sound transmission paths (STPs), twice as much as Orientation 45° (4 different STPs), its STL values are only slightly lower than Orientation 45° but prominently lower than Orientation 0° (2 different STPs). It suggests that the increase of lay-up orientations has an effective influence on the decrease of sound insulation property; however, this effect has a limit when the sound transmission paths in the fabric have reached a certain amount.

3.3. Effect of tufting density on sound insulation
The samples with different tufting densities are tested to study the effect of the embedded tufting yarns on the sound insulation property. The tufting density is defined as the tufting points per unit area. Three comparable test samples are tufted in a similar pattern and composed of 18, 27 and 36 tufting points respectively (table 1). The experimental results for the curves of STL have been illustrated in figure 6(a). It can be observed that the critical frequency between the stiffness control and mass control regions of each STL curve is no longer equal to 4000 Hz, due to the increasing insertion of tufting yarns. In order to better describe this phenomenon, the sample (layer2) with the same layer numbers and fewer tufting points mentioned in section 3.1 is selected and
compared with the samples of this group. Their critical frequencies have been indicated in figure 6(b). It can be seen that the critical frequency drops dramatically from 4000 Hz to 2500 Hz, as the tufting points rise from 4 to 27. When the tufting points further increase to 36, this decline trend of critical frequency seems to be stopped and stays at 2500 Hz. Although this unchanged frequency value is probably caused by the measurement accuracy. However, it also hints that the tufting density can affect the stiffness of material so as to modify the critical frequency and this effect will be restricted when the tufting density reaches a certain level.

On the other hand, in figure 6(a), different from the previous cases concerning the effect of fabric layers, the effect of tufting yarns on sound insulation is more effective in the frequency range between 500 and 4000 Hz, which is thought to be a relatively sensitive range for humans [38]. The best sound insulation property occurs in the sample with the minimal tufting points of 18. However, the worst sound insulation property occurs in the sample with the medium tufting points of 27, rather than in the sample with the maximal tufting points of 36. It can be seen more clearly in figure 6(c), the STL values are compared as a function of the tufting points at the frequency of 1000, 1500 and 2000 Hz. The curves present a similar trend, where the STL values decrease first and then increase again along with the increase of tufting points.

In the current study for the effect of tufting density, a radiation tufting pattern is used, as illustrated schematically in figure 7(a). It is observed that although most tufting threads stretch on the front surface of fabric in a radial form, the rest of them need to penetrate the fabrics through thickness at each tufting node and form a loop on the reverse side. Every triangle vertex near the centre (marked as a red dot in figure 7(a)) requires a tufting loop, in order to guarantee the continuity of tufting process. Therefore, a large number of tufting loops are distributed very closely and intensively in the centre. Due to the increase of tufting density, more through-thickness tufting threads are regarded as the so-called ‘sound bridges’ (figure 7(b)). These ‘sound bridges’ are just in the direction of sound transmission, making the sound waves pass through the fabric more easily and leading to a degradation of the sound insulation property. However, along with the further increase of tufting points, the test sample becomes heavier, making the mass law regain the leading role and improving the STL finally.

### 3.4. Effect of tufting patterns on sound insulation

Further studies concentrate on the effect of tufting patterns on the sound insulation. For this analysis, the tufting points of the three test samples with different tufting patterns remain identical (equal to 36), namely radiation, short radiation, wheel and ring respectively, as shown in figure 8. The same tufting points is to ensure the comparable test samples have the same quantity of the ‘sound bridges’ and tufting loops, so that the interference caused by these factors can be eliminated. On the contrary, the main difference between these samples is the
Figure 6. STLs of samples with different tufting density (a), effect of tufting points on STLs at three selected frequency (c).

Figure 7. Schematic of sound bridge in the multilayer structure.
length of tufting yarn on the front surface and the distribution of tufting nodes. The results of the STLs have been demonstrated in figure 8. Again, the STL curves present a nonlinear increase with the frequency in the whole test band. Due to the influence of resonance and stiffness of structures, the STL curves undergo an obvious fluctuation and a decline in the range below 2500 Hz. Then the STL complies with the mass law and continues to increase in the range of 2500–6300 Hz. On the other hand, similar to the previous case for the tufting density, the effect of tufting patterns on sound insulation is more apparently in the range between 500 and 4000 Hz. It can be observed that the radiation pattern has the best acoustic insulation ability compared to the other test patterns, whose STL values are relatively low and similar. It can be explained that the inserted tufting yarns covering the entire surface in the radiation pattern improve the overall stiffness of fabric, contributing to a relatively higher STL (The greater the stiffness, the larger the STL [36]).

Furthermore, the distributions of tufting nodes of these test samples are represented by the yellow dots in figure 9. Some small gaps are thought to be inevitable at these tufting nodes due to the damage caused by the tufting process. When the distribution of tufting nodes is relatively concentrated, these gaps are also closer to each other resulting in the sound waves to penetrate the fabrics more easily reflected by a reduction in STL.

4. Conclusion

The present study has shown that the sound insulation property can be influenced by both the fabric structure and the tufting parameters. Some conclusions can be achieved as follows:

1. The non-linear trends of the STL curves suggest that the mass law could be broken using the glass woven fabrics in the low-middle frequency ranges.
2. The sound insulation of glass woven fabrics can be significantly improved following the increase of layer numbers, as more acoustic reflection and absorption is generated on the interface of each layer. The results also indicate that the increase rate of STL is lower than the change rate in the number of layers.

3. For the multilayer structure, the more uniform the lay-up orientation is, the better the sound insulation becomes. As the identical lay-up orientation causes the mechanical vibration of each layer appearing in the same direction, this overlapping vibration effect leads to a higher consumption of sound energy.

4. At the scale of tufting yarns, owing to the occurrence of ‘sound bridge’, the sound insulation property will be reduced. However, this downward trend can be reversed by further increasing the tufting density, as the mass law plays a leading role in the later period.

5. By examining the effect of different tufting patterns, it can be thought that a discrete tufting distribution can increase the sound insulation to some extent.

6. Based on the results achieved in this paper, more effective approaches may be applied in the future for the product design of composite materials, in order to not only ensure the impact damage resistance but also improve the sound insulation performance.

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