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Sound absorption properties of polyurethane-based warp-knitted spacer fabric composites

Si Chen[1,a] , Hong-xia Chen[1], Xiao-ping Gao[1] & Hai-ru Long[2]

[1]College of Light Industry and Textile, Inner Mongolia University of Technology, Hohhot, China

[2] Key Laboratory of Textile Science & Technology, Ministry of Education, Shanghai, China

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Sound absorption properties of polyurethane-based warp-knitted spacer fabric composites (PWSF) have been studied. The warp-knitted spacer fabrics (WSF) are produced on a double-needle bar warp knitting machine using different structural parameters including inclination angle of spacer yarn, thickness, spacer yarn's diameter and surface layer structure. The composites are fabricated based on a flexible polyurethane foam. Accordingly, the acoustical behaviors of composites are evaluated properly by using two-microphone transfer function techniques in impedance tube. The findings reveal that the composites possess excellent sound absorption properties and their sound absorbability can be tailored to meet the specific end-use requirements by varying the fabric structural parameters.

Keywords: Impedance tube, Polyurethane-based composites, Sound absorption properties, Structural parameters, Warp-knitted spacer fabrics

1 Introduction

Noise pollution has great adverse effect on the environment, human health and social economy[1]. How to reduce the adverse effect has drawn a lot of attention of scientists and engineers in recent years. The most widely used method to decrease noise is the use of porous materials for sound absorption applications[2]. The mechanism of sound absorption in porous materials is basically based on the viscous effects due to the internal friction between the material and airflow, thus the heat loss due to the friction[3].

As a kind of porous materials, textile structures such as spacer fabrics have attracted great attention for sound absorption applications due to their low-cost and low environment impact. The spacer fabrics were first introduced by Dias and Monaragala.[4] The sound absorption properties and theoretical sound-absorbing modeling of weft-knitted spacer fabrics were investigated in their study. These fabrics are made of two plain-knitted outer layers and a spacer area. The spacer fabrics were characterized for sound absorption behaviors and the experimental results show that the sound absorbency of spacer fabric is effective from 2000 Hz onwards. Furthermore, this kind of fabric can provide reasonable absorbability at mid-high frequencies, but with a narrower absorption frequency range. Liu and Hu[5] studied the sound absorption behavior of knitted structure spacer fabrics. In their study, both weft-knitted and warp-knitted spacer fabrics were used because of their different structure features. The weft-knitted spacer fabric used was composed of two varied plain-knitted surface layers while the warp-knitted spacer fabric used was made with mesh structure on the outer layers. According to the test results, it is revealed that the sound absorbability can be improved by laminating different layers of fabrics. Specifically, for the weft-knitted spacer fabric, the sound-absorbing properties significantly increase from one layer to four layers and thereafter it is no longer effective with more layers. However, for the warp-knitted spacer fabric, the sound absorption coefficient can continuously be improved with an increase in fabric layers. Furthermore, the combination of weft-knitted and warp-knitted spacer fabrics can significantly improve their sound absorbability, but the arrangement sequence has obvious effect on the sound absorption behavior. Liang and Long[6] measured the sound absorption coefficient of warp-knitted spacer fabric with different structural parameters. The findings obtained indicate that the fabrics with higher thickness, higher density and small porosity rate possess better sound-absorbing performance. And the

[a]Corresponding author.
E-mail: ansn9119@126.com

spacer fabrics endow superior sound absorption properties as compared to the sponge fabrics with the same thickness. However, despite their excellent sound absorption properties and low-cost, the sound absorption materials used for above mentioned spacer fabrics cannot meet the end-use requirements of strength and stiffness. As a result, the spacer fabrics are usually draped with composite materials in the sound-absorption-use. In these circumstances, a series of multi-functional composites have been made based on textiles so that both the mechanical and acoustical functions can be achieved. Narang[7] filled the polyester fibres into the light walls made with sandwich composites, and the influence of material parameters such as mass/area, fibre type, crimpness, and fibre content on the sound transmission loss and absorption of a lightweight wall system has been discussed. Cao *et al.* [8] reported the acoustic properties of three-dimensional spacer fabric composites. It is found that the composites have excellent acoustic behaviors, especially for the middle sound frequency. The results show that the acoustic properties increase as the thickness and surface density increase, but decrease with the increasing of density of fabric spacer area. Fu *et al.*[9] made the composites with glass fabrics and PVC under normal pressure. The findings indicate that the composites can cut off the noise effectively in middle and low frequency. Gliscinska *et al.*[10] has investigated the sound absorption properties of thermoplastic nonwoven composites, each of which consists of needled nonwoven layers with various percentage of viscose (filling fibres) and PLA (matrix material). The results show that the percentage of filling fibres in the thermoplastic matrix positively influences the composites sound absorption. Lin *et al.*[11] fabricated the basic porous composites made of polyester nonwoven and low-melting polyester fibers. Then, the nonwoven was attached with polyurethane foam as composite planks for sound absorption applications. The finished composite planks were characterized for sound absorption behaviors to obtain the optimum sound absorption coefficient. Huang *et al.* [12] introduced a sound-absorbing nonwoven composite made by laminating the coconut fibre (CF) with 2D and 12D polyester nonwoven fabrics respectively. The experimental results reveal that the average sound absorption coefficient increases as the amount of CF increases. According to the published investigations, it can be found that most of the composites used for absorbing sound waves were nonwoven composites. This is attributed to the inbuilt advantages of nonwoven composites such as porous structure, light weight, bulky in nature and their versatility. However, it is difficult to produce the textured surface for nonwoven composites with an aesthetical appearance[13], and the mechanical responses of nonwoven composites do not meet the end-use application requirements[14-16]. It is also observed that the sound absorbency of nonwoven composites is only effective when the sound wave is below 1000 Hz, indicating that the range of their applications is limited[17-19]. Thus, nonwoven composites are usually draped with woven or knitted fabric reinforced composites in sound-absorbing end-use applications.

Many researchers have reported the acoustic properties of spacer fabrics and nonwoven composites, as mentioned above. However, none of studies focuses on the sound absorption behaviors of composites made with warp-knitted spacer fabrics [4-19]. In this study, the novel composites, composed of two porous materials [warp-knitted spacer fabrics (reinforced component) and flexible polyurethane foam (matrix)] have been developed for sound-absorbing applications. The sound absorption properties of composites are studied from the experimental results. With an attempt to discuss the effect of fabric structural parameters on the sound absorption properties of composites, a series of warp-knitted spacer fabrics with different structural parameters including inclination angle of spacer yarn, thickness, spacer yarn's diameter and surface layer structure have been produced. It is expected that a regular pattern for tailoring polyurethane-based warp-knitted spacer fabric composites with promising sound absorption properties could be obtained from this study.

2 Materials and Methods

2.1 Samples

2.1.1 Warp-knitted Spacer Fabrics

The warp-knitted spacer fabrics (WSF) were produced on a double-needle-bar Raschel warp knitting machine of E18. The PET monofilament of 0.2 mm and 0.16 mm in diameter were used as spacer yarns, and 300D/96F PET multifilament was used to knit the surface layers of fabrics. Four different structures, i.e. Locknit (L), Chain+Inlay (C), Rhombic Mesh (R) and Hexagonal Mesh (H) were involved for knitting surface layers. The chain notations for each

Table 1 — Chain notations for outer-layer structures

Structure	Chain notation
Locknit	GB1:1-0 0-0/ 3-2 3-3// fully threaded GB2:2-1 1-1/ 1-0 0-0// fully threaded GB5:0-0 2-1/ 1-1 1-0// fully threaded GB6:3-3 1-0/ 0-0 3-2// fully threaded
Chain+Inlay	GB1: 0-0 0-0/5-5 5-5// fully threaded GB2: 1-0 0-0/1-0 0-0// fully threaded GB5: 0-0 1-0/0-0 1-0// fully threaded GB6: 0-0 5-5/5-5 0-0// fully threaded
Rhombic mesh	GB1:1-0 0-0/1-2 2-2/2-3 3-3/2-1 1-1// 1 fully 1 empty threaded GB2:2-3 3-3/2-1 1-1/1-0 0-0/1-2 2-2// 1 fully 1 empty threaded GB5:1-0 1-0/0-0 1-2/2-2 2-3/3-3 2-1// 1 fully 1 empty threaded GB6:2-3 2-3/3-3 2-1/1-1 1-0/0-0 1-2// 1 fully 1 empty threaded
Hexagonal mesh	GB1: (1-0 3-3/3-2 1-1)×2/(1-0 3-3/3-2 4-4)/(5-4 3-3/3-2 4-4)×2/5-4 3-3/3-2 2-2// 2 empty 2 thread GB2: (5-4 3-3/3-2 4-4)×2/(5-4 3-3/3-2 1-1)/(1-0 3-3/3-2 1-1)×2/1-0 3-3/3-2 4-4// 2 empty 2 thread GB5: (1-1 1-0/3-3 3-2)×3/(4-4 5-4/3-3 3-2)×3// 2 empty 2 thread GB6: (4-4 5-4/3-3 3-2)×3/(1-1 1-0/3-3 3-2)×3// 2 empty 2 thread

Table 2 — Structural parameters of spacer yarns

Type	Diameter mm	Lapping movement
I	0.2	GB3:1-0 2-1/2-1 1-0// 1 full 1 empty GB4:2-1 1-0/1-0 2-1// 1 empty 1 full
II	0.2	GB3:1-0 3-2/3-2 1-0// 1 full 1 empty GB4:3-2 1-0/1-0 3-2// 1 empty 1 full
III	0.2	GB3:1-0 4-3/4-3 1-0// 1 full 1 empty GB4:4-3 1-0/1-0 4-3// 1 empty 1 full
IV	0.16	GB3:1-0 4-3/4-3 1-0// 1 full 1 empty GB4:4-3 1-0/1-0 4-3// 1 empty 1 full

outer layer structure are listed in Table 1. Four types of spacer yarns were used to connect the two outer layers with different inclination angles. The detailed parameters of spacer yarns are presented in Table 2. By considering different types of spacer yarns, different thickness and different outer layer structures, 9 warp-knitted spacer fabrics were produced. The structural parameters of the warp-knitted spacer fabrics are shown in Table 3

2.1.2 Preparation of Composites

Polyurethane-based warp-knitted spacer fabric composites (PWSF) were produced by impregnating the warp-knitted spacer fabrics with a flexible polyurethane foam, consisting of a mix of 1.21 g/cm^3 isocyanate and 0.78 g/cm^3 polyol, in a 100/43.7 polyol-isocyanate mixing ratio (by weight). The density, tensile modulus and elongation at break of polyurethane foam are 0.15 g/cm^3, 89.8 kPa and 147.5% respectively. The filling and foaming works were done in a mould at 23 ^{0}C. After foaming, all the specimens were placed for 72 h at 23 ^{0}C, until the foams were cured. The nine types of polyurethane-based composites produced are provided in Table 4.

2.2 Density Profile Tests

A compact X-RAY density profile analyzer (IMAL DPX300-LTE, Italy) was used to evaluate the density distribution of composites. The DPX300-LTE is a compact laboratory machine, used to supply the density profile of particle board, measured along the thickness. The samples may be of varying thickness and may be measured individually or in groups so as to highlight any particular differences in material distribution at various points on the same board (e. g. different distribution on the two sides of the same board). By a given scanning object, the X-RAY moved along the *x*-axis and the interval of the *x*-axis is 1 mm.

2.3 Sound Absorption Tests

The impedance tube for the transfer function method according to the standard ISO 10534-2-1998, which calculates the transfer function between the sound pressures, was employed to measure the sound absorption coefficient of composites. The instruments are made by BSWA Technology Co., Ltd. and the

Table 3 — Structural parameters of warp-knitted spacer fabrics

Sample	Thickness mm	Course-wise density w/5cm	Wale-wise density c/5cm	Surface layer structure	Spacer yarn
WSF1	7.57	34.95	28.25	C	I
WSF2	7.58	35.35	27.86	C	II
WSF3	7.62	34.17	28.2	C	III
WSF4	5.64	33.42	27.05	C	II
WSF5	10.62	35.12	28.05	C	II
WSF6	7.58	35.75	28.52	C	IV
WSF7	7.52	34.65	27.56	R	II
WSF8	7.62	35.32	29.18	H	II
WSF9	7.64	34.86	29.12	L	II

C–Chain+Inlay, R–Rhombic Mesh, H–Hexagonal Mesh and L–Locknit.

Table 4 — Details of polyurethane-based composites

Sample	Thickness mm	Fibre volume fraction, %	Density kg/m^3
PWSF1	8.68	7.63	270.4
PWSF2	8.74	7.33	266.3
PWSF3	8.72	6.32	249.7
PWSF4	6.68	8.91	284.1
PWSF5	11.58	7.59	246.7
PWSF6	8.46	6.57	250.3
PWSF7	8.76	6.42	252.1
PWSF8	8.82	2.25	249.2
PWSF9	8.86	8.25	284.1

experiment was conducted at 23 °C and 65% relative humidity according to the ISO 10534-2:1998 standard. The impedance tubes with diameters of 80 mm and 30 mm were used for measuring frequencies 100-800 Hz and 800-6300 Hz respectively.

3 Results and Discussion

3.1 Density Distribution of Composites

X-Ray density profile analyzer has been used to give an indirect measurement to investigate the density distribution of composites during the composite manufacturing process. The density distribution of composites is supposed to be even, keeping the fact that the density values in the spacer area are constant, while the density values in the top and bottom layers are nearly the same.

The density values of samples PWSF2, PWSF3, PWSF7 and PWSF9 are chosen as the representative of nine samples, are presented in Fig.1. The beginning thickness value ～0-1.5 mm and the end thickness value ～7.5-8.5 mm of the curves, representing the density values in top and bottom layers of composites respectively, while the middle of curves (thickness value ～1.5-7.5 mm) reflects the density values in spacer area of composites. It can be seen that the density values in surface layers are higher as compared to the density values in the spacer area.

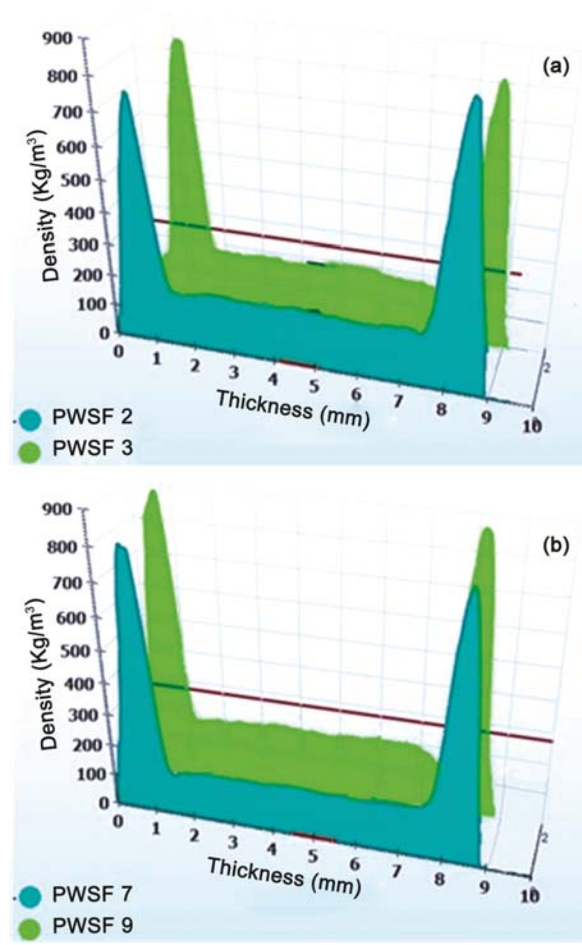

Fig. 1 — Density profile of composites (a) the density distribution of PWSF2 and PWSF3, and (b) the density distribution of PWSF7 and PWSF9

This is because the density values in the outer layers of spacer fabrics are higher, compared to the density values in the spacer area of spacer fabrics. However, it is obviously observed that the density values in the spacer area are nearly constant along thickness direction, indicating that the distribution of polyurethane foam is uniform in the spacer area of composites. Additionally, the density values in top and bottom layers of composites are also very close. All the results significantly demonstrate that the density is fairly well-distributed in composites.

3.2 Sound Absorption Behavior of Composites

3.2.1 Effect of Spacer Yarn Inclination Angle

The spacer yarn inclination angle is defined as the angle between spacer yarns and outer layers. It depends on the number of needles underlapped by spacer yarns between front- and back-needle bars. In order to investigate the effect of inclination angle on the sound absorption behaviors of composites, three composite samples (PWSF1, PWSF2 and PWSF3) with different spacer yarn's numbers of needles underlapped, such as 1-0/2-1, 1-0/3-2, and 1-0/4-3, have been employed for comparison study. At the same time, the other parameters of composites are kept the same. It can be concluded that the inclination angle decreases as the number of needles underlapped by spacer yarns increases[5,6]. The sequence of the inclination angle for the samples is PWSF1＞PWSF2＞PWSF3.

The relationship between frequency and absorption coefficient at different spacer yarn inclination angles is shown in Fig.2. It can be seen that the absorption coefficient changes with the change in spacer yarn inclination angle and each composite has its certain sound absorption properties at different frequencies and the difference is great. At lower frequency of less than ～1000 Hz, sample PWSF3 has the highest coefficient. However, after this frequency, at frequency range 1000—3000 Hz, the performance of sample PWSF1 is the inverse of sample PWSF3. When the frequency moves to a higher level i.e. more than 3000 Hz, the sound absorbing coefficient of PWSF3 is the highest, whereas sample PWSF1 has the lowest coefficient. Sample PWSF2 exhibits moderate performance in all the conditions. Furthermore, the resonance frequencies (peak absorption) of composites shift towards to the higher frequency region with a decrease in inclination angle, leading to an increase of sound absorption for the composites with smaller inclination angle at higher frequency. The analysis implies that the composites with different spacer yarn inclination angles have their own frequency range of applications.

The above phenomena can be best illustrated by the fact that when the sound waves reach the internal

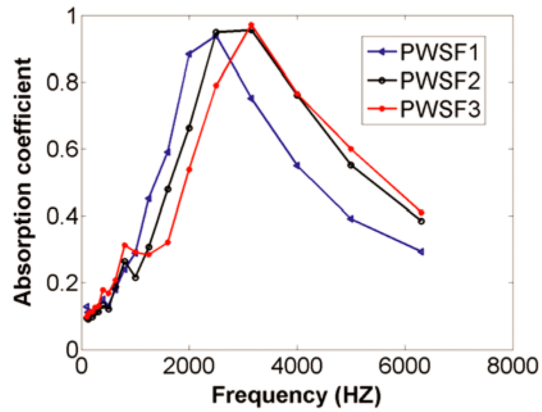

Fig. 2 — Sound absorption coefficient for different inclination angles of composites

part of composites, the paths of scattering, reflection and refraction of the sound waves are different due to the different lapping movements of spacer yarn, resulting in varied dissipation degree of sound waves.

3.2.2 Effect of Diameter of Spacer Yarn

To investigate the influence of spacer yarn diameter on the sound absorption behaviors, two samples (PWSF3 and PWSF6) with the same lapping movement of spacer yarn, but with different spacer yarns diameters (0.2 mm and 0.16 mm), have been used. These two samples also have the similar thickness and their outer layer densities are also very close.

Figure 3 shows the acoustical performances of these two samples. It is realized that these two samples exhibit different sound absorption behaviors. Composite made with coarser spacer yarn exhibits lower sound absorption coefficient as compared to composite made with finer spacer yarn when the frequency is less than ～800 Hz. However, after this frequency, composite made of finer spacer yarn has better performance on sound absorption properties. When the frequency is higher than ～3000 Hz, it is clearly seen that the sound absorbing behavior of these two samples is comparable to each other, except a slight increase in absorption coefficient for composite with finer spacer yarn. This indicates that the sound absorption properties of composites show little dependence on the diameter of spacer yarn at high frequency range.

The difference in sound absorbability of these two samples can be explained as follow. The propagation path and energy consumption of sound waves will be

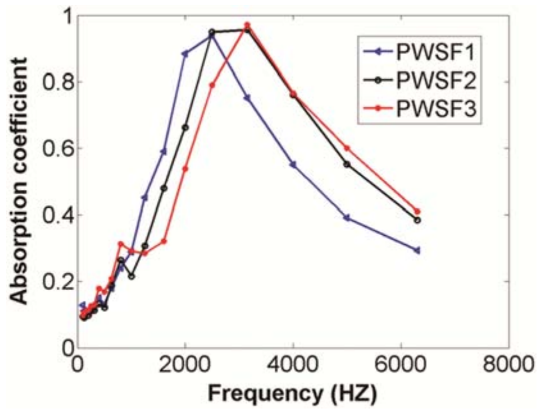

Fig. 3 — Sound absorption coefficient for different spacer yarn's diameter of composites

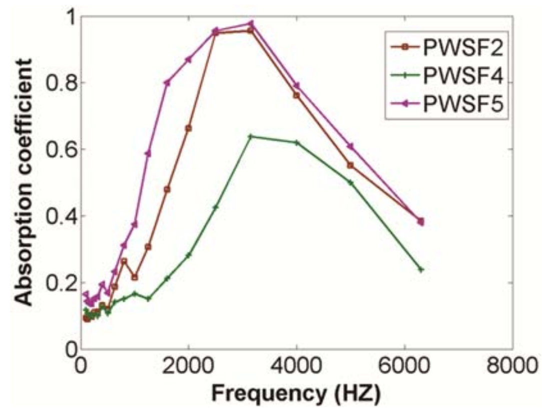

Fig. 4 — Sound absorption coefficient for different thickness of composites

changed with the changes of apparent density of the composites. In this section, the composites with different diameter of spacer yarn will lead to the difference in fibre volume fraction, resulting in the different apparent density of composites. Thus, the composites with different spacer yarn diameters exhibit varied sound-absorbing performance.

3.2.3 Effect of Thickness

Three samples (PWSF2, PWSF4 and PWSF5) with the same type of spacer yarn and surface layer density and different thicknesses are used.

Figure 4 shows that the sound absorbing coefficient increases with increasing the thickness of samples. The findings obtained show great agreement with the published results[20,21]; the thicker the material, the better is the sound absorption properties. It is clear that the sound absorbing coefficient can be improved by increasing the thickness of composites which increases the sound transmission path, resulting in the increase of frictional losses and dampened sound energy. However, it should be noted that the effect of increasing thickness to improve the sound absorption coefficient for sample PWSF2 and sample PWSF5 is not very significant, since the sound absorption coefficient will no longer increase after the thickness reaches a critical value. Therefore, the critical thickness can be used as the limiting factor when the composites are selected for sound absorption applications.

3.2.4 Effect of Surface Structure of Spacer Fabric

The distribution, binding condition and spacer yarn inclination angle are influenced by the outer layer structure of spacer fabric since the monofilaments in the spacer area are bound by multifilament loops in the outer layer [22]. In this section, four wide-used composites (PWSF2, PWSF7, PWSF8 and PWSF9) with different outer layer structures, i.e. Chain+Inlay, Rhombic mesh, Hexagonal mesh and Locknit are used to study the effect of fabric surface structure on the sound absorption properties of composites. These samples have the same number of underlapped needles for spacer yarns and nearly the same thickness. It has been known that the surface layer structures could slightly influence the outer layer density and inclination angle of spacer yarn, although these parameters are kept constant during the knitting process.

The sound coefficient diagram (Fig.5) indicates that composites made of different surface layer structures exhibit different sound absorption properties. It can be found that the composite with closer outer layer structure has higher sound absorbing coefficient than that of the composite made with opener surface layer structure at the frequency less than about 3000 Hz. However, their sound absorption coefficients reverse in case of the frequency higher than 3000 Hz. Composite with Rhombic in outer layer structure exhibits the highest sound absorption coefficient. In addition, the opener outer layer structure moves the resonance frequency (peaks absorption) towards higher frequency range, resulting in an increase of sound absorption at higher frequency for this composite.

One reason for the above results may be the different surface layer structures which results in different degree of internal friction between fibres and polyurethane foam. The other reason is the fact that the composites made with different outer layer structure possess different apparent density, which may also lead to the difference in sound absorbing behavior.

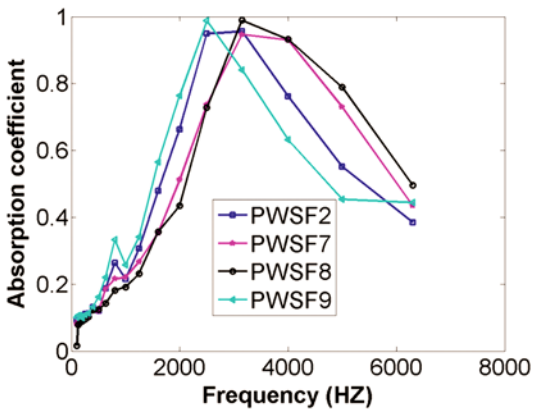

Fig. 5 — Sound absorption coefficient for different surface structure of composites

3.3 Comparison among Composites, Warp-knitted Spacer Fabrics and Polyurethane Foam

In order to compare the sound absorption behavior of composites, polyurethane foam and warp-knitted spacer fabrics, three warp-knitted spacer fabrics (WSF1, WSF5 and WSF6) and a fabric-free polyurethane foam panel with 10 mm in thickness are employed to characterize the sound absorption properties. The comparison results are presented in Fig.6. It is evident that no obvious resonance phenomena can be observed for spacer fabrics. Furthermore, the spacer fabrics show different sound absorption responses when compared to the composites and polyurethane foam. This is due to different internal structures of composites, polyurethane foam and spacer fabrics as a result of the changes of mechanism of sound absorbing process. On the other hand, the polyurethane foam has better sound absorbability than spacer fabrics, but poorer sound absorption abilities than composites. It moves the resonance frequency towards higher frequency range and results in a decrease of sound absorption at lower frequency, as compared to the composites. All the results imply that the composites endow the superior sound absorption abilities, compared to polyurethane foam and spacer fabrics. The reason can be explained by three facts, namely (i) the composites increase the frictional resistance between sound waves and materials, leading to more energy dispersion of sound waves; (ii) the composites make sound wave vibrations in air to transfer into material vibrations more easily since the internal structure of composites is more irregular and loose than that of polyurethane foam, and hence the composites can convert acoustical energy into mechanical energy more efficiently, leading to more dissipation of sound energy; and (iii) air compression and sound waves expansion might occur not only between the fibres and the polyurethane foam but also in the volume and cavities obtained during the process of composite manufacturing, resulting in further dissipation of acoustical energy.

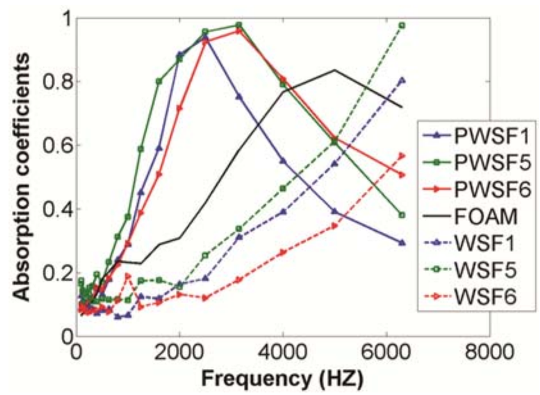

Fig. 6 — Sound absorption coefficient for composites, fabrics and polyurethane foam

4 Conclusion

The acoustical properties of polyurethane-based warp-knitted spacer fabric composites have been evaluated in the frequencies range 100—6300 Hz. Findings show that the composites possess promising acoustical damping performance due to their special structure, especially at the sound wave frequency lower than 3000 Hz. Furthermore, the sound absorption properties of composites are significantly affected by the fabric structural parameters, indicating that the variation of fabric structural parameters could be an approach to adjust the sound absorption properties of composites to meet the specific end-use applications. All the findings would offer helpful references on the structural parameters optimization and properties analysis of the polyurethane-based warp-knitted spacer fabric composites.

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