

Optimization Analysis of Sound Insulation Performance of Carbon Fiber Composite Structure

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Abstract

Carbon fiber composite structure is gradually applied to rail vehicles due to its light structure and high rigidity. Because the sound insulation performance of this structure is not as good as that of the aluminum alloy structure, using this structure will result in an increase in noise inside the vehicle. In this paper, the carbon fiber sandwich plate was taken as the research object and the original structure was optimized through different methods such as optimizing the skin thickness, changing the density of the sandwich foam and increasing the structural damping. The different effects were evaluated through simulation calculations. And different experimental samples were made and tested to evaluate the final sound transmission loss. The results will provide an effective reference for the optimal design of the structure.

Keywords

Carbon Fiber Composite Structure, Sound Transmission Loss, Simulation, Test

1. Introduction

The increase of train running speed and operating mileage puts forward new requirements for the energy conservation and environmental protection performance of trains that cause the structural lightweight design of vehicles to gradually become the research focus. Due to the high specific strength, specific modulus, low density, high temperature resistance, corrosion resistance and other characteristics, carbon fiber materials have been gradually being applied to different fields such as rail vehicles, automobiles, and aircraft [1]. However, with the increase of the speed, the sound pressure level of the wheel-rail noise also increases,

and the impact of the wheel-rail noise on the interior noise becomes more outstanding, so it is necessary to improve the sound transmission loss (STL) of the car body to have a better control of the interior noise. Compared with the traditional structures made with aluminum and steel materials, due to the reduction in mass, the carbon fiber composite plate is more easily excited to produce vibration and the sound insulation of the plate is much lower than that of other structures, which will result in the interior noise of the vehicle easy to exceed the limits and will seriously influence the ride comfort during the operation.

Therefore, the research on the STL of panels, especially the double-layer composite structures, has become a focus. Fan Yuling, Wang Mingqing conducted an analysis of the sound insulation performance of composite panels [2]. Cui Chengxun conducted experimental research on the sound insulation amount of double-layer lightweight panel structures [3]. Sun Yan, Wang Hongzhen analyzed and studied the transmission performance of double-layer panels [4]. For carbon fiber structures, due to the unique characteristics, it is of great research significance to take effective methods to improve the STL of the panels while ensuring the weight advantage. In this paper, the sandwich composite plate structure with carbon fiber skin on both sides and foam filling inside is taken as the research object and will be optimized the thickness of the skin, the density of the foam, the damping performance of the structure and the sound insulation optimization effect will be evaluated and analyzed through simulation and test to determine the effective method, which will provide a reference for the design of the structure.

2. Sound Transmission Loss of the Original Structure

For the STL analysis of composite panels, it can refer to the sound insulation theory of single layer panels. The STL curve is mainly divided into four main areas that are stiffness control area, damping control area, quality control area and fitting effect area [5].

Assume that the impedance of the air is R_1 , the thickness of the skin of the composite plate is d , the impedance of the skin is R_2 , the thickness of the foam layer in the middle is L , and the impedance of the foam is R_3 . When the transmitted sound wave P_t in a plane sound wave P_i passes through the skin and enters the middle foam layer, due to the change of the impedance, a part of it will be reflected and finally enters the air and becomes the reflected wave. This part consists of the sound reflected back from the middle foam layer and the sound reflected back through the skin. Another part of the sound wave will penetrate into the middle foam layer, when this part of the sound wave reaches the next skin layer, it will be reflected and transmitted again and some of the sound will pass through the skin and into the air to become the transmitted sound P_t finally, as shown in **Figure 1**.

The thickness of the original structure skin is 2.5 mm and the middle foam is 55 mm. The STL test was carried out according to the "ISO 140-3 Acoustic insulation measurement of buildings and building components Part 3: Laboratory

Measurement of Air sound Insulation of Building Components". The STL was tested in the reverberation acoustic laboratory and the frequency band is 100-5000Hz. The test method is as follows: first to install the test sample on the test window between the two reverberation rooms, and second to compact it with a wooden frame around it and then plug the gap of the sample with plasticine. There are five microphones placed in each reverberation room and the sound pressure level of the sound source room and the receive room will be test by the microphones, and the STL is calculated according to formula (1).

$$R_w = L_S - L_R + 10 \log(S/A_R) \quad (1)$$

where, R_w is STL, in decibels; L_S is average sound pressure level in the sound source room, in decibels; L_R is average sound pressure level in the receiving room, in decibels; S is the area of test specimen, in square metres; A_R is sound absorption quantity in the receiving room, in square metres. The test photo is shown in **Figure 2** and the test result is shown in **Figure 3**.

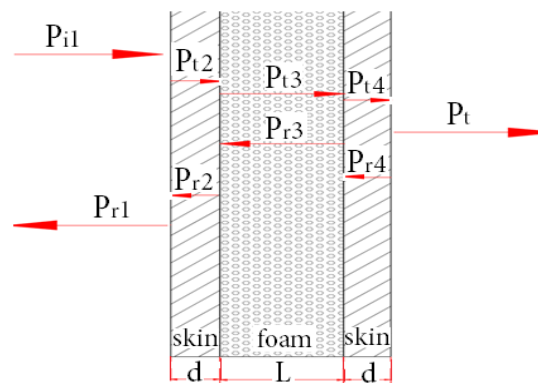


Figure 1. The Sound transmission loss schematic of the sandwich plate.

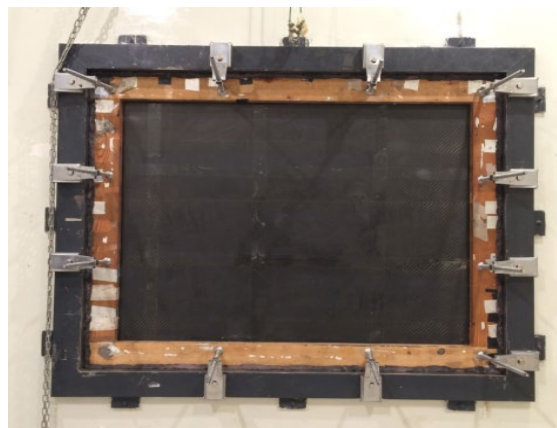


Figure 2. The photo of the STL test.

As shown in **Figure 3**, it can be seen that although the total thickness of the carbon fiber plate is 60 mm, the sound transmission loss (STL) of the carbon fiber plate is only 25 dB, while the STL of the aluminum alloy structure with the same thickness is 32 dB. Due to the relatively large stiffness, the carbon fiber composite

plate has a high STL in the stiffness control area in the low frequency band. With the increase in the frequency, the STL curve begins to decline. When the frequency in the damping control area, the STL curve has multiple troughs, but on the whole, it shows an upward trend. The carbon fiber composite plate has a light weight which caused the STL in the quality control area to be relatively poor which result in the sound insulation effect of the plate can't meet the sound transmission loss requirement of the car body. Therefore, it is necessary to improve the sound insulation capacity of the structure through effective methods on the premise of not obvious weight increase.

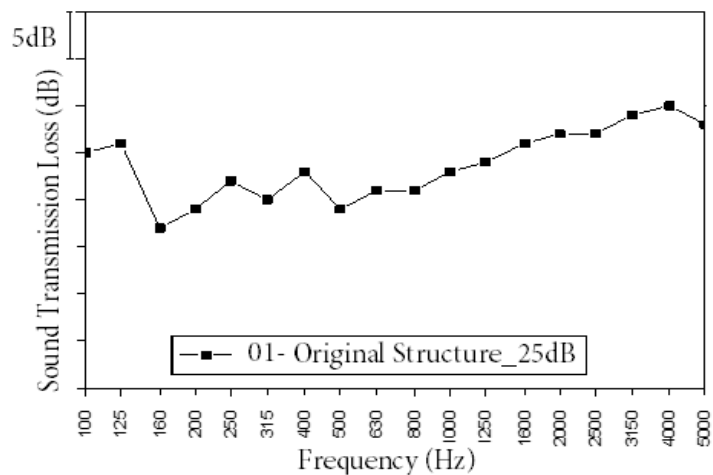


Figure 3. The STL curve of the original structure.

3. Simulation Evaluation of the Optimization Structure

According to the relevant theoretical analysis of the sound insulation principle, in the low frequency area, improving the stiffness and damping performance of the plate will be useful to improve the STL of the plate. In the medium and high frequency area, especially in the quality control area, improving the quality can improve the STL. Therefore, according to the characteristics of the carbon fiber composite plate, the thickness of the skin, the density of the foam, the whole damping of the structure will be optimized to increase the STL. In order to reduce the cost of the tests, it is necessary to establish a simulation model to simulate and analyze the different methods to determine which one is the effective optimization scheme.

In this paper, the influence factors will be simulated by VAone acoustic simulation software based on the statistical energy analysis (SEA) method. Because the statistical energy analysis (SEA) method is based on the mode density to simplify the complex system, the analysis of the energy transfer and balance between subsystems is based on the statistical methods, the coupling of sound field and structure can be calculated very quickly. In the simulation model, the sound source room, carbon fiber composite plate and the receiving room are established, as shown in **Figure 4**. The carbon fiber composite plate is modeled by multilayer

plate structure. The material-related parameters, structural damping and the environmental parameters of sound generating chamber and receiving chamber are set. The STL curve of the original structure is calculated and compared with the test result to verify the effectiveness of the model. The results are shown in **Figure 5**.

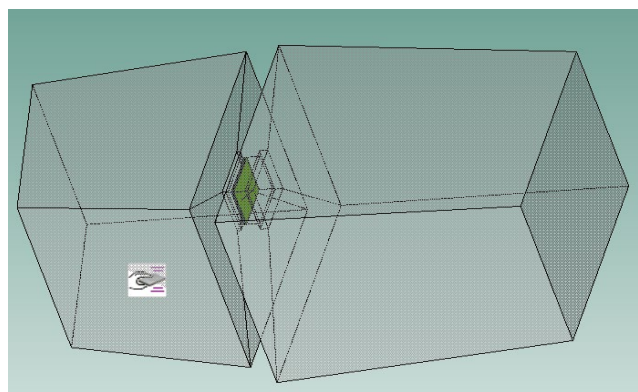


Figure 4. The simulation model of the STL.

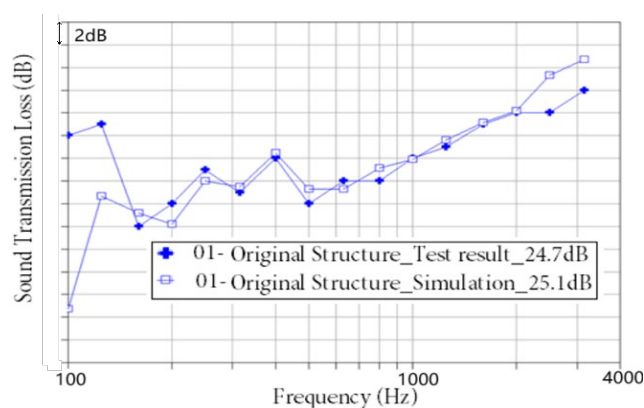


Figure 5. Simulation and test result curves.

According to the results in **Figure 5**, the simulation results are consistent with the experimental results on the whole, especially in the frequency band above 200Hz. Although there are some deviations between the simulation model and the actual constraints in the laboratory which caused some deviations in the low frequency band below 160Hz, from the overall view, the accuracy of the model meets the simulation requirements, so that the simulation model can be used to analyze the improvement effect of different structural optimization schemes.

The improvement effect of the optimization of skin thickness on the STL was first analyzed, and then the optimization analysis of foam density was carried out. Based on the original structure, on the premise that the thickness and density of the foam layer remain unchanged, the thickness of the skin was gradually increased and named with No. 02~05. Based on the original structure, on the premise that the thickness of the skin and the thickness of the foam remain unchanged, the density of the foam is gradually increased and named with No.06~09. The STL

of the different structures were calculated respectively, the results are shown in **Table 1**, the STL curves are shown in **Figure 6** and **Figure 7**.

Table 1. Different structures and corresponding calculation results.

Number	skin mm	density kg/m ³	Total thickness mm	mass kg	STL dB
01-Original structure	2.5	60	60	20.1	24.7
02-Optimized skin	2.8	60	60.6	20.6	25.1
03-Optimized skin	3.0	60	61	21.1	25.5
04-Optimized skin	3.2	60	61.4	21.6	26
05-Optimized skin	3.5	60	62	22.1	26.6
06-Optimized foam	2.5	65	60	20.5	25.1
07-Optimized foam	2.5	70	60	20.9	25.3
08-Optimized foam	2.5	75	60	21.3	25.6
09-Optimized foam	2.5	80	60	21.6	25.9

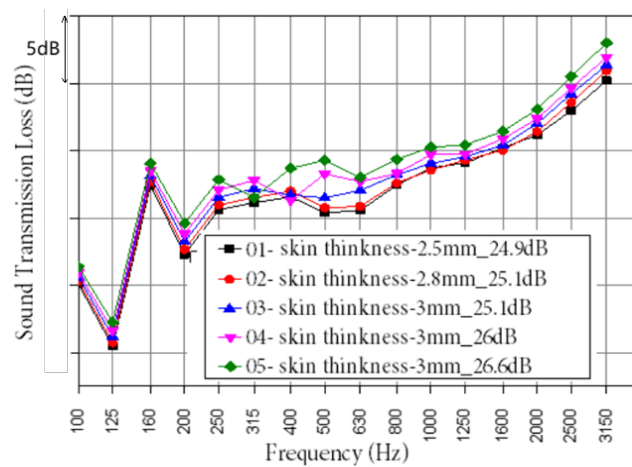


Figure 6. Simulation results of different skin.

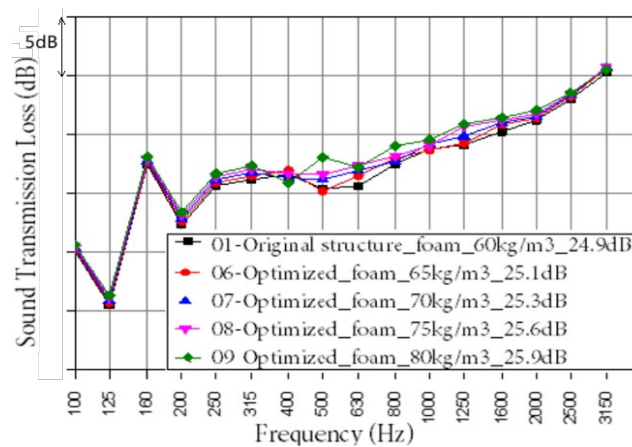


Figure 7. Simulation results of different foam.

It can be seen from **Figure 6** that the STL of the plate increases with the skin thickness increases, mainly in the frequency band above 200 Hz, which shows an overall upward shift. As shown in **Figure 7**, when the density of foam is increased, the STL of the plate also increases, mainly in the frequency band between 200 - 2500 Hz while the increase in the frequency band above 2500 Hz is not obvious. When increases the skin thickness, the relationship between the STL and the mass of the plate is referenced as Equation 2. When increases the density of foam, the relationship between the STL and the mass of the plate is referenced as Equation 3. It can be seen that it will be more useful to increase the density of skin rather than the density of foam, as shown in **Figure 8**. Considering the influence of the actual process, there is a deviation between the theoretical thickness of the adhesive layer and the actual thickness of the product. In this paper, based on the thickness of the model remains unchanged, the damping loss factor of the original structure is improved by more than 30% on the whole, and compares the different STL of the plate with different damping. The results are increased 3 dB with high damping, as shown in **Figure 9**.

$$y = 0.1532x^2 - 5.7346x + 78.25 \tag{2}$$

$$y = 0.0123x^2 - 0.1264x + 22.434 \tag{3}$$

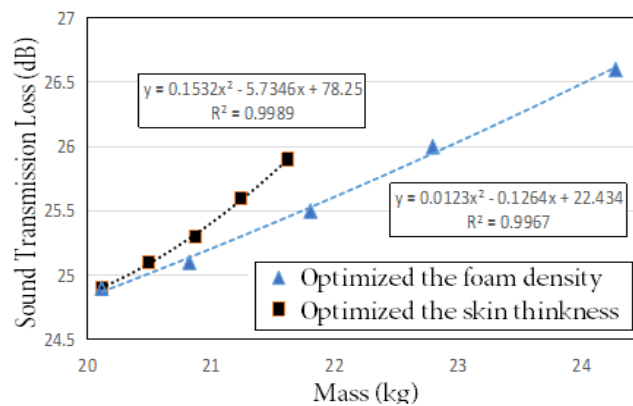


Figure 8. The relationship between STL and the mass.

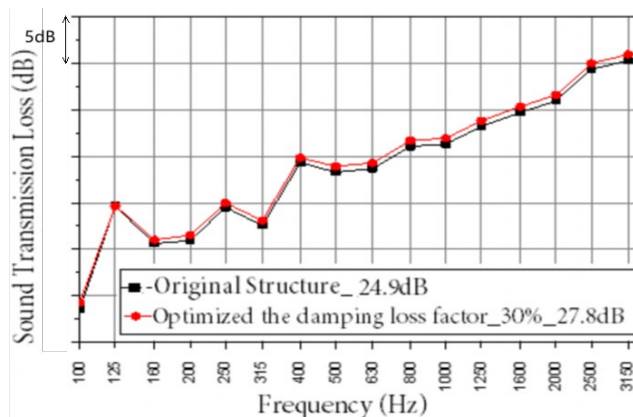


Figure 9. The simulation results of different damping.

4. Test of the Optimization Structures

According to the simulation results in the second part, it can be seen that increasing the thickness of the skin, the density of the foam and the damping performance of the structure can have an effective effect on the STL. In order to verify the simulation results, different test plates have been made for the STL test. The plate named S01 is a composite plate with optimized skin thickness based on the original structure named 01, the plate named S02 is a composite plate with optimized foam density based on the original structure 01, and S03 is composite plate with 3 mm new damping material sprayed on the skin of the original structure 01. The test plates were installed on the laboratory window respectively and were tested according to the method described in “ISO 140-3:1995 Acoustic-Measurement of sound insulation in buildings and of building elements -Part 3: Laboratory measurements of airborne sound insulation of building elements” to verify the effect of the different optimization methods. The test photos are shown in **Figure 10**. According to the test results, compared with the original structure, the STL can be improved about 1.3 dB by the increase the thickness of the skin and the STL can be improved about 0.9 dB by the optimization of foam density. The increased frequency band mainly in the band above 315 Hz. While the STL can be improved about 2.4 dB by optimized the damping performance of the structure which has better effect than other optimizations. The test results are shown in **Table 2**, the test photo is shown in **Figure 10** and the STL curves are shown in **Figure 11**.

Table 2. Test results of different optimized structures.

Number	skin mm	density kg/m ³	Total thickness mm	mass kg	STL dB
01-original structure	2.5	60	60	20.1	24.7
S01-Optimized skin	3.5	60	62	23	26
S02-Optimized foam	2.5	75	60	25.2	25.6
S03-Optimized damping	2.5	75	63	24	27.1

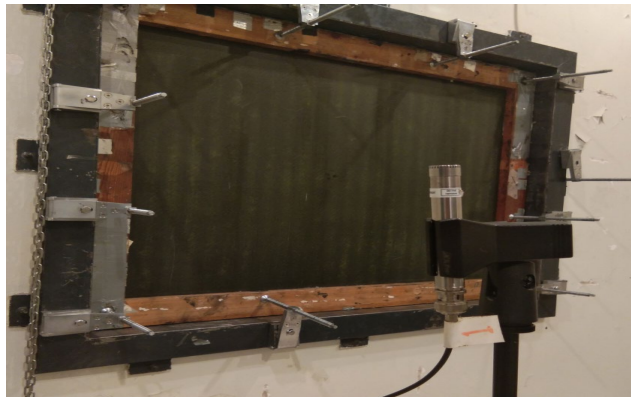


Figure 10. Photo of the sound transmission loss test.

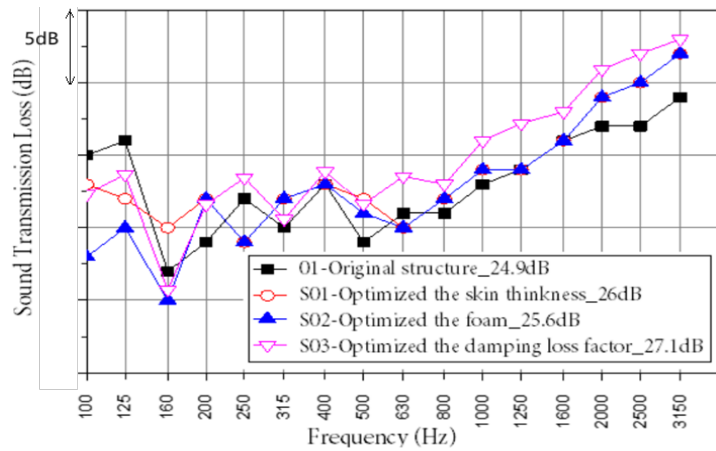


Figure 11. The test results of the different plates.

In order to analyze the effect of the method to pasted damping paint on the structural, the structural damping of the original structure and the plate with damping paint have been tested using the hammer excitation method. The vibration sensor was arranged on the plate surface to test the vibration instantaneous time T60 of the plate after the hammer excitation and the damping is calculated according to [7]. The structural damping test photo is shown in Figure 12. As is shown in Figure 13, the structural damping loss factor of the structure with 3 mm



Figure 12. Photo of the damping test.

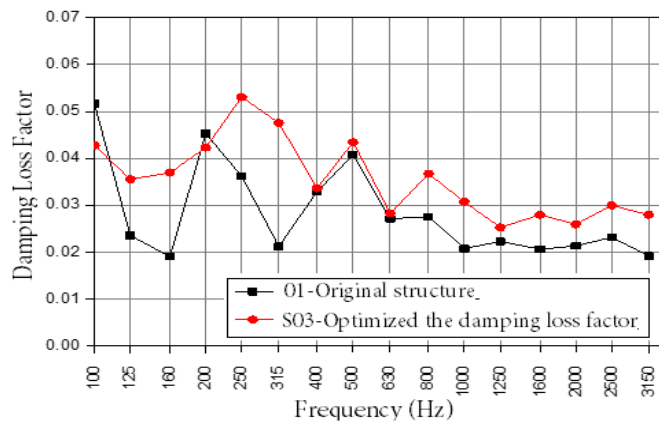


Figure 13. The damping loss factor test result.

damping paint is greatly increased compared with the original structure. The increased frequency band mainly in the band below 500 Hz. The overall increase effect is 20% - 30% eliminating the influence of experimental test error. For the high frequency band, the damping performance is improved but the overall effect is still small due to the small damping loss factor of the original structure.

The damping paint has two main influence on the increase of the STL, the first one is the improvement of the STL in the low frequency band, the second one is that it caused the increase of the mass that leads to the improves of the STL in the quality control area which is coincide with the mass law.

5. Final Comments and Conclusions

Based on the combination of experiment and simulation, we have analyzed the affect of the optimization of the thickness of the skin, the foam density and the structural damping on the STL of the carbon fiber composite plate. The main conclusions are as follows:

(1) Increasing the thickness of the skin of carbon fiber composite structure and the foam density can improve the sound insulation performance. On the premise of increasing the mass per unit, increasing the skin thickness has a better effect on the improvement of STL than improving the foam density.

(2) Damping paint paste on the surface of the structure can effectively increase the damping of the structure and improve the STL of the structure. The reason is that the damping paint improves both the damping performance of the structure and the quality of the structure as the damping paint itself has a certain mass, which will increase the STL of the damping control area and the quality control area.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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