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RESEARCH ARTICLE

Xiaojun DENG, Yanju ZHAO, Haijin ZHANG, Renzhong SHUAI, Leiwei ZHU

Design of noise-reduction seats for high-speed trains

Abstract Noise-reduction seats have been successfully used in concert halls, theaters, and other places that reduce noise. In this study, a new noise-reduction seat design was proposed for high-speed trains, which have unique interior noise spectral characteristics. First, before the noise-reduction seat models were fabricated, the parameters of high-performance sound-absorbing materials and perforated plates were selected by conducting a standing-wave tube test. The sound-absorption effects of the noise-reduction seats and normal seats were investigated and compared in a reverberation chamber. Test results showed that, compared with normal seats, the noise-reduction seats obtained a significantly improved sound-absorption coefficient in the entire frequency band. Furthermore, the test results were used to establish a simulation model for calculation, and the simulation results proved that the noise-reduction seats substantially reduced the noise in an entire train car. Finally, the noise-reduction seats were fabricated and installed in a full train car of an actual high-speed train. The test results showed that, compared with the normal seats, the noise-reduction seats decreased the noise level at a standard point in the passenger car by 1.5 dB. Therefore, the noise-reduction seats are effective in noise reduction.

Keywords high-speed train, sound-absorbing materials, perforated board, noise-reduction seats

1 Introduction

Passenger comfort requires more attention with the rapid development of high-speed trains. Interior noise level is an important index in vehicle performance evaluation [1,2]. A high-speed train provides an airtight space. Its interior noise consists of the direct noise due to the train structure itself and reverberant noise. Improving train damping or using sound-insulating materials can reduce direct sound. However, sound insulation design does not apply to reverberant sound reduction. By contrast, sound-absorbing structures that can absorb the reverberant sound and consequently reduce the noise can be integrated in a train. As a developing design, which combines ergonomics and acoustics, sound-absorbing seats can absorb interior noise without adding extra weight or occupying extra space while maintaining stable and reliable sound-absorption efficiency; the seats can absorb a wide range of noise frequencies and work particularly well in absorbing low- and medium-frequency sounds [3,4]. Currently, sound-absorbing seats are widely used in concert halls, opera houses, meeting rooms, and places with strict noise limits. An experiment comparing the reverberation time in a room before and after seat installation showed that the seats absorbed 30%–50% of the gross sound volume of the entire hall, proving that the seats significantly reduced noise and improved sound quality [4]. However, only few studies on sound-absorbing seats in high-speed trains have been conducted. Thus, in this study, sound-absorbing seats are designed to absorb the reverberant sound in high-speed trains and reduce interior noise on the basis of the successful application of sound-absorbing seats in music halls, opera houses, and similar places. The seat models were tested in a laboratory and subsequently in an actual train to validate the laboratory results.

2 Design of the sound-absorbing seat

The proposed seat for a high-speed train mainly consisted of a cushion, backrest, support structure, fireproof plate. The cushion and backrest were filled with elastic materials. A specialized acoustic design was applied to the limited contact area between the seat and air to improve the sound-absorption effect of the seat. Elastic sound-absorbing materials were used for the backrest and the cushion in contact with people to improve the absorption performance of the backrest while ensuring its elasticity and fireproof

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Xiaojun DENG, Yanju ZHAO (✉), Haijin ZHANG, Renzhong SHUAI, Leiwei ZHU
CRRC Qingdao Sifang Locomotive and Rolling Stock Co. Ltd-2, Qingdao 266111, China
E-mail: zhaoyanju@cqsf.com

capability. The outer part of the backrest was also made of a sound-absorbing material to enlarge the absorption area of the entire seat and improve the absorption effect. Perforated sound-absorbing boards were used for the backrest plate, cushion support plate, and fireproof plate, and their parameters were set on the basis of the absorption bands to improve the sound-absorption performance further.

2.1 Preliminary studies on the properties of sound-absorbing materials and structure

For the selection of the material that can provide optimal sound-absorption effect, polyurethane foam and melamine material, both with 50 mm thickness, were tested, and their absorption coefficients were measured. The polyurethane foam had a higher absorption coefficient in the low-frequency range (200–600 Hz), whereas the absorption performance of the melamine material is better in the 700–1100 Hz frequency range. Studies on the properties of the layer structure of the sound-absorbing material, seat cover, and flame retardant adhesive are essential to ensure that the materials are fireproof and applicable. Additional sound-absorption tests were performed on different layer structures with different combinations of sound-absorbing material, adhesive, and cover to verify the advantages of these structures. Polyurethane foam, which by itself performed well in sound absorption, also performed well compared with other elastic sound-absorbing materials. The performance of the melamine in absorbing sound improved in the entire frequency range because the flame retardant adhesive and the seat cover increased the absorption coefficient of the melamine.

The sound-absorption mechanism of the perforated plate is that each perforation in the plate and its corresponding air layer or the sponge material with small holes work together as a system similar to a Helmholtz resonator. The resonant sound-absorbing structure of the perforated plate can be viewed as a parallel connection of several Helmholtz resonance absorbers with high efficiency in sound absorption. Several perforated plate designs were considered, and the sound-absorption coefficients were calculated using a formula based on the mechanism given mechanism [5,6]. The sound-absorption performances of the perforated aluminum plates of various thicknesses, apertures, and perforation rates were tested in a standing-wave tube. The results show that different apertures and perforation rates lead to different absorption bands. The absorption band shifts to low frequency when the plate is thick. A small aperture leads to a high absorption coefficient and a wide absorption band, which shifts to the low frequency. The main contributors to the interior noise in high-speed trains are in the mid- and low-frequency range of 200–800 Hz. A perforated plate with 1 mm thickness, 1 mm aperture, and 3.14% perforation rate and another with 1.4 mm thickness, 5 mm aperture, and 1% perforation rate both exhibited high absorption coefficients in the frequency range of 200–800 Hz. Therefore, these two types of plates were selected and applied to the sound-absorbing seat design.

2.2 Structural design of the sound-absorbing seat

The high-speed train seat mainly consisted of a cushion, backrest, support structure, chassis protective plate, and fireproof plate. The cushion and backrest were filled with elastic materials. On the basis of structural properties of the seat and the results of the tests on different sound-absorbing materials and perforated plates, the design details of the sound-absorbing seats (Fig. 1) were as follows:

1) The area of the backrest riveted support plate was large, and the contribution of the backrest support plate to the noise absorption in the passenger section was more substantial than those of the other parts. Thus, the aluminum backrest support plate was a perforated plate

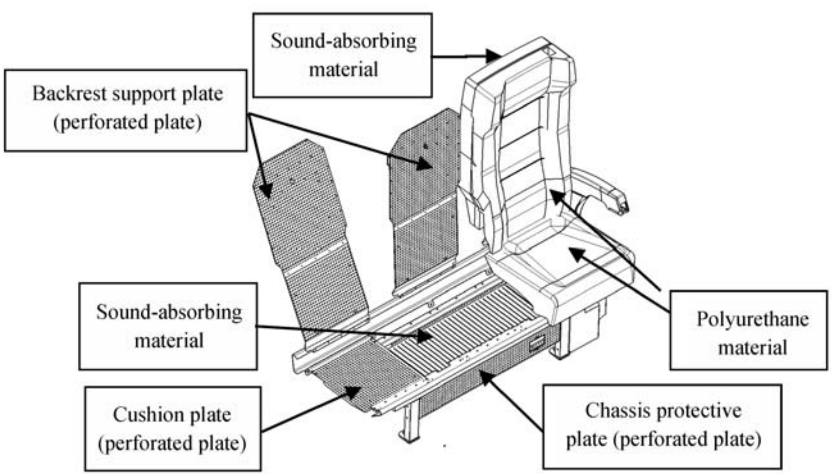

Fig. 1 Design scheme of the sound-absorbing seat

with 1.4 mm thickness, 5 mm aperture, and 1% perforation rate. This design would aid in absorbing high-frequency noise.

2) Elastic polyurethane foam was selected for the backrest and cushion, and a melamine sound-absorbing material with 50 mm thickness adheres to the backrest perforated plate. Both can enlarge the absorption area of the seat. As a result, the seat absorbs the interior noise, and the perforated plate forms a Helmholtz resonator structure to enhance absorption effect.

3) The cushion was designed with a perforated plate with 1.4 mm thickness, 5 mm aperture, and 1% perforation rate, and melamine sound-absorbing materials were mounted beneath the cushion.

4) The protective panel and baseplate were designed with a perforated plate with 1 mm thickness, 1 mm aperture, and 3.14% perforation rate to absorb the low-frequency noise coming from the train floor.

3 Sound-absorption test in the laboratory

Seat models based on the sound-absorbing seat design were fabricated, and the reverberation chamber method was employed in the sound-absorption test [7–9]. The volume of the chamber was 227 m^3. The frequency of the sound resource was 50–5000 Hz, and its power level was 122 dB. For comparison, 15 sound-absorbing seats and 15 normal seats were arranged in 3 rows in the reverberation room in accordance with the current train seat arrangement. The sound-absorbing coefficient of each seat type was tested, as shown in Fig. 2.

Fig. 2 Absorption coefficient test of the sound-absorbing seats

The gross volume of the absorbed sound before seat installation in the reverberation chamber, can be represented by, A_1, which is calculated as follows by using the Sabine formula:

$$A_1 = \frac{55.3V}{c_1 T_1} + 4m_1 V. \quad (1)$$

The gross volume of the absorbed sound after seat installation can be represented by

$$A_2 = \frac{55.3V}{c_2 T_2} + 4m_2 V. \quad (2)$$

In Eqs. (1) and (2), T_1 and T_2 stand for the reverberation time of the empty room and that of the room equipped with seats, respectively; V is the volume in m^3 of the reverberation chamber; c_1 and c_2 stand for the sound velocities in m/s of the empty room and the room equipped with sound-absorbing materials, respectively; and m_1 and m_2 stand for the air absorption attenuation coefficients of the empty room and the room equipped with absorption materials, respectively.

If the interval between the two measurement instants is relatively short or the interior temperatures and humidity levels are nearly equal between these instants, then $c_2 = c_1 = c$ and $m_2 = m_1 = m$. Thus, the difference in the sound volume absorbed after seat installation can be expressed as

$$\Delta A = \frac{55.3V}{c}\left(\frac{1}{T_2} - \frac{1}{T_1}\right). \quad (3)$$

The area of the absorption material was very small compared with the surface area of the reverberation room; thus, the sound-absorption coefficient of the floor that is covered by the seats is likewise very small and can be represented by

$$\alpha_s = \frac{\Delta A}{S} = \frac{55.3V}{cS}\left(\frac{1}{T_2} - \frac{1}{T_1}\right), \quad (4)$$

where S is the area in m^2 of the seats to be tested and α_s is the random incidence sound-absorption coefficient of the seats to be tested. Therefore, on the basis of the obtained values of the reverberation time before and after seat installation, the volume of the reverberation chamber, and the area of the seats, the random incidence sound-absorption coefficient was obtained using Eq. (4). The test results are shown in Fig. 3.

The test results showed that the sound-absorbing seats exhibited a higher sound-absorption coefficient than the normal seats did in the range of 160–4000 Hz, particularly in the range of 250–600 Hz, in which the coefficient increased from 0.45 to 0.8. Thus, the sound-absorbing seats design effectively absorbed the sound.

4 Simulation prediction of the sound-absorption effect

A statistical energy analysis was performed to establish the noise simulation model of a high-speed train for calculation and verify the effects of the normal seats and sound-absorbing seats on the interior noise of high-speed trains. In the model, the damping loss factors of the interior acoustic space subsystem with the normal seats and sound-

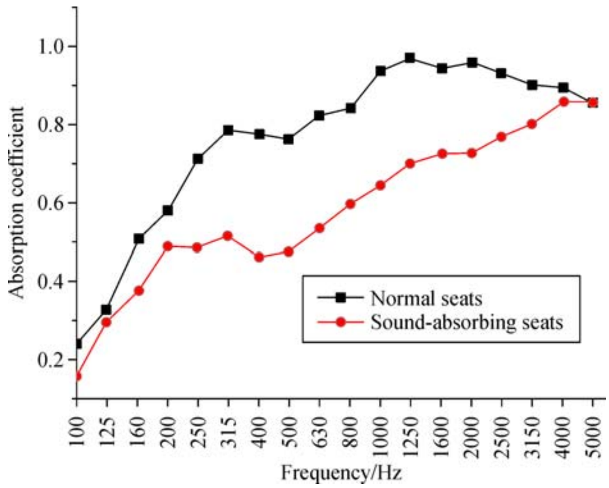

Fig. 3 Comparison between the test results of the sound-absorbing seats and normal seats

absorbing seats, respectively, are

$$\eta_1 = \frac{22}{fT_1}, \quad (5)$$

$$\eta_2 = \frac{22}{fT_2}, \quad (6)$$

where T is the reverberation time, which is calculated by

$$T \approx 0.161\frac{V}{S\alpha}, \quad (7)$$

where V, S, and α are the interior volume, surface area, and average sound-absorption coefficient respectively, and $S\alpha$ is the gross volume of the absorbed sound in the train.

The damping loss factors for the sound-absorbing seats and normal seats were calculated using the test results and Eqs. (5)–(7). The pressure levels of the interior noise of the compartment with the sound-absorbing seats and that with the normal seats can be obtained by taking the damping loss factors as the input parameters of the corresponding cavity subsystem in the statistical energy model. Thus, the increase in the volume of the noise absorbed by the sound-absorbing seats with respect to that by the normal seats can be obtained accordingly.

Figure 4 presents the simulation model of the entire middle car constructed on the basis of an actual high-speed train. Figure 5 shows a comparison of simulated sound pressure before and after the installation of the sound-absorbing seats. As shown, the noise in the entire frequency band decreased after installing the sound-absorbing seats. The noise when the normal seats were installed was 67.6 dBA, whereas that when sound-absorbing seats were installed was 65.8 dBA. Thus, the noise of the entire train car decreased by 1.8 dBA when the normal seats were replaced with the sound-absorbing seats.

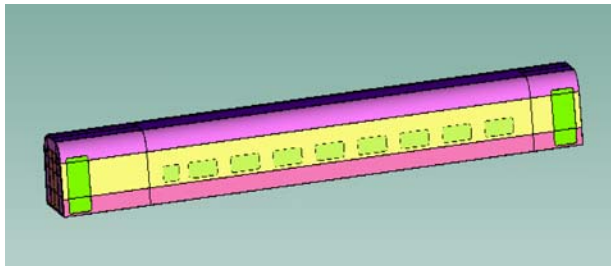

Fig. 4 Noise simulation model of the high-speed train car

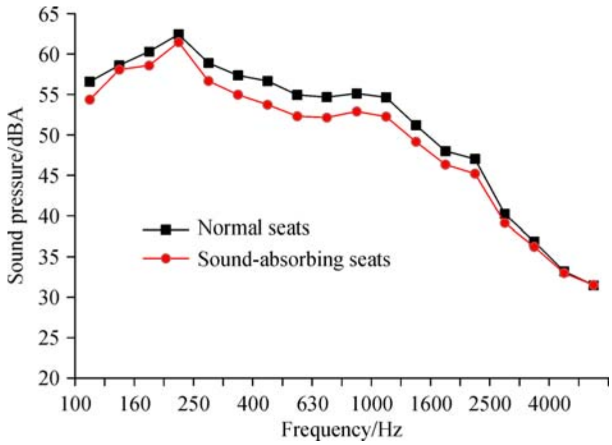

Fig. 5 Comparison of sound pressure before and after the installation of sound-absorbing seats

5 Results of railway experiments

Seats were fabricated and installed in an entire car of a real high-speed train to verify the sound-absorption effect further. Three standard microphone measurement points were arranged in the middle and at both ends of the passenger room at a height of 1.2 m from the floor to measure the sound pressure level, as shown in Fig. 6. The real line test was conducted under open-air 200 km/h velocity conditions.

Fig. 6 Line test site in the train

After the sound-absorbing seats were installed, the noise decreased significantly, and nearly the entire reverberation noise was absorbed because the seats enlarged the sound-absorption area. Table 1 compares the noise before and after the installation of the sound-absorbing seats. The measurement was conducted under open-air 200 km/h velocity conditions. The sound-absorbing seats reduced the noise in the middle of the train by approximately 1.5 dB. However, the effect was relatively poor at both ends where the noise decreases were approximately 1 dB. Both ends were near the interior door, and the quantity of the seats was relatively small. Consequently, the absorption area was relatively smaller; as a result, the sound-absorption effect of the seats was reduced. In general, sound-absorbing seats have several advantages and wide-ranging applications because they neither add extra weight nor occupy extra interior space. They are effective in decreasing the noise.

Table 1 Line test result in the train

Type of seat	Noise/dB		
	End 1	Middle	End 2
Normal seats	66.7	66.5	67.5
Sound-absorbing seats	65.7	65.0	66.6

6 Conclusions

In this study, a sound-absorbing seat design for high-speed trains is proposed. The use of high-performance, elastic, and fireproof sound-absorbing materials and perforated plates for the backrest and the cushion improves the seat absorption effect. In the actual line tests, the noise level decreases by 1.5 dB in the middle of the train and 1 dB at both ends after the installation of the sound-absorbing seats. Therefore, the sound-absorbing seats play a significantly positive effect on sound-absorption without occupying extra interior space or adding extra weight. Sound-absorbing seats could have a broad application prospect in the future.

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