Suspended Floor Structure for Reducing Structure-borne Sound of Interior Noise

Tomonori GOTO

Katsuya YAMAMOTO

Mineyuki ASAHINA

Vehicle Noise & Vibration Laboratory, Vehicle Structure Technology Division

As part of a study to reduce the interior noise of railway vehicles, RTRI investigated the vibration characteristics of a bullet train-type vehicle body. The vertical vibration of the side structural panels was found to be smaller than that of the floor panels. Thus, to reduce the structure-borne sound from the bogie, RTRI invented a suspended floor structure in which the floor panels were suspended from the side structural panels. Several prototypes were fabricated in the test vehicle and excitation tests were conducted with the vehicle stationary. The results showed reduced level of radiated sound power from the floor panel.

Keywords: interior noise, structure-borne sound, suspended floor structure

1. Introduction

In recent years, railway vehicle speeds have increased to over 300 km/h, whereas their weights have been reduced by using aluminum car bodies. With the increase in speed, has come an increase in wheel-rail rolling noise, and with the weight reductions, more vibrations propagate, which can increase the interior noise level. Typical the interior noise spectra for a bullet train are shown in Fig. 1. The interior noise of a bullet train contains low-frequency components (less than 400 Hz). The noise generated by the bogie is particularly dominant in the track section. It is difficult to prevent the propagation of these low-frequency components to the passenger cabin by using lightweight material such as sound absorbing materials.

The interior noise of a railway vehicle consists of:

- (1) Structure-borne noise caused by the propagation of vibration from the bogie to the floor panels, and
- (2) Transmitted noise from the aerodynamic noise generated on the vehicle body.

The distribution of sound pressure level in the 200 Hz band in a typical passenger cabin is shown in Fig. 2 [1]. The noise levels are highest in the 3rd and 18th seat rows, which are just above the bogie. Thus, the cabin tends to be quieter in the middle, and louder at the ends.

When considering the structure-borne noise radiated from the panels of a conventional floor structure, it should be noted that the floor panels are supported on joists

Fig. 1 Typical interior noise spectra for a bullet train

Fig. 2 Sound pressure distribution in a passenger cabin (200 Hz band)

mounted on the floor structural panels as shown in Fig. 3. Bogie vibration propagates through the traction link, yaw dampers, and air springs to the floor structural panels, from which it is propagated to the floor panels through the joists. Finally, the floor panels radiate structure-borne sound into the cabin. The adoption of a “floating floor structure” with vibration insulators between floor panels and joists is one practical countermeasure against floor panel vibration. However, this solution is only effective in the high frequency range: to dampen low frequency noise, the vibration insulator must be soft, which gives passengers a “strange” sensation when they walk on the floor.

This study aims to develop a new type of floor structure that reduces structure-borne sound. First, the vibra-

Fig. 3 Generic car body structure of a bullet train

tion characteristics of the floor and the side structural panels of a bullet train-type test vehicle were measured. The vertical vibration of the side structural panels was found to be smaller than that of the floor structural panels. Then, RTRI invented a suspended floor structure in which the floor panels were suspended from the side structural panels [2]. Several prototypes were fabricated in the test vehicle and stationary excitation tests were conducted. The tests showed that the low-frequency vibration of the floor panel was reduced. Floor panels are typically connected to each other. This paper reports the effect on vibration when the suspended floor panels are disconnected and connected.

2. Vibrational characteristics of a car body

2.1 Outline of the vibration measurement

To investigate the vibrational characteristics of a car body, car body vibration of a stationary bullet train-type test vehicle was measured at the Railway Technical Research Institute (Fig. 4).

The car body structure of the test vehicle was based on current bullet train vehicles. It had an aluminum alloy double skin structure, and was equipped with interior panels and seats. As low-frequency (less than 400 Hz) sound is dominant in the interior noise of a bullet train, as mentioned before, the tests focused on the frequency range up to 1,000 Hz. The traction link frame (Fig. 5) was excited by a random wave of 20 to 1000 Hz using an exciter (ASAHI Limited, SW-1015).

In this test, the vertical vibration characteristics of the side and floor structural panel and the vertical vibration distribution of the floor structural panel were investigated.

Fig. 4 Bullet train-type test vehicle

Fig. 7 Measurement points at the side and floor structural panels

Fig. 5 Exciter mounted on the traction link frame

2.2 Results of the vibration measurements

2.2.1 Vertical vibration of the side and floor structural panels

In this type of test the horizontal vibration of the side structural panel is typically measured, but in this test the vertical vibration of the side structural panel was measured. (Fig. 6)

The vertical vibration of the car body was measured near the 4th seat row from the end at six points on the side structural panel (three points on each side) and at six points on the floor structural panel. All vibrations were measured with piezo acceleration pickups (RION, PV-94).

The averaged power spectral densities (PSD) of the vertical vibrations of the floor and side structural panels

Fig. 6 Vibration measurement at the side structural panel

Fig. 8 Comparison of floor and side panel vertical vibrations

Fig. 9 Vibration shape of the floor structural panel

are compared in Fig. 8. The vibration of the side structural panel is shown to be smaller than that of the floor structural panel by 10 to 20 dB in the frequency range of 50 to 500 Hz. Then the vibration shape of the floor structural panel was investigated, and found to be an out-of-plane vibration. (Fig. 9) On the other hand, the side structural panel is likely to vibrate as in-plane vibration and the amplitude is likely to be smaller. Therefore, it seems that in the conventional floor structure the larger vibration of the center of the floor structural panel is propagated by the joists, and structure-borne sound is loud.

2.2.2 Vertical vibration distribution of the floor structural panel

The vertical vibration of the floor structural panel was measured from the end to the center of the cabin as shown in Fig. 10. Six piezo acceleration pickups (RION, PV-94)

Fig. 11 Comparison of vertical vibrations at points 1, 5 and 9

were attached laterally across the floor panel. (Fig. 10(b))

The averaged PSDs of measuring points 1, 5 and 9 are shown in Fig. 11. These results show a difference of up to 20 dB between point 1 (the closest point to the exciter) and point 9 (the farthest point from the exciter). The vibration power at the middle point 5 is between that at points 1 and 9. Thus, the closer the measuring point is to the exciter, the larger the vibration of the floor structural panel, which appears to be partly responsible for the difference in the interior noise shown in Fig. 2.

From these results RTRI clarified that with respect to the vertical vibration of the car body, the vibration of the side structural panel is smaller than that of the floor structural panel, and that the vertical vibration of the floor structural panel tends to increase closer to the exciter.

3. Proposed suspended floor structure

Section 2 clarified that the vertical vibration of the side structural panel is smaller than that of the floor structural panel, and that the vertical vibration of the floor panel is larger nearer the exciter. Thus, it is possible to reduce the structure-borne sound transmitted from the bogie by suspending the floor panel from the less vibratory side structural panel instead of the conventional method of supporting it on the joists mounted on the floor structural panel.

Thus, RTRI invented a suspended floor structure in which the floor panels are suspended from the side structural panel by suspension members (Fig. 12). In the suspended floor structure, the vibration of the floor panels and the structure-borne sound should be reduced as only

Fig. 10 Vibration measuring points

Fig. 12 Concept of the suspended floor structure

the smaller vertical vibration of the side structural panel is propagated through the suspension members to the floor panels.

4. Verification of the suspended floor structure by stationary excitation tests

4.1 Outline of the verification tests

The following characteristics of the suspended floor structure were investigated:

- (1) Suspending point and suspension length
- (2) Material and rigidity of the suspension member

Three prototypes were constructed as described in Table 1 and Fig. 13. There were two suspending points: overhead rack as a high point, interior panel mount as a low point and three types of suspension members: band plate, wire, and plate. The conventional floor structure was also tested as a reference. In the suspended floor structure, the floor panel was supported only at its edges; so, a thick reinforced floor panel was fabricated and used in these tests.

The traction link frame was excited with a random wave of 20 to 1000 Hz using an exciter in the same way as that described in Section 2, and the vertical vibration of

the floor panel was measured using thirteen acceleration pickups: six pickups on each longitudinal edge of each floor panel, and one pickup on the center as shown in Fig. 14. Then the radiated sound power from the floor panel was calculated from the vibration at each measuring point.

4.2 Comparison of the vibration characteristics of each type of the test floor panels

The comparison of the vibration characteristics between each type of the tested suspended floor structures and the conventional structure is shown in Fig. 15(a) ~ (c). Firstly, in the band plate suspension, as shown in Fig. 15(a), the vibration is generally reduced by 5 to 15 dB. A maximum reduction effect exceeding 15 dB was found around the frequencies of 90, 300, 750, and 900 Hz. Secondly, in the wire suspension, as shown Fig. 15(b), vibration reduced compared with the conventional floor structure by approximately 5 dB over most of the frequency ranges. At 160, 260, 360, 420, 460, 800, and 860 Hz the vibration is the same or slightly higher compare to the conventional floor structure. Finally, in the plate suspension, as shown in Fig. 15(c), vibration was reduced by approximately 10 dB around the frequencies of 50, 330, and 750 Hz. However, the vibration increased by approximately 10 dB at 250, 480, 550 Hz and

Table 1 Suspended floor structure prototype characteristics

Floor structure	Suspender	Suspend from	Notes
(a) Suspended by band plate	Band plate made of austenite stainless steel eq. AISI 304 $t = 1 \text{ mm}$, $w = 115 \text{ mm}$ $l = 1475 \text{ mm}$	Side structural panel rack	Long suspender
(b) Suspended by wire	Steel wire $\phi = 6 \text{ mm}$, $l = 1000 \text{ mm}$	Side structural panel rack	Long suspender
(c) Suspended by plate	Plate with hinge made of austenite stainless steel eq. AISI 304 $t = 1 \text{ mm}$, $w = 835 \text{ mm}$ $l = 118 \text{ mm}$	Side structural panel Interior panel mount	Short suspender with longitudinal fix
Conventional floor structure			Floor panels are fixed on joists

(a) Suspended by band plate

(b) Suspended by wire

(c) Suspended by plate

Fig. 13 Prototype of the suspended floor structure

Fig. 14 Measuring points on the floor panel

in the range 600 to 700 Hz.

Comparing the vibration reduction effect from the suspending point and suspension length, longer suspension members from high points (Figs. 15(a) and 15(b)) were more effective than the short suspender (Fig. 15(c)). When comparing it from the point of view of material and rigidity of the suspension member, further reduction was found in the wire suspension (Fig. 15(b)) which was less rigid than the band plate suspension (Fig. 15(a)). This may have been due to the wire's damping effect.

On the other hand, vibration increased at frequencies over 550 Hz in the plate suspension, which has the most rigid suspension member. This may have been caused by the rattling of the hinges used to connect the suspending plate to the side structural panel and the floor panel. In the suspended floor structure, since the floor panel has less

restraint against the plate vibration, peaks caused by the elastic vibration of the floor panel appeared in the frequency range of 70 to 140 Hz for each method, and vibration increased approximately by 10 dB at these peaks.

4.3 Radiated sound from the floor panel

The characteristics of the vibration and the radiated noise of a structure are not always the same, so the reduction effect of the radiated sound from each type of the suspended floor structure was evaluated. The radiated sound power is obtained by integrating the acoustic intensity on the surface of a vibrating plate and is calculated using (1) [3]:

$$P(\omega) = \frac{\omega \rho_0}{4\pi} \iint_S v(x_1) \frac{\sin kr}{r} v^*(x_2) dx_2 dx_1 \quad (1)$$

where ρ_0 is the density of air; ω , the frequency in radians/s; S , the surface domain of the plate; k , the wave number; $v(x_1)$ and $v(x_2)$, vibration velocities at the arbitrary points: x_1 , x_2 ; r , the distance between x_1 and x_2 ; and $*$ indicates a complex conjugation. In this case, the vibration velocities were calculated by numerical integration of the acceleration of the floor panel.

The radiated sound power was calculated by substituting the vibration velocity of each point into (1), and the result of each type of the suspended floor structure was compared with that of the conventional floor structure. The results of these comparisons are shown in Fig. 16.

Firstly, in the band plate suspension, as shown in Fig. 16(a), the radiated sound power was reduced approximately by

(a) Suspended by band plate

(b) Suspended by wire

(c) Suspended by plate

Fig. 15 Comparison of the vibration of each type of the tested floor panels

(a) Suspended by band plate

(b) Suspended by wire

(c) Suspended by plate

Fig. 16 Radiated sound power by each type of suspended floor structure compared with the conventional floor structure

10 dB in the frequency range up to 50 Hz, around 300 Hz, and around 800 Hz, where the vibration was also reduced. On the other hand, at 63 Hz and around 80 Hz, where the elastic vibration of the floor panel occurred, the radiated sound power was almost at the same level as the conventional floor structure. Secondly, in the wire suspension, as shown in Fig. 16(b), at frequencies around 100 Hz, where the vibration was reduced by 10 to 20 dB, the radiated sound power was reduced by up to 25 dB, and it was also reduced by 10 to 20 dB in the broad frequency range of 50 to 1000 Hz. Finally, in the plate suspension, as shown in Fig. 16(c), as the vibration increased in some frequency ranges, the radiated sound power increased approximately by 5 dB around 80, and 630 Hz; however, it was reduced by 5 to 10 dB in the other frequency ranges.

From these results, it was determined that the radiated sound power from each type of suspended floor panels was reduced by approximately 10 dB in the frequency up to 500 Hz compared to the conventional floor structure. This

is the frequency range where the structure-borne sound from the bogie is known to be significant. In the same way for the vibration reduction, the wire suspension, the band plate suspension, and the plate suspension came first, second, and third in effectiveness for reducing the radiated sound power; therefore, a flexible and long suspension member such as wire was found to be the most effective.

5. Connecting suspended floor panels

Section 4 explained the excitation tests that were conducted by constructing the suspended floor structure for one row of seats in the test vehicle. In practice, the floor panels are connected to each other and the floor surface is covered with carpet. Therefore, it is inferred that the vibration of a floor panel is propagated to other panels and the propagation influences each panel's vibration characteristics.

To investigate the effect of the connected floor panels on the vibration reduction of the suspended floor structure, an excitation test was conducted with three floor panels suspended by wire (Fig. 10(a), floor panel 3 to 5). A photograph of the test is shown in Fig. 17. The test conditions are described in Table 2. The vibration characteristics were compared in three test conditions: the conventional floor structure, the suspended floor structure with the three panels not connected to each other, and the suspended floor structure with the three panels connected to each other by 2-mm-thick stainless-steel band plates.

The results are shown in Fig. 18. Firstly, the vibration of the three floor panels in the conventional floor structure increased nearer the exciter as shown in Fig. 18(a). Secondly, in the suspended floor structure without the floor panel

Fig. 17 Suspended floor structure with floor panel connection

Table 2 Multiple panel test conditions

Floor structure	Floor support	Floor panel
(a) Conventional	Fixed on joists	Not connected
(b) Suspended	Suspended by wire from window frame	Not connected
(c) Suspended		Connected by stainless-steel band plate ($t = 2 \text{ mm}$)

connection, the vibration of a floor panel also increased nearer the exciter. The difference was up to 20 dB between the floor panels 3 and 5 in the frequency range 100 to 400 Hz as shown in Fig. 18(b). For floor panel 3, which is the closest to the exciter, vibration peaks were in the frequency range 150 to 250 Hz. Finally, in the suspended floor structure with the floor panels connected to each other, the vibration characteristics for each floor panel were approximately similar. The peaks at the suspended floor panel 3 were reduced by connecting three panels. It is inferred that by connecting multiple floor panels in the suspended floor structure, the panels vibrate like one plate.

The overall vibration power was calculated under each test condition. As shown in Fig. 19, in the conventional floor structure, where the floor panels are mounted on joists, there was a difference of about 10 dB in the overall vibration power between the floor panels 3 and 5. When the floor panels are suspended individually, the power of

(a) Conventional floor

(b) Suspended floor (not connected)

(c) Suspended floor structure (connected)

Fig. 18 Vibration characteristics of floor panels

Fig. 19 Overall vibration power of the floor panels

each floor panel was reduced equally by 5 to 6 dB regardless of the position of the floor panel. However, when the floor panels are suspended and connected to each other, the overall vibration power of each floor panel was almost on the same level.

It is known that, as shown in Fig. 2, the interior noise level around the middle area in a cabin is smaller than that around the end area; however, the noise levels can be equalized by connecting floor panels to each other in the suspended floor structure.

6. Conclusion

In this study, to reduce the noise inside a rail vehicle, RTRI proposed a suspended floor structure with floor panels suspended from the side structural panel. The reduc-

tion in vibration and radiated sound of the floor panels were evaluated by excitation tests. The results of the excitation tests lead to the following conclusions:

- (1) The vertical vibration of the side structural panel is smaller than that of the floor structural panel, and the vertical vibration of the floor structural panel tends to be larger nearer the exciter.
- (2) The radiated sound power from the prototype of the suspended floor structure was approximately 10 dB lower than from the conventional floor structure.
- (3) When multiple floor panels are suspended and connected to each other, the vibration characteristic of each panel is averaged.

RTRI plans to verify the effect of the suspended floor structure on the test vehicle in railway operation. RTRI also plans to confirm a similar benefit can be achieved by applying this type of floor structure to spaces other than the passenger cabin.

References

- [1] Yamamoto, K., Ishimori, A. et al., "Search for interior noise," *RRR*, Vol. 73, No. 8, pp. 16-19, 2016 (in Japanese).
- [2] Yamamoto, K., Asahina, M. et al., "A countermeasure against the structure bone sound in a railway vehicle by the suspended floor structure," *J-RAIL 2014*, S5-1-4, 2014.
- [3] Tanaka, N., *Control of Structural Sound*, CORONA PUBLISHING Co. LTD., Tokyo, Japan, pp. 78-80, 2009.

Authors

Tomonori GOTO
Assistant Senior Researcher, Vehicle Noise & Vibration Laboratory, Vehicle Structure Technology Division
Research Areas: Interior Noise Evaluation, Ride Comfort Evaluation

Mineyuki ASAHINA
Assistant Senior Researcher, Vehicle Noise & Vibration Laboratory, Vehicle Structure Technology Division
Research Areas: Interior Noise Evaluation, Ride Comfort Evaluation

Katsuya YAMAMOTO, Dr. Eng.
Senior Chief Researcher, Laboratory Head, Vehicle Noise & Vibration Laboratory, Vehicle Structure Technology Division
Research Areas: Interior Noise Evaluation, Ride Comfort Evaluation