Interior Noise Prediction of High-Speed Train Based on Hybrid FE-SEA Method

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Summary. Interior noise in rolling stock is an important index in the evaluation of passenger ride comfort. In this paper, the hybrid FE-SEA method was used to predict the interior noise of high-speed trains. In this process, the hybrid model of the car body was established based on FE models. Then according to the characteristic of the car body, the beams and stiffeners were described by a FE subsystem and thin, light plates and panels were divided into a SEA subsystem. As for the special structure of hollow aluminium alloy extrusion which makes up the car body profile, the equivalent model of a General Laminate was proposed to simplify this structure in the paper. Through theoretical calculation and test, subsystem parameters and external excitations were obtained, and then imported into the prediction model. Finally noise at the central section of the high-speed train was predicted by using the hybrid FE-SEA model. Compared with the test results, in the frequency range of 100 ~ 1000 Hz, the predicted and test noise spectra followed basically the same trend, so the proposed Hybrid FE-SEA method can be efficiently applied to the railway field.

1 Introduction

The prediction of a mid-frequency problem in vibro-acoustic systems has always been a challenge in the past decades. Neither the deterministic method such as FEM-BEM nor the statistical method such as SEA is appropriate for this problem. FEM-BEM is mainly used to analyze noise and vibration systems at low frequencies. SEA is very effective at high frequencies, but due to the small number of modes, the prediction accuracy is not precise enough in the low frequency range. Therefore, Shorter and Langley suggested a new approach in 2005 called the Hybrid FE-SEA Method which combined FE and SEA to avoid the shortcomings of using FE or SEA separately. Recently, the Hybrid FE-SEA method has been widely used to predict car interior and exterior noise in the mid-frequency range.

Although the Hybrid FE-SEA method has been applied successfully in the automotive field, due to the difference in the structure of the train and the motorcar, this method needs to be further investigated to be applied to the railway sector. In this paper, the Hybrid FE-SEA method was used to predict the interior noise of a high-speed train. First, the subsystems of car body were divided to set up a Hybrid FE-SEA model. Then, through theoretical calculation and test, subsystem parameters

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such as modal density, interior loss factor of the body structure and coupling loss factor were obtained. The external noise and vibration excitations were acquired from running tests. Finally, the noise at the central section of a high-speed train was predicted by using the Hybrid FE-SEA model. Compared with test results, in the frequency range of 100 ~ 1000 Hz, the predicted and test noise spectra followed basically the same trend, so the proposed Hybrid FE-SEA method can efficiently be applied to the railway field.

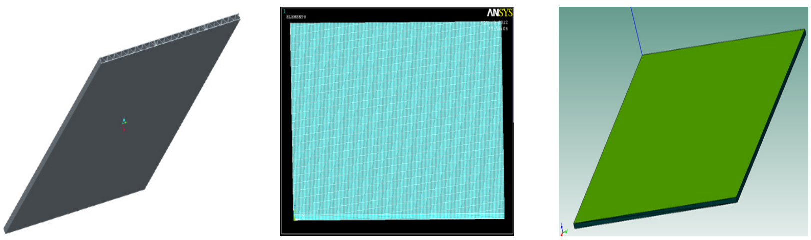
2 Hybrid FE-SEA of Car Body

The study object in this paper is a middle car of a high-speed EMU at a speed of 350 km/h. The whole car body of this EMU is a complex structure formed by several layers and components. The outermost frame is made of beams and hollow aluminum alloy extrusion. The interior trim layer is composed of light composite panels like aluminum honeycomb and corrugated sheet. Between the hollow profile and interior trim, there is an air layer and filling material for sound absorption and fireproof insulation. The side windows are multilayered glass panels. The under-frame is composed of draft sill and bolster and cross beams.

2.1 Equivalent Method of Aluminum Alloy Extrusion

The aluminum alloy extrusion is composed of two layers with corrugated rib panels in between, as shown in Fig. 1(a). If this structure is directly divided into a SEA subsystem, there will be too many thin but long plates, which not only increases the amount of computation but also aggravates the coupling errors of subsystems. Therefore, a method using the equivalent model of a General Laminate to simplify the body profile was proposed in this paper.

According to the theory of mode analysis and sound insulation, the equivalent simplification principle is as follows: first, the equivalent model and original structure have the same thickness and area density. Second, their dynamic characteristic is the same; the last, they have the same insulation performance. Based on this principle, the equivalent model is a three-layer board structure. The upper and lower layers are the same material and thickness as before, and interlayer is the virtual material, in order to make sure that the equivalent model and original structure have the same thickness and area density.



a) b) c)

Fig. 1. (a) Geometry model, (b) Equivalent multilayer FE model, (c) General laminate model in Va One

Taking a local model of the aluminum alloy extrusion for example, the model area size is $1m \times 0.95m$, and the thickness is 30 mm. According to the above principle of equivalence, a same size equivalent multilayer finite element model was built by means of ANSYS software (see Fig. 1(b)); the specific material parameters are shown in Table 1. Then, the modes of the equivalent model and original structure are computed, Table 2 shows the computation results for the first five modes; the comparison results indicate that the modes frequencies are basically the same, with errors within 5 %.

Table 1. Specific material parameters of the equivalent multilayer FE model

Structure \ parameters		material	Thickness (mm)	Density (Kg/m^3)	elastic modulus (Pa)	Poisson's ratio
aluminum alloy extrusion	Upper Layer	aluminum	2.5	2700	7.1e10	0.3296
	Inter-layer	virtual material	24.5	299.96	4.0e9	0.3
	Lower layer	aluminum	3	2700	7.1e10	0.3296

The equivalent multilayer finite element model is imported into VA One software. Due to the different thicknesses of the upper and lower layers of the aluminum alloy extrusion, the General Laminate plate in the VA One software is adopted to build a SEA subsystem (see Fig. 1(c)). Then, the sound insulation of the SEA equivalent model is calculated, and Fig. 2 shows the corresponding graph of the simulation result and test result. The results show that in the 100 Hz ~ 1000 Hz frequency range, the sound insulation performance of the SEA equivalent model and original structure is similar, with errors in each frequency band of not more than 2.5 dB.

Table 2. The first five modes of equivalent model and original structure

Structure \ modes		First (Hz)	Second (Hz)	Third (Hz)	Forth (Hz)	Fifth (Hz)
aluminum alloy extrusion	equivalent model	69.803	96.789	148.45	168.82	195.89
	original structure	70.807	94.175	151.70	169.91	199.99

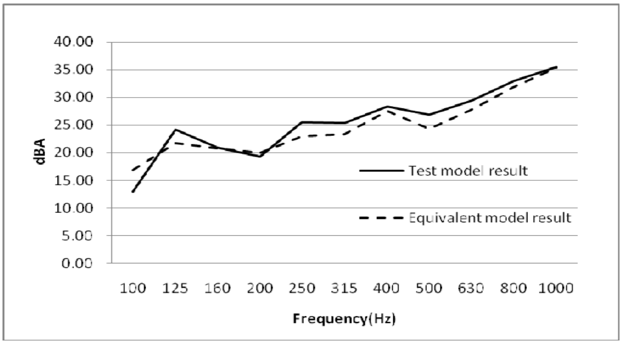
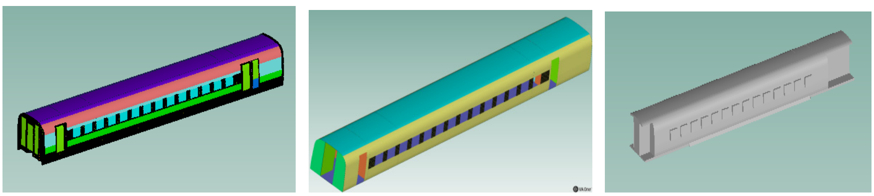


Fig. 2. Sound insulation graph of equivalent computation result and test result

Based on comprehensive comparison analysis of sound insulation for the first five order modes, the original aluminum alloy extrusion and equivalent multilayer model have consistent dynamic characteristics similar sound insulation performance. Therefore, this equivalent method can be used to simplify the car body profile to build SEA subsystems.

2.2 Establishment of the Hybrid FE-SEA Model

The Hybrid FE-SEA model of the car body was established based on geometry and FE models by means of commercial VA One software. According to the characteristics of the car body and the basic principle of the Hybrid FE-SEA method, the beams and stiffeners, such as the draft sill and bolster and cross beams with low modal density were described by a FE subsystem, and the hollow aluminum alloy extrusion of the body frame, trim, glass windows and other thin and larger plates and panels with high modal density compared to the beams were divided into a SEA subsystem. The acoustic cavities of car body and the air layer between the profile and interior trim are modeled as a SEA acoustic cavity, connected to FE and SEA subsystems. Fig. 3 (a) is the hybrid FE-SEA model of whole car body, Fig. 3(b) and Fig. 3(c) are the interior structure and the interior cavity of the acoustic subsystem, respectively.



a) b) c)

Fig. 3. (a) Hybrid FE-SEA model of whole car body, (b) interior trim, (c) interior SEA acoustic cavity

3 Calculation and Test of Parameters and Excitations

3.1 Subsystem Parameters Calculation and Test

Parameters in the SEA model include modal density, internal loss factor and coupling loss factor which may be obtained through either theoretical or experimental means. In this paper, modal density and coupling loss factor are obtained through theoretical means. The details are given in the references [3]. However, in order to obtain a higher accuracy in prediction, we have adopted the Steady Energy Flow Method to measure the internal loss factor. As shown in Fig. 4, the body structure is hoisted using a soft elastic rubber band and kept in a free state. Then we fit six acceleration sensors on the surface which is excited by a random noise source. Excitation and vibration acceleration signals from each of the sensors are recorded. We select three positions to receive excitation and each position is measured three times. Fig. 5 shows the measured result of internal loss factor of the body structure.

Fig. 4. Internal loss factor test

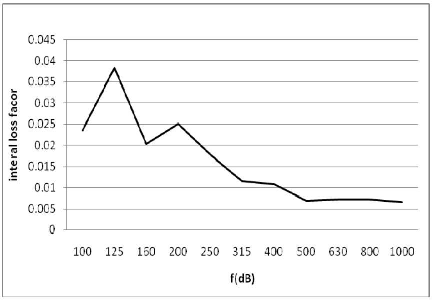


Fig. 5. Internal loss factor curve test result

3.2 External Excitations Test

The interior noise of high-speed trains comes mainly from wheel-rail noise, aerodynamic noise, pantograph arc friction noise and equipment noise and vibration. In order to obtain parameters and external excitations, we have carried out many line running tests. In this project, the excitations of vibration and noise are collected at a constant speed of 350 km/h. During the test, measurement points of wheel-rail excitation are located at connecting points between bogie suspensions and structures such as the anti-yaw damper, air spring, traction rod and anti-roll bars. The test result shows that the main contributor for bogie structure-borne paths is the traction rod link and that the noise energy is concentrated between 100 and 1000 Hz. The acoustic excitations of equipment are measured in the cabin and the vibration of equipment is acquired at the support points between the car body and the equipment.

The external aerodynamic noise is measured by surface acoustic sensors. Due to the limited distribution, we just take three sections of car body: two ends and the middle part. Each section respectively has three measuring points on the roof, side-top arc and window. The measured aerodynamic noise on the roof of the first end of the car body is shown in Fig. 6. It can be seen from this figure that the spectrum of exterior aerodynamic noise demonstrates broadband characteristics.

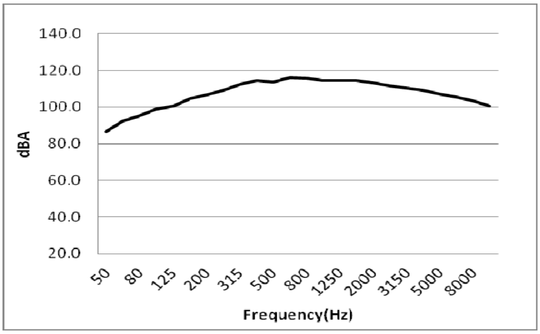


Fig. 6. Spectrum of external aerodynamic noise

4 Test and Prediction Results Comparative Analysis

Parameters and measured external excitations are loaded into the prediction model. Fig. 7 shows the hybrid model with imported excitations. Then, this model is used to predict the interior noise of the car body. The prediction results of noise at a 1.2 m standard point in the central section of the car body are shown in Fig. 8. A comparison between prediction and test results can be seen in this figure; in the low frequency range of 100~500 Hz, there is a mean deviation of 2.5 dB below the test result, but in the range of 500 ~ 1000 Hz, the mean deviation only approaches 2 dB. We are justified in observing that the prediction and the test results follow basically the same trend. Therefore, the proposed Hybrid FE-SEA model can meet engineering needs and the Hybrid FE-SEA method can efficiently be applied to the railway field.

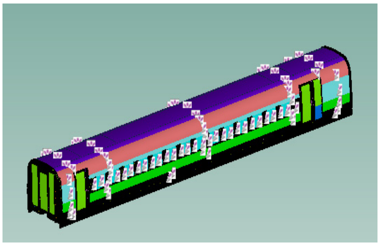


Fig. 7. Hybrid model with imported excitations

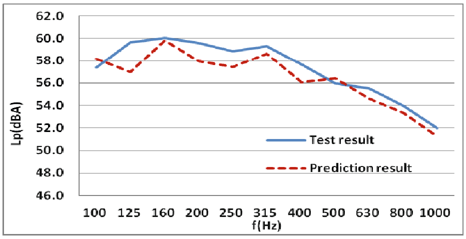


Fig. 8. Prediction and test result comparison

5 Conclusions

In this paper, the Hybrid FE-SEA method is presented to predict the interior noise of a high-speed train. First, the equivalent model of a General Laminate was proposed to simplify the special structure of hollow aluminium alloy extrusion in the paper. According to the characteristic of the car body and the basic principle of the Hybrid FE-SEA method, the subsystems of the car body are divided to set up a hybrid

FE-SEA model. Then, through theoretical calculation and test, subsystem parameters such as modal density, interior loss factor of body structure and coupling loss factor are obtained. The external excitations are acquired from running test. Finally, the noise at the central section of car body is predicted by using the Hybrid FE-SEA model. Compared with the test results, in the frequency range of 100 ~ 1000 Hz, the predicted and test noise spectra follow basically the same trend, so we can effectively use the proposed Hybrid FE-SEA method to predict the interior noise of rolling stock to evaluate passenger ride comfort.

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