Study on Sound Radiation Characteristics and Sound Insulation of Extruded Aluminium Plate

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Abstract. The use of extruded aluminium plates in the subway car body can reduce the weight of the car body, but it will bring about the negative result of increased noise in the car. The extruded aluminium panels belong to rib-stiffened plate structure in which both local short wave deformation and whole long wave deformation coexist. Studying the vibro-acoustic characteristics of this structure helps to effectively control the noise in the car. In this paper, Acoustic model of extruded aluminium plate and equivalent plate were both built up based on the hybrid method of finite element and statistical energy analysis(FE-SEA) and the statistical energy method (SEA) respectively. According to the theory of statistical energy analysis(SEA), the equivalent modelling method of the aluminium extrusion was presented using a single plate. This paper focuses on the sound radiation characteristics and sound insulation of extrude and equivalent structures. Results show that no matter what method is used, the calculation of the sound power and sound insulation of the two structures has the same trend. However, the results of the FE-SEA method can capture the natural frequency of the board and be more accurate reflect vibro-acoustic characteristics of extruded aluminium panels in the middle and low frequency. Equivalent plate can well predict the sound radiation characteristics and sound insulation in the mid and high frequency by using the SEA parameters of the aluminium extrusion.

1. Introduction
With the rapid development of urban rail transit in China, the problem of vibration and noise caused by rail transit has received increasing attention. Urban rail vehicle noise can be divided into internal noise and external radiation noise. The noise inside the car not only fatigues passengers and drivers, but also affects the intelligibility of speech. Complaints about the noise inside the subway car happen frequently. The noise in the subway car is generated by multiple excitation sources, the dominant frequencies are 80-250 Hz and 400-1000 Hz [1, 2], and it is introduced into the car through two propagation paths of structure sound and airborne sound. Based on the refined production requirements of rail transit trains and the research trend of lightweight car bodies, lightweight vehicles are becoming more and more common. However, lightweight car bodies are likely to cause insufficient local rigidity of the car body, decrease in overall sound insulation effect, and easily lead to vibration acceleration in the car. At present, the urban subway car body usually uses stainless steel and aluminium alloy. Although aluminium alloy materials are beneficial to the lightweight of the car body, their strength and rigidity do not meet the requirements. In order to ensure sufficient load-bearing
strength and rigidity of subway vehicles, aluminium alloy vehicles generally use large hollow sections and their assemblies.

The car body panel is an important medium for the transmission of noise from outside the car and vibration under the car to the inside of the car. The study of the vibration characteristics and sound insulation performance of the train car body is of great significance for reducing the noise inside the car [3], which is a necessary link in the acoustic design of the car body the acoustics of the car body. A necessary link in the design [4]. In this paper, I mainly study the middle and high frequency and sound radiation characteristics and sound insulation characteristics of car body panels. The methods for studying the acoustic and vibration characteristics of extruded profiles mainly include deterministic analysis methods (finite element method, boundary element method, etc.), statistical analysis methods (statistical energy method) and hybrid model method (hybrid FE-SEA). The deterministic analysis method is suitable for low frequencies, while the statistical analysis method is fit to high frequencies. As for the problem of intermediate frequencies, the hybrid model method is first choice [5]. The hybrid FE-SEA method was proposed by Langley [6-10]. It is a method suitable for analysing complex dynamic systems. It combines low-frequency deterministic analysis with high-frequency statistical analysis, and the system degrees of freedom are divided into "global" sets and "partial" set and it can effectively solve the intermediate frequency problem.

Xie [11] et al. coupled the global and local mode subsystems and establish a simulation model of the acoustic characteristics of rail vehicle aluminium profiles based on statistical energy analysis. Besides, they compared simulation results with the experimental results and found both results are similar under mechanical load excitation, but under the excitation of acoustic load, the agreement between the two is not ideal. Wu J [12-13] studied the influence of the thickness changes of the web, lower and upper plates on the vibration and sound radiation of aluminium profiles and analysed the effect of viscoelastic damping on the acoustic radiation characteristics of aluminium profiles. Shen HM [14] established a simulation model of the acoustic characteristics of the corrugated board outer floor using the hybrid finite element-statistical energy method, He analysed the sound insulation performance of the corrugated board structure, and obtained the best combination of web inclination and structure under different frequency noises. Luo L [15] et al. applied the structure-acoustic coupling method to study the sound insulation of aluminium profiles on the roof, side walls, and floors in the mid-frequency range. The results showed that appropriately increasing the acoustic bridge angle and panel thickness can improve the sound insulation of aluminium profiles. Zhang YL [16] calculated the sound radiation of vehicle aluminium profiles in 100-2500 Hz through the finite element method, and analysed the influence of the distance between the profile panels and the thickness of the reinforcement on the sound insulation of the structure. The study showed that by changing the car body profile The structural size has many limitations in optimizing its sound insulation, but it can be optimized by increasing the honeycomb sandwich structure.

Various methods are used to research car body aluminium profiles, but they lack a systematic research programs, and the current car body extruded profile models cannot well predict the sound transmission loss of extruded panels. This requires further research on the structural vibration and acoustic radiation of the extruded panel. In this paper, I studied the sound radiation characteristics and sound insulation of the extruded aluminium plate and equivalent plate by using FE-SEA method and the statistical energy method. What’s more, the simulation prediction results of the two methods was be compared. These studies can provide theoretical support for in-vehicle noise control.

2. Sound radiation and sound insulation

2.1 Acoustic radiation characteristics

The sound energy radiated is expressed by the radiated sound power when the panel vibrates under excitation, and the radiated sound power is:

\[ W = \sigma \rho c v S \left( \frac{\partial^2}{\partial t^2} \right) \]  

(1)
where: \( \sigma \) — Acoustic radiation efficiency; \( \rho_0 \) — Density of fluid medium; \( c_0 \) — The speed of sound in a fluid medium; \( S \) — Surface area of the structure; \( \langle \vec{v}^2 \rangle \) — Root mean square structure vibration velocity averaged in a certain time and space.

### 2.2 Sound insulation

The ability of the component to transmit sound energy is expressed by the transmission sound coefficient, which is equal to the ratio of the transmitted sound power to the incident sound power.

\[
\tau = \frac{W_t}{W_i} = \frac{I_t}{I_i} = \frac{P_t}{P_i}
\]

where: \( W_i \) — Incident sound power; \( W_t \) — Transmitted sound power; \( I_t \) — Transmitted sound intensity; \( I_i \) — Incident sound intensity; \( P_t \) — Transmission sound pressure; \( P_i \) — Incident sound pressure.

The transmission sound coefficient is also called the sound transmission coefficient. Its value is between 0 and 1. The smaller the value, the better the sound insulation effect of the component.

Since it is not convenient to use the transmission sound coefficient to express the sound insulation of a component, the sound insulation TL (Transmission Loss) is used to express the sound insulation performance. The larger the TL value, the better the sound insulation performance.

\[
TL = 10 \log_{10} \left( \frac{1}{\tau} \right) = 10 \log_{10} \left( \frac{W_i}{W_t} \right)
\]

### 3. Simulation of sound and vibration characteristics of extruded profiles

#### 3.1. Model building

The vibro-acoustic characteristics of the extruded aluminum plates of subway trains were taken as the research object. The specific geometric dimensions and structural attribute parameters of the extruded aluminum plate are shown in Table 1 and the three-dimensional model is shown in Figure 1.

| Name             | Material | Elastic Modulus (Pa) | Poisson's ratio | density (kg/m³) | Damping coefficient |
|------------------|----------|----------------------|-----------------|------------------|---------------------|
| extruded aluminium plate | AL       | 7.1e+10              | 0.3296          | 2700             | 0.01                |

| Name             | Length (mm) | width (mm) | Upper board thickness (mm) | Lower plate thickness (mm) | Rib thickness (mm) | Total thickness (mm) |
|------------------|-------------|------------|----------------------------|----------------------------|-------------------|---------------------|
| extruded aluminium plate | 1500       | 1200       | 2.8                        | 2.8                        | 1.8               | 75.6                |

Figure 1. 3D model of extruded aluminum plate.
Hybrid FE-SEA model and SEA model in VA-One was established. Based on the characteristics of the noise in the subway car, the frequency range of the study is limited to 100-2500 Hz, and the sound radiation characteristics and sound insulation of the frequency of 100-1000 Hz are focused on. The extruded aluminum plate is divided into three subsystems, the upper plate, the lower plate and the middle stiffened plate. When the FE-SEA hybrid method was used, the upper and lower plates are represented by the SEA subsystem due to the high modal density, resulting in short-wave deformation, while the middle stiffened plate produces long-wave deformation due to the low modal density which was divided into FE subsystem.

In order to analyse the sound radiation characteristics of the extruded aluminium plate of the subway car, a unit load was applied to the middle of the lower plate of the model, and a semi-infinite fluid was added to the upper plate, and each plate was connected. In the middle and low frequency bands, the hollow extruded aluminium profile is controlled by the overall mode. In order to simplify the calculation, the influence of the hollow extruded aluminium profile on the sound and vibration response was ignored. The FE-SEA model is shown in Figure 2 and the SEA model was shown in Figure 3. The local modal deformation of the hollow extruded aluminium profile in the frequency band above 500 Hz begins to play a leading role. In order to analyse the sound insulation of the extruded aluminium profile of the car body, a sound source sound cavity and a receiving sound cavity were added on both sides of the profile structure. In this paper, the TL standard calculation method was adopted, that is, the sound source room and the receiving room were simulated by large-volume sound cavity. As shown in Figure 4.

3.2. Modal simulation
In the modal calculation of the extruded aluminium plate, the structure is not affected by any external force, nor is there any restriction, that is, the free modal of the plate was calculated. The natural frequency distribution of the first 16 steps of extruded aluminium plate is relatively wide, and the first 16 steps can be directly selected. The results are shown in Table 2.
Table 2. Natural frequency of extruded aluminium plate simulation

| Order | Frequency/Hz | Order | Frequency/Hz |
|-------|--------------|-------|--------------|
| 1     | 7.79         | 9     | 941.16       |
| 2     | 9.55         | 10    | 1006.81      |
| 3     | 231.89       | 11    | 1024.50      |
| 4     | 362.18       | 12    | 1134.82      |
| 5     | 416.32       | 13    | 1202.14      |
| 6     | 568.16       | 14    | 1204.01      |
| 7     | 600.36       | 15    | 1216.71      |
| 8     | 927.18       | 16    | 1224.00      |

Selecting the second, fourth, seventh, and tenth modes of the extruded aluminium plate, as shown in Figure 5-8.

![Figure 5. The fifth-order mode.](image)

![Figure 6. The seventh-order mode.](image)

![Figure 7. The tenth mode.](image)

![Figure 8. The thirteenth mode.](image)

Through the low-order mode shape, it can be seen that in the lower frequency band, the car body floor is controlled by the overall mode and basically presents overall vibration, and the local vibration is very small. The modes of each order show a regular symmetrical distribution and has a sufficiently high accuracy. Higher-order modes include many local modes. The frequency of the modes is dense and the coupling phenomenon is serious, the accuracy is insufficient, and the actual reference and application value is not high.

3.3. Vibration and Acoustic Radiation Characteristic Simulation

The sound power level of the extruded aluminium plate was calculated by the hybrid method and the statistical energy method, and the results are shown in Figure 9. As the frequency increases, the sound power levels calculated by the two methods show a trend of first decreasing and then increasing, and the curve trends are consistent. However, the FE-SEA hybrid method has a large range of sound power level changes in the frequency range of 100 to 2500 Hz. The minimum sound power is 38.5dB and the maximum sound power level is 89.7dB. The results of SEA calculation are mainly concentrated around 70 Hz, and the fluctuation range is not large. Both curves have a peak around 1300 Hz. Since the fifth-order natural frequency of the extruded aluminium plate is 416.32 Hz, the plate has resonance...
in this frequency band. When the FE-SEA method is used for calculation, a large peak appears at this frequency. It can be seen that in the middle and low frequency bands, compared with the SEA method, the FE-SEA hybrid method can capture the natural frequency of the panel, and can more accurately reflect the sound radiation characteristics of the extruded aluminium panel.

Figure 9. Radiated sound power of extruded aluminum plate.

3.4. Sound insulation simulation

The calculation results of the sound insulation of extruded aluminium panels are shown in Figure 10. The valley of the sound insulation in the low frequency band is caused by the resonance of the car body panels. The valley does not completely correspond to the natural frequency of the extruded plate, mainly because the sound insulation at the 1/3 octave band was only considered. When the frequency reaches 800 Hz, the sound insulation decreases. This is mainly because bending waves are easily generated in the plate structure. When the incident sound wave reaches a certain frequency, the projection of the bending wavelength generated by the plate in the direction of the incident sound wave is exactly equal to the wavelength of the incident sound wave and the sound insulation of the extruded aluminium plate is reduced. The FE-SEA simulation curve can more vividly reflect the change trend of the sound insulation curve above 400 Hz, but because the boundary condition setting around the extruded aluminium plate is different from the actual situation, the calculation result has a large error in the low frequency band. The calculation result of the SEA curve is larger than the calculation result of the hybrid method, and the calculation time is relatively short. Both the hybrid method and the statistical energy method can reflect the general trend of the sound insulation curve. However, compared with the statistical energy method, the hybrid method is more accurate in the mid- and low-frequency region.
4. Equivalent plate

Car body panels are an important medium for the transmission of external noise and under-vehicle vibration to the inside of the car. When establishing the finite element and acoustic boundary element models of the car body, considering the calculation accuracy and calculation time, the subway car body is usually simplified and we often extract the middle layer of the structure of each part of the car body as the middle surface, and give the thickness of the original structure of the middle surface. The finite element calculation of the car body is carried out according to the theory of plate and shell mechanics. However, the extruded aluminum panels belong to rib-stiffened plate structure which have a complex coupled motion. Both local short wave deformation and whole long wave deformation coexist in middle and high frequency, and the acoustic and vibration characteristics are more complex than the equivalent single-layer plate. Domestic researchers have done relevant research on how the extruded profile is equivalent to a single plate. Zhang Y Y [17] and others analyzed the influence of the natural frequency and cut-off frequency of the aluminum profile size. The results showed that the aluminum profile plate below the cut-off frequency can be equivalent to a homogeneous thin plate, and the local modal deformation of the profile plate above the cut-off frequency cannot be ignored. Song S K [18] established an equivalent model of the hollow profile of the car body floor, and verified the rationality and correctness of the equivalent model through simulation. Zhang J et al. [19] studied the acoustic and vibration characteristics of aluminum profiles for high-speed trains through experimental testing and simulation analysis, and proposed an equivalent modeling method for predicting the acoustic and vibration characteristics of aluminum profiles by using a single plate in the middle and high frequency range.

In this paper, to equate the extruded aluminum plate equivalent as a single plate, the key parameters of SEA such as the modal density of the subsystem, the internal loss factor and the coupling loss factor of the subsystem components based on the SEA principle were reset. What’s more, the quality of the single-layer board is equal to that of the floor aluminum profile.

4.1. Vibration and Acoustic Radiation Characteristic Simulation

Establishing the FE-SEA model and the SEA model of the equivalent plate respectively, obtaining the radiated sound power, and comparing it with the calculated results of the extruded aluminium plate. As shown in Figure 11, Similar to the extruded aluminium plate, the radiated sound power level calculated by the equivalent FE-SEA model has a large variation range, while the radiated sound power calculated by the SEA model is mainly concentrated in the range of 60-70dB. Besides, the change trend is consistent with the actual profile. The two profiles calculated by two methods are consistent in the mid-high frequency band, but have a little difference below the 800 Hz frequency.
band. This may be related to the principle of SEA. The number of modes does not meet the prerequisites for using the SEA principle.

![Figure 11. Radiated sound power of extruded aluminum plate and equivalent plate.](image1)

4.2. Sound insulation simulation

The sound insulation results of extruded aluminium plates and equivalent plates calculated by two methods can be seen from Figure 12. Whether it is the hybrid method or the statistical energy method, the sound insulation of the equivalent plate is less than that of the actual extruded aluminium plate. The sound insulation change trend of the two in the middle and high frequency bands is similar. It can be seen that this method is suitable for equivalent modeling of aluminium profiles in medium and high frequency.

![Figure 12. Sound insulation of extruded aluminum plate and equivalent plate.](image2)

5. Conclusions

The sound radiation characteristics and sound insulation of car body panels have a great influence on the noise inside the car. In this paper, calculation model for the sound radiation characteristics and sound insulation of the subway train extruded aluminium plate and the equivalent plate was established. The calculation results of the two methods are compared and analysed, and the main conclusions are as follows:
1) Whether it is an extruded aluminum plate or an equivalent plate, the radiated sound power level and sound insulation curve change trends calculated by the FE-SEA method and the hybrid method are consistent;

2) In the middle and low frequency bands, compared to the SEA method, the FE-SEA hybrid method can capture the natural frequency of the panel, and can more accurately reflect the sound radiation characteristics and sound insulation of the extruded aluminum panel;

3) In the mid-high frequency band, the radiated sound power level and sound insulation of the extruded aluminum plate are not much different from the equivalent plate which is built by SEA principle, so as to verify the feasibility of the equivalent plate.

References

[1] Liu C Z, Li L, Bu Z, et al. (2021) Experimental Study on the Influence of Different Track Structures on Metro Vehicle Interior Noise. Railway Standard Design, 65(1): 1-5.

[2] Yan L, Chen Z, Zou Y F, et al. (2020) Field Study of the Interior Noise and Vibration of a Metro Vehicle Running on a Viaduct: A Case Study in Guangzhou. International Journal of Environmental Research and Public Health, 17(8)

[3] Bu Z, Li L, Liu C Z, et al. (2020) Research of Metro Vehicle Structure-borne Reduction Noise Optimization Based on Modal Contribution Analysis Noise. Urban Mass Transit, 23(03): 131-135.

[4] Zhang Y Y, Sheng H M (2010) On Vibration and Sound Transmission Loss of External Floor of High-speed Trains. Noise and Vibration Control, 31(4): 101-104.

[5] Ji L (2013) Intermediate Frequency Vibration Analysis Method—Analysis of Hybrid Model. Machinery Industry Press, Bei Jing, china.

[6] LANGLEY R S, BREMNER P. (1999) A hybrid method for the vibration analysis of complex structural-acoustic system. Journal of the Acoustical Society of America, 105(3), p1657-1671.

[7] LANGLEY.R.S. (1996) The response of two-dimensional periodic Structures to point harmonic forcing. Journal of Sound and Vibration, 197(4): p447-469.

[8] LANGLEY R S. (1997) The response of two-dimensional periodic structures to impulsive point loading. Journal of Sound and Vibration, 201(2): 235-253.

[9] LANGLEY R S, BARDELL N S. (1997) The response of two-dimensional periodic structures to harmonic point loading: a theoretical and experimental study of a beam grillage. Journal of Sound and Vibration, 207(4): 521-535.

[10] LANGLEY R S, BARDELLNS, LOASBYPM. (1997) The optimal design of near-periodic structures to minimize vibration transmission and stress levels. Journal of Sound and Vibration, 207(5): 627-646.

[11] Xie G, Thompson D.J, Jones C.J.C. (2005) A modelling approach for the vibroacoustic behaviour of aluminium extrusions used in railway vehicles, Journal of Sound and Vibration, 293(3): 921-932.

[12] Wu J, Zhou X, Xiao X, B, et al. (2014) Sound Radiation Characteristics of Extruded Aluminum. Noise and Vibration Control, 34(04): 14-18.

[13] Wu J, Xiao X, B, Zhang Y M, et al. (2015) Sound Radiation Prediction and Control of Section Aluminum of High-speed Train’s Car-body Based on Hybrid FE-SEA Method. Noise and Vibration Control, 35(03): 33-36+107.

[14] Sheng H M, Zhang Y M, Xiao X B, et al. (2011) Low-noise optimization design of external corrugated floor for high-speed train. Journal of Traffic and Transportation Engineering, 11(02): 65-71.

[15] Luo L, Zheng X, Hao Z Y, et al. (2015) Sound insulation performance analysis of high-speed train aluminum extrusions based on structure-sound coupling method. Journal of Central South University(Science and Technology), 46(09): 3513-3519.

[16] Zhang Y L, Wang K S, Zhao Y J, et al.(2019) Sound Insulation Performance Optimization of
Vehicle Structures. Noise and Vibration Control, 39(05): 84-88+101.

[17] Zhang Y Y, Sheng H M, Xiao X B, et al. (2014) Research on Vibration and Transmission Loss of Aluminum Alloy External Floor for High-Speed Train. Journal of Chongqing University of Technology(Natural Science), 28(01): 28-32.

[18] Song S K 2014 The Study on Equivalent Model of Hollow Aluminum Extrusion. Master Thesis, Beijing Jiaotong University, Beijing, China.

[19] Zhang J, Xiao X B, Wang Q R, et al. (2017) Vibro-acoustic characteristics measurement and equivalent modeling of aluminum extrusion of high-speed trains. Journal of Zhejiang University(Engineering Science). 51(03): 545-553.