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Analysis of Car Body Vibration of High-speed EMU Based on Modal Vibration Decomposition Method

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Abstract

In order to grasp the modal vibration characteristics of the elastic car body of the high-speed EMU, the rigid–flexible coupled dynamic model of the high-speed EMU vehicle including an elastic car body is established, and according to the modal superposition theory, a modal vibration decomposition method based on singular value decomposition (SVD) and least squares fitting is proposed, and the physical vibration response of the car body is decoupled into the modal vibrations of the car body. The results show that the rigid–flexible coupled dynamic model of the vehicle established can effectively reflect the modal information of the car body, and the proposed modal vibration decomposition method can decouple the physical response into modal vibrations of various orders, moreover, the contribution of each order modal vibration of the car body to the physical vibration of the concerned position on the car body can be accurately analysed. The modal vibration decomposition method proposed can provide a basis for the vibration control of the car body and the improvement of the running quality of the vehicle.

Keywords: high-speed EMU, car body vibration, modal vibration decomposition, singular value decomposition, least squares fitting.

1 Introduction

With the continuous improvement of the running speed of the EMU and the application of the lightweight technology of the car body, the elastic modal vibration problem of the high-speed EMU car body has gradually become prominent. When the wheel-rail excitation is transmitted to the car body through the bogie suspension system, the overall and local elastic modal vibration of the car body is easily excited. Since the main modal vibration frequencies of the car body (such as diamond-shaped deformation mode and first-order vertical bending mode) are close to the frequency range where the human body is sensitive to vibration [1], it greatly affects the ride comfort. And as the running speed of the vehicle increases gradually, the running stability of the vehicle will deteriorate rapidly [2]. In order to suppress the elastic resonance of the car body, D. Gong installed a dynamic vibration absorber at the bottom of the car body, and optimized the parameters of the dynamic vibration absorber according to the bending frequency of the car body. The results show that the optimized dynamic vibration absorber can effectively suppress the elastic resonance of the car body and show good robustness [3].The purpose of the presented study is to propose a modal vibration decomposition method based on singular value decomposition (SVD) and least squares fitting according to the modal superposition theory, analyse the modal vibration characteristics of the elastic car body, and then provide a basis for the modal vibration control of the high-speed EMU car body.

2 Methods

In order to grasp the modal vibration characteristics of the elastic car body of the high-speed EMU, according to the modal superposition theory, a modal vibration decomposition method based on SVD and least squares fitting is proposed, and the physical vibration response of the car body is decoupled into the modal vibrations of the car body. Combined with finite element condensation calculation [4] and multi-body dynamics theory, the rigid–flexible coupled dynamic model of the high-speed EMU vehicle including an elastic car body is established. Figure 1 (a) and Figure 1 (b) show the finite element model of the car body and the rigid–flexible coupled dynamic model of the vehicle, respectively. As for the elastic car body structure, the relationship between its physical vibration $\{V\}$, modal shape $[\boldsymbol{\Phi}]$ and modal vibration $\{\boldsymbol{q}\}$ is

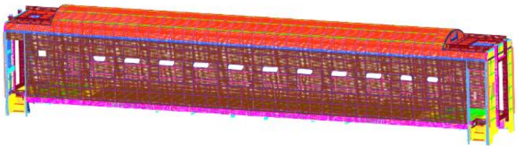
$$\{V\} = [\boldsymbol{\Phi}]\{\boldsymbol{q}\} \tag{1}$$

where the modal shape $[\boldsymbol{\Phi}]$ can be obtained by analyzing the finite element model of the car body in Figure 1 (a), and physical vibration $\{V\}$ can be obtained by 32 accelerometers arranged on the car body of the rigid–flexible coupled dynamic model of the vehicle in Figure 1 (b), and then modal vibration $\{\boldsymbol{q}\}$ can be obtained.

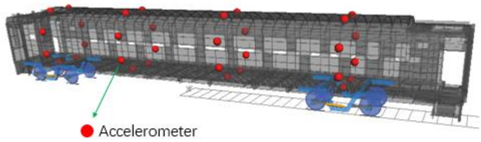
However, there are too many degrees of freedom of the car body to consider the complete modal shape $[\boldsymbol{\Phi}]$ of the car body. It is necessary to truncate the modal shape $[\boldsymbol{\Phi}]$ into $[\boldsymbol{\Phi}']$, and the error between the superposition of modal vibration and the physical vibration is

$$\{R\} = [\boldsymbol{\Phi}']\{\tilde{\boldsymbol{q}}\} - \{V\} \tag{2}$$

Where $\{\tilde{\boldsymbol{q}}\}$ is the approximate solution of the modal vibration $\{\boldsymbol{q}\}$ after modal truncation. Based on the least squares fitting method, the minimum error $\{R\}_{\min}$ is taken as the objective function. Since $[\boldsymbol{\Phi}']$ is a singular matrix, SVD method is applied on it and then the approximate modal vibration $\{\tilde{\boldsymbol{q}}\}$ after modal truncation is obtained. The first 20Hz mode of the car body is selected for modal truncation. And the proposed method can decouple the physical vibration response of any position on the car body.



(a)



(b)

Figure 1: (a)The finite element model of the EMU car body; (b)The rigid–flexible coupled dynamic model of the vehicle.

3 Results

Table 1 shows the modal frequency errors of the car body generated by the condensation calculation during the establishment of the rigid–flexible coupled dynamic model. It can be seen that the maximum modal frequency error of the car body is about 2%. Figure 2 shows the errors generated by the modal vibration decomposition for the physical vibration of the car body floor above the bogie when the vehicle running speed is 200 km ħ$^{-1}$. As can be seen, the vibration decomposition errors of lateral and vertical vibration are very small (the magnitude of the errors in the time domain are within 3% of the magnitude of the vibration of the car body floor), showing that the method presented in this paper has reliable accuracy.

Mode	FE model [Hz]	After condensation calculation [Hz]	Error
Diamond-shaped deformation	7.48	7.59	1.47%
First-order torsion	8.98	9.10	1.34%
First-order vertical bending	11.12	11.03	-0.81%
Breathing	12.46	12.70	1.93%
First-order lateral bending	14.25	14.10	-1.05%

Table 1: The modal frequency errors of the car body.

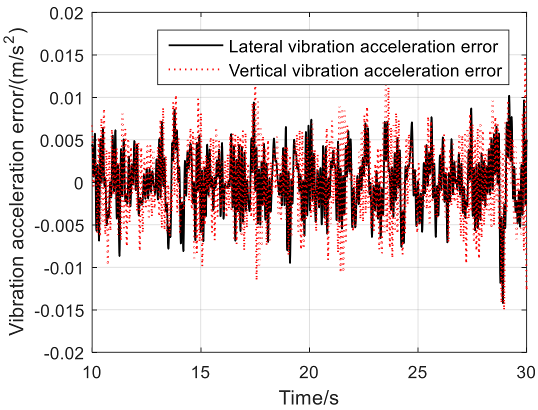


Figure 2: The errors generated by the modal vibration decomposition.

Figure 3 and Figure 4 are the amplitude-frequency curves of the lateral and vertical vibration acceleration of the car body floor above the bogie in physical space, respectively, and the amplitude-frequency curves of the first seven orders modal vibration of car body. For the lateral vibration, the rigid body modes of lateral rigid motion and yaw motion are considered, and for the vertical vibration, the rigid body modes of bounce motion and pitch motion are considered. As can be seen from Figure 3, for the lateral vibration of the car body floor, first-order torsion modal vibration at 8.98 Hz and first-order lateral bending modal vibration at 14.25 Hz contribute the most, and the vibration of the car body below 5Hz is mainly contributed by the rigid body modes of lateral rigid motion and yaw motion. It can be seen from the results in Figure 4 that for the vertical vibration of the car body floor above the bogie, bounce motion and pitch motion below 5 Hz and the first-order vertical bending modal vibration at 11.12 Hz contribute the most.

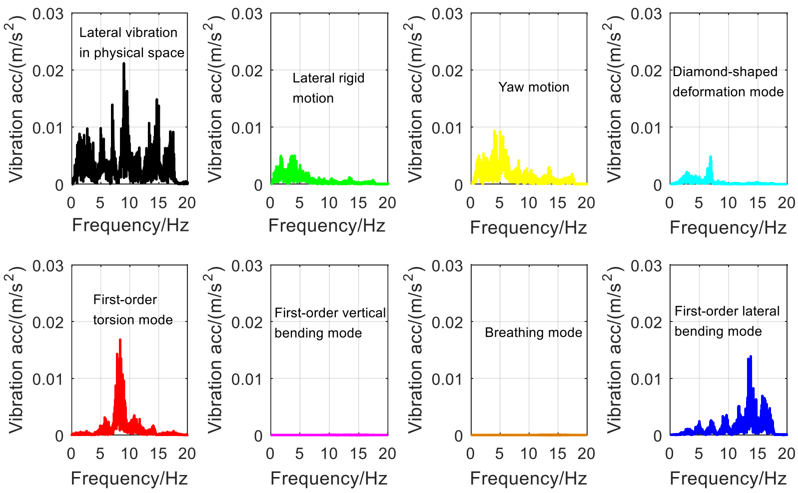


Figure 3: Acc spectrum of car body floor lateral vibration above the bogie.

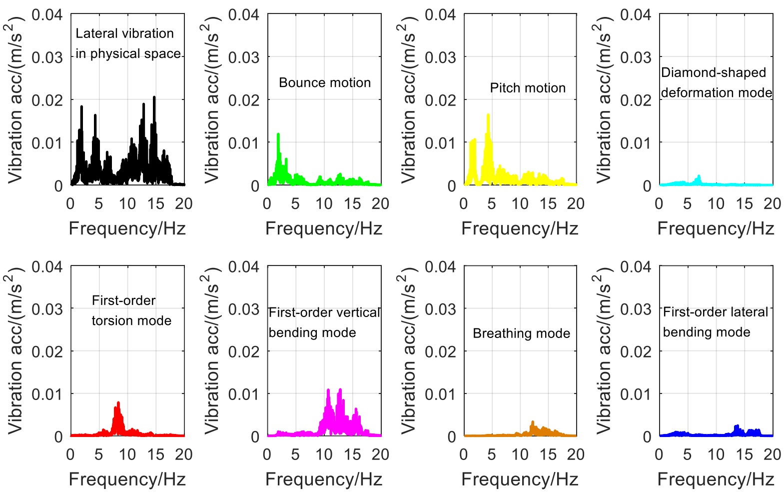


Figure 4: Acc spectrum of car body floor vertical vibration above the bogie.

4 Conclusions and Contributions

The rigid–flexible coupled dynamic model of the vehicle established can effectively reflect the elastic modal information of the car body, and the maximum error of the modal frequency is only about 2%. The proposed modal vibration decomposition method based on singular value decomposition(SVD) and least squares fitting can decouple the physical response into modal vibrations of various orders, and the error of the modal vibration decomposition relative to the physical vibration is within 3%, ensuring the decomposition accuracy, the contribution of each order modal vibration of the car body to the physical vibration of the concerned position on the car body can be accurately analysed. In addition, the amplitude of the physical space vibration is slightly different from the amplitude of the modal vibrations at the same frequency, because the physical space response is the superposition of all modal vibrations with different phase relationship. The method proposed in this paper can provide a basis for the vibration control of the car body and the improvement of the running quality of the vehicle, such as designing the suspension position and frequency of the under-chassis equipment to suppress the modal vibration that contributes greatly to the vibration of the car body.

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