Proceedings of the Sixth International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 7, Paper 5.3
Civil-Comp Press, Edinburgh, United Kingdom, 2024
ISSN: 2753-3239, doi: 10.4203/ccc.7.5.3

Coupled Dynamic Modeling of Car Body and Underchassis Equipment Considering the Dynamic Evolution Characteristics of Rubber Elements

X. Deng and D. Gong

Institute of Rail Transit, Tongji University
Shanghai, China

Abstract

Rubber elements are widely used to suspend underchassis equipment beneath high-speed trains' car body.The mechanical properties of rubber elements change significantly with ageing and temperature changes. This article is focused on the coupled dynamic modelling of the car body and underchassis equipment in high-speed vehicles considering the dynamic evolution characteristics of rubber elements. In combination with the experimental results, a mathematic model of the V-shaped rubber element dynamic evolution by combining the rubber viscoelastic constitutive model, the three-dimensional dynamic stiffness calculation method of the V-shaped rubber element and the Arrhenius equation is established. Utilizing the rigid-flexible coupled dynamics modeling approach, a coupled dynamic model of the car body and underchassis equipment considering the dynamic evolution of rubber components is established. The results indicated that when rubber elements are used between the car body and underchassis equipment, two first-order vertical bending modes are generated. Compared to currently commonly used dynamic models, the proposed coupled dynamics model considering the dynamic evolution of rubber components in this article can better account for the effects of temperature and aging time on dynamics.

Keywords: rubber element, dynamic evolution, high-speed train, constitutive model, suspension system, coupled dynamics modelling

1 Introduction

To improve the comprehensive operating performance of high-speed trains, rubber-metal composite elements are widely used in high-speed train vibration-damping suspensions. As shown in Figure 1, the high-speed train car body and underchassis equipment are elastically connected through V-shaped rubber elements. Compared with metal springs, composite elements can not only reduce weight and simplify the design structure of the suspension system, but also provide stiffness and damping in the X, Y, and Z directions to better absorb and attenuate noise and vibration. However, the rubber will undergo performance ageing over time and temperature changes, and the performance of rubber elements made of it will evolve, which will have a significant impact on the overall operating performance of high-speed trains [1,2].

The characteristics of rubber materials are the focus of research for relevant scholars, including dynamic energy and damping, frequency dependency, amplitude dependency, and temperature dependency [3,4]. Meanwhile, due to the inherent material properties of rubber, its ageing has also been a focal point of scholars' attention [5,6]. In practical engineering applications, rubber test data is mostly fitted nonlinearly to establish viscoelastic constitutive models. However, the parameters fitted by this method do not have physical significance and cannot touch the essence of the material [7, 8]. In this paper, a constitutive model based on the mechanical properties of rubber is established, in which the relevant parameters have actual physical meanings. The vibration of the underchassis equipment of a distributed dynamic high-speed train set is usually connected to the car body through rubber elements, and the vibration of the underchassis equipment has recently become a research topic [9,10]. However, in the above-mentioned studies, the research mainly focuses on the dynamic changes of rubber materials and the vibration and control of underchassis equipment separately. The coupled dynamic characteristics caused by the dynamic evolution of rubber performance have not been thoroughly studied.

In this paper, a coupled dynamic model of the underchassis equipment and car body in high-speed railway vehicles that considers the dynamic evolution characteristics of rubber elements is established. Changes in train operating performance caused by rubber dynamic evolution are studied.

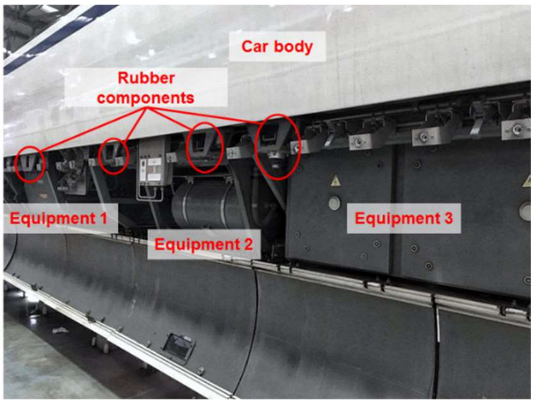


Figure 1: Elastic connection between high-speed train body and under-train equipment.

2 Methods

As shown in Figure 2, the V-shaped rubber element consists of two rectangular rubber pads and metal part. The rubber material is natural rubber (NR), and the metal frame is made of ductile iron QT550. Cut the rubber part of the V-shaped rubber element into multiple rectangular test specimens with a length of 60 mm, a width of 10 mm, and a thickness of 4 mm. The accelerated thermal-oxidative ageing test and dynamic mechanical property test of the test specimens were designed regarding industry standards [11,12]. The temperature of the hot air ageing test environment box is set to 70°C. After complete preheating, the test sample is placed in the test environment box for thermal oxygen ageing. According to the time-temperature equivalence principle, the observation time can be shortened. When each section of the test specimen reaches the set time, the sample is taken out and the dynamic thermomechanical analysis test is carried out. In this paper, the forced resonance method instrument is used to conduct dynamic thermomechanical analysis tests to measure the relationship between the dynamic mechanical performance parameters of the rubber part of the V-shaped rubber element under vibration load as it changes with temperature and frequency. In this work, the vibration characteristics in the frequency range of 0Hz~20Hz are mainly studied. Since the human body is more sensitive to low-frequency vibrations, and the main vibration frequency of the elastic car body of high-speed trains is relatively concentrated in the range of 0Hz~20Hz, and the vibration in the frequency range of 0Hz~20Hz has a greater impact on the vehicle's operating comfort, stability and other operating indicators. The scanning range of the dynamic temperature scanning test (temperature spectrum test) is set to -80°C ~80°C, and the constant test loading frequencies are set to 2 Hz, 10 Hz, 15 Hz, and 20 Hz respectively to measure the changes in the dynamic mechanical properties of the rubber with temperature. The dynamic frequency scanning test (frequency spectrum test) has a scanning range of 0.1 Hz ~ 20 Hz, and the constant test temperatures are set to -10 ℃, 0 ℃, 10 ℃, and 20 ℃ respectively. The dynamic mechanical properties of the rubber are measured with load at different constant temperatures. Based on the test results, the constitutive coefficients of the Four-parameter, three-element fractional Zener model (FZ Model) were identified to obtain a viscoelastic constitutive model that can reflect the rubber stress-strain relationship.

Combining the actual shape parameters of the V-shaped rubber element and the FZ model, the shape coefficient is introduced to establish a dynamic stiffness model of the V-shaped rubber element.

Combining the Arrhenius equation which can reflect the relationship between the thermal oxygen aging reaction rate of rubber elements and temperature and the ageing degree equation of rubber dynamic mechanical properties, a ternary mathematical model *P-T-t* is established to represent the variation of the viscoelastic dynamic mechanical performance of rubber elements with ageing temperature (*T*) and ageing time (*t*). Additionally, the ageing degree of rubber can be represented by the change rate of dynamic stiffness at any ageing time. Based on the above, a dynamic stiffness model of V-shaped rubber element that can reflect the changing relationship between dynamic stiffness and ageing time at different temperatures is established.

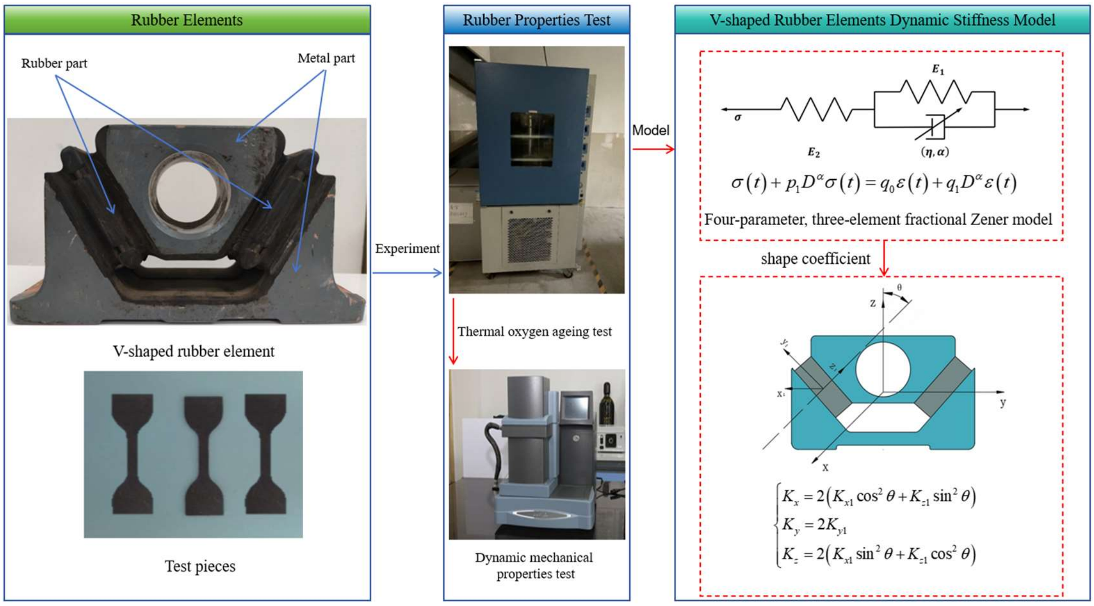


Figure 2: Calculation method of dynamic stiffness of the V-shaped rubber elements.

The polycondensation theory[13] is used to reduce the computational freedom of the rigid-flexible coupling dynamic model of high-speed trains while ensuring that the calculation accuracy meets the requirements. The process is shown in Figure 3. First, the finite element modal information is calculated, the finite element model is subjected to polycondensation calculation processing, and the polycondensation results are imported into Simpack to establish a high-speed train dynamics model with elastic car body information shown in Figure 4. In the finite element model, the V-shaped rubber element between the underchassis equipment and the car body is simulated using the RBE3 unit in the 1D unit. The elastic connection RBE3 unit usually needs to be used in conjunction with the CBUSH spring unit in the 1D unit to set the three-way dynamic stiffness and damping of the V-shaped rubber element. In the rigid-flexible coupling dynamic model, force element No. 5 (spring damping unit) and force element No. 102 are used to simulate the V-shaped rubber element. The No. 5 force element is used to input different stiffness and damping of rubber elements to simulate the effects of external temperature and ageing time. Meanwhile, the dynamic stiffness of the V-shaped rubber element changes with frequency, which can be described by the stiffness-frequency curve. Force element No. 102 is used in Simpack to represent the stiffness-frequency curve.

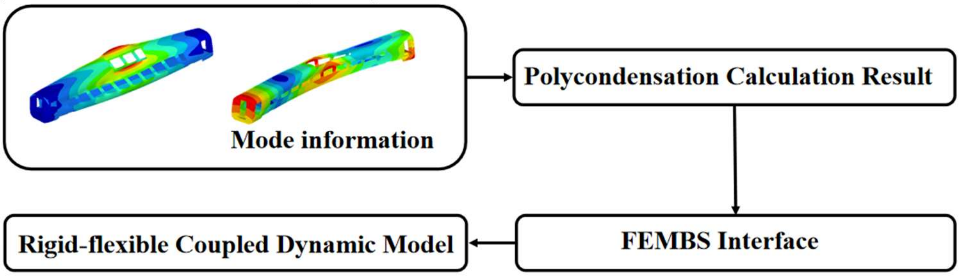


Figure 3: Rigid-flexible coupling dynamic model modeling process.

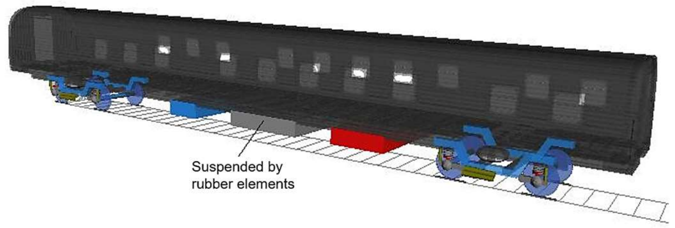
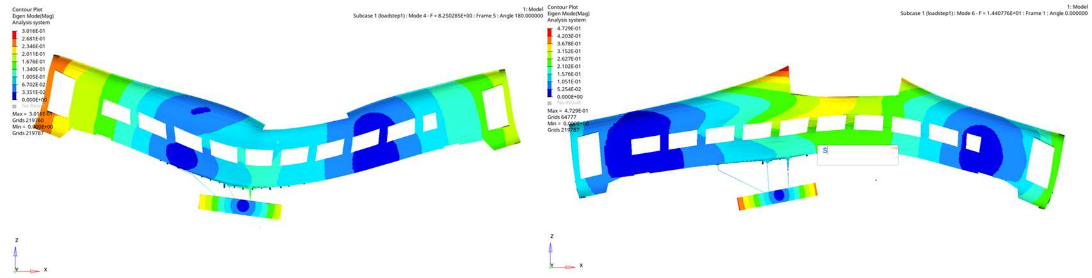


Figure 4: Rigid-flexible coupling dynamics model of train.

3 Results

In the finite element analysis results, when the elastic rubber elements are used to connect the car body and the underchassis equipment, two first-order vertical bending modes are observed in the car body. In the low-frequency bending mode, the car body and underchassis equipment vibrate in phase, referred to as the first-order low-frequency bending mode, as shown in Figure 5. In the higher frequency bending mode, the car body and underchassis equipment vibrate out of phase, referred to as the first-order high-frequency bending mode. The first-order low-frequency bending mode is caused by the natural frequency of the equipment, resulting in the vertical bending motion of the train car body. The first-order high-frequency bending mode is mainly due to the mutual coupling effect between the vertical bending natural mode of the car body and the underchassis equipment.

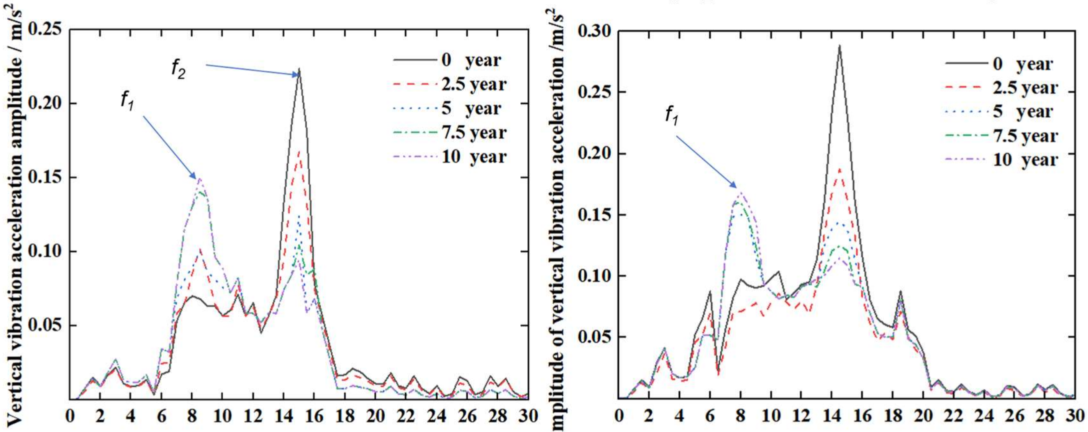


(a) First-order low-frequency bending mode.(b) First-order high-frequency bending mode.

Figure 5: First-order mode figure.

Set acceleration measuring point on the underchassis equipment and the corresponding floor of the car body above the equipment to analyze the vibration transmission characteristics between the two. The vertical hanging frequencies of the rubber elements at temperatures from -20 ℃° to 40 ℃° are within the damping hanging frequency range, and the vertical transmissibility is within the passenger-sensitive vertical low frequency range (4 Hz ~ 8 Hz), the transmissibility is less than 1, and rubber element has an attenuating effect on vibration. Changes in external ambient temperature mainly have a greater impact on the vertical transmissibility in the range of 7 Hz ~ 10 Hz. As the external ambient temperature increases, the attenuation effect weakens.

Calculate the degree of rubber ageing under the annual average temperature, and study the impact of rubber ageing on the vibration of the high-speed train body and underchassis equipment from 0 to 10 years. Set up an acceleration measurement point on the underchassis equipment and the corresponding floor above it to analyze the vertical vibration characteristics of the two points. As shown in Figure 6, with the increase in ageing time, there are changes in the vertical vibration energy distribution and frequency shift phenomenon between the car body and the underchassis equipment. The vibration energy at frequency f_2 of the underchassis equipment gradually decreases, while the vibration energy at frequency f_1 increases. The vibration energy near frequency f_1 of the car body gradually increases. This is due to the ageing of the rubber elements, leading to an increase in the dynamic stiffness of the rubber elements. As a result, the underchassis equipment gradually transitions from elastic suspension to rigid suspension, and the counter-phase motion between the underchassis equipment and the car body gradually weakens, leading to an increase in the vibration between the underchassis equipment and the car body.



(a) Train operation speed of 300 km/h, vibration amplitude spectrum of under-chassis equipment.(b) Train operation speed of 300 km/h, vibration amplitude spectrum of vehicle body above underchassis equipment

Figure 6: Vibration amplitude spectrum.

4 Conclusions and Contributions

The article describes the modeling process of the coupled dynamics model of the car body and underchassis equipment in high-speed railway vehicles, considering the dynamic evolution characteristics of the rubber components. The influence of the rubber elements on the modal properties of the car body and the effect of the dynamic performance evolution of the rubber elements on the coupled vibration of the car body and underchassis equipment are investigated. The results indicate that when elastic rubber elements are used between the car body and underchassis equipment, the car body exhibits two first-order vertical bending modes. With the increase in external environmental temperature, the vibration attenuation effect of the rubber elements in the passenger-sensitive low-frequency range is reduced. As the rubber ages, the dynamic stiffness of the rubber components gradually increases, causing the transition of the car body and undercarriage equipment from elastic suspension to rigid suspension, resulting in changes in vibration energy distribution and frequency shift phenomena between the car body and underchassis equipment.

Acknowledgements

The work presented in this paper is funded by the National Natural Science Foundation of China (grant number 52375115).

References

[1] Vibration and Control on Railway Vehicles, Fudan Univ., Shanghai, China,2019.

[2] C. Zong, D. Chen, Y. Zhou, and G. Shen, ‘‘Parameter optimal design of railway vehicle based on genetic algorithm,’’ Electr. Drive Locomotives,vol. 263, no. 4, pp. 33–36, 2018.

[3] Tiwari, V., S.C. Sharma and S.P. Harsha, Ride comfort analysis of high-speed rail vehicle using laminated rubber isolator based secondary suspension. Vehicle System Dynamics, 2023. 61(10): p. 2689-2715.

[4] Ahmad, N., et al., Predicting the effect of temperature on the performance of elastomer-based rail damping devices. Journal of Sound and Vibration, 2009. 322: p. 674-689.

[5] Shaafaey, M., et al., Investigation of hygrothermal aging on the polyurethane-based (PUB) adhesive: substantiating competition scenario between sub-aging thermo-oxidation and hydrolytic phenomena. Journal of Polymer Research, 2021. 28.

[6] Bahrololoumi, A., et al., A multi-physics approach on modeling of hygrothermal aging and its effects on constitutive behavior of cross-linked polymers. Journal of the Mechanics and Physics of Solids, 2021. 156: p. 104614.

[7] Mohammadi, H., et al., Constitutive Modeling of Elastomers During Photo- and Thermo-oxidative Aging. Polymer Degradation and Stability, 2021. 191: p. 109663.

[8] Mulliez, M.A., C. Schilling and T. Grupp, Influence of Irradiation Temperature on Oxidative and Network Properties of X-Ray Cross-Linked Vitamin E Stabilized UHMWPE for Hip Arthroplasty. BioMed Research International, 2020. 2020: p. 1-9.

[9] You, T., et al., Frequency response function-based model updating of flexible vehicle body using experiment modal parameter. Vehicle System Dynamics, 2021. 60: p. 1-25.

[10] Gong, D., et al., Frequency veering between car body and under-chassis equipment of railway vehicles in vertical bending mode. Mechanical Systems and Signal Processing, 2023. 185: p. 109768.

[11] ISO 188:2011,Rubber, vulcanized or thermoplastic — Accelerated ageing and heat resistance tests.

[12] ISO 37:2017,Rubber, vulcanized or thermoplastic — Determination of tensile stress-strain properties.

[13] Sun, Y., et al., Research on multi-point connection of under-chassis equipment suspension system in high-speed trains. AIP Advances, 2021. 11: p. 125315.