Sensitivity study of vibration responses on vehicle body to typical damages of ballastless track structures

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Abstract. A method is proposed to investigate the sensitivity of the vibration responses on vehicle body to typical damages of ballastless track structures based on a coupled rigid vehicle body and flexible track model. Firstly, a coupled rigid vehicle body and flexible track model is established by combining SIMPACK and ANSYS software, and the reasonableness of the model is verified by coupling analysis. And then, the sensitivity of the vibration signals from different parts of the vehicle body to the typical damages of the ballastless track is investigated by simulating several typical damages on the flexible track model, and the feasibility of inversion of track damage based on the responses on vehicle body is investigated. The results show that a reasonable coupled vehicle-track model can be established by combining the finite element and multi-body dynamics method. The changes in the vibration responses of the vehicle body can reflect the typical track damages such as the loosening of rail fasteners, the debonding of CA mortar layer and cracks in track plate. The wheel-set axle box is the optimal location for installing vertical vibration sensors.

1. Introduction

With the rapid development of high-speed railroad, ballastless track, as one of the main track forms with high stability and high smoothness, has been laid in a large scale in China, among which type of CRTSII plate ballastless track with good stability and smoothness has been applied in many high-speed railroads. However, with the growth of vehicle operation period and adapting to the changing natural environment, the track structure system will inevitably appear various damage diseases, such as cracks in track plate, debonding of CA mortar layer, loosing of fasteners, cracks in bearing layer, and separation of wide and narrow joints. At present, the common detection technologies of ballastless track include roughly manual detection, track inspection vehicle detection and other acoustic photoelectric nondestructive testing technologies. However, some of these detection technologies can not effectively determine the location and degree of damage, some are too expensive to realize real-time monitoring. Therefore, the development of rapid detection, identification and diagnosis methods for ballastless track disease has important engineering significance. In recent years, there has been preliminary research on damage detection for track structures based on vehicle vibration information. However, since there are many factors affecting the measured vehicle vibration response, it is difficult to diagnose track defects by using the measured data directly. Therefore, numerical simulation based on the methods to establish the vehicle-track system dynamics model, and through the numerical simulation of the disease to study the impact of the track structure damage on the dynamic characteristics of the vehicle body has been widely concerned. With the development of numerical simulation technology, in order to fully consider the complexity of the vehicle system, wheel-rail contact relationship, the combination of finite element theory and multi-body dynamics theory to
simulate vehicle-track coupling model came into being. SIMPACK is a multi-body dynamics software with obvious advantages in building vehicle models and solving wheel-rail contact. Compared to the wheel-rail contact simulation for sliding contact vehicle-track coupling, the wheel-rail contact in SIMPACK simulated as rolling contact is closer to the actual situation than the finite element software that simulates wheel-rail contact as sliding contact. However, it is more difficult to simulate the elastic track structure in SIMPACK as accurately as in the structural finite element software [1], and the combination of the two is more beneficial to establish a reasonable vehicle-track coupling model. Studies have confirmed the feasibility of using SIMPACK and ANSYS for joint simulations, but few studies are conducted to verify the feasibility of applying this type of coupled model to analyze the sensitivity of the dynamic responses to typical track diseases.

Based on this, this paper uses SIMPACK and ANSYS to establish a rigid vehicle body and flexible track coupling model, and on the basis of verifying the reasonableness of the model, simulates typical track damages to obtain the abnormal vibration signals of the vehicle body caused by ballastless track damages, and explores the sensitivity of the vibration signals from different parts of the vehicle body to the typical damages of the track through sensitivity analysis.

2. Establishment of coupling model of rigid vehicle body and flexible track

2.1. Modeling of rigid body dynamics of passenger vehicles

SIMPACK software is used to model a high-speed railroad passenger vehicle. In this model, the vehicle mainly consists of the body, bogies and wheelsets. The whole vehicle has front and rear bogies, and each bogie has two sets of wheelsets. The wheelsets are connected to the bogies through the first system of suspension, and the bogies are connected to the vehicle body through the second system of suspension. Air springs, transverse dampers and anti-snake dampers are installed between the body and the frame. Springs, vertical dampers and positioning rubber damping elements are provided between the axle-box and frame to provide the corresponding stiffness and damping [2]. The established vehicle model is shown in Figure 1.

2.2. Finite element modeling of flexible track and rail

Here CRTSII plate ballastless track is taken as the research object and is modeled by using ANSYS software. A beam-body finite element model is adopted in the modelling, which is modeled according to the actual size and material parameters of each member of its structure, which can better define the interlayer relationship between each member and is closest to the actual situation of the slab ballastless track structure [3]. The structure of CRTSII plate ballastless track from top to bottom is rail, fasteners, track slab, CA mortar layer, and support layer in order. Since the next step is the coupling analysis with the vehicle model, so the constraint with the roadbed is done in SIMPACK. The established finite element model of CRTSII plate ballastless track is shown in Figure 2, and the specific component parameters are as follows.

![Figure 1. Vehicle-ballastless track coupling model](image1)

![Figure 2. Finite element model of CRTSII ballastless track](image2)

The rails are standard 60 rails with modulus of elasticity of $2.06 \times 10^5$ MPa, Poisson's ratio of 0.3 and density of 7850 kg/m³. Solid unit of solid185 is used instead of beam unit to model the rail,
considering the stress concentration problem, the top and bottom surface of the rail are treated with CE rigid area.

The fasteners are modeled as three-way spring unit of combin14 with vertical and transverse stiffness of 50kN/mm and longitudinal stiffness of 28.5kN/mm. The vertical damping is taken as 60kN·s/m and the transverse and longitudinal damping are taken as 50kN·s/m.

The track slab is 6.5m long, 2.55m wide and 0.2m high. The solid185 elements are used for simulation, and its modulus of elasticity is $3.6 \times 10^{10}$Pa, Poisson's ratio is 0.2 and density is 2500 kg/m³.

The CA mortar layer is 0.03 m thick. The spring unit combin14 is used for simulation, and its modulus of elasticity is $7.0 \times 10^{3}$ MPa.

The support layer is a trapezoidal body of 6.5 m long, 2.95 m and 3.25 m wide on the upper and lower surfaces respectively, and 0.3m thick. It is simulated by solid unit of solid185, and its modulus of elasticity is $3.0 \times 10^{4}$MPa, Poisson's ratio is 0.2, and density is 2500 kg/m³.

2.3. Coupling analysis of rigid vehicle body-flexible track model

In order to implement the vehicle-track coupled model, it is needed to interact with ANSYS and SIMPACK software through FEMBS port. FEMBS is the interface program between the finite element analysis program and SIMPACK that generates the standard input files required for the simulation of elastomers and elastic structures in multi-body systems. In finite element analysis, the motion of a complex elastomer is represented by a large number of nodal motions, while the multi-body system dynamics program uses a relatively small number of orders of modal superposition to represent its elastic motion [4]. The coupled vehicle-track system model is shown in Figure 1.

Most of the literature does not introduce the detailed steps to realize the coupling or the introduction method is very abstract, so the whole coupling process is described in detail from four parts as follows.

(1) Firstly, the finite element modeling of the ballastless track structure is carried out in ANSYS, and then the model is generated into a cdb file and saved for sub-structure analysis, which is divided into three steps: generating part, using part and extending part. The generation part is the process of coalescing ordinary finite element units into one unit; the calculation of the use part includes the coalescence of the superunit and all calculations of the non-superunit; the extension part is the calculation of the entire superunit from the coalescence calculation results all degrees of freedom from the coalescence calculation results [4, 5]. The first two stages are covered in section 2.1 and 2.2, and the last one is the generated sub file.

(2) After practical verification, the required fbi files can be generated by SIMPACK software, and the generation of fbi files requires only cdb files and sub files.

(3) The generated fbi file needs to be called, and then it needs to write ftr file, the specific writing method can be found in SIMPACK's help file. The file can complete the constraint problem between the support layer and the foundation and the tandem problem between multiple rails and multiple track plates, and thus realize the multiple calls to the fbi file to achieve the ideal length of the ballastless track model.

(4) Store the fbi file and ftr file in the same folder, make the wheel-rail contact relationship modification in the wheelset, set up the solution method, vehicle speed and vehicle running time, and then the dynamic response calculation of the whole vehicle can be carried out.

After the rigid vehicle body and flexible track coupling model is set up, the vehicle dynamic response is calculated based on the established health coupling model. The vehicle speed is 200km/h, the calculation frequency is 500Hz, the running time is 5s, and the SODASRT2 solver is used for the calculation. Since the dynamic responses of the vehicle in the vertical direction are large, the vertical accelerations are used as the analysis criterion, and the vertical accelerations at the carriage, bogie and wheelset under the condition of no track unevenness are derived respectively (as shown in Figures 3 to 5).
From Figure 3, it can be seen that the amplitude of vertical acceleration at the front of the carriage is around 0.04m/s², which is much smaller than the limit value of 2.5m/s² specified in the Specification for the Test of High Speed EMUs [6]. As can be seen in Figure 4, after removing the abnormal vibration of the bogie at both ends due to the boundary conditions when the passenger vehicle is on and off the track, the smooth section vertical acceleration amplitude is around 0.1m/s². The calculated data in Figure 5 shows that the vertical acceleration amplitude of the wheelset is around 2m/s² and is more regular. Since track irregularities are not considered in this calculation and the calculation accuracy is high, the vertical acceleration amplitudes of the carriage, bogie and wheelset are small, about 10%-15% of the measured data. For the vehicle body vibration caused by the elastic deformation of the track itself only, it is close to the data in the literature [7]. This shows that the vehicle-track coupling model established in this paper has some reasonableness.

3. Sensitivity of vibration responses on vehicle body to typical damages of ballastless tracks

3.1. Typical damage simulation of ballastless track structure
The length of the track structure simulated in this paper is 32.5m, consisting of five track plates, with the starting point at 17.4m and the end point at 49.9m. In order to remove the boundary effect and ensure the accuracy of data results, the simulated damage location can be on from the second to the fourth plate, and here the damage location is uniformly set on the fourth track plate. The damage types are fastener loosening, track plate cracking, CA mortar layer debonding and bearing layer cracking. At the same time, in order to effectively verify and reflect the sensitivity of the vibration responses of each part of the vehicle to typical damages, the calculation is carried on without track unevenness external excitation, and simulation will be appropriately increase the degree of various types of damage. Specific damage simulation conditions as shown in Table 1.

3.2. Sensitivity analysis of vehicle body vibration responses to typical track damages
This section reflects the sensitivity of the vibration responses to various types of track damages by comparing the difference in vertical acceleration of each representative part of the vehicle before and after the damage for the four damage types simulated in Table 1. The differences in vertical acceleration of the front of the carriage, the bogie and the wheelset before and after the damage are presented in Figures 6 to 8.
Table 1. Simulation conditions of track damages

| Case No. | Type of damage     | Simulation method of damage | Damage location | Damage degree          |
|---------|--------------------|-----------------------------|-----------------|------------------------|
| 1       | Rail fastener loosing | Reduce three-way spring unit stiffness | Fourth track plate at 40.41m | 10% discount of spring stiffness |
| 2       | Track plate cracking | Reduce stiffness of some units | Fourth track plate at 40.02m | 50% discount of unit stiffness in length 0.39m |
| 3       | CA mortar layer debonding | Delete part of the spring unit | Fourth track plate at 40.02m | Full penetration type debonding in length 0.26m |
| 4       | Bearing layer cracking | Reduce stiffness of some units | Fourth track plate at 40.02m | Complete discount of unit stiffness within 0.13m length |

As can be seen from Figure 6, for the acceleration response of the front of the carriage, the amplitude change caused by the fastener loosening damage is the most obvious, and its vertical acceleration difference amplitude suddenly changes to about 0.0015m/s² when it is close to 0.5s, and there is also a large fluctuation after 0.5s. The remaining three types of damage can also be reflected visually, and its vertical acceleration difference amplitude is about 0.00025m/s². The four types of damage amplitude waveform is close to each other. It can also be seen from Figure 7 that the change is most obvious at the front bogie when the front bogie fasteners are loosened and damaged, around 0.01m/s². The remaining three types of damage compared to the fastener loosening damage amplitude is smaller, and the four types of damage amplitude waveform is also relatively close. Figure 8 shows the vertical acceleration difference of wheelset are more intuitive and clear than the other two vibration responses in reflecting the four types of track damages. Among them, for the fastener loosening damage, the vertical acceleration difference is the most significant with amplitude of about 0.15m/s² or so. The above results show that the vibration responses of each part of the vehicle body...
are the most sensitive to the fastener loosening damage, and can also clearly reflect the CA mortar layer debonding and track plate cracking. Compared to the previous three types of damage, the sensitivity to the bearing layer crack damage is relatively weak. For the same type of damage, the vibration response on the wheelset is more sensitive than that on the bogie and carriage, so the wheelset can be chosen as the priority measurement point of the vibration response of the vehicle body.

4. Conclusions
In this paper, a rigid vehicle body and flexible track coupling model is established by combining SIMPACK and ANSYS software, and the sensitivity of the vibration signals from different parts of the vehicle body to the typical damages of the track is systematically investigated by using the coupling model as the analysis object. The results show that a reasonable vehicle-track coupling model can be established by combining finite element and multi-body dynamics, which can be used to effectively explore the sensitivity of the dynamic response of the vehicle body to the damage state of typical damage of CRTSII plate ballastless track. The vibration response of each part of the vehicle body is most sensitive to fastener loosening damage, and relatively sensitive to CA mortar layer debonding damage and track plate cracking, but less sensitive to bearing layer cracking. Compared with the carriage and bogie, the wheelset is the most obvious component of the vehicle reflecting various types of track damage. Thus, it is feasible to study the sensitivity of vehicle dynamic response to typical track damage through the rigid-flexible coupling model, which can provide reference value for the subsequent related work. Typical track damages including rail fastener loosening, CA mortar layer debonding and track plate cracking and other track damages will cause sudden changes in the vehicle vibration responses. Analyzing the vehicle vibration responses is expected to inverse the damage state of the track structure. The wheelset axle box is the optimal location for installing vertical vibration sensors.

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