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An iterative method for solving the dynamic response of railway vehicle-track coupled systems based on prediction of wheel-rail forces

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ABSTRACT

An iterative method based on prediction of wheel-rail forces is presented to determine the dynamic response of railway vehicle-track coupled systems. The key idea of the present method lies in the modification of the starting value of each step during the iteration by prediction. The conventional iterative method begins iteration of the current step at the previously converged value of the wheel-rail forces. However, in the present method, the predicted wheel-rail forces by the Weighted Least-Squares Error (WLSE) predictor are used as the starting value for the current step. The equations of motion of the vehicle and the track subsystems are established separately and solved iteratively. According to the response of the wheelsets and the rails, and considering the track irregularity, the predicted wheel-rail forces are corrected by the wheel-rail interaction model in which detailed wheel rail contact geometry relations and nonlinear wheel rail creep forces are taken into account. The relaxation technique is adopted to solve the problem of numerical diffusion in the iterative process.

A moving vehicle travelling on a two layer flexible track is considered in this study. The accuracy of the proposed method is verified by comparing the results obtained from the present method with the results from the commercial software NUCARS and the efficiency are verified by comparing with the conventional iterative method. Numerical results show that the present method not only gives results comparable to those using the NUCARS software in terms of accuracy, but also saves at least 25% computational cost compared with the conventional iterative method. With the nonlinear wheel-rail contact relation fully considered, the present method can get more detailed results of the vehicle-track coupled model. Meanwhile, the efficiency of the present method is enhanced by means of prediction of wheel-rail forces with the WLSE predictor.

1. Introduction

The dynamic model of the vehicle-track coupled system and its solution method are essential to a series of advanced studies, such as evaluation of running safety and ride comfort performance of high speed trains, prediction of wheel wear and vibration noise. The numerical results can be used as a theoretic guidance for finding out the cause of some practical engineering problems such as out of round wheels, rail corrugation, identifying the sources of vibration or noise, and developing solutions or treatments to those problems. Therefore, it is of significance to solve the dynamic response of the vehicle-track coupled system efficiently and accurately.

The dynamic response of the vehicle-track coupled system can be solved in either the frequency or the time domain [1]. The frequency method is applicable for efficient solution of infinite length or periodic track structures, especially for the solution of wheel-rail dynamic interaction at high frequencies, but the time domain solution appears to be necessary where there are significant nonlinearities such as wheel rail contact geometry relation and stick-slip.

For solving the dynamic response of the vehicle and track system in time domain, there are mainly two methods available: the coupled method and the iterative method. The coupled method considers the vehicle and the track subsystems as a whole and solves the coupled system equations without any iteration by a step-by-step integration method. However, the system coefficient matrices vary according to the position of the vehicles on the track and must be updated and decomposed at every time step. This will reduce the computational efficiency. Another drawback is that the

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formulation of coefficient matrices depend on both the vehicle and track models, that is to say, all coefficients must be changed if a new type of vehicle or track is introduced. The iterative method can effectively avoid these shortcomings.

In the iterative method, the whole system is divided into two subsystems at the interface of vehicle and track. The two subsystems are coupled by enforcing equilibrium of forces and compatibility of displacements at the contact points between the wheels and the rails. The equations of motion of the two subsystems are solved separately with an iterative procedure. Green and Cebon [2,3] involved convolution of the vehicle loads with modal response of the bridge to predict its dynamic response under a given set of vehicle wheel loads and extended this method to include dynamic interaction between the vehicle and bridge by an iterative procedure. Yang and Fonder [4] presented an iterative method to solve the dynamic response of the Yangtze-River Bridge at Wuhan under a moving train with 2 locomotives and 4 freight vehicles. Xu et al. [5] performed dynamic analysis of coupled train and cable-stayed bridge systems in cross winds with an iterative procedure. Majka and Hartnett [6] developed a numerical model which incorporated a three dimensional multi-body train and a finite element bridge to investigate the effects of various parameters, such as the speed of the train, train-to-bridge frequency, mass and span ratios, bridge damping, on the dynamic response of railway bridges with a modified Newton-Raphson iterative procedure. Zhang et al. [7] proposed a coupled wind-vehicle-bridge dynamic model which considered the shielding effect of bridge tower with triangular wind barriers and solved the vehicle-bridge dynamic equations with time-varying external loads. Nguyen et al. [8] considered the vehicles and substructure as two separate systems interacting though a proposed wheel-rail contact model and proposed a new iterative scheme for solution of wheel-rail contact forces and checking contact loss. Hawk and Ghali [9] proposed an analytical procedure called the iterative dynamic substructuring method (IDSM) to solve the response of a beam-slab bridge system traversed by multi-axle trucks without consideration of roughness effects. Marchesiello et al. [10] dealt with the interaction of a multi-span continuous bridges modelled by isotropic plates with a vehicle modelled by seven degrees of freedom mass-spring-damper system moving at constant speed and computed the dynamic response of the vehicle and the bridge iteratively. Feriani et al. [11] studied the dynamic interaction between a travelling vehicle and a bridge and compared both the performance and the efficiency of the two iterative procedures which performed either on the whole time history (WTH) or in the single time step (STS). Vincenzi et al. [12] analyzed the dynamic interaction between trains and a bridge and carried out a parametric investigation, including the influence of the travelling speed and the weight of the train on dynamic response. Lei et al. [13] presented a cross iteration algorithm to solve the dynamic response of the China's high speed train CRH3 vehicle and slab track coupling system. Li et al. [14] developed a computer-aided numerical method for analyzing coupled railway vehicle-bridge systems of nonlinear features and investigated the convergence of iterative computation schemes with and without wheel jumps. In the iterative method, the decomposition of the coefficient matrices at every time step can be avoided and thus a more efficient solution method can be developed separately according to the structural characteristics of each subsystem. But it is worth noting that the iteration process may not be easy to converge or converge slowly, especially for large-scale structures. These disadvantages restrict the scope of application of the iterative method.

To overcome the drawbacks of the aforementioned solution methods, an iterative solution method based on prediction of wheel rail forces is proposed and verified in this paper. The wheel-rail forces are predicted by the WLSE predictor and then substituted into the equations of motion of the vehicle and track separately to solve the dynamic response of each subsystem. According to the response of the wheelsets and the rails, considering the track irregularity, the predicted contact forces are corrected by the wheel-rail interaction model. If the difference between the corrected and the predicted forces is greater than the specified tolerance, iteration continues until convergence is achieved. The relaxation technique is adopted to avoid the problem of numerical diffusion in the iterative process. Taking the CRH2 vehicle [15] running on a straight track as an example, the dynamic response of the vehicle to different types of track irregularities is solved in time domain by the present method, the conventional iterative method and NUCARS, respectively. The accuracy of the present method is demonstrated through a detailed comparison of numerical results with NUCARS and the efficiency is verified by comparing the computation cost with the conventional iterative method.

2. Vehicle-track coupled dynamic model

The iterative method proposed in this paper is not limited to the types of vehicles and track. Due to the limitation of the modelling capabilities of the track structure in NUCARS, the track is modelled as two parallel Euler beams with a finite length laid on two-layer flexible point supports. The vehicle is modelled as a mass-spring-damper system with 35 DOFs. The predicted wheel-rail forces are corrected by the wheel-rail interaction model to consider the nonlinear effects related to wheel-rail contact.

2.1. Equations of motion of vehicle subsystem

The CRH2 is one of the high-speed trains running in China, with the operating speed of 200 km per hour. Based on the structural characteristics of the CRH2 vehicle, a three dimensional dynamic model for one single vehicle is developed in this paper, composed by one car body resting on two frames and four wheelsets, as shown in Fig. 1. The car body, frames and wheelsets are all modelled as rigid bodies. Each rigid body is assigned with 5 DOFs, which are the lateral y, vertical z, roll ϕ, pitch β and yaw ψ, while the longitudinal motion is supposed to be known and characterized by a constant speed V. Thus the total number of DOFs of the vehicle model is 35. For convenience, the front and rear frames are numbered 1 and 2 respectively; the wheelset at the front of the vehicle along the running direction is numbered 1 and others are numbered 2, 3 and 4 consecutively. The left wheels or rail refer to the wheels or rail on the left when viewed from the front. Such a 35-DOF model is widely used, for example, in [16,17].

By assuming motion about the static equilibrium position, the equations of motion of the vehicle can be written as

$$\boldsymbol{M}_v\ddot{\boldsymbol{X}}_v + \boldsymbol{C}_v\dot{\boldsymbol{X}}_v + \boldsymbol{K}_v\boldsymbol{X}_v = \boldsymbol{F}_{vt} \tag{1}$$

where $\boldsymbol{X}_v$, $\dot{\boldsymbol{X}}_v$ and $\ddot{\boldsymbol{X}}_v$ are the vectors of displacement, velocity and acceleration of the vehicle subsystem, respectively. The displacement vector $\boldsymbol{X}_v$ can be written as

$$\boldsymbol{X}_v = \left\{\boldsymbol{x}_c^{\mathrm{T}}, \boldsymbol{x}_{t_1}^{\mathrm{T}}, \boldsymbol{x}_{t_2}^{\mathrm{T}}, \boldsymbol{x}_{w_1}^{\mathrm{T}}, \boldsymbol{x}_{w_2}^{\mathrm{T}}, \boldsymbol{x}_{w_3}^{\mathrm{T}}, \boldsymbol{x}_{w_4}^{\mathrm{T}}\right\}^{\mathrm{T}} \tag{2}$$

Subscripts "c", "t_1", "t_2", "w_1", "w_2", "w_3" and "w_4" denote the car body, front frame, rear frame and wheelsets 1–4 respectively.

$$\boldsymbol{x}_i = \{y_i, z_i, \phi_i, \beta_i, \psi_i\}^{\mathrm{T}}, \quad i = c, t_1, t_2, w_1, w_2, w_3, w_4 \tag{3}$$

$\boldsymbol{M}_v$, $\boldsymbol{K}_v$, $\boldsymbol{C}_v$ are the mass, stiffness and damping matrices of the vehicle system respectively and can be expressed as follows

$$\boldsymbol{M}_v = \mathrm{diag}\left[\boldsymbol{M}_c, \boldsymbol{M}_{t_1}, \boldsymbol{M}_{t_2}, \boldsymbol{M}_{w_1}, \boldsymbol{M}_{w_2}, \boldsymbol{M}_{w_3}, \boldsymbol{M}_{w_4}\right] \tag{4}$$