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Dynamic analysis of coupled vehicle–bridge system based on inter-system iteration method

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ABSTRACT

An inter-system iteration method is proposed for dynamic analysis of coupled vehicle–bridge system. In this method, the dynamic responses of vehicle subsystem and bridge subsystem are solved separately, the iteration within time-step is avoided, the computation memory is saved, the programming difficulty is reduced, and it is easy to adopt the commercial structural analysis software for bridge subsystem. The calculation efficiency of the method is discussed by case study and an updated iteration strategy is suggested to improve the convergence characteristics for the proposed method.

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1. Introduction

The dynamic effect of the vehicle is an important problem in railway bridge design, especially for high-speed railway and heavy-haul railway bridges. In recent years, the dynamic analysis of vehicle–bridge interaction system has been carried out for lots of cases to ensure the safety of bridge structure and running train vehicles and the riding comfort of passengers. For example, the lateral amplitude of steel plate girders with 20–40 m spans was found too large after the raise of train speed during 2000–2003 in China. To enhance the lateral stiffness of the girders, Xia et al. [1] performed numerical analysis on vehicle–bridge system to over 100 reinforcement measures and decided the final ones. Through in site experiments, the reinforcement measures were validated that they can effectively reduce the lateral amplitude as predicted.

In most of the researches, the vehicle is modeled by the multi-body dynamics, while the bridge is modeled by the FEM (finite element method) discretized with the direct stiffness method or the modal superposition method. In these analyses, the wheel–rail interaction assumptions are quite different, which they can be divided into three categories:

(1) *Moving loads*. By neglecting the local vibration and the mass effect, the vehicle can be simplified into a series of moving loads. The method is widely used in analytical studies and the cases with low bridge stiffness. Only the bridge model is adopted in the method and the system can be analyzed by a time history integral method.

(2) *Compatible motion relationship*. The vehicle and the bridge are linked with the wheel–rail relative motion relationship. In vertical direction, the wheel-set is commonly assumed to have the same motion with the track at the wheel–rail contact point. In lateral direction, Xia et al. [1] and Xu et al. [2] used the hunting movement to define the wheel–rail relative motion, while Guo et al. [3] took the measured bogie hunting movement as the lateral system exciter.

(3) *Force–motion relationship*. The wheel–rail interaction force is defined as the function of wheel–rail relative motion. Zhai et al. [4] adopted the Kalker's linear theory and the Hertz contact theory to define the wheel–rail interaction force, in which the lateral/tangent wheel–rail force is the product of the creep coefficient and the wheel–rail relative velocity, the vertical/normal wheel–rail force has a non-linear relationship to wheel–rail relative compression deformation. Zhang et al. [5] simplified the Zhai's definition to meet the linear wheel–rail relation both in lateral and vertical directions. Torstensson et al. [6] and Fayos et al. [7] modeled the rotating wheel-set and derived the wheel–rail interaction force by kinematics methods.

Some researches focused on the effect of the parameters in the vehicle–bridge interaction system, including the effects of the ratio of train/bridge natural frequency, the ratio of train/bridge mass, the ratio of train/bridge length [8], the track irregularity, the bridge skewness [9], the bridge stiffness and the bridge damping [10].

The numerical method in solving the vehicle–bridge interaction equations is dependent on the wheel–rail interaction assumption. Gao and Pan [11], Li et al. [12] and Jo et al. [13] modeled the vehicle and the bridge subsystem separately, and solved them with time

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history integral method TSI (time-step iteration), where the two subsystems meet the equivalent equations within each time-step by iteration. Xia et al. [1], Antolin et al. [14] and Yang and Yau [15] coupled the two subsystems into global equations with varying coefficients by adopting the wheel–rail interaction into the non-diagonal sub-matrices. Feriani et al. [16] and Shi et al. [17] used a complete time history iteration method in which the two subsystems was analyzed separately and linked by an interface program, but their studies only concerned the vertical interaction force for highway bridges and trucks.

The lateral and the torsional interaction forces are not necessary for analysis of highway bridges but are very important for railway bridges. In this paper, an iteration method for solving the railway vehicle–bridge interaction system is proposed, considering the vertical, lateral and torsional interaction between the bridge and the railway vehicle, and adopting the track irregularity and the wheel–rail force–motion relationship (inter-system iteration, ISI). In the ISI method, firstly, the bridge subsystem is assumed rigid, while the vehicle motion and wheel–rail force histories are solved by the independent vehicle subsystem for the complete simulation time; next the bridge motion can be obtained by applying the previously obtained wheel–rail force histories to the independent bridge subsystem. Following, the updated bridge deck motion histories are combined with the track irregularities to form the new excitation to the vehicle subsystem for the next iteration process, until the given error threshold is satisfied.

2. The ISI analysis method for vehicle–bridge interaction system

The vehicle–bridge interaction system is composed by the vehicle subsystem and the bridge subsystem; the two subsystems are linked by the wheel–rail interaction; the given track irregularity is taken as an additional system exciter.

The same coordinate systems are adopted for the both subsystems and the track irregularity: *X* denotes the train running direction, *Z* upward, and *Y* is defined by the right-hand rule. *U*, *V* and *W* denote the rotational directions about the axes *X*, *Y* and *Z*, respectively.

The coordinate systems of both vehicle and bridge subsystem are absolute, and they have the same coordinate direction and length unit. Each rigid body in the vehicle has its independent coordinate system, with the origin in *Y* and *Z* directions at the static equilibrium position of each rigid body. According to the assumptions in Section 2.1, there is no X-DOF considered in the vehicle subsystem, so it is no need to define the origin of coordinates in *X* direction.

2.1. Vehicle model

The following assumptions are adopted for the vehicle model and the wheel–rail interaction:

(A1) The train runs over the bridge at a constant speed.
(A2) The train can be modeled by several independent vehicles by neglecting the interaction among them.
(A3) Each vehicle is composed of one car-body, two bogies, four or six wheel-sets and the spring-damper suspensions between the components.
(A4) By the Kalker's Linear theory, the lateral (*Y*) displacement of the wheel-set is the product of the creep coefficient and the wheel–rail relative velocity.
(A5) By the wheel–rail corresponding assumption, the wheel-set and the rail have the same vertical (*Z*) and rotational (*U*) displacements at the wheel–rail contact point.
(A6) Each car-body or bogie has five independent DOFs in directions *Y*, *Z*, *U*, *V* and *W*; each wheel-set has 1 independent DOF in direction *Y* and 2 dependent DOFs in directions *Z* and *U*.

Some measured results indicated that the wheel-set yaw angle in high-speed trains is much smaller than that in the traditional trains, partly due to the special structure of yaw dampers mounted on the high-speed trains, thus the wheel-sets' DOF in *W* direction (yaw angle) is not considered in the vehicle model.

From assumption (A2), the vehicle subsystem can be considered as several vehicles separately. Thus the dynamic equations for an individual vehicle are:

$$\mathbf{M}_{\mathrm{V}}\ddot{\mathbf{X}}_{\mathrm{V}} + \mathbf{C}_{\mathrm{V}}\dot{\mathbf{X}}_{\mathrm{V}} + \mathbf{K}_{\mathrm{V}}\mathbf{X}_{\mathrm{V}} = \mathbf{P}_{\mathrm{V}} \tag{1}$$

where $\mathbf{M}_{\mathrm{V}}$, $\mathbf{C}_{\mathrm{V}}$ and $\mathbf{K}_{\mathrm{V}}$ are the mass, damping and stiffness matrices of the vehicle, which are constant matrices [5]; $\mathbf{P}_{\mathrm{V}}$ is the force vector; $\mathbf{X}_{\mathrm{V}}$ is the displacement vector, containing the independent DOFs of the car-body, the bogies and the wheel-sets. There are 19 independent DOFs and 8 dependent DOFs for a 4-axle vehicle; 21 independent DOFs and 12 dependent DOFs for a 6-axle vehicle. For example, the displacement vector $\mathbf{X}_{\mathrm{V}}$ of a 4-axle vehicle is:

$$\mathbf{X}_{\mathrm{V}} = [y_{\mathrm{C}}, z_{\mathrm{C}}, u_{\mathrm{C}}, v_{\mathrm{C}}, w_{\mathrm{C}}, y_{\mathrm{T1}}, z_{\mathrm{T1}}, u_{\mathrm{T1}}, v_{\mathrm{T1}}, w_{\mathrm{T1}}, y_{\mathrm{T2}}, z_{\mathrm{T2}}, u_{\mathrm{T2}}, v_{\mathrm{T2}}, w_{\mathrm{T2}}, y_{\mathrm{W1}}, y_{\mathrm{W2}}, y_{\mathrm{W3}}, y_{\mathrm{W4}}]^{\mathrm{T}}$$

where the subscript C stands for the car-body, T1 and T2 for the front and rear bogie, W1 and W2 for the wheel-set linked to the front bogie, W3 and W4 for the wheel-set linked to the rear bogie, respectively.

2.2. Bridge model

The bridge model can be established by the FEM. The dynamic equations for the bridge subsystem can be written as:

$$\mathbf{M}_{\mathrm{B}}\ddot{\mathbf{X}}_{\mathrm{B}} + \mathbf{C}_{\mathrm{B}}\dot{\mathbf{X}}_{\mathrm{B}} + \mathbf{K}_{\mathrm{B}}\mathbf{X}_{\mathrm{B}} = \mathbf{F}_{\mathrm{B}} \tag{2}$$

where $\mathbf{M}_{\mathrm{B}}$, $\mathbf{C}_{\mathrm{B}}$ and $\mathbf{K}_{\mathrm{B}}$ are the global mass, damping and stiffness matrices, $\mathbf{F}_{\mathrm{B}}$ and $\mathbf{X}_{\mathrm{B}}$ are the force and displacement vectors of the bridge subsystem, respectively.

It is very important to note that the lumped mass method cannot be adopted for the mass matrix. Because if the diagonal elements related to the torsional (*U*) DOFs in $\mathbf{M}_{\mathrm{B}}$ is zero, the torsional moment of the vehicle may cause unreasonable angular acceleration for the bridge deck.

In some cases, the modal superposition method may be used in modeling the bridge subsystem to reduce the number of DOFs. The equations of the bridge subsystem are expressed as:

$$\ddot{\mathbf{X}}_{\mathrm{B}} + 2\xi_{\mathrm{B}}\boldsymbol{\omega}_{\mathrm{B}}\dot{\mathbf{X}}_{\mathrm{B}} + \boldsymbol{\omega}_{\mathrm{B}}^2\mathbf{X}_{\mathrm{B}} = \Phi_{\mathrm{B}}^{\mathrm{T}}\mathbf{F}_{\mathrm{B}} \tag{3}$$

where ξ_{B} and ω_{B} are the damping ratio and circular frequency diagonal matrices, respectively; Φ_{B} is the modal matrix.

For the same reason, if lumped mass method is adopted, there is no torsional mode in Φ_{B} and the torsional moment and angle cannot be included in calculation. Therefore, the consistent mass matrix for the bridge subsystem is used to reflect the torsional dynamic characteristics of the bridge.

2.3. Track irregularity

The track irregularity is the distance of the actual position and the theoretical position of the rail. According to the definition in rail engineering, the track irregularities are defined as:

$$\begin{cases} y_{\mathrm{I}} = \frac{y_{\mathrm{R}}+y_{\mathrm{L}}}{2} \\ z_{\mathrm{I}} = \frac{z_{\mathrm{R}}+z_{\mathrm{L}}}{2} \\ u_{\mathrm{I}} = \frac{z_{\mathrm{R}}-z_{\mathrm{L}}}{g_0} \end{cases} \tag{4}$$

where y_{L} and y_{R} are the lateral irregularities for the left and the right rail; z_{L} and z_{R} are the vertical irregularities for the left and the right rail; g_0 is the rail gauge; y_{I}, z_{I} and u_{I} are the align (lateral), vertical

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