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Effect of track irregularity on the dynamic response of a slab track under a high-speed train based on the composite track element method

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ABSTRACT

Slab tracks are common track structures in high-speed railways. In this study, a vehicle/slab track interaction model is developed based on vehicle–track coupling dynamics theory, and composite track elements are used to rapidly model the finite element equations of the slab track based on the stationary value theory of total potential energy. In the model, the rail is represented as a discretely-supported infinite beam, the slab and the base are considered as continuously-supported free beams, and the connections of the track structure are modelled as viscoelastic spring–damping elements. The composite track element method effectively derives the equations of motion with high or low degrees of freedom by increasing or decreasing the number of track elements; therefore, it can be applied to the dynamic analysis of the track and to investigate the dynamic responses of the slab track system, including the rail, pad, slab, Cement asphalt mortar (CA mortar) and base. The equations of motion of the vehicle system are also proposed using the finite element method. The vehicle system and the slab track system interact through the vertical wheel/rail force, which is approximated using Hertz contact theory. The dynamic responses of a slab track subjected to moving vehicle loads are analysed using dynamic simulations and are compared with another classic simulation method. The effects of random track irregularity and vehicle velocity on the dynamic responses of the slab track system are discussed.

1. Introduction

In recent years, slab tracks have been widely applied in ballastless tracks of high-speed railway lines because they have several operational advantages, such as lower maintenance (70–90% less than ballasted tracks [1,2]), higher lateral and longitudinal permanent stability that is sensitive to non-uniform and uneven settlement, the prevention of ballast particles being churned up under high-speed trains, and better ride comfort and safety due to the higher stability and better track performance. In Japan, slab tracks were first investigated and used widely in the Shinkansen high-speed railway in the 1960s [3]. In China, 42 high-speed passenger railway lines and intercity railways with a total length of 10,000 km were in operation by 2012 [4]. Fig. 1 shows the CRTS-I slab track and its components. The main components of the slab track system are the rails, rail pads, prefabricated slabs, CA mortar layers, and concrete bases.

Most research on slab tracks has focused on structural design and static analysis, and several studies have concentrated on the development and design of new slab tracks [1]. Only a few studies have focused on the dynamic analysis of slab tracks under moving vehicles. Steenbergen et al. [5] performed a dynamic parameter analysis of a slab track system. They used the classical model of a beam subjected to a moving load in an elastic half-space to assess the application of the slab track on soft soil by analysing the effect of the generalised dynamic stiffness of the track system. Their aim was to minimise the slab vibrations and to prevent deterioration of the slab. Auersch [6] calculated the dynamic interaction within the slab track system in detail using a combination of the finite element method and the boundary element method. Bezin et al. [7] developed a flexible track model and used multi-body dynamics software to simulate the dynamic interaction between a vehicle and two new kinds of slab track and compare their performance to conventional ballasted track. Gulgou-Carter et al. [8] performed an analytical and experimental study of the SAT S 312 sleeper in a Sateba slab track system (consisting of a SAT 312 double block concrete sleeper in two rigid hulls made of synthetic material with strict geometric tolerances). Their papers developed a simple prediction technique for a slab track system composed of two rails with rail pads, sleepers with sleeper pads, and a concrete base based on a two-dimensional (2D) model. The dynamic stiffness of

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the sleeper pads in the full-width section of the track was tested experimentally, and the effect of the dynamic stiffness of the sleeper pads on the vibration reduction was studied in detail. Galvin et al. [9] used a general three-dimensional multi-body finite element–boundary element model to study the vibrations of ballastless tracks under train loads. With the development of high-speed railways in China, an increasing number of researchers have recently focused on the dynamic behaviours of slab track-high-speed train coupling systems. Zhai et al. [10] developed a vehicle–slab track vertical interaction model in which the vehicle was considered as a multi-body system, and the track was considered as an Euler beam on a continuous elastic foundation. The dynamic properties of a slab track in a high-speed railway were investigated, and the effects of elasticity and damping of the CA mortar layer under the slab on system dynamics were analysed. Later, Cai and Zhai [11] developed a spatial model to investigate the dynamic behaviour of a track slab based on thin plate theory that considered the vertical and lateral movements of the slab track and vehicles. Zhao et al. [12] investigated the dynamic behaviour of a high-speed train–slab track coupling system based on composite track elements, and the track model only included the rail, pad, slab and CA mortar layers and ignored the concrete base. Lou and Xiang et al. [13,14] proposed a new dynamic analysis model of the lateral finite strip and slab segment element. The vertical displacements of the rail were obtained using the traditional static model, and the vertical displacements of the slab were obtained using the dynamic analysis model of the lateral finite strip and slab segment element. The maximum vertical static displacements and the maximum dynamic displacements of the rail and the slab were compared. Lei and Zhang [15] proposed the vehicle and track elements method to study the dynamic behaviour of the CRTS II slab track in high-speed railways in China. In this method, the entire vehicle was considered as a special element, a massless rail beam modelled the wheel–rail interaction, and the track was considered as a composite beam element on a continuous elastic foundation consisting of the rail, slab and concrete base layers. This method can improve the calculation efficiency, whereas the passing frequencies of the distance between the bogie centres at a given speed, which are related to the track slab vibration, were ignored.

In this paper, a vehicle/slab track interaction model is developed based on vehicle–track coupling dynamics theory, and composite-track elements are adopted to rapidly model the finite element equations of the slab track based on the stationary value theory of total potential energy. In the model, the rail is represented as a discretely-supported infinite beam, both the slab and the base are considered as continuously-supported free beams, and the connections of the track structure are modelled as viscoelastic spring–damping elements. The composite-track element method can effectively derive the equation of motion with high or low degrees of freedom by increasing or decreasing the number of track elements; therefore, it can perform a dynamic analysis of the track and investigate the dynamic responses of the slab track system, including the rail, pad, slab, CA mortar, and base. The equations of motion of the vehicle system are also proposed using the finite element method. The vehicle system interacts with the slab track system through the wheel/rail vertical force, which is approximated using Hertz contact theory. The associated stiffness matrix, mass matrix, and damping matrix for the elements are deduced based on the model. To validate the proposed model, an example using the same computational conditions as those described in a previous study is analysed. Several of the dynamic behaviours of the slab track structure, such as the wheel/rail force, the reduction in wheel load resulting from the vehicle–track interaction, the vibration acceleration and displacement, and the surface dynamic strain of the CA mortar and subgrade, are investigated under the excitation of random track irregularities with wavelengths of 1–50 m and 0.01–50 m. To fully understand the dynamic behaviour of the slab track, the effects of the train speed on the track vibration are evaluated.

2. The vertical dynamic model of the high-speed train and slab track coupling system

Based on the theory of vehicle–track coupling dynamics and considering the high-speed vehicle and slab track as a system, a vertical dynamic analysis model for the high-speed train–slab track coupling system is developed. The following assumptions are made in the model.

(1) The vehicles and the railway track are considered to be symmetrical about the centreline of the track, and the longitudinal motion of the track has no effect in railway tangent track; only half of the coupling system and only vertical vibrational behaviour are considered in the simplified calculation.
(2) The full vehicle is represented by a rigid body model of a car body, two bogies, and four wheelsets connected to each other with springs and dampers. The wheelset and the bogie are connected by the primary suspension, and the body is supported on the bogie by the secondary suspension. Vertical and pitch motions for the body and bogie and vertical motion for the wheelset are considered. Vertical downward displacements and clockwise rotations of the vehicle system are regarded as positive. Therefore, there are ten degrees of freedom of the vehicle model: seven vertical motions and three pitch motions.
(3) The vehicle system and the slab track system interact through the wheel/rail vertical force, which is approximated by Hertz contact theory.
(4) The rail is considered as an Euler beam that is supported discretely by linear viscoelastic springs, and the slab and the base are considered as Euler beams that are supported continually by linear viscoelastic springs. The connections between them and the subgrade are modelled as viscoelastic spring–damping elements.

In Fig. 2, M_c and J_c are the mass and rotational inertia of the car body, respectively; M_t and J_t are the mass and rotational inertia of the bogie, respectively; M_w is the mass of the wheelset; K_{s1} and C_{s1} are the stiffness and damping coefficients of the primary suspension, respectively; K_{s2} and C_{s2} are the stiffness and damping coefficients of the secondary suspension, respectively; $z_c(t)$ and $\varphi_c(t)$ are the vertical displacement and pitch motion of the car body, respectively; $z_t(t)$ and $\varphi_t(t)$ are the vertical displacement and pitch motion of the bogie, respectively; $z_w(t)$ is the vertical displacement of the wheelset; $P_{w1}(t)$, $P_{w2}(t)$, $P_{w3}(t)$ and $P_{w4}(t)$ are the vertical wheel/rail forces; $Z_{01}(t)$, $Z_{02}(t)$, $Z_{03}(t)$ and $Z_{04}(t)$ are the vertical track irregularities; l_c is the distance between the bogie centres; l_t is the distance between the two axles of a bogie; the material constants of the rail are the Young's modulus, E_r, the second moment of area, I_r, and the mass per unit length, m_r; the material constants of the slab are the Young's modulus, E_s, the second moment of area, I_s, and the mass per unit length, m_s; the material constants of the base are the Young's modulus, E_b, the second moment of area, I_b, and the mass per unit length, m_b; K_p and C_p are the stiffness and damping coefficients of the rail pad, respectively; K_{CA} and C_{CA} are the stiffness and damping coefficients of the CA mortar, respectively; K_b and C_b are the stiffness and damping coefficients of the subgrade, respectively; and $z_r(t)$, $z_s(t)$ and $z_b(t)$ are the vertical displacements of the rail, slab and base, respectively.