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Development of a railway wagon-track interaction model: Case studies on excited tracks

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ABSTRACT

In this paper, a theoretical framework for modeling the railway wagon-ballast track interactions is presented, in which the dynamic equations of motion of wagon-track systems are constructed by effectively coupling the linear and nonlinear dynamic characteristics of system components. For the linear components, the energy-variational principle is directly used to derive their dynamic matrices, while for the nonlinear components, the dynamic equilibrium method is implemented to deduce the load vectors, based on which a novel railway wagon-ballast track interaction model is developed, and being validated by comparing with the experimental data measured from a heavy haul railway and another advanced model. With this study, extensive contributions in figuring out the critical speed of instability, limits and localizations of track irregularities over derailment accidents are presented by effectively integrating the dynamic simulation model, the track irregularity probabilistic model and time-frequency analysis method. The proposed approaches can provide crucial information to guarantee the running safety and stability of the wagon-track system when considering track geometries and various running speeds.

1. Introduction

The modelling of the dynamic behavior of railway wagon-track systems due to the excitations of track geometric deformations and traversing traffic is a rather complex but important problem. In the last decade, high-speed lines have maintained a rapid development in China, for example, the speed of passenger trains has reached 300 km per hour, while the speeds of railway trucks are raised slowly because of the emergence of serious problems on running safety, stability and heavier loads. For solving a series of dynamic issues involving with the railway freight transportation, the wagon-track interaction model, which not only are effective representations of the railway wagon and track systems but also depicts the dynamic interactions between these components, needs to be properly constructed.

Except the fundamental nonlinearity in wheel/rail contact geometries, there also exist other sources of nonlinearities in railway wagon-track dynamics [1,2], e.g., dry friction contact, nonlinear responses of suspensions, etc. These nonlinear elements make the modelling of railway wagon-track interactions a far more complicated work than that of the passenger

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Nomenclature

L_1	left side-rack of the front bogie frame
R_1	right side-rack of the front bogie frame
L_2	left side-rack of the rear bogie frame
R_2	right side-rack of the rear bogie frame
W_i	the ith wheelset, i = 1, 2, 3, 4
H_{bt}	the vertical distance between the bottom plane of the secondary suspension and the center of mass of the bogie
H_{tw}	the vertical distance between the centroid of side frame and the center line of wheel-set
H_{cb}	the vertical distance between centroids of car body and side bogie
L_t	the semi-longitudinal distance between wheel-sets in a bogie
L_c	the semi-longitudinal distance between bogies
Y_{1d}	the semi-horizontal distance of the primary suspension
Y_{2d}	the semi-horizontal distance of the primary suspension
K_{cx}	the longitudinal spring stiffness between wheel axle-boxes and side frames
C_{cx}	the longitudinal damping coefficient between wheel axle-boxes and side frames
K_{cy}	the lateral spring stiffness between wheel axle-boxes and side frames.
C_{cy}	the lateral damping coefficient between wheel axle-boxes and side frames
K_{sz}	the spring stiffness supporting the bolster
C_{sz}	the damping coefficient supporting the bolster
K_{sy}	the stiffness coefficient of the secondary suspension along the Y axis
C_{sy}	the damping coefficient of the secondary suspension along the Y axis
K_{sx}	the stiffness coefficient of the secondary suspension along the X axis
C_{sx}	the damping coefficient of the secondary suspension along the X axis
a_0	the half distance in the lateral direction between two wheel-rail contact points
r_{li}	the rolling radius of left wheel
r_{ri}	the rolling radius of right wheel
Ω	the nominal rolling angular velocity
$\dot{\beta}_{wi}$	the velocity of pitch motion of the ith wheelset
$\dot{\psi}_{wi}$	the velocity of yaw motion of the ith wheelset
ψ_{wi}	the yaw angle of the ith wheelset
$\dot{\phi}_{wi}$	the velocity of rolling motion of the ith wheelset
I_{wY}	the moment of inertia of wheel around Y axis
I_{wZ}	the moment of inertia of wheel around Z axis
M_w	the mass of the wheelset
$\tilde{g}$	the acceleration of gravity
R_i	the radius of curvature of rail subjected to the ith wheelset
φ_{wi}	the angle of superelevation corresponding to the center of the ith wheelset
r_0	the nominal radius of the rolling circle of wheel
$\dot{\lambda}_{wi}$	the first-order derivative of curvature of the ith wheelset
M_c	the mass of car body
I_{cX}	the moments of inertia of car body around X axis
I_{cZ}	the moments of inertia of car body around Z axis
R_c	the radius of curvature of the car body center
φ_c	the angle of superelevation of rail with respect to the car body center of gravity
$\ddot{\varphi} c$	the second-order derivative of φ_c
$\dot{\varsigma}_c$	the first order derivative of superelevation angle corresponding to the center of car body
$M_{\tilde{k}}$	the mass of the side frame
$\varphi_{\tilde{k}}$	the yaw displacement of the side frame
$\ddot{\varphi}_{\tilde{k}}$	the yaw acceleration of the side frame
$R_{\tilde{k}}$	the radius of curvature of the $\tilde{k}$ th side bogie
F_p	the pre-stress of the side bearing
μ_s	the frictional coefficient of the side bearing
l_{rp}	the friction torque radius of the center plate

trains. Luckily, pioneering work conducted by researchers worldwide offered significant methodologies on describing the nonlinear interactions among wagon/track components, see, for instance, Knudsen et al. [3] and Slivsgaard and True [4] early presented a simple model of a wheelset supporting one end of a railway freight wagon by springs with linear characteristics and dry friction damper; Zhai et al. [5,6] carried out a series of advanced work to investigate the dynamics of vehicle-track systems from aspects of theoretical modelling, numerical simulation and experimental validation; Sun et al. [7,8] developed