Journal of Sound and Vibration 407 (2017) 209–225

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Stochastic analysis model for vehicle-track coupled systems subject to earthquakes and track random irregularities

Lei Xu *, Wanming Zhai

Train and Track Research Institute, Southwest Jiaotong University, State Key Laboratory of Traction Power, Chengdu 610031, China

ARTICLE INFO

Article history:
Received 21 February 2017
Received in revised form
22 June 2017
Accepted 23 June 2017
Handling editor: L.G. Tham

Keywords:
Vehicle-track coupled systems
Stochastic analysis
Earthquake
Track irregularity probabilistic model
Probability density evolution method

ABSTRACT

This paper devotes to develop a computational model for stochastic analysis and reliability assessment of vehicle-track systems subject to earthquakes and track random irregularities. In this model, the earthquake is expressed as non-stationary random process simulated by spectral representation and random function, and the track random irregularities with ergodic properties on amplitudes, wavelengths and probabilities are characterized by a track irregularity probabilistic model, and then the number theoretical method (NTM) is applied to effectively select representative samples of earthquakes and track random irregularities. Furthermore, a vehicle-track coupled model is presented to obtain the dynamic responses of vehicle-track systems due to the earthquakes and track random irregularities at time-domain, and the probability density evolution method (PDEM) is introduced to describe the evolutionary process of probability from excitation input to response output by assuming the vehicle-track system as a probabilistic conservative system, which lays the foundation on reliability assessment of vehicle-track systems. The effectiveness of the proposed model is validated by comparing to the results of Monte-Carlo method from statistical viewpoint. As an illustrative example, the random vibrations of a high-speed railway vehicle running on the track slabs excited by lateral seismic waves and track random irregularities are analyzed, from which some significant conclusions can be drawn, e.g., track irregularities will additionally promote the dynamic influence of earthquakes especially on maximum values and dispersion degree of responses; the characteristic frequencies or frequency ranges respectively governed by earthquakes and track random irregularities are greatly different, moreover, the lateral seismic waves will dominate or even change the characteristic frequencies of system responses of some lateral dynamic indices at low frequency.

1. Introduction

To the running rail vehicles subject to the guiding tracks, it is continuously a research focus in assessing the riding comfort, running safety and stability of the rolling stocks as well as the vibrations of track substructures under different exciting sources [1,2]. With the rapid development of railway lines possessing higher speeds and heavier loads, the dynamic performance of vehicle-track systems has been one of the most important concerns to the railway community, especially under the condition of large lateral excitation directly leading to the failure of wheel-rail constraint.

* Corresponding author.
E-mail addresses: leix_2014@my.swjtu.edu.cn (L. Xu), wmzhai@swjtu.edu.cn (W. Zhai).

http://dx.doi.org/10.1016/j.jsv.2017.06.030
0022-460X/

As a natural phenomenon, the earthquakes may possess destructive power. For the rail network with wide ranges of distribution and high operation density, the possibility of a train that coincidentally runs over an earthquake zone increases, it is therefore a necessity to estimate the dynamic responses of vehicle-track systems ahead of schedule to judge the running conditions of the vehicle and the vibration modality of the track. In the past few decades, the dynamic interactions between the rail vehicles and the tracks subject to earthquakes have attracted attentions from many researchers, for instance, Nishimura et al. [3] developed a model to analyze the rocking motion of a vehicle and the working mechanism of anti-derailing guard rails in large ground excitations. Cheng et al. [4] investigated the derailment of a tilting rail vehicle on curved tracks experiencing the coupling effects of rail irregularities and an earthquake, and drawing the conclusions that the rail irregularities and earthquakes both have non-negligible influence on the derailment of a tilting railway vehicle. Tanabe et al. [5] gave a simple and efficient numerical method to model the dynamic interactions between a high-speed train and railway structures under an earthquake. By assuming the vehicle-track system as a multi-rigid-body system and the earthquakes as sinusoid waves applied on the track slabs, Miyamoto et al. [6,7] proposed a vehicle-track dynamic model with 58 degrees-of-freedom to study the issues of running safety of railway train due to earthquakes, their researches showed that the transverse seismic waves played leading role in the train derailment. Nishimura et al. [8] arranged the experimental setup with 1/10 scale vehicle and roller rig to simulate the wheel-rail rolling contact and large amplitude excitations, and verifying the derailment mechanism of the high speed vehicle based on the experimental results. Ju and Li [9] developed a finite element method to simulate the derailment of trains moving on embankments with seismic loads at time-domain by applying the seismic displacements to the bottom of the mesh. It was shown that the maximum derailment coefficients were quite linear in proportion to the peak ground acceleration (PGA) of the earthquake if the structural behaviors and soil properties were linear. Luo et al. [10] put an emphasis on studying the methodologies for the running safety assessment (RSA) of trains undergoing seismic motio. Besides, investigations about the dynamics of the train-bridge system under earthquakes had also been significantly conducted by numerous researchers, see Refs. [11–20] for example.

The seismic motions are essentially non-stationary random processes, and generally being represented by seismic spectrum [21]. Wheel-rail contacts are perhaps the most representative trait of rail transportations, thus track random irregularities, as a more universal excitation in wheel-rail interactions, should be considered with an emphasis in the computational process. For a random system, it is perhaps a primary approach to adopt random vibration theory into the analytical procedures in order to precisely obtain the dynamic reliability and statistical results. However, in the above pioneering work, most of the researches ignored the random nature of earthquakes and track irregularities or mainly used deterministic methods to analyze system responses. In Refs. [12,13], pseudo-excitation method (PEM) [22], an efficient algorithm in random vibration analysis, was employed to obtain the random characteristics of earthquakes and track irregularities represented by spectrums. However, they ignored the spatial variability of track random irregularities along the whole railway line, namely the track irregularity spectrum used in their papers is just the statistical one. It is well known that the occurrence site of the earthquake is equally random in nature. In other words, track random irregularities and earthquakes possess the characteristics of random combination. However, the statistical average spectrum of track irregularities doesn't contain all of the amplitude-frequency properties of track irregularities that the earthquakes may encounter. Moreover, the nonlinearity of the wheel-rail contact hasn't been considered in Refs. [12,13].

In the present study, a new comprehensive model will be developed to fully investigate the dynamic performance of vehicle-track systems under coupling effects of lateral horizontal earthquakes and track random irregularities. Firstly, the random simulation approaches for earthquakes and track random irregularities accompanied by their combination strategy will be presented. Secondly, a vehicle-track coupled model that properly considers the wheel-rail nonlinear contacts and the excitations of seismic waves is developed, in which a probability density evolution method (PDEM) [23] is introduced to solve the probabilistic transmission between excitation inputs and response outputs. Finally, the analytical procedures are presented and the vibration responses of dynamic indices are concerned with respect to statistics, reliability and frequency in an illustrative example with some concluding remarks.

2. Random simulation and selection for system excitations

2.1. Earthquakes

The earthquakes can be characterized by the one-dimensional non-stationary random process $f_0(t)$, and being expressed by the following discrete integral form [24–26]

$$f_0(t) = \sum_{k=0}^{\infty} [\cos(\omega_k t)\mathrm{d}\tau_t(\omega_k) + \sin(\omega_k t)\mathrm{d}\upsilon_t(\omega_k)] \tag{1}$$

where $\Delta\omega$ is the frequency interval, and $\omega_k = k\Delta\omega$; $\tau_t(\omega)$ and $\upsilon_t(\omega)$ denote the spectral processes of $f_0(t)$ that both satisfy the general condition of the spectral expression for real non-stationary process, and the incremental quantities $\mathrm{d}\tau_t(\omega_k)$ and $\mathrm{d}\upsilon_t(\omega_k)$ can be further expressed by [27]

$$\mathrm{d}\tau_t(\omega_k) = D_{t,k}X_k,\ \ \mathrm{d}\upsilon_t(\omega_k) = D_{t,k}Y_k \tag{2}$$