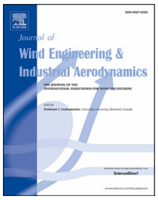
Journal of Wind Engineering & Industrial Aerodynamics 174 (2018) 103–118

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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



Assessment of overturning risk of high-speed trains in strong crosswinds using spectral analysis approach

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ARTICLE INFO

Keywords:
Crosswind
Moving vehicle
Unsteady aerodynamic forces
Aerodynamic admittance function
Dynamic response
Overturning risk

ABSTRACT

This study introduces a spectral analysis framework for assessing overturning risk of high-speed trains in strong crosswinds. The wind turbulence relative to moving vehicles is used to model stochastic wind excitation, whose spectral characteristics are determined by a newly introduced general method from the spectrum and coherence function of turbulence relative to ground. The unsteady aerodynamic forces on vehicles are modeled with consideration of longitudinal, lateral and vertical turbulence components. Based on the wind tunnel experiments of a typical China railway high-speed train model, the side and lift force coefficients and aerodynamic admittance functions associated with different turbulence components are extracted, where the effects of spatial coherence of turbulence are explicitly accounted for. The probabilistic overturning risk is then evaluated through unloading rate of wheel-rail contact force, which leads to the determination of probabilistic characteristic wind curve. The results demonstrated that the dynamic wheel-rail contact force induced by track irregularities is lower than that by wind turbulence. In addition to the traditionally considered longitudinal turbulence, the lateral and vertical turbulence components also have great contribution to vehicle response. Adequate modeling of aerodynamic admittance functions is also important for better quantifications of vehicle response and overturning risk.

1. Introduction

The study of overturning risk of high-speed trains in high crosswinds has attracted great attention (e.g., Baker, 1991, 2009; 2013; Carrarini, 2007; Ding et al., 2008; Cheli et al., 2012; Zhang, 2015). The assessment of overturning risk under crosswinds involves four major tasks: characterization of wind turbulence, calculation of aerodynamic forces on moving vehicles, quantification of dynamic response of vehicle system, and evaluation of overturning risk.

The wind turbulence is often represented by an equivalent average wind gust, known as ‘Chinese hat’ in a simplified deterministic analysis approach (TSI, 2008; EN 14067-6, 2010). However, a random response analysis framework requires the modeling of wind turbulence as stochastic field characterized by spectral and coherence functions (e.g., Cheli et al., 2012). The vehicle response analysis is often carried out in the time domain, where the stochastic time histories of turbulent wind field at large number of ground locations have to be simulated with huge computational cost (e.g., Xu and Ding, 2006). On the other hand, the wind turbulence seen by the running vehicles can be directly modeled and used in the analysis, which facilitates the use of spectral analysis approach and is computationally more effective (e.g., Balzer, 1977; Cooper, 1984; Baker, 2010; Wu et al., 2014).

The vehicle overturning is directly relevant to the rolling moment around the leeward rail, which is the resultant moment of side force, lift force and torsional moment around the axis of vehicle body. The torsional moment of vehicle body is generally small enough to be neglected (Baker et al., 2009). The side and lift forces are characterized by static force coefficients and aerodynamic admittance functions, determined through wind tunnel test using stationary vehicle model at various yaw angles and angles of attack (Cheli et al., 2010; Schober et al., 2010). The aerodynamic admittance function is the transfer function between wind turbulence and unsteady aerodynamic force, which is used to correct the quasi-steady aerodynamic force model. The wind tunnel test using a moving vehicle model can better represent the interaction of wind and moving vehicle, but is generally more difficult to implement (e.g., Cooper, 1981; Humphrey and Baker, 1992; Bocciolone et al., 2008). An improved stationary model test approach was proposed where the model was kept as stationary but the slope of embankment was adjusted to better simulate the actual wind boundary condition around the vehicle (Suzuki et al., 2003). The

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https://doi.org/10.1016/j.jweia.2017.12.024
Received 10 October 2017; Received in revised form 20 November 2017; Accepted 25 December 2017

aerodynamic admittance functions can be readily accounted in the frequency domain analysis. In the time domain analysis, it is accounted by using the aerodynamic weighting functions (Baker, 2010).

The vehicle dynamics can be represented by a multiple degrees of freedom vehicle model with the inputs of aerodynamic forces and track irregularity excitations (e.g., Thomas et al., 2010; Zhang, 2015; Yu et al., 2016). Since the crosswind stability of vehicles is related to overturning rather than the derailment, the nonlinear wheel-rail contact models can be simplified by the linear model or directly ignored (Carrarini, 2007). Previous studies showed that the crosswind stability analysis is not sensitive to the complexity of vehicle model (Diedrichs et al., 2004; RSSB, 2009; Baker, 2013). Therefore, a linear vehicle dynamic model can be adopted, which permits the analysis to be carried out in frequency domain.

The overturning risk is evaluated by the wheel unloading rate (e.g., Zhai and Xia, 2011; Cheli et al., 2012; Baker, 2013). The analysis predicts the critical wind speed for vehicle safely running as a function of vehicle speed and wind direction, known as characteristic wind curve (CWC). When the randomness of wind turbulence and track irregularity, and uncertainties of various model parameters are considered, the CWC with a target failure probability can be determined, referred to as probabilistic characteristic wind curve (PCWC). The failure probability conditional on wind speed and direction can be further integrated with the probability of wind speed and direction to determine the overall failure probability or risk of the vehicles along the whole rail route.

This study introduces a frequency domain framework for the analysis of overturning risk of high-speed trains in crosswind. A general procedure is presented to determine the spectral characteristics of wind turbulence relative to moving vehicles from the power spectrum and coherence function of turbulence on ground. The unsteady side and lift forces on vehicles are modeled with consideration of longitudinal, lateral and vertical turbulence components. The aerodynamic force coefficients and aerodynamic admittance functions are determined from wind tunnel measurements. The traditional definition of aerodynamic admittance functions also involves the reduction effect caused by spatially partial correlation/coherence of aerodynamic forces, which is described in terms of joint acceptance functions. Special attention of this study is placed to extract the aerodynamic admittance functions by removing this reduction effect with the assumption that the coherence of aerodynamic force is identical to that of turbulence. The aerodynamic admittance functions associated with different components of turbulence are also identified. The roles of crosswind and track irregularity excitations are clarified. The response characteristics affected by wind speed and direction, as well as vehicle speed are investigated, which lead to the determination of probability of overturning risk and PCWC.

2. Analytical framework

2.1. Aerodynamic forces

The modeling of aerodynamic forces on a moving vehicle is considered. The mean wind speed U has a wind angle of φ_0 with respect to the moving direction of vehicle. The vehicle speed is denoted as V_{tr}. The longitudinal, lateral and vertical components of wind turbulence are denoted as u-, v- and w-components. As shown in Fig. 1, the instantaneous wind speed V_R relative to moving vehicle is expressed as

$$V_R = \sqrt{\left[(U+u)\cos\varphi_0 + V_{tr} + v\sin\varphi_0\right]^2 + \left[(U+u)\sin\varphi_0 - v\cos\varphi_0\right]^2 + w^2} \tag{1}$$

Neglecting the high-order terms of wind turbulence, we have

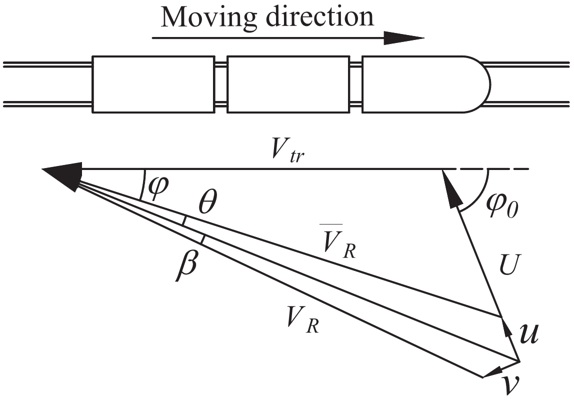

Fig. 1. Speed vector diagram.

$$V_R \approx \sqrt{\overline{V}_R^2 + 2u(U + V_{tr}\cos\varphi_0) + 2vV_{tr}\sin\varphi_0} \tag{2a}$$

$$\overline{V}_R = \sqrt{(V_{tr} + U\cos\varphi_0)^2 + (U\sin\varphi_0)^2} \tag{2b}$$

where $\overline{V}_R$ is the vector summation of U and V_{tr}.

Based on the quasi-steady theory, the aerodynamic side force can be calculated as:

$$\overline{F}_S + F_S(t) = \frac{1}{2}\rho V_R^2 HLC_S(\alpha, \varphi + \theta + \beta) \tag{3}$$

$$\alpha \approx \frac{w}{\overline{V}_R}\ ;\ \varphi = \arctan\frac{U\sin\varphi_0}{V_{tr} + U\cos\varphi_0};\ \theta \approx \frac{u\sin(\varphi_0 - \varphi)}{\overline{V}_R};\ \beta \approx \frac{v\cos(\varphi_0 - \varphi)}{\overline{V}_R} \tag{4}$$

where $\overline{F}_S$ and $F_S(t)$ are mean and fluctuating components of side force; ρ is air density; H is height of vehicle body; L is length of vehicle body; $C_S(\alpha, \varphi + \theta + \beta)$ is side force coefficient; α is angle of attack; and angles φ, θ and β are illustrated in Fig. 1.

The side force coefficient $C_S(\alpha, \varphi + \theta + \beta)$ can be expressed in Taylor's series expansion around the angle of attack $\alpha = 0$, and yaw angle φ:

$$C_S(\alpha, \varphi + \theta + \beta) \approx C_S(\varphi) + \frac{dC_S(\varphi)}{d\varphi}\theta + \frac{dC_S(\varphi)}{d\varphi}\beta + \frac{dC_S(\varphi)}{d\alpha}\alpha \tag{5}$$

where $C_S(\varphi)$ is the simplified expression of $C_S(0, \varphi)$.

Accordingly, the mean (static) and fluctuating components of side force are expressed as

$$\overline{F}_S = \frac{1}{2}\rho\overline{V}_R^2 HLC_S(\varphi) \tag{6}$$

$$F_S(t) = \frac{1}{2}\rho\overline{V}_R^2 HL\left[C_{Su}\frac{u(t)}{\overline{V}_R} + C_{Sv}\frac{v(t)}{\overline{V}_R} + C_{Sw}\frac{w(t)}{\overline{V}_R}\right] \tag{7}$$

where

$$C_{Su} = \frac{dC_S(\varphi)}{d\varphi}\sin(\varphi_0 - \varphi) + 2C_S(\varphi)\frac{V_{tr}\cos\varphi_0 + U}{\overline{V}_R} \tag{8a}$$

$$C_{Sv} = \frac{dC_S(\varphi)}{d\varphi}\cos(\varphi_0 - \varphi) + 2C_S(\varphi)\sin\varphi_0\frac{V_{tr}}{\overline{V}_R} \tag{8b}$$

$$C_{Sw} = \frac{dC_S(\varphi)}{d\alpha} \tag{8c}$$

Accordingly, the unsteady side force is given as