Journal of Wind Engineering & Industrial Aerodynamics 164 (2017) 34–43

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

An analytical model for the fluctuating wind velocity spectra of a moving vehicle

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ARTICLE INFO

Keywords:
Moving train
Fluctuating wind velocity spectrum
Cooper's theory
Taylor's frozen turbulence hypothesis
Doppler effect

ABSTRACT

An analytical model for both the longitudinal and lateral fluctuating wind velocity spectra of a moving train in the random wind field has been developed based on Cooper's theory (Cooper, 1984). The fluctuating wind velocity spectrum of a moving point can be derived through the weighted linear superposition of the longitudinal and lateral spectra of the stationary point with both frequency and amplitude scaling. The proposed analytical model has been validated systematically, and based on the Simiu spectrum (Simiu and Scanlan, 1996), parametric studies were conducted for the influence on the fluctuating spectra of a moving train by wind flow angle from 0°, 30°, 60°, 90°, to 150° and varying speed ratios between vehicle and wind (mean wind velocity of 20 m/s) from 1 to 4. It is revealed that the fluctuating wind velocity spectrum experienced by a moving train exhibits a Doppler effect phenomena due to the train movement, especially in the longitudinal case. The proposed spectrum model can provide an efficient simulation scheme for the fluctuating wind velocity time series of the moving train with adequate accuracy and can provide a rigorous analytical scheme for the subsequent aerodynamic response analysis of the moving train within the random wind field.

1. Introduction

With the increased tendency for higher speed of the public transportation system like the high-speed trains, the aerodynamic environment of the moving train has gradually become more of an essential factor than the wheel-rail system in design and development of those high-speed trains. Under a strong crosswind, the transverse force of the train will experience an abrupt increase so that the train's aerodynamic performance will degrade significantly, resulting in the risk of train derailment or overturning and severe threats to the safe operation of a high-speed train. There have been many severe train derailment or overturning accidents worldwide owing to a strong cross wind. For example, on February 28, 2007, a strong crosswind has caused a serious train derailment accident in Xinjiang Province, China (shown in Fig. 1a) and led to at least 4 fatalities and more than 30 injured. The accident region is known as a "hundred-kilometer wind zone" (with at least level 8 Gale wind more than 320 days of each year) where the traffic of the train can be affected significantly. Similarly, a strong wind overturned three trucks driving on the Fujian Qingzhou Bridge (in Qingzhou City, Fujian Province, China) on September 1, 2005 (shown in Fig. 1b).

To investigate the wind effects on the safe operability and serviceability of moving train, it is essential to derive a random fluctuating wind velocity model that can be used for the subsequent aerodynamic analysis of a moving train. The majority of the existing studies tend to focus on the simulation of the wind velocity field in the time domain (wind loading) based on the fixed-point multivariable stationary random process method.

By utilizing the simulated fluctuating wind velocity time series for a moving train, the dynamic response analysis of wind-train-track system or wind-train-bridge coupling system can then be performed in the time domain (Cai and Chen, 2004; Li et al., 2005; Xu and Guo, 2003). The traditional way of obtaining the transient fluctuating wind velocity time series is based on the discrete point extraction and neighbor interpolation methods within the multivariable random process simulation scheme (Shinozuka, 1971). However, the traditional simulation method usually has a drawback with simulation error due to the artificial dispersion and therefore requires an increase of the simulation points to compensate the error, as a result, significant computation effort has been induced. Although some improvements on the multivariable random process simulation method had been made by several researchers (Ding et al., 2011; Huang et al., 2013; Chen

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http://dx.doi.org/10.1016/j.jweia.2017.02.007
Received 25 August 2016; Received in revised form 5 February 2017; Accepted 6 February 2017
0167-6105/

Fig. 1. Vehicles overturn due to the strong wind [http://news.xinhuanet.com/society/2007-02/28/content_5781677.htm; http://news.sina.com.cn/c/2005-09-02/09236844314s.shtml?qq-pf-to=pcqq.c2c]. a) Train overturn in Xinjiang Province, China. b) Lorry overturn on bridge in Fuzhou City, China.

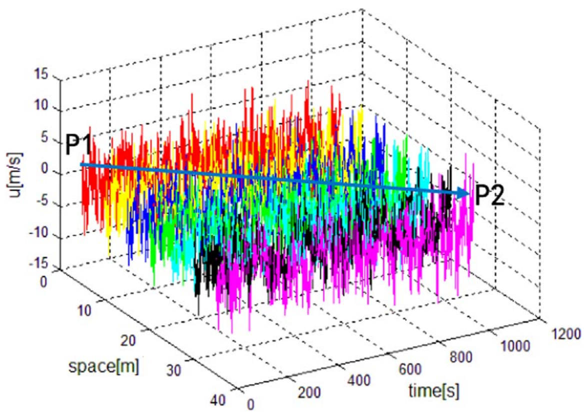

Fig. 2. Wind velocity extraction scheme for the moving train in the simulated fluctuating wind field (Chen et al., 2014).

et al., 2014); however, there are still challenging issues needing to be addressed. For example, the time domain method lacks of a comprehensive systematic analytical scheme in accounting for the effect of different wind flow angle with the moving train and significant computation efforts are induced by increase of the number of simulation and discretion points.

In addition to the time domain method, Cooper (1984) initially derived an analytical model in the frequency domain for the longitudinal fluctuating wind velocity spectrum (normal to the train moving direction) of a moving point based on Von Karman spectrum. Using Cooper's theory (Cooper, 1984), Wu et al. (2014) developed both the longitudinal and lateral fluctuating wind velocity spectra of a moving point through the semi-analytical fit of the autocorrelation coefficient function corresponding to the Simiu spectrum (Simiu and Scanlan, 1996). The analytical method in the frequency domain differs from the time domain simulation method in that the multivariate random process can be converted into a fluctuating wind velocity spectra (the longitudinal and lateral), then the simulation of a fluctuating wind velocity time series become more efficient based on the univariate random process. Based on the analytical fluctuating wind velocity model by Cooper (1984), both the steady and unsteady aerodynamic responses of the moving train within the random wind field have been investigated (Baker, 1991a, 1991b, 2010; Cheli et al., 2003a, 2003b, 2007; Yu et al., 2016).

Following these discussions, based on Cooper's theory, this paper develops a systematic analytical model for both the longitudinal and lateral fluctuating wind velocity spectra of moving train in the random wind field, considering the effects of different wind flow angle and ratios of train speed to wind velocity. The proposed spectrum model can provide an efficient simulation scheme for the fluctuating wind velocity time series acting on the moving train with adequate accuracy. Based on the developed analytical model, parametric studies were conducted to investigate the influence on the fluctuating wind velocity spectrum of moving train by wind flow angle and speed of train. The results drawn from this paper can be used to qualitatively explain the frequency shift phenomenon on fluctuating wind velocity spectrum and can also provide a rigorous analytical scheme for the subsequent aerodynamic response analysis of the moving train within the random wind field.

2. Analytical model and the validation

2.1. Problem statement

This section briefly presents the typical fluctuating wind velocity time series simulation results for a moving train in the random wind field based on multivariate random process (which is the stationary ergodic process) simulation scheme by Chen et al. (2014). This section can be taken as a problem statement for the developed analytical model of this paper. Details of the time domain simulation scheme by Chen et al. (2014) are not presented for brevity.

Fig. 2 presents a typical spatial-temporal wind-field simulation result of the fluctuating wind velocity component and the wind velocity extraction scheme from the simulated fluctuating wind field for a moving train. When the train moves to the point P1/P2 at time t1/t2, respectively, the transient fluctuating wind velocities (loadings from the natural wind) exerting on the train equal to the transient fluctuating wind velocity value of the fixed point P1/P2 at time t1/t2 in the spatial-temporal wind-field. In this paper, the equivalent wind velocity resulting from the moving of the train (which is opposite to the velocity of train) is considered to be an average wind velocity component without fluctuation. It is seen that the way of obtaining the wind velocity time history of a moving train by simulating the entire fluctuating wind velocity field is obviously inefficient.

Based on the scheme in Fig. 2, the wind velocity time history of a moving point will be extracted and the corresponding spectrum will be compared with that for the stationary point in the following example. Taking the average wind velocity of U=20 m/s, height of z=10 m, surface roughness of z_0=0.03, Von Karman constant of k=0.4, train speed of V=60 m/s, simulated time step of 0.1 s, simulated spacing interval of 6 m, and wind field spatial and temporal simulation points of 4096. Since the distance travelled by moving point at each time interval equal the simulated spacing interval ($60m/s \times 0.1s = 6m$), the moving point is always located at the spatial simulation point at each sampling time point, making the extracted instantaneous wind velocity of the moving point being exactly same as the simulated value at each simulation point of the wind field. The time histories of fixed stationary points (travel path of moving train) and moving point extracted are presented in Fig. 3. The comparison of estimated power spectrum between the stationary point and moving point is given in Fig. 4.