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Wind spectrum and correlation characteristics relative to vehicles moving through cross wind field

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ABSTRACT

In this study, based on Taylor's frozen turbulence hypothesis and isotropic turbulence model, the auto-correlation coefficient function of lateral wind fluctuation and cross-correlation coefficient functions of lateral and longitudinal wind fluctuations are derived from the Kaimal spectrum of longitudinal wind fluctuation. Based on the same hypothesis, this study also derived formulations for calculating the power spectra and correlation coefficient functions of wind turbulence relative to moving vehicles. The results can be applied for any vehicle moving direction, and for both longitudinal and lateral components of wind turbulence. The effects of speed ratio of moving vehicle to mean wind velocity and vehicle direction on the characteristics of wind turbulence relative to moving vehicles are investigated. In addition, a closed-form expression is also proposed to approximately represent the square-root coherence function of wind turbulence relative to moving vehicles. It provides useful insights for better understanding the characteristics of turbulent wind relative to moving vehicles, and also provides a theoretical foundation for solving the discontinuity of sudden change of wind fluctuations while the wind fluctuations are simulated using traditional fixed-point spectrum.

1. Introduction

The safety and comfort of running vehicles in strong crosswind conditions become one of increasingly important issues needing to be addressed as vehicle operating speed increases and weight decreases (Baker, 1991a, 1991b, 1991c, 2013; Diedrichs, 2006; Gawthorpe, 1994; Johnson, 1996). Currently, time domain simulation frameworks are often used to quantify dynamic response of running vehicles in crosswind conditions. The time histories of random wind velocity fluctuations at finite discrete fixed-locations are generated with prescribed spectral characteristics (Cai and Chen, 2004; Li et al., 2005; Xu and Guo, 2003). The wind fluctuations on the running vehicles are then approximately estimated from these wind fluctuations using some kind of spatial extrapolation scheme (e.g., Liu, 2011), or simply taking the values at the nearest fixed-locations. These approximate modeling of wind fluctuations on vehicles often causes discontinuity and may even introduce sudden changes in the wind fluctuations, which is clearly inconsistent with the actual situation. As a result, the corresponding aerodynamic forces on vehicles and the estimated vehicle dynamic response, especially, the peak response, are noticeably affected. The estimations with this type of modeling of wind fluctuations may not well represent the actual performance of vehicles in crosswind conditions. This is particularly true in cases when wind speed and/or vehicle speed are high.

In order to more accurately and also more effectively model wind fluctuations on running vehicles, a random process model for atmospheric turbulence seen from a running vehicle is required. This modeling also facilitates calculation of the aerodynamic forces and dynamic response of moving vehicles in frequency domain by spectral analysis. Balzer (1977) discussed the effect of atmospheric turbulence on moving vehicles and derived the power spectral density (PSD) function of turbulence encountered by a high-speed ground transport vehicle, where the contribution of crosswind component of wind fluctuation was neglected. Cooper (1984) calculated the PSD, cross-correlation and coherence of wind fluctuations normal to a moving vehicle using von Karman spectrum for wind turbulence at fixed-locations. Based on the wind characteristics with respect to a moving vehicle derived in Cooper (1984), Baker (1991b and 1991c) presented a comprehensive study on unsteady aerodynamic forces and dynamic response of vehicles in frequency, amplitude and time domains. A more comprehensive framework was proposed in Baker (2013) for the consideration of the effects of crosswinds on trains, which can be applied in the train authorization and route risk analysis.

In present study, based on Taylor's frozen turbulence hypothesis and isotropic turbulence model, the auto-correlation

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coefficient function of lateral wind fluctuation and cross-correlation coefficient functions of lateral and longitudinal wind fluctuations are derived from the Kaimal spectrum of longitudinal wind fluctuation. The power spectra and correlation coefficient functions of wind turbulence relative to moving vehicles are also deduced based on the same hypothesis. The results can be applied for any vehicle moving direction, and for both longitudinal and lateral components of wind turbulence. The effects of speed ratio of moving vehicle to mean wind velocity and vehicle direction on the characteristics of wind turbulence relative to moving vehicles are investigated. A closed-form expression is also proposed to approximately represent the square-root coherence function of wind turbulence relative to moving vehicles.

2. Turbulence characteristics at fixed points

2.1. *Power spectrum of longitudinal turbulence*

In this study, it is defined that the mean wind velocity $U(z)=\overline{U}$ at the height z above the ground is along the x-axis, and u, v and w are the instantaneous longitudinal, lateral and vertical components of fluctuating wind velocities along the x-, y- and z-axes, respectively, as shown in Fig. 1. In the following analysis, only the u- and v-components of wind fluctuations are discussed as they are relevant to vehicle aerodynamics. The PSD of u-component, $S_u(n)$, is given as the Kaimal spectrum (Kaimal et al., 1972):

$$\frac{nS_u(n)}{u_*^2}=\frac{200\hat{n}}{(1+50\hat{n})^{5/3}} \tag{1}$$

where n is the frequency in Hz; $\hat{n}=nz/\overline{U}$ is the non-dimensional frequency; u_* is the shear velocity of the flow. The standard deviation (STD) of u-component is then given as $\sigma_u=\sqrt{6}u_*$.

2.2. *Taylor's frozen turbulence hypothesis and isotropic turbulence assumption*

Taylor's frozen turbulence hypothesis originated in the paper (Taylor, 1938) which mainly discussed the connection between the spectrum of turbulence at a fixed point and the correlation between simultaneous values of velocity at two points. It is postulated that if the mean wind speed is sufficiently high, the flow pattern of the turbulence field then does not have time to change, and passes a fixed point with the mean wind speed. The sequence of changes in fluctuation at the fixed point is simply due to the passage of an unchanging pattern of turbulent motion over the point. Furthermore, it's worth noting that Taylor's hypothesis has been verified by wind tunnel tests conducted by Mr L.F.G. Simmons (Taylor, 1938). Based on this hypothesis, the wind fluctuations at two points along the mean wind speed direction are related as follows:

$$u(x,t)=u(x-\overline{U}t,0),\ v(x,t)=v(x-\overline{U}t,0) \tag{2}$$

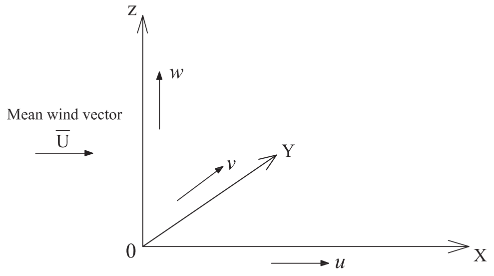

Fig. 1. The mean wind vector and three components of fluctuating velocities, (symbol: u=longitudinal component of fluctuating wind velocity; v=lateral component of fluctuating wind velocity; w=vertical component of fluctuating wind velocity).

Taylor (1938) also proved that the turbulence was in fact isotropic, as the measurements in wind tunnel tests had good agreement with those obtained from the theoretical analysis by Karman (1937). Landahl and Christensen (1992) pointed out that Taylor's hypothesis is based on the isotropic turbulence assumption, which means the isotropic turbulent coordinate system is moving along with the mean wind velocity.

Some studies (Lin, 1953; Gifford, 1956; Lappe and Davidson, 1963) proved that Taylor's frozen turbulence hypothesis had a validity range. Both the investigations from Lin (1953) and Gifford (1956) indicated that there was a range where Taylor's hypothesis was certainly valid for atmospheric motions and that this region was generally in the high frequency portion of the spectrum. Furthermore, a unique tower-airplane experiment was conducted by Lappe and Davidson (1963), which permitted a comparison between airplane and concurrent tower measurements of atmospheric turbulence. It indicated that the Taylor's hypothesis was approximately correct for wavelength ($\overline{U}/n$) less than about 300 m. If the mean wind velocity $\overline{U}=30$ m/s, then the Taylor's hypothesis is valid for the frequency range $n>0.1$ Hz. The significant frequency range for ground vehicles is above 0.1 Hz. Thus, it is valid for engineering application that Taylor's frozen turbulence hypothesis can be applied to study the unsteady aerodynamics of moving vehicles.

Admittedly, both the Taylor's frozen turbulence hypothesis and isotropic turbulence assumption are not strictly true and involve certain approximation of the real atmospheric wind filed. However, as discussed above, for our research purpose and the concerned frequency range, both the Taylor's hypothesis and isotropic turbulence assumption are approximately correct, and the resulted observations are useful in practical engineering application.

For the moving vehicle submerged in the actual turbulence, there indeed exists interaction between the surface of the vehicle and the around wind flow field. This aerodynamic interaction between vehicle and the around wind field is actually reflected by aerodynamic coefficients including aerodynamic admittance, which can be determined in wind tunnel or from CFD simulation under given turbulent wind field. The study on aerodynamics coefficients is beyond the scope of this study.

2.3. *Auto-correlation coefficient functions of turbulence*

Auto-correlation and power spectral density functions are Fourier transform pair. The auto-correlation coefficient function at a stationary point can be obtained from the Kaimal longitudinal spectrum by Fourier transformation as shown in Eq. (3):

$$\begin{aligned}\rho_u(\tau)&=\frac{1}{\sigma_u^2}\int_0^{+\infty}S_u(n)\cos(2\pi n\tau)dn\\&=1-0.036\tilde{r}^2+0.2\tilde{r}^{7/6}LommelS2\left(\frac{11}{6},\frac{1}{2},\frac{\pi}{25}\tilde{r}\right)\end{aligned} \tag{3}$$

where $\tilde{r}=\tau\overline{U}/z$ is a non-dimensional variable; and $LommelS2$ (p,q,x) is a special function with three parameters, which is the second kind of solutions of equation $x^2y''+xy'+(x^2-q^2)y=x^{p+1}$ (Gradsbteyn and Ryzbik, 2000).

For the convenience of subsequent calculations, Eq. (3) is numerically fitted as the following formulation of non-dimensional variable $\tilde{r}$, i.e., $\rho_u(\tau)=f(\tilde{r})$. As shown in Fig. 2, both are almost identical.

$$\begin{aligned}f(\tilde{r})=&0.013+0.467\exp(-\tilde{r}/4.296)+0.201\exp(-\tilde{r}/0.797)\\&+0.281\exp(-\tilde{r}/15.742)\end{aligned} \tag{4}$$