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Typhoon-induced non-stationary buffeting response of long-span bridges in complex terrain

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ABSTRACT

This paper presents a framework for predicting typhoon-induced non-stationary buffeting response of long-span cable-supported bridges located in a complex terrain. First, a non-stationary typhoon wind model is proposed based on observations from measured typhoon wind data. The wind model includes mainly time-varying mean wind speed, mean wind speed profile and evolutionary power spectral density (EPSD) function. Typhoon-induced wind loading on a bridge deck is then represented by time-varying mean wind forces, non-stationary buffeting forces associated with time-dependent aerodynamic coefficients and self-excited forces characterized by time-dependent aerodynamic derivatives. A nonlinear static analysis is performed to determine time-varying mean wind response, whereas the pseudo excitation method is employed to compute the EPSD-expressed non-stationary buffeting response of a long-span cable-supported bridge. The proposed framework is finally applied to predict non-stationary buffeting responses of a long-span cable-stayed bridge located in a complex terrain during a strong typhoon as a case study. The case study demonstrates how to apply the proposed framework and the results show that the proposed framework is feasible and necessary.

1. Introduction

Many innovative long-span cable-supported bridges emerge in recent years. If these bridges are located in typhoon prone regions, their functionality and safety under typhoons are of the utmost concern. This requires not only analytical models for near-ground typhoon winds over a complex terrain, mean wind forces, aerodynamic forces, and aeroelastic forces on the bridge but also computational methods for predicting typhoon-induced buffeting response of the bridge.

The buffeting analysis of long-span bridges has been performed for almost fifty years. It is indispensable for wind resistance design of long-span bridges [1]. It also plays an important role in the analyses of wind-vehicle-bridge interaction [2,3] and the assessment of wind or wind-vehicle-induced fatigue problem [4,5]. Davenport [6] first presented a framework for buffeting analysis of long-span bridges to include the effects of unsteadies and spatial variations of wind turbulence. Scanlan [7] then introduced flutter derivatives to the buffeting analysis to account for self-excited forces. The inability of involving effects of multi-modes and inter-mode coupling was circumvented later by fully-coupled 3D buffeting analysis methods [8–11]. Nevertheless, these methods are all based on stationary and Gaussian assumptions.

Typhoon winds actually exhibit different characteristics from monsoon winds. Although monsoon winds can be probabilistically described by a stationary process, this may not be the case for typhoon winds because of their vortex origins. Particularly, if a bridge site is close to typhoon eye walls, changes in wind direction and convective turbulence are considerable, and consequently the stationary assumption on typhoon winds cannot be accepted. Furthermore, if the bridge site is surrounded by a complex terrain, the profile of typhoon mean wind speed and the structure of turbulence become more complicated and evolve with time [12]. Therefore, it is more realistic to model typhoon winds as a non-stationary process than a stationary process and to perform non-stationary buffeting analysis of long-span bridges in a complex terrain.

Chen and Letchford [13] proposed a three layer model for describing non-stationary winds resulting from downbursts, where the three layers represent time-varying mean wind speed, time-varying variance and time-varying spectral content. The fluctuating wind speed components of downbursts were characterized by either evolutionary power spectral density (EPSD) function [13,14] or time-varying auto-regressive model [15] or wavelet [16]. Chen and Letchford's model has been used to predict downburst-induced responses of building structures and transmission

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towers [17–19]. Xu and Chen [20] characterized typhoon winds as a time-varying mean wind speed plus a stationary fluctuating component. This concept was also implied in the modeling of Hurricane Lili by Wang and Kareem [21]. Kawai [22] conducted non-stationary buffeting analysis of structures by introducing a modulating function to account for time-varying variances of wind speeds.

This paper will present a relatively systematic study on typhoon-induced non-stationary buffeting response of long-span bridges in a complex terrain. First, a non-stationary typhoon wind model is proposed based on observations from measured typhoon wind data. The wind model includes mainly time-varying mean wind speed, mean wind speed profile, and EPSD function. Typhoon-induced wind loading on a bridge deck is then represented by time-varying mean wind force, non-stationary buffeting forces associated with time-dependent aerodynamic coefficients and self-excited forces characterized by time-dependent aerodynamic derivatives. A nonlinear static analysis is performed to determine time-varying mean wind response, whereas the pseudo excitation method is employed to compute the EPSD-expressed non-stationary buffeting response of a long-span cable-supported bridge. The proposed framework is finally applied to a long-span cable-stayed bridge located in a complex terrain during a strong typhoon as a case study to demonstrate how to predict its non-stationary buffeting response in terms of measured typhoon winds.

2. Typhoon-induced non-stationary winds

For a long-span cable-supported bridge, wind components which should be considered in its buffeting analysis are the longitudinal wind component $U(t)$ that is perpendicular to the longitudinal axis of the bridge deck in the horizontal plane and the vertical wind component $W(t)$ that is perpendicular to the longitudinal wind component in the vertical plane. The conventional buffeting analysis is based on the assumption that wind speed components are stationary Gaussian stochastic processes and requires four basic elements: (1) mean wind speed; (2) mean wind speed profile; (3) wind power spectrum; and (4) wind coherence function. The parameters in the four elements are all time-invariant. Nevertheless, the boundary layer wind speed components $U(t)$ and $W(t)$ induced by typhoons may not comply with the stationary assumption, and their statistical properties may evolve with time. Therefore, a non-stationary wind model will be presented in the following by extending the stationary model with instantaneous statistical properties. The term "instantaneous" here means that for each time instant the corresponding statistical properties are estimated over a specified short time interval whose center is the current time instant.

2.1. Time-varying mean wind speed

In the proposed non-stationary typhoon wind model, the longitudinal component $U(t)$ is regarded as the sum of time-varying mean wind speed $\overline{U}(t)$ and zero-mean fluctuating wind speed component $u(t)$.

$$U(t) = \overline{U}(t) + u(t) \tag{1}$$

where $\overline{U}(t)$ is determined by short-time averaging over a short time interval T_0:

$$\overline{U}(t) = \frac{1}{T_0}\int_{t-T_0/2}^{t+T_0/2} U(t)\mathrm{d}t \tag{2}$$

The value of time interval T_0 can be chosen with reference to the time interval of mean wind speed used in conventional stationary buffeting analysis, which is commonly taken as one hour or 10 min. Clearly, this requires the length of wind speed time history being at least twice the time interval. Eq. (2) implies that $\overline{U}(t)$ contains frequency contents lower than $1/T_0$. Therefore, the time-varying mean wind speed actually varies with time very slowly compared with the fluctuating wind speed component $u(t)$.

To consider the mean wind speed profile in the vertical plane, the time varying mean wind speed can be further expressed as

$$\overline{U}(t) = \overline{U}_0(z)\cdot\eta_0(t) \tag{3}$$

where $\overline{U}_0(z)$ is the mean value of the time-varying mean wind speed $\overline{U}(t)$, which is almost the same as the conventional time-invariant mean wind speed [20] depending on the height above the ground z; $\eta_0(t)$ is the time-varying function of mean wind speed, which is assumed to be independent of the height above the ground in this study. In such a way, the mean wind speed profile can be readily incorporated into the non-stationary wind model. Furthermore, it is assumed that the vertical wind component $W(t)$ is zero mean, which is similar to the assumption used in the stationary buffeting analysis. As a result, the vertical component $W(t)$ is regard as the fluctuating wind speed $w(t) = W(t)$ only.

2.2. Typhoon mean wind speed profile

During the passage of a typhoon, the mean wind speed profile at a bridge site surrounded by a complex terrain generally does not conform to the traditional logarithmic law or power law. A numerical method for predicting directional typhoon mean wind speed profiles over a complex terrain, $\overline{U}_o(z)$, has been recently proposed by Xu et al. [23]. The method they proposed involves a refined typhoon wind field model, Monte Carlo simulation, computational fluid dynamics (CFD) simulation, and artificial neural networks (ANN).

2.3. Evolutionary spectra

After extracting the time-varying mean wind speed from $U(t)$, the remaining fluctuating wind speed component $u(t)$ may still possess time-varying characteristics of wind turbulence. Therefore, $u(t)$ is represented by a zero-mean oscillatory process that admits the representation [24]:

$$u(t) = \int_0^{+\infty} A(\omega,t)e^{i\omega t}\mathrm{d}\xi(\omega) \tag{4}$$

where $i = \sqrt{-1}$; $A(\omega, t)$ is a slowly varying function with time; and $\xi(\omega)$ is a zero-mean Gaussian orthogonal increment process having the properties

$$\mathrm{E}[\mathrm{d}\xi(\omega)\mathrm{d}\xi(\omega')^*] = \begin{cases} 0 & \omega \neq \omega' \\ \mu(\omega)\mathrm{d}\omega & \omega = \omega' \end{cases} \tag{5}$$

in which the superscript "*" denotes the complex conjugate; and $\mu(\omega)\mathrm{d}\omega$ is variance of the increment process. The EPSD of $u(t)$ at the time instant t can then be written as:

$$S_{uu}(\omega,t) = |A(\omega,t)|^2\mu(\omega) \tag{6}$$

Based on observations on measured typhoon wind data [20], a closed-form formula for $S_{uu}(\omega, t)$ can be proposed by incorporating time-varying parameters into stationary power spectral density functions. In this study, the von Karman spectrum [25,26] is selected and extended to the evolutionary von Karman spectrum with time-varying variance, mean wind speed, and integral length scale.

$$\frac{S_{uu}(\omega,t)}{\sigma_u^2(t)} = \frac{1}{2\pi}\frac{\frac{4L_u(t)}{\overline{U}(t)}}{\left[1+70.8\left(\frac{\omega L_u(t)}{2\pi\overline{U}(t)}\right)^2\right]^{\frac{5}{6}}} \tag{7}$$