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Buffeting Response Analysis of a Long-Span Bridge under Nonstationary Mountain Winds

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ABSTRACT

In this paper, an effective scheme based on pseudo excitation method is established to predict non-stationary buffeting response of a long-span bridge located in a complex mountainous wind environment. First, a three layer non-stationary wind model is recommended based on full-scaled wind speed samples in bridge site. Second, complex mode decomposition technique at each mean wind speed was employed to investigate the full-bridge aeroelastic performance in order to provide valuable information to buffeting analysis. Third, the bridge aerodynamic system can be represented as a linear time-variant (LTV) system or a simplified linear time-invariant (LTI) system to quantify the buffeting response using pseudo excitation method. Once pseudo excitation method is used, the non-stationary buffeting response of a bridge structure is converted to transient analysis in time domain under a series of deterministic harmonic loadings. Finally, the effectiveness of the proposed scheme is verified through Monte Carlo simulations implemented in ANSYS platform.

1. INTRODUCTION

Different from the atmospheric-boundary-layer (ABL) wind, where the original wind speed is modelled as the summation of a constant mean and a stationary fluctuation, and the mean can be derived simply by averaging original wind speed sample in 10-min or 1-h time interval. Extreme winds such as hurricane /typhoon, tornadoes, downburst and gust fronts are often regarded as non-stationary random processes based on recently field observations, which compose of a deterministic time-varying mean wind and a random non-stationary fluctuation wind (e.g., Chen and Letchford, 2007; Kwon and Kareem, 2009; Huang et al. 2015).

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Currently, the number of measured non-stationary samples is limited (often only one available sample), which makes the modeling non-stationary winds very challenging including a three layer model for describing non-stationary winds, that is the determination of time-varying mean wind velocity, time-dependent envelop function and evolutionary power spectral density (EPSD) for wind fluctuations.

With the increase in span length of modern long-span bridges, wind-induced buffeting response becomes more and more significant. Despite buffeting response does not generally lead to catastrophic failures, its frequently occurrence may cause fatigue damage to flexible long-span bridges and significant discomfort to vehicles as well as pedestrians. In the past fifty years, the classical spectral analysis approach has widely been used to investigate multimode coupled buffeting random response. Also, time domain Monte Carlo simulations for wind-bridge interaction have also been studied. However, the assumption that the turbulence field is statistically stationary in time was taken into consideration in aforementioned studies. The stationary assumption of wind fluctuations with a constant mean wind speed is feasible only for synoptic winds. Due to the lack of knowledge for excitation non-stationarity and tremendous consumptions in time and computer memory when buffeting analysis is performed for complex system under non-stationary wind excitations, and thus the related report is few. In this paper, an effective scheme based on pseudo excitation method is established to predict non-stationary wind-induced buffeting random response of a long-span suspension bridge.

2. NONSTATIONARY WIND FILED MODELS

At the bridge spanwise location *x*, the longitudinal wind speed is generally modelled as the summation of a mean and a fluctuation component

$$U(x,t) = \bar{U}(x,t) + u(x,t) \tag{1}$$

where $\bar{U}(x,t)$ is a time-varying mean component and $u'(x,t)$ is a non-stationary fluctuation component.

$$w'(x,t) = \bar{w}(x,t) + w(x,t) \tag{2}$$

where $w(x,t)$ is vertical turbulent wind after the time-varying trend is removed; $\bar{w}(x,t)$ is the trend of original vertical wind speed.

In the following, time-varying mean and wind fluctuation are derived from full-scaled wind samples using SWT, and a separable non-stationary turbulence wind spectrum is modeled by multiplying intensity envelop function with normalized stationary wind spectrum, where the intensity envelop function is determined by Hilbert transform (HT) and the normalized wind spectrum is estimated by autoregressive (AR) model.

3. THEORETICAL BACKGROUND

Utilizing the Cholesky decomposition, the EPSD matrix of buffeting forces can be divided into the summation of r sub-matrices

$$\mathbf{S}_{Qb}(\omega,t)=\sum_{j=1}^{r}\left[S_{Qb}(\omega,t)\right]_j \tag{3}$$

Thus, the jth pseudo excitation force column vector is defined as

$$\tilde{\mathbf{F}}_{b,j}(\omega,t)=\mathbf{Q}_{b,j}(\omega,t)e^{i\omega t} \tag{4}$$

The jth pseudo displacement response can be readily determined by

$$\tilde{\mathbf{q}}_j(\omega,t)=\int_{t_0}^{t}\mathbf{h}_q(t,\tau)\mathbf{Q}_{b,j}(\omega,\tau)e^{i\omega\tau}d\tau \tag{5}$$

in which, the impulse matrix of displacement response can be expressed as (Chen, 2015)

$$\mathbf{h}_q(t,\tau)=\mathbf{\Phi}(t)e^{\int_t^{\tau}\mathbf{\Lambda}(t)dt}\mathbf{\Upsilon}_d^T(\tau) \tag{6}$$

After consideration of all r pseudo force column vectors, the displacement response spectrum as described as

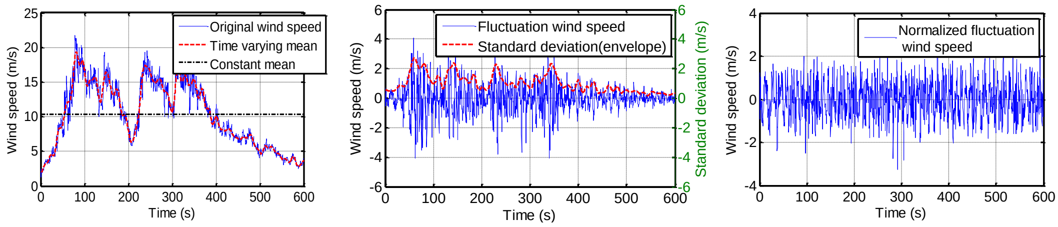
$$\mathbf{S}_q(\omega,t)=\sum_{j=1}^{r}\tilde{\mathbf{q}}_j^*(\omega,t)\tilde{\mathbf{q}}_j^T(\omega,t) \tag{7}$$

4. NUMERICAL EXAMPLE AND DISCUSSIONS

The Puli Bridge is a suspension bridge with a main span of 628 m located in China. As shown in Fig.1, the bridge site is surrounded by a mountainous topography.

Fig.1 Puli suspension bridge in mountainous topography

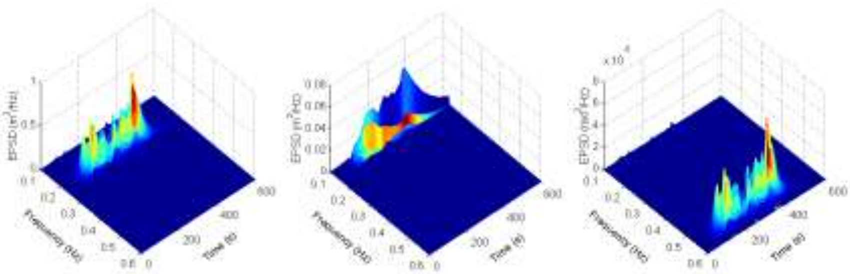
Take u component as an example, the longitudinal component of the measured record and its time-varying mean are shown in Fig. 2(a). The fluctuation wind of u component and its intensity envelope are displayed in Fig. 2(b). The normalized fluctuation wind is presented in Fig. 2(c).



(a) (b) (c)

Fig 2. Full-scale wind speed: (a) longitudinal wind speed and mean; (b) longitudinal fluctuation wind and standard deviation; (c) longitudinal normalized fluctuation wind

Fig. 3 (a-c) shows the EPSDs of the displacements at main span center and it is observed that the bridge responses also exhibit a significant non-stationarity. Take lateral RMS displacement as an example, Fig. 4 (a) displays the time-varying RMS value and Figure. 4 (b) shows the maximum RMS value along the bridge deck. Table. 1 lists the comparison of max RMS displacement with steady state and transient state.



(a) (b) (c)

Fig 3. EPSD of main girder displacements at middle center: (a) vertical displacement; (b) lateral displacement; (c) torsional displacement

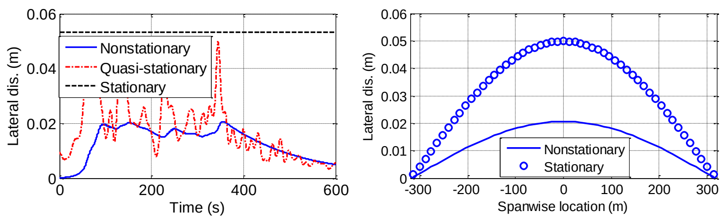


Fig 4. RMS displacements: (a) at middle center; (b) along bridge deck

Table 1. The comparison of max RMS displacement with steady state and transient state

Max RMS dis.	Vertical (m)	Lateral (m)	Torsional (rad)
Stationary	0.4839	0.0498	0.003347
Non-stationary	0.2301	0.0205	0.001581
Ratio	2.10	2.42	2.11

5. CONCLUSIONS

An efficient scheme for predicting the buffeting response of a long-span suspension bridge to non-stationary transient wind is developed by employing pseudo excitation method. Due to lack of “building-up” time to attain its steady-state value, non-stationary nature of mean wind and wind fluctuation results in lower response compared to quasi-stationary or stationary case. Traditional stationary treatment (10-min constant mean plus stationary wind fluctuation) may underestimate buffeting response.

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