Measurements and Analysis of Non-stationary Wind Characteristics at Sutong Bridge in Typhoon Damrey

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Abstract: Recent measurements of the wind field during extreme wind events (tropical and extratropical storms) indicate that the wind speed fluctuations exhibit strong non-stationary features echoing similar observations reported at other locations. In this study, the wind data of Typhoon Damrey recorded by the Structural Health Monitoring System (SHMS) at the Sutong Bridge were analyzed to examine the non-stationary features. Following stationarity test, the wind data were analyzed by both the stationary and non-stationary wind speed models utilizing conventional time- or frequency-domain as well from the time-frequency perspective. Wind

characteristics, e.g., the mean wind speed, turbulence intensity, gust factor and power spectral density including the evolutionary power spectral density (EPSD) of the wind were evaluated. The EPSD, which represents the distribution of the local turbulent energy in both time and frequency domains, was estimated using a wavelet-based scheme. The results of this study exhibit strong non-stationary characteristics in the measured wind data at the Sutong Bridge site. The findings of the data at the Sutong Bridge in the tropical storm reaffirm results from earlier studies and emphasize the need to incorporate non-stationary features of winds in the analysis and design of bridges from aerodynamic view point.

Keywords: Wind Characteristics; Non-stationarity; Sutong Bridge; Time-Frequency Analysis Tool; Evolutionary Power Spectrum.

INTRODUCTION

Conventional analysis of wind effects on bridges is usually carried out in the frequency domain (Davenport 1962) with the implicit assumption that the wind fluctuations are stationary (or weakly stationary). Recent measurements of wind records during extreme events (both tropical and extratropical storms) indicate that wind fluctuations exhibit non-stationary features. To investigate the importance of non-stationary aspects in the analysis of wind effects on bridges, it is important to first accurately understand and establish non-stationary characteristics of wind utilizing observed data.

Traditional wind speed model decomposes wind data into a constant mean wind speed and a zero-mean fluctuating component. The analysis of statistical properties of wind speed is based on this decomposition. However, for a typical non-stationary wind process, there is a trend (time-varying mean values) which needs to be extracted from the wind data. This feature can be

identified with the traditional time-averaged mean wind speed with an appropriately selected averaging interval. One possible approach to extract the time-varying mean values is based on the time-frequency analysis tools such as the empirical model decomposition (EMD) (Huang et al. 1998; Xu and Chen 2004) or discrete wavelet transform (DWT) (Olhede and Walden 2004; Wang and Kareem 2004; Wang et al. 2013). For non-stationary wind processes, the definition of statistical properties needs to be updated accordingly so that the time-varying mean values could be naturally integrated. A non-stationary wind speed model, in which the constant mean wind speed is replaced by the time-varying mean values, is an effective scheme for this purpose (Wang and Kareem 2004; Chen et al. 2007; McCullough et al. 2014).

The non-stationary wind data is actually characterized not only by the time-varying mean values but also by amplitude modulation that may be modeled in simple cases by an envelope function (e.g., Shinozuka and Deodatis 1988). Also in some cases these features may be frequency dependent. These features influence the power spectral density (PSD). The time-dependent PSD may affect the structural response as noted earlier specifically for nonlinear cases (Yeh and Wen 1990). One important issue in the time-dependent spectrum for engineering applications is to maintain the physical interpretation of conventional spectrum of a stationary process, where the concept of *frequency* is well defined and widely understood. In the development of evolutionary spectral theory, Priestley (1965) preserved the physical interpretation of the spectrum and the conventional definition of frequency. Hence, it has been widely implemented since its introduction. One approach to calculate the evolutionary power spectral density (EPSD) is to introduce the predefined amplitude and frequency modulation functions. However, this scheme is usually unable to fully characterize all the necessary non-stationary features that may be present in a wind field. Another way is to estimate the EPSD with

a single realization of the non-stationary process (Kameda 1975), where the short-time multi-window scheme is frequently employed. One obvious shortcoming of this approach is that the optimal adjustment of the resolution in both time and frequency domains cannot be achieved. Wavelet-based scheme has recently been introduced to effectively estimate the EPSD (Spanos and Failla 2004; Huang and Chen 2009) to alleviate the resolution issue. High accuracy can be obtained based on the assumption that the time-varying rate of modulation function of the spectrum is slow with respect to the duration of the selected wavelet (Spanos and Failla 2004; Kijewski-Correa and Kareem 2006).

The wind data recorded by the Structural Health Monitoring System (SHMS) of bridges include the effects of surrounding terrains on the wind characteristics and may present a most representative wind input for bridge aerodynamics analysis. In this study, a selection of data during Typhoon Damrey recorded by the SHMS at the Sutong Bridge was analyzed to investigate the non-stationary properties of the recorded extreme wind event. After the test for stationarity using the run test, the wind data were analyzed by the traditional stationary wind speed model and the non-stationary wind speed model based on the DWT. The wind characteristics obtained in this manner such as the mean wind speed, turbulence intensity, gust factor and power spectral density were compared. Finally, the EPSD of the wind speed time history, which can present the local turbulent energy distribution in both time and frequency domains, was estimated using a wavelet-based method. It is anticipated that the data and analysis in this study would add to much needed information on non-stationary winds to assess the need for necessary changes in wind load specifications for bridge and other structures design.

BACKGROUND OF THE SHMS OF SUTONG BRIDGE AND RECORDED DATA

The Sutong Bridge, which connects Suzhou and Nantong cities of Jiangsu Province in China, is a twin-tower two-cable, steel box girder cable-stayed bridge with a main span of 1088m. At the time of its opening in 2008, it was the longest cable-stayed bridge in the world. The bridge has three other features that top the list in the world including the main tower height of 306m, the cable-stayed length of 580m and the footprint of the group pile foundation equal to 113.75m×48.1m. An extensive SHMS was installed to monitor the natural environment and the corresponding bridge response during construction and post-construction. There are 15 types of sensors employed for the SHMS including four anemometers.

Layout of Anemometers on Sutong Bridge

Four 3D ultrasonic anemometers (ANE) were installed (Wang et al. 2013a). The wind angle 0° is defined for the north and 90° east with subsequent values in the clockwise direction. To record the progress of wind direction change accurately, polar coordinates were chosen for data output in a horizontal plane. Sampling frequency of anemometers was set as 1Hz for convenient data storage and management. The layout of anemometers is shown in Fig.1. As shown in the figure, two of the anemometers are installed at upstream (MS4) and downstream (MS4') sides, respectively at the midpoint of the deck (76 m in elevation), and the other two are at the top of the north (MS2) and south (MS6) towers (306 m in elevation), respectively.

Wind Speed Samples from SHMS

The long-term monitored wind data used for this study covered around five months including two summer typhoons. The wind data utilized in the analysis of wind characteristics were measured from the MS4 (windward side). Recorded data during 00:00-20:00 on 3 August, 2012 in Typhoon Damrey is shown in Fig. 2. Unfortunately, the two-dimensional mode of the

ultrasonic anemometer was activated during the measurement, where the vertical turbulence was not recorded.

ANALYSIS OF WIND CHARACTERISTICS

The mean wind speed and several typical statistical properties, such as the turbulence intensity, gust factor and power spectral density, will be discussed based on the recorded wind data obtained from the SHMS of the Sutong Bridge.

Stationarity Test

In the fixed averaging interval models (both stationary and non-stationary wind speed models), the averaging interval T for the calculation of mean wind speed is usually selected as 1 hour (e.g., National Research Council 2005), 10 minutes (e.g., Architectural Institute of Japan 2004; Professional Standard PRC 2004), or 3 seconds (ASCE 2010). Obviously, the analysis of non-stationary properties depends on the selected averaging interval. In the non-stationarity evaluation of the recorded wind data $T=10, 20, 30, 40, 50$, and 60 minutes were considered.

The run test and the reverse arrangement test are two popular schemes to test stationarity (Bendat and Piersol 2010). In this study, conventional run test, which is a non-parametric statistical test, was employed due to its simplicity. The principle of the run test is to count the number of runs in the view of hypothesis testing. The wind record will be considered as stationary in the desired level of significance if the number of runs falls within the acceptance range, otherwise it will be treated as nonstationary. More details for the run test can be found in Bendat and Piersol (2010).

The mean wind speeds (either constant value in the stationary wind speed model or time-varying values in the non-stationary wind speed model) were extracted from the recorded wind

data utilized in this study. Details of the mean removal will be discussed in the next Section. Table 1 presents the non-stationarity evaluation results (the percentage of data that fails to pass the stationarity test) of the recorded wind data based on the run test.

As shown in Table 1, the recorded wind data of Typhoon Damrey present strong nonstationary characteristics. Hence, it may be necessary to further understand nonstationary characteristics of wind for more accurately analysis of the wind effects on bridges. Obviously, the nonstationarity becomes more critical as the averaging interval increases. Based on the traditional stationary wind speed model, around 90% of the measured wind records cannot pass the stationarity check at $T=60$ minutes; on the other hand, only 38.61% of the wind records for Typhoon Damrey cannot pass the stationarity check for $T=10$ minutes. Removing the time-varying mean wind speed results in more wind records that pass the stationarity check.

Mean Wind Speed

In the stationary wind speed model, the wind process in the longitudinal, lateral and vertical directions, respectively, can be expressed as

$$U(t) = \bar{U} + u(t) \quad (1a)$$

$$V(t) = \bar{V} + v(t) \quad (1b)$$

$$W(t) = \bar{W} + w(t) \quad (1c)$$

where $\bar{U}$, $\bar{V}$ and $\bar{W}$ are the constant mean wind speed in the longitudinal, lateral and vertical directions, respectively; $u(t)$, $v(t)$ and $w(t)$ are corresponding zero-mean fluctuating components.

Usually, both $\bar{V}$ and $\bar{W}$ are equal to zero. The constant mean wind speed are calculated by averaging the wind process with an averaging interval $T=1$ hour in this study. Other fixed intervals are also possible candidates.

In the nonstationary wind speed model, the wind in the longitudinal, lateral and vertical directions, respectively, can be expressed as

$$U(t) = \bar{U}^*(t) + u^*(t) \quad (2a)$$

$$V(t) = \bar{V}^*(t) + v^*(t) \quad (2b)$$

$$W(t) = \bar{W}^*(t) + w^*(t) \quad (2c)$$

where $\bar{U}^*(t)$, $\bar{V}^*(t)$ and $\bar{W}^*(t)$ are the deterministic time-varying mean wind speed (or temporal trend) in the longitudinal, lateral and vertical directions, respectively; $u^*(t)$, $v^*(t)$ and $w^*(t)$ are corresponding zero-mean fluctuating components. Usually, both $\bar{V}^*(t)$ and $\bar{W}^*(t)$ are equal to zero. The time-varying mean wind speed can be calculated by the time-frequency analysis tools. Here, the DWT (Olhede and Walden 2004; Wang and Kareem 2004; Wang et al. 2013) was utilized to extract the temporal trend information of the recorded wind data. The DWT can be treated as a class of filter banks, which can decompose the wind process into a series of band-pass component processes. The lowest-frequency component (or called approximation) denotes the time-varying mean wind speed, which is a continuous function of the time. In this study, the Daubechies wavelet (Daubechies 1992) of order 10 was utilized. To obtain a selected averaging interval (1 hour here), the wind data may need to be resampled before the wavelet analysis. Figure 3 presents comparisons of the constant hourly mean and the time-varying mean wind speeds based on the recorded wind data.

A typical set of non-stationary longitudinal wind speed time histories and corresponding mean wind speed are presented in Fig. 3(a). As shown in the figure, for the Typhoon Damrey, the constant hourly mean wind speed $\bar{U}$ based on the traditional stationary wind speed model is 11.79 m/s, while the maximum, minimum and hourly averaged values of the time-varying mean wind speed are 13.60 m/s, 10.21 m/s and 11.70 m/s, respectively. It is noted that the hourly averaged

value of the time-varying mean wind speed is very close to the corresponding constant hourly mean wind speed, which suggests application of the non-stationary wind speed model in practice (Chen et al. 2007). Typical nonstationary lateral wind speed time histories and corresponding mean wind speed are presented in Fig. 3(b). As indicated in the figure, the maximum, minimum and hourly averaged values of the time-varying mean wind speed for the fluctuating component $v^*(t)$ are 0.32 m/s, -0.89 m/s and -0.13 m/s, respectively.

Similar observations in typhoons and hurricane winds have been reported in Xu and Chen (2004), Wang and Kareem (2005) and Wang et al. (2013). The reaffirmation of these nonstationary trends and their modeling suggest that such a framework be given a serious consideration as we begin to move from the tacit assumption of stationarity to more realistic non-stationary winds.

Turbulence Intensity

The turbulence intensity based on a stationary wind speed model is defined as the ratio of the standard derivation (SD) of the fluctuating wind speed component to the constant mean wind speed

$$I_{\alpha} = \frac{\sigma_{\alpha}}{\bar{U}} \quad (3)$$

where the subscript $\alpha=u(t), v(t), w(t)$; σ denotes the SD of the fluctuating component over the user-defined averaging interval T . In the non-stationary wind speed model, the turbulence intensity using a definition similar to the stationary model will be time dependent due to the time-varying mean wind speed. Hence, the turbulence intensity in a non-stationary wind speed model is given by the expected value of the time-dependent turbulence intensity over the user-defined averaging interval T .

$$I_{\alpha}^* = E_T \left[\frac{\sigma_{\alpha^*}}{\bar{U}^*(t)} \right] \quad (4)$$

where $E_T[\cdot]$ denotes the expected value over the averaging interval T ; the subscript $\alpha^* = u^*(t), v^*(t), w^*(t)$ (Xu and Chen 2004; Wang and Kareem 2005; Wang et al. 2013).

Figure 4 presents the longitudinal and lateral turbulence intensities of 1-hour averaging interval for the Typhoon Damrey, and the corresponding averaged, maximum and minimum values are listed in Table 2.

As shown in Fig. 4 and Table 2, both longitudinal and lateral turbulence intensities of 1-hour averaging interval obtained using the traditional stationary wind speed model are larger compared to those obtained using the non-stationary wind speed model. This indicates that the turbulence intensity based on 1-hour averaging interval may be overestimated if the traditional stationary wind speed model is utilized. Although the vertical turbulence was not recorded and hence not analyzed, it is reasonable to consider similar observation is valid for the vertical case. The difference between the results of these two models is heavily dependent on the non-stationary characteristics of the investigated wind speed time history. For example, during the first three hours period of the Typhoon Damrey wind data, where the wind speed and direction vary significantly according to Fig. 2, the ratios of turbulence intensities based on stationary and non-stationary models I_u/I_u^* and I_v/I_v^* are around 1.30 and 1.20, respectively. The calculated longitudinal turbulence intensity is always larger than the lateral turbulence intensity. For example, based on the traditional stationary wind speed model the ratio of the averaged value of the longitudinal and lateral turbulence intensities for the Typhoon Damrey is 0.7534; while the result based on the non-stationary wind speed model is 0.7321. This observation follows results based on theoretical considerations and experimental results of turbulence characteristics in

atmospheric boundary layer [e.g., reported in Simiu and Scanlan (1996) and Tamura and Kareem (2013)].

The longitudinal and lateral turbulence intensities of 10-minute averaging interval for the Typhoon Damrey are also calculated based on the traditional stationary and nonstationary wind speed models. If the traditional stationary wind speed model is utilized, the turbulence intensity obtained with 10-minute averaging interval is a little smaller than that with 1-hour averaging interval. Whereas, if the non-stationary wind speed model is employed, there is no obvious difference between the results with different averaging intervals. This indicates that the difference between the turbulence intensities of these two models becomes smaller as the averaging interval decreases. Other observations based on the calculation of 10-minute averaging interval are similar with those based on the calculation of 1-hour averaging interval.

Gust Factor

The gust factor of t_0 duration in a stationary wind model is defined by the ratio of the maximum t_0 -averaged wind speed within the averaging interval T to the constant mean wind speed

$$G_{t_0} = \frac{\max \left[\bar{U}_{t_0}(t) \right]}{\bar{U}} \quad (5)$$

where $\bar{U}_{t_0}(t)$ is the gust wind speed of t_0 duration ($t_0 \leq T$) in the stationary wind speed model.

Accordingly, the gust factor of t_0 duration in the non-stationary wind speed model is given by the maximum ratio of t_0 -averaged wind speed to the corresponding t_0 -averaged time-varying mean wind speed over the averaging interval T

$$G_{t_0}^* = \max \left[\frac{\bar{U}_{t_0}(t)}{\bar{U}_{t_0}^*(t)} \right] \quad (6)$$

where $\bar{U}_{t_0}^*(t)$ is the gust wind speed of t_0 duration ($t_0 \leq T$) in the non-stationary wind speed model (Xu and Chen 2004; Wang and Kareem 2005; Wang et al. 2013). In this context, the averaging interval T is selected as 1 hour.

Figure 5 presents gust factors with the duration of 10 minutes based on the traditional stationary and non-stationary wind speed models. It is shown that the calculated results using these two models are quite close to each other.

Power Spectral Density

The power spectral density (PSD) of the fluctuating wind speed component is an important feature in the bridge aerodynamic analysis. In this study, the fast Fourier transform in conjunction with Hamming window, overlapping data and piecewise smoothing were employed in estimating the PSD. Wind sample from 9th to 11th hour in Fig. 2 was used for the PSD estimation. The results are compared in Fig. 6 to the Kaimal spectrum, which has been adopted in the "Wind-resistant Design Specification for Highway Bridges" in China (Professional Standard PRC 2004). It should be noted that the signal was analyzed after a low-pass filtering, and hence the aliasing phenomenon was alleviated to some extent. The upper frequency in Fig. 6 is 0.5Hz due to the Nyquist sampling theorem with a sampling frequency of 1Hz. The relatively low sampling frequency has little effects on the calculation of structural buffeting responses in time domain since an empirical-model based PSD obtained from the curve fitting, where high frequency components are included, will be utilized in buffeting analysis (Wang et al., 2013b).

It is shown that, due to the removal of the time-varying mean wind speed, the low-frequency part of PSD values based on the non-stationary wind speed model are smaller than those based on the traditional stationary wind speed model. The estimated PSD values based on both stationary and non-stationary wind speed models are slightly larger than those of the Kaimal

spectrum for the high-frequency part. For the low-frequency part, the PSD values based on the traditional stationary wind speed model are larger than those of the Kaimal spectrum while opposite trend can be seen in the non-stationary wind speed model.

EVOLUTIONARY POWER SPECTRAL DENSITY OF RECORDED STRONG WIND

A wavelet-based analysis as a consequence of the flexible window sizes provides high resolutions at both high and low frequencies. Gurley and Kareem (1999), Iyama and Kuwamura (1999), and Kijewski and Kareem (2003) presented a general relationship between the mean-square values of the wavelet transform at various scales and the time-dependent spectrum for a random process. The procedure to evaluate evolutionary power spectral density (EPSD) of a scalar non-stationary random process based on the wavelet analysis has been developed by Spanos and Failla (2004), which was extended by Huang and Chen (2009) for vector-valued non-stationary processes. The evaluation utilizes the weighted summation of wavelet coefficients at different scales to obtain the relationship between wavelet coefficient and EPSD at each time instant.

Utilizing the EPSD framework in wavelet domain, the EPSD of recorded wind data of Typhoon Damrey (from 9th to 11th hour in Fig. 2), was evaluated and given in Fig. 7(a). The EPSD of Typhoon Damrey is then averaged in the time domain and compared to the traditional Fourier-based PSD, as shown in Fig. 7(b). The results show good comparison and attest to the high fidelity of the EPSD estimation. To further investigate the non-stationary characteristics of the recorded wind data, slices of EPSD at certain time instants and frequencies are presented in Figs. 7(c) and 7(d), respectively. These conditional slices of EPSD in both time and frequency domains present inherent instantaneous variations in wind fluctuations. These features are not

discernable via traditional Fourier-based PSD and offer a portrait of the inherent time-frequency variations in the turbulent fluctuation in a non-stationary wind field. Modeling of these features may be very important in the simulation of wind field and associated response of bridge aerodynamic and aeroelastic behavior under non-stationary winds.

CONCLUDING REMARKS

A selection of wind data during Typhoon Damrey recorded by the SHMS at the Sutong Bridge in PROC was analyzed to investigate the non-stationary features of the recorded wind event. The stationarity of the wind speed was first tested using the run test method. It was shown that the recorded wind data of Typhoon Damrey exhibited strong non-stationary features. The use of nonstationary wind speed model, by removing the time-varying mean wind speed, resulted in wind records that passed the stationarity check. The wind data was analyzed by the traditional stationary wind speed model and nonstationary wind speed model based on the DWT. A comparison of wind characteristics, e.g., the mean wind speed, turbulence intensity, gust factor and power spectral density based on the stationary and non-stationary models showed that the non-stationary wind model can better characterize the recorded wind. It should be noted that the hourly averaged values of the time-varying mean wind speed were very close to the corresponding constant hourly mean wind speed. Both longitudinal and lateral turbulence intensities of 1-hour averaging interval obtained using the traditional stationary wind speed model were higher as compared to the non-stationary wind speed model. However, the difference between the results of these two models became smaller as the averaging interval decreased, suggesting that shorter averaging interval be standardized. Due to the removal of the time-varying mean wind speed, the low-frequency part of PSD values based on the non-stationary wind speed

model was smaller than the traditional stationary wind speed model. Finally, the EPSD of the wind speed time history, which can present the local turbulent energy distribution in both time and frequency domains, highlighted obvious inherent non-stationary features present in the wind records analyzed. This study further reaffirms the findings of the earlier studies on the subject (Xu and Chen 2004; Wang and Kareem 2005; Wang et al. 2013) and reinforces the case for shifting design consideration from the tacit assumption of stationarity to a non-stationary analysis framework.

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Table 1: The non-stationarity evaluation results of the recorded wind data based on the run test
(%: percentage of data that fails to pass the stationarity test).

Wind Type	Wind Speed Model	Time Interval (minute)					
		10	20	30	40	50	60
Typhoon Damrey	Stationary	38.61%	67.78%	77.50%	83.33%	87.50%	91.67%
	Non-stationary	21.39%	24.44%	23.33%	37.78%	41.67%	76.67%

397 Table 2: The averaged, maximum and minimum values of the 1-hour turbulence intensities.

Wind Type	Wind Speed Model	Turbulence Intensities (I_u I_v)			
		Averaged		Maximum	
Typhoon Damrey	Stationary	0.2875	0.2166	0.3929	0.4738
	Non-stationary	0.2729	0.1998	0.3023	0.2508

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- 400 Figure 1: Layout of anemometers on Sutong Bridge (Unit: m).
- 401 Figure 2: A samples of recorded wind speed and direction in Typhoon Damrey
- 402 Figure 3: Comparison of constant mean and time-varying mean wind speeds: (a) Longitudinal
- 403 component; (b) Lateral component.
- 404 Figure 4: Comparison of the 1-hour turbulence intensities of Typhoon Damrey.
- 405 Figure 5: Comparison of the 1-hour gust factors of Typhoon Damrey with a 10-minute duration.
- 406 Figure 6: Comparison of the measured longitudinal spectra of Typhoon Damrey and the Kaimal
- 407 spectra.
- 408 Figure 7: EPSD of Typhoon Damrey: (a) EPSD; (b) The averaged EPSD and the Fourier-based
- 409 PSD; (c) Slices of EPSD at certain times; (d) Slices of EPSD at certain frequencies.
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Figure 1:

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