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Evolutionary power spectral density of recorded typhoons at Sutong Bridge using harmonic wavelets

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ABSTRACT

The rapid development of structural health monitoring system (SHMS) over last decades makes the accurate monitoring of structural responses and surrounding environments possible. The obtained wind speed data during recorded typhoons typically show significant non-stationary features. Run-test method was employed to verify the stationarity of the recorded wind speed data. To investigate the non-stationary characteristics of recorded typhoons, the evolutionary power spectral densities (EPSDs) of four typhoons at Sutong Bridge site were estimated based on the wavelet transform (WT). A numerical experiment was conducted to identify the proper wavelet bases in the estimation of the EPSDs for non-stationary turbulent wind flows. Specifically, recorded data of typhoons Fung-wong, Meari, Damrey, and Matmo from the SHMS on Sutong Bridge were utilized to calculate the EPSDs using the generalized harmonic wavelet (GHW) and the filtered harmonic wavelet (FHW). The EPSDs estimated by GHW and FHW were comparatively investigated. The normalized Kaimal EPSDs were also compared with the normalized recorded EPSDs of the four typhoons. Results show that the HW-based EPSD estimations for the recorded typhoon data are accurate and reliable. The EPSDs estimated by FHW show the optimum time resolution in comparison with GHW and Morlet wavelet. The energy of the recorded wind speed data mainly concentrates in low-frequency band. The Kaimal EPSDs may be not appropriate to depict the evolutionary features of recorded data during typhoons Fung-wong and Matmo in this study. This observation may provide reference values for wind effect analysis on the long-span bridges with low natural frequencies.

1. Introduction

With global change in climate, wind hazards are attracting ever-increasing attention due to the wind-induced destructive damages on large-scale infrastructures (e.g., Xu and Zhan, 2001; Wang et al., 2009; Li et al., 2017). As one of the most significant winds, typhoons are responsible for large numbers of casualties and considerable economic losses. As a result, the study on wind characteristics of typhoons plays an important role in structural wind resistance (Kareem, 2008; Snaiki and Wu, 2017a,b). The typical approach for analyzing the wind characteristics assumes the fluctuating component of wind speed time histories as a zero-mean stationary random process by subtracting the mean wind speed (e.g., Wang and Kareem, 2004; Chen et al., 2007). As one of the major wind characteristics, the power spectral density (PSD) (e.g., Deodatis, 1996; Wang et al., 2013a,b) is essential for the simulation of wind-related processes (e.g., Davenport, 1962; Adhikari and Yamaguchi, 1997) and becomes one of the key issues in structural wind engineering. In the past sixty years, some meaningful researches have been conducted and several conventional wind spectra were established using data collected from field measurements (Davenport, 1961; Kaimal et al., 1972). These commonly-used wind spectra exhibit the wind energy distributions in the frequency domain.

Structural health monitoring system (SHMS), which aims at real-time detection of the structural performance and surrounding environments, is installed to enhance structural safety and to significantly reduce life-time operation costs for maintenance. Thus, by utilizing the SHMS equipped on critical structures, the extreme wind events, such as typhoons, downbursts, and tornados could be recorded and analyzed to promote the structural wind engineering (e.g., Simiu and Scanlan, 1996; Taha et al., 2006; Wang et al., 2017). With the development of the SHMS, a large number of field measurements have been performed to investigate wind characteristics in different regions (e.g., Xu et al., 2000; Miyata et al., 2002; Hui et al., 2009; Li et al., 2009; Tao et al., 2016). It has been shown that many recorded time histories of typhoons present

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non-stationary features (e.g., Chen and Xu, 2004; Xu et al., 2015; Wang et al., 2016). Since the commonly used Fast Fourier Transform (FFT) or Discrete Fourier Transform are based on the stationary hypothesis, the joint time-frequency techniques fit for non-stationary hypothesis have been employed for processing the recorded typhoon signals (e.g., Gurley and Kareem, 1999; Huang and Chen, 2009; Ma et al., 2016).

To capture the time-dependent frequency content of a signal, Wigner (1932) and Ville (1948) proposed a time-dependent spectrum which was defined as the Fourier transform of an instantaneous correlation function with time lag centered at local time. This approach is well known as the Wigner-Ville method (WVM). Alternatively, using the Fourier transform to “short windowed” data at various time locations, the traditional Fourier transform was improved as short-time Fourier transform (STFT) (Cohen, 1995). However, the time-frequency resolutions of WVM and STFT are insufficient for many practical applications (Spanos et al., 1996). In order to simultaneously enhance the time and frequency resolutions, wavelet-based analysis was applied to overcome the inherent limitations of WVM and STFT (e.g., Grossmann and Morlet, 1984; Mallat, 1987). Wavelet transform (WT) provides a time-frequency representation based on a windowing technique with basic function called “wavelet”. By scaling and shifting the “mother” function, wavelet analysis can well capture the low frequency information with large window and high frequency information with small window (Hubbard, 2005). Hence, WT is an appropriate tool to analyze non-stationary typhoons based on its multi-resolution analysis.

Priestley (1965) developed an approach to analyze the spectra of non-stationary processes based on the evolutionary power spectral density (EPSD). In this approach, spectral functions are time-dependent and have a physical interpretation as local energy distributions over frequency. Spanos and Failla (2004) proposed a wavelets-based method to estimate the EPSD. The EPSD is regarded as a sum of frequency-dependent shape functions that were modulated by time-dependent coefficients. A linear system of equations was solved to obtain it. Both orthogonal and non-orthogonal wavelet bases were proved to be feasible to provide a desirable accuracy in the estimation of the EPSDs of Priestley's oscillatory processes. Among a large number of wavelets, the harmonic wavelet (HW) introduced by Newland (1993, 1994) presented a simple structure, whose shape can be expressed in functional form. Subsequently, based on the property of non-overlapping Fourier transforms, explicit mathematical expressions were derived to elucidate the representation of EPSD with the various members of the HW family, including the generalized harmonic wavelet (GHW) and the filtered harmonic wavelet (FHW) (Spanos et al., 2005). Using the developed procedure, the EPSDs of earthquakes in Kocaeli and Turkey were analyzed. It shows that the FFT scheme utilized in the generalized harmonic wavelet transform (GHWT) and the filtered harmonic wavelet transform (FHWT) offers a significant advantage to increase computational efficiency when long sequences and huge amount of samples are considered. It is noted that the FHWT cannot define an orthogonal transform, which is different from the GHWT (Spanos et al., 2005).

In this study, the EPSDs of typhoons are estimated using the efficient GHWT and FHWT. The recorded data from SHMS equipped on Sutong Bridge during typhoons Fung-wong, Meari, Damrey, and Matmo are selected for non-stationary analysis. The stationarity of the turbulence is testified using run test method. The efficiency of the EPSD estimation using both HWs is then demonstrated and compared with Morlet wavelet using a numerical example. Finally, the EPSDs of the recorded typhoons are estimated with wavelet-based method using GHW and FHW. The averaging EPSD is defined and compared with the PSD obtained by Pwelch method to validate the reliability of the estimated EPSD.

2. Field recorded non-stationary wind records

2.1. Anemometers on Sutong Bridge

Opened to traffic on 25 May 2008, Sutong Bridge (see Fig. 1) connects Suzhou and Nantong cities in Jiangsu Province, China. With the main span of 1088 m, the Sutong Bridge is 108 km away from the estuary of the Yangtze River to the Yellow Sea. The streamline-shaped steel box girders enhance the aerodynamic stability of the whole bridge. The two inverted Y-shaped towers are about 300-m high and bear the load of bridge deck held by two parallel wire cables (Wang et al., 2013a).

The SHMS is installed on the Sutong Bridge to evaluate the bridge conditions during the construction and operation period. The sensory subsystem in the SHMS is composed of 15 types of sensors, such as anemometer, accelerometer, temperature sensor, and global positioning system, etc. Data collected from these sensors can provide further evaluation of structural safety status (Deng et al., 2015). The layout of anemometers utilized for surrounding wind monitoring is shown in Fig. 2. The bases of the anemometers are fixed stably to make the recorded data reliable.

Fig. 1. Location of Sutong cable-stayed Bridge.

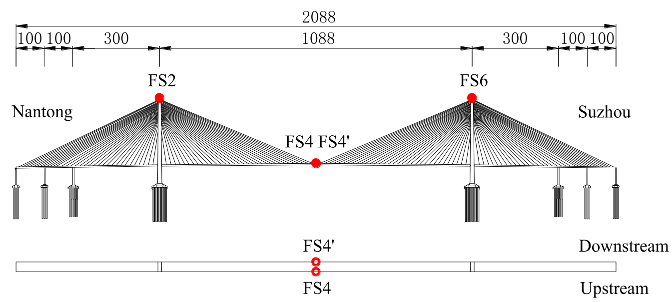

Fig. 2. Layout of the anemometers on Sutong Bridge (Unit: m).

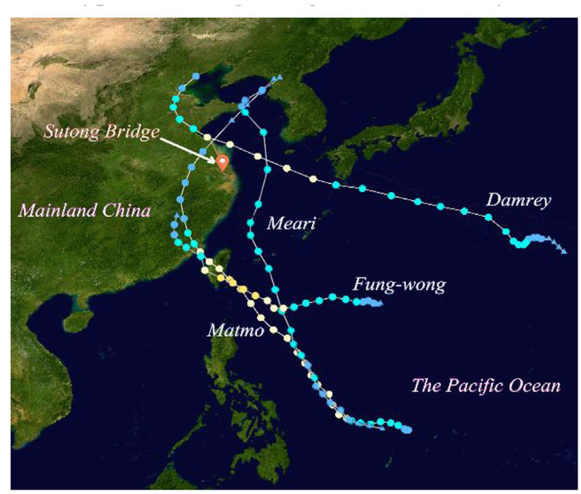

Fig. 3. Moving tracks of typhoons.