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Modeling typhoon wind power spectra near sea surface based on measurements in the South China sea

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ABSTRACT

This study focuses on enhancing our understanding of the spectral features of typhoon winds with critical implications on the mitigation of disproportionate damage experienced in typhoons-prone coastal regions. Examination of data suggests that generally used empirical models of wind power spectrum for extratropical storms may not adequately represent the tropical cyclone winds. In this paper, a data-driven model is proposed for wind power spectrum in tropical cyclone winds over the sea surface. Rather than fitting data to a universal spectral description, first the physical meaning of parameters in such a model is carefully examined and the contribution of each parameter is delineated. With these backgrounds, field measurements in typhoon Hagupit are used to model these spectral parameters in terms of the Monin–Obukhov length, mean wind speed and roughness length. Finally, the proposed spectral model is validated using arbitrarily selected four hours of data in different sectors of typhoon Hagupit wind field. The model shows a good agreement with the measurements.

1. Introduction

In recent years, many high rise buildings and long span bridges have been built in southern China, where typhoons frequently make landfall each year exposing dynamically sensitive structures to typhoon wind field. The fluctuations in typhoon winds are critical in establishing buffeting and other flow induced loads on these structures, which emphasizes the need to accurately describe typhoon wind characteristics and power spectrum density. Current codes and standards have instituted the premise that wind field characteristics in tropical cyclones are similar to those observed in the boundary layer winds of extratropical storms, which is formed based on careful analysis of the commonly used gust factors (ratio of peak wind speed and mean wind speed over a defined averaging interval) in a number of landfalling hurricanes in the Atlantic and Gulf coasts. Despite these apparent similarities in the nature of typhoon/hurricane wind fields, there have been questions raised regarding the role of convective features in the wind field. While these aberrations may magnify wind speeds and velocity spectra, they are also known to be transient, sporadic, and spatially patchy in the typhoon/hurricane wind field.

The wind power spectrum statistically represents the energy distribution in a turbulent flow field, which can be viewed as a superposition of eddies ranging spatially from millimeters to kilometers and temporally from a fraction of a second to hours. The behavior of turbulence spectrum within the atmospheric boundary layer follows the Kolmogorov hypotheses in the inertial sub-range, which ensures spectral description to have a universal shape when scaled appropriately in a certain range of frequencies or wave-numbers. Based on homogeneous, isotropic turbulence and field measurements, a number of spectral descriptions have been advanced primarily in strong extratropical winds (Karman, 1948; Davenport, 1961; Fichtl and McVehil, 1970; Miyake et al., 1970; Kaimal et al., 1972; Simiu, 1974; Kareem, 1985a, 1985b; Solari, 1993; Tieleman, 1995). However in tropical cyclones, the downward transport of convective cells from aloft modulates the typhoon/hurricane near sea surface, and convective turbulence and mesoscale motion may play a more prominent role in energy transport at different scales, so that the turbulent energy distribution may not exactly mirror features observed in neutral, homogeneous, and isotropic turbulence flow. Such a conjecture was made by the third author following hurricane Alicia while examining radar data, wind observations at ground level and damage patterns. It is recently being discussed in wind engineering field (e.g., Florida Coastal Monitoring Program, NatHaz Modeling Laboratory).

To better understand tropical cyclone wind characteristics and their power spectra, a number of measurements have been

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conducted near top of structures or over open flat smooth land in typhoon or hurricane conditions (Xu and Zhan, 2001; Fu et al., 2008; Cao et al., 2009; Schroeder et al., 2009; Hui et al., 2009a, 2009b; Masters et al., 2010; Wang et al., 2011). A majority of these measurements found that tropical wind spectra matched von Karman spectrum (Karman, 1948). However, some measured results noted that the energy distribution did not exactly follow the empirical spectra and the frequency associated with the peak value of the normalized spectrum $nS_u(z,n)/\sigma_u^2$ either shifted to a low frequency or a high frequency range (Schroeder and Smith, 2003; Yu et al., 2008; Caracoglia and Jones, 2009; Zhang, 2010). The variance of fluctuations in tropical cyclones also exceeds those observed in extratropical storm boundary layer flows modeled in terms of the surface shear wind speeds. This may answer the role of energetic convective cells and their contribution to variance in fluctuations.

This paper first summarizes the theoretical background of turbulence energy spectra from a micrometeorological perspective. This is followed by an examination of the physical meaning of parameters in the universal wind spectral model and the number of parameters needed to define the spectral model is reduced from six to four. Subsequently, typhoon wind data and its turbulence wind characteristics are detailed and spectral parameters are expressed in terms of salient flow features. Finally, a data-driven model for determining power spectra for typhoon winds over the sea surface is proposed and the validation of the proposed model is examined with four hours of data in different locations of typhoon Hagupit wind field and concluding remarks are given.

2. Theoretical background of turbulence in the atmospheric boundary layer

One of the critical features of the atmospheric turbulence in the definition of structural loads is the spectral description of wind velocity fluctuations. The turbulent energy spectrum is often divided into three main ranges of frequency (Kaimal and Finnigan, 1994): (1) the energy-containing range with the bulk of the turbulent energy produced by buoyancy and shear; (2) the inertial sub-range, where energy is neither produced nor dissipated but transferred down to smaller scales; (3) the dissipation range. Following the Kolmogorov hypotheses and the dimensional considerations the spectrum in the inertial sub-range is given by

$$S(K) = a_u \varepsilon^{2/3} K^{-5/3} \tag{1}$$

where a_u is a constant around 0.5 (Kaimal et al., 1972), ε is the rate of energy transfer, and K is the wave number.

In the surface layer, the Monin–Obukhov similarity theory (Monin and Obukhov, 1954) is applied, which implies that the various atmospheric parameters and their statistics, such as gradients, variance and covariance normalized by appropriate powers of the friction velocity u_* or temperature T_*, become universal functions of z/L. However, it has been noted that the variance of the horizontal velocity does not always follow the Monin–Obukhov similarity theory due to the influence of eddies originating outside the surface layer (Olesen et al., 1984; Högström, 1990). It is also noted that the peak factor in the hurricane winds has non-Gaussian feature and exhibits some dependences on the wind speed and turbulence (Balderrama et al., 2012). The rate of energy transfer (Panofsky and Dutton, 1984) in the surface layer can be expressed as

$$\varepsilon = u_*^2 \frac{\partial U}{\partial z} = \frac{u_*^3 \phi_\varepsilon}{kz} \tag{2}$$

where k is the von Karman constant, u_* is the friction velocity and ϕ_ε is the dimensionless Monin–Obukhov function for wind shear, U is the mean wind speed in meter per second.

Substituting Eq. (2) into (1), the turbulence energy spectrum can be expressed as

$$\frac{nS_u(z,n)}{u_*^2 {\phi_\varepsilon}^{2/3}} = A_u f^{-2/3} \tag{3}$$

where A_u is a non-dimensional parameter and typically equals to 0.27 (Yu et al., 2008), and f is the Monin coordinate, defined as $f = nz/U$ herein.

In the neutral atmospheric stratification $\phi_\varepsilon = 1$ (Panofsky and Dutton, 1984), the turbulence energy spectrum can be rewritten as

$$\frac{nS_u(z,n)}{u_*^2} = A_u f^{-2/3} \tag{4}$$

Measurements suggest that for engineering applications Eq. (4) provides a good estimate of the power spectrum in the high frequency range ($f > 0.2$) (Fichtl and McVehil, 1970; Simiu, 1974).

Most expressions for wind power spectra have been derived based on Eq. (4) and Monin–Obukhov similarity theory (Karman, 1948; Davenport, 1961; Kaimal, 1973; Kareem, 1985a, 1985b; Solari, 1987; Tieleman, 1995). The following universal expression for these wind power spectra has accordingly been advanced (Olesen et al., 1984):

$$\frac{nS_u(n)}{u_*^2} = \frac{AR^2 f^\gamma}{(C + Bf^\alpha)^\beta} \tag{5}$$

where $f = n\Lambda/U$, $\Lambda$is a length scale, which can be chosen as the height z above ground or the longitudinal integral scale L_u^x at height z or a constant length over the entire height; A,B,C,α,β and γ are six parameters, R is the ratio between the standard deviation of the turbulence component and the friction velocity, which is akin to turbulence intensity and it has been referred to as turbulence ratio in Masters et al. (2010)

$$R = \frac{\sigma_u}{u_*} \tag{6}$$

3. Spectral properties and model criteria in surface layer

3.1. Parameter sensitivity analysis

Typically, parameters for the most currently used spectral models were obtained by fitting the spectral model to satisfy the inertial sub-range and the low frequency range. Instinctively, one could expect that each parameter in the universal model would have its own physical meaning and influence on the energy distribution. In order to investigate the physical meaning of each parameter in Eq. (5), a sensitivity analysis was conducted. The range of values considered for each parameter is listed in Table 1. The influence of a particular parameter was examined while

Table 1
Ranges of values for parameter sensitivity analysis.

Parameters	L_u^x/U	A	B	C	α	β	γ
Value	60	15:5:45	20:10:80	0.4:0.2:1.6	0.5:0.4:2.9	0.4:0.2:1.6	0.4:0.2:1.6