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Wind characteristics of Typhoon Dujuan as measured at a 50 m guyed mast

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Abstract. This paper presents the wind characteristics of Typhoon Dujuan as measured at a 50 m guyed mast in Hong Kong. The basic wind speed, wind direction and turbulent intensity are studied at two measurement levels of the structure. The power spectral density of the typhoon is compared with the von Karman prediction, and the coherence between wind speeds at the two measurement levels is found to compare with Davenport's prediction. The effect of typhoon Dujuan on the response of the structure will be discussed in a companion paper (Law, *et al*. 2006).

Keywords: guyed mast; nonlinear; typhoon; turbulence; correlation; power spectral density.

1. Introduction

Guyed mast is widely used in the telecommunication industry and there is a stringent requirement on the vibration of the microwave dishes. Knowledge on the dynamic characteristics of the guyed mast under different dynamic loads is essential for an optimal performance of the telecommunication system.

Compared with other structures, the static and dynamic behavior of guyed mast is fairly complex due to its slenderness and compliant guy-support system. The non-linearity mainly comes from the

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guy force and its displacement, the non-linearity due to the high axial force in the mast shaft (second order effect) and the unknown damping. Furthermore the bending, shear and torsional deformations of the guyed mast are easily coupled, and the associated natural frequencies are close to each other.

The natural frequency of the structure is low enough to be excited by turbulence in the natural wind. Dynamic excitation of the mast is mainly caused by the gustiness of the wind. Many researchers have studied the characteristics of guyed mast by theoretical analysis and wind tunnel tests. Peil and Nölle (1992) determined the wind-profiles and statistical parameters of the turbulence by measuring the wind speeds at seventeen levels with relatively small vertical distances up to the height of 341 m of a guyed mast. Madugula, *et al*. (1998) studied the natural frequencies of a guyed mast due to the effect of icing, initial guy tension and torsion resistors. Harikrishna, *et al*. (2003) presented the characteristics of measured wind and the associate dynamic response of a 50 m tall guyed mast under ambient wind conditions.

This paper presents the wind characteristics of Typhoon Dujuan which passed over Hong Kong in 2003. The wind characteristics of Typhoon Dujuan as measured from a 50 m guyed mast located on the coast of Hong Kong is studied. Its effect on the structure will be addressed in a companion paper (Law, *et al*. 2006) This study aims to provide a reference on the design and fatigue life assessment of a guyed mast under typhoon conditions.

2. The guyed mast and instrumentation

The 50 m high mast is located in an open space with few building blocks in adjacent at the north shore of the Stonecutters Island in Hong Kong. It has an equilateral triangular cross-section 1.2 m long each side. The three vertical legs are of 219.1 mm diameter 10 mm thick hollow steel tubes for the lowest 5.8 m length and 6.35 mm thick for the upper length of the legs. The diagonals and horizontal members are 60 mm steel tubes of 5 mm thickness. Two arms 3 m long each, extend from the mast structure at 30 m and 50 m above ground level supporting the anemometers at the ends as shown in Fig. 1. The accelerometers are housed inside an instrument box on one of the sides of the triangle at these two levels. A cat ladder fixed to one side of the triangle provides

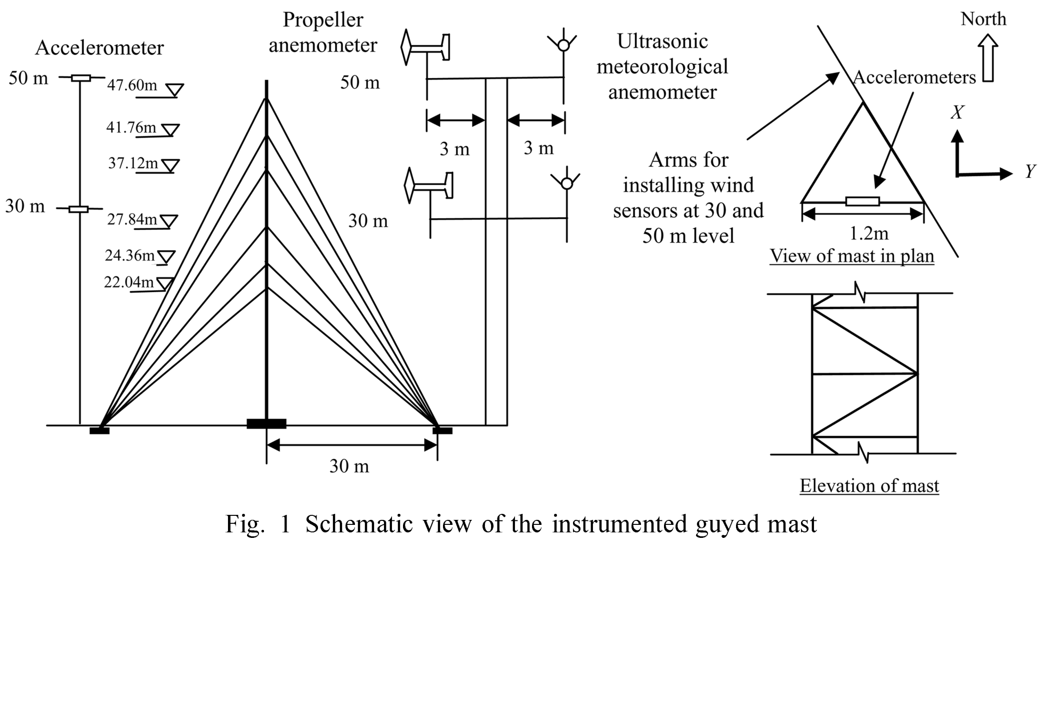


Fig. 1 Schematic view of the instrumented guyed mast

vertical access throughout the height of the structure.

The mast is divided into 43 vertical segments with the first 40 segments 1.16 m high each and the others 1.2 m high. It is tied to the ground by cables at six levels of 22.04, 24.36, 27.84, 37.12, 41.76, and 47.60 m above ground level with three cables at each level as shown in Fig. 1. The cables are of 17.5 mm diameter each consisting of 19 numbers of 3.55 mm diameter galvanized steel wires, and the initial tension in each cable is 23520 N. The Young's modulus of material is 2.05×10^{11} N/m^2 and 1.2×10^{11} N/m^2 for the mast and cables respectively. The mass density and Poisson ratio for the mast are 7850 kg/m^3 and 0.25 respectively while those for the cables are 7820 kg/m^3 and 0.20 respectively. Three 5 m$\times$4 m$\times$2.5 m deep reinforced concrete blocks are provided at a radial distance of 30 m from the center of the mast serving as reaction anchors, and they are located along lines radiated from the centre of cross-section passing through one of the vertical legs. Cables aligned in one vertical plane are anchored to one reaction block. The mast is supported on a 4 m$\times$4 m$\times$2.1 m deep reinforced concrete pedestal which is founded on firm soil.

The coordinate system used in the following analysis is referred to Fig. 1. The Z- axis passes through the centroid of the cross-section of the guyed mast, and the origin of coordinates is set at the ground level.

The mast is instrumented with propeller type anemometers of RM Young Marine Model 05106 and ultrasonic anemometers of Gill Windmaster Solvent at 30 m and 50 m above ground level. Honeywell QA700 accelerometers installed at these two levels monitor the acceleration responses in two orthogonal directions, i.e., the X- and Y- directions as shown in Fig. 1. All the sensors are connected to a data acquisition system recording data continuously 24 hours a day at a sampling frequency of 50, 4 and 5 Hz for the accelerometers, the ultrasonic meteorological anemometers and the propeller type anemometers respectively. The signals collected were low-passed at 20 Hz for the accelerometers and at 2 Hz for the propeller type anemometers. The ultrasonic meteorological anemometers have their own built-in low-pass filter.

3. Analysis on measured data

3.1. Wind and terrain characteristics

Typhoon Dujuan skirted 30 km to the north of the Hong Kong Observatory Headquarters at the closest and its track over Hong Kong is shown in Fig. 2. Number 8 Northwest Storm Signal was hoisted at 14:20 on 2nd September and number 9 Storm Signal was hoisted at 20:10. Number 8 Southwest Storm Signal was hoisted at 22:10 and then number 3 Signal was hoisted at 01:30 on 3rd September 2003. Data collected in 12 hours from 14:00 2nd September to 02:00 3rd September 2003 is analyzed. The wind speed and direction, turbulence intensity, gust factor, power spectrum and coherence function of the measured data from the propeller type anemometers at the two equipment levels are studied.

The measured wind speed and direction are shown in Fig. 3(a). The wind speed is large during the period 18:00 to 22:00 when the typhoon is closest. There are two short periods of low wind due to unknown reasons. The direction of wind is mainly around 300^o true bearing when it is approaching and 160^o when departing from Hong Kong. The 10-minute mean wind speed and mean wind direction are shown in Fig. 3(b). Mean wind speed as high as 25 m/s is recorded at 21:00 when the typhoon is closest to Hong Kong. The mean wind speed is greater than 10 m/s for almost the whole duration of the typhoon. The wind speed varied sharply when the wind direction changed

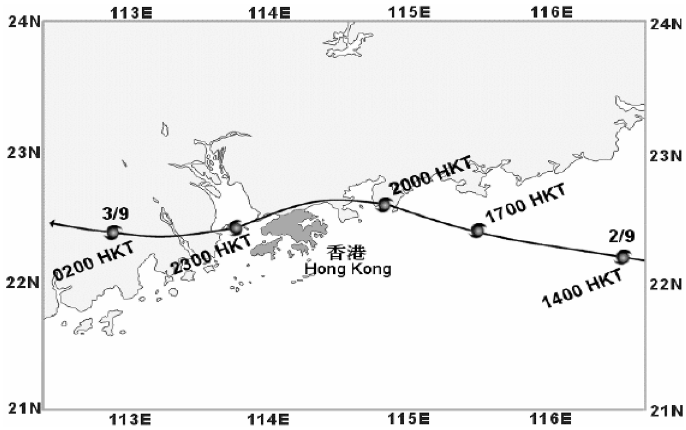


Fig. 2 Track of Typhoon Dujuan over Hong Kong

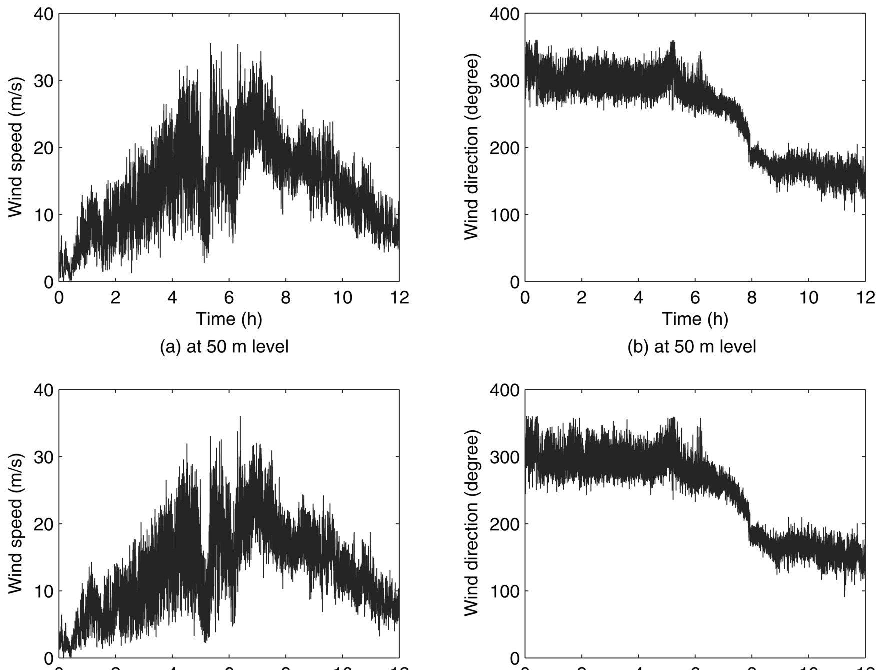


Fig. 3(a) Measured wind speed and direction for 12 hours (from 14:00 2 Sept. to 02:00 3 Sept.)

between 19:00 to 21:00, 2nd September 2003.

3.2. Turbulence intensity and gust factor

The 10-minute and one hour turbulence intensities (*TI*) are shown in Fig. 4. The *TI* is highest at the beginning and reduces gradually as the wind passes through Hong Kong, and all *TI* values are

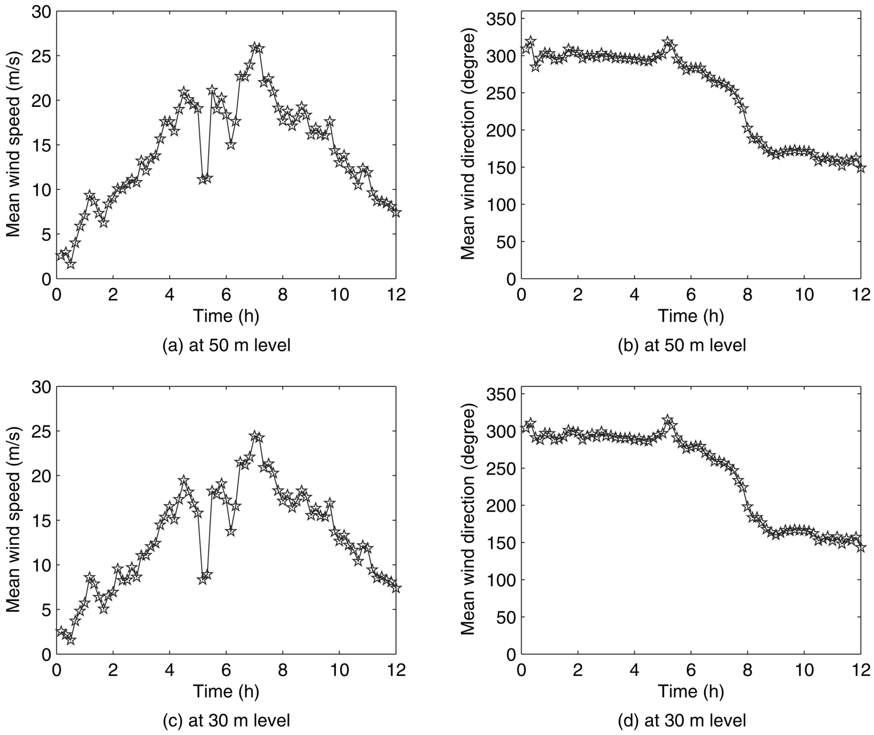


Fig. 3(b) 10-minute mean wind speed and direction (from 14:00 2nd Sept. to 02:00 3rd Sept.)

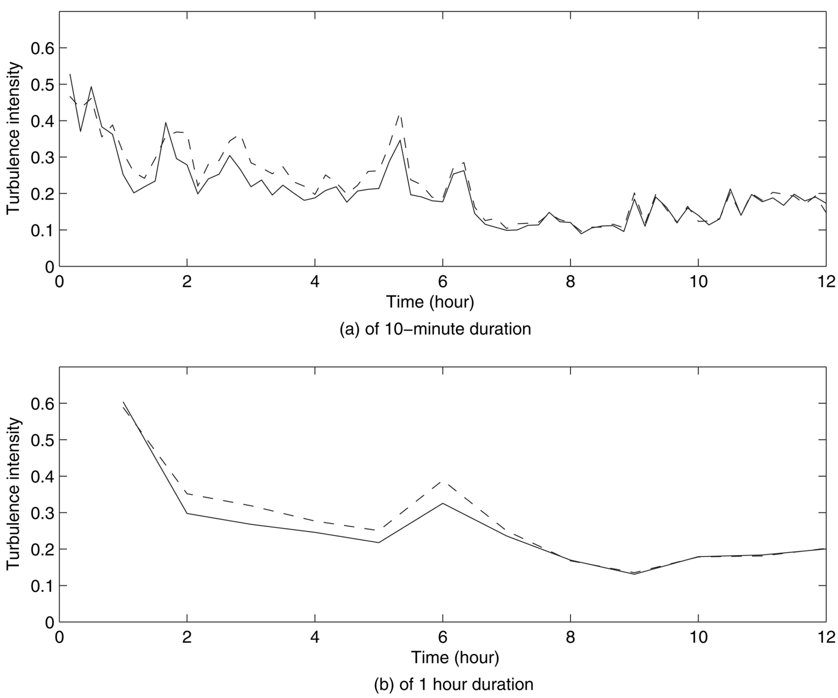


Fig. 4 Turbulence intensity of 10-minute and one hour duration (—— at 50m level, - - - at 30m level)

Table 1 *t*-second averaged Gust Factor of Typhoon Dujuan

Hour	*t*-second											
	at 50m level						at 30 m level					
	1	3	10	60	600	3600	1	3	10	30	600	3600
1st	3.16	3.02	2.83	2.26	1.75	1.00	3.17	2.98	2.62	2.25	1.67	1.00
2nd	1.77	1.69	1.61	1.40	1.14	1.00	2.03	1.97	1.92	1.77	1.25	1.00
3rd	1.81	1.74	1.63	1.37	1.20	1.00	2.09	2.04	1.88	1.58	1.19	1.00
4th	1.71	1.64	1.60	1.34	1.17	1.00	1.89	1.74	1.60	1.45	1.21	1.00
5th	1.66	1.55	1.43	1.26	1.09	1.00	1.69	1.68	1.48	1.37	1.14	1.00
6th	2.05	1.88	1.75	1.45	1.25	1.00	2.14	2.04	1.93	1.67	1.28	1.00
7th	1.61	1.53	1.43	1.31	1.22	1.00	1.77	1.70	1.54	1.35	1.23	1.00
8th	1.57	1.51	1.42	1.33	1.21	1.00	1.53	1.51	1.41	1.36	1.19	1.00
9th	1.41	1.39	1.32	1.19	1.07	1.00	1.41	1.38	1.37	1.30	1.07	1.00
10th	1.52	1.49	1.45	1.25	1.12	1.00	1.56	1.49	1.47	1.36	1.12	1.00
11th	1.53	1.48	1.45	1.32	1.14	1.00	1.54	1.50	1.45	1.40	1.12	1.00
12th	1.77	1.74	1.70	1.40	1.13	1.00	1.79	1.76	1.67	1.56	1.13	1.00

larger than 0.1 in the 10-minute plot. The two peaks close to 19:00 and 20:00 correspond to the two periods of low mean wind speed. The one hour plot gives TI values larger than those from the 10-minute plot, and the values from the 30 m level are larger than those from the 50 m level in general.

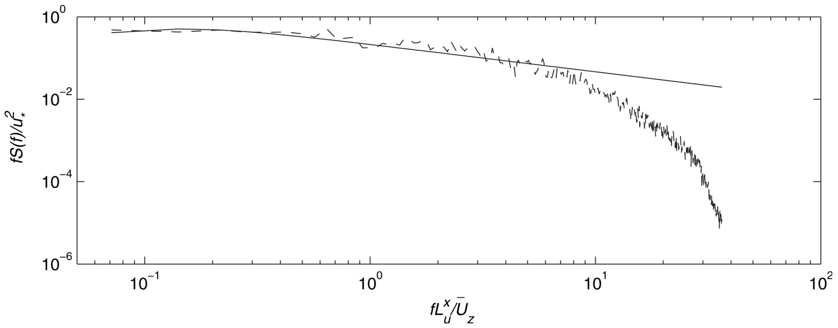
The gust factor defined as the ratio of the largest wind gust speed of duration *t*-second, $U(t)$, to the hourly mean wind speed, $\overline{U}$, is shown in Table 1. It is noted that for a given gust duration, a higher gust factor indicates a higher fluctuating wind speed. The gust factor decreases with the duration of *t*, and the value from the 30 m level is larger than that from the 50 m level in general, and the maximum value occurs with the largest *TI* values. Both the *TI* and the gust factor give clearly the characteristics of the wind speed.

3.3. Auto-power spectral density

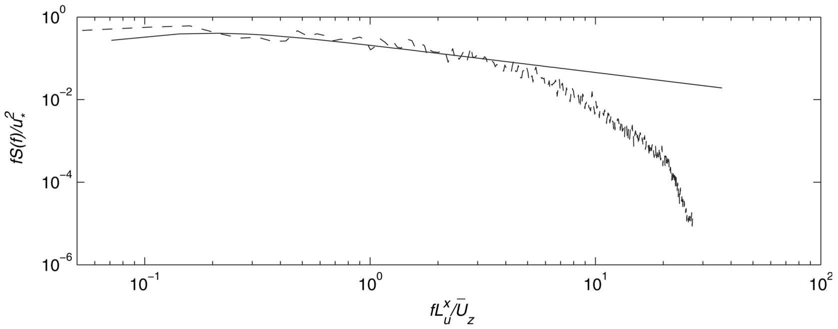
The recorded data on the wind speed and direction of Typhoon Dujuan over one hour duration (22:00-23:00 on 2nd September, with a corresponding mean wind speed of 17.9 m/s at 50 m level) and one hour weak wind speed and direction record (16:00-17:00 on 12th September, with a corresponding mean wind speed of 2.3 m/s at 50 m level) are chosen for subsequent analysis.

Fig. 5(a) shows the auto-power spectral density of the wind speeds. The size of Fourier transforms is 1024 with a frequency increment of 0.00488 Hz between two adjacent data points. The spectrum is compared with the turbulence spectrum evaluated from the expression suggested by von Karman (1996), defined as

$$\frac{fS(f)}{u_*^2} = \frac{4\beta\dfrac{fL_u^x}{\overline{U}}}{\left[1 + 70.8\left(\dfrac{fL_u^x}{\overline{U}}\right)^2\right]^{\frac{5}{6}}} \tag{1}$$



(a) Power spectral density at 50 m level



(b) Power spectral density at 30 m level

Fig. 5(a) Power spectral density of typoon at 30 m and 50 m levels (—— von Karman, - - - measured)

where f is frequency of the wind speed, $\bar{U}$ is mean wind speed. L_u^x is the horizontal turbulence length scales, at different levels evaluated from auto-correlation analysis using Taylor's hypothesis (1967). u_* is the wind friction speed and defined as

$$\bar{U}_z = \frac{1}{k}u_*\ln\left(\frac{z}{z_0}\right) \tag{2}$$

where k can be approximately taken as 0.4, z_0 is the roughness length, It is commonly assumed that β does not vary with height, and β and z_0 can be found in reference (Karman 1996).

The two measured spectra at 30 m and 50 m levels are close to each other indicating a uniform turbulence in the wind speed close to ground. The von Karman spectrum compares well with the measured spectra of the typhoon up to a frequency of 0.6 Hz beyond which the measured spectra are observed to be decaying faster than the von Karman spectrum. This is due to the poor performance of the mechanical anemometers at higher frequency. Fig. 5(b) gives a similar plot but for the period of weak wind conditions recorded on 12th September 2003. It shows that the auto-power spectral density of weak wind varies unsteadily, especially in higher frequency region, and the plot does not compare very well with the von Karman spectrum. This indicates that the von Karman spectrum can be used to describe only the strong wind conditions.

3.4. Coherence function of wind speeds

The coherence function between the wind speeds and directions at 30 m and 50 m levels for the

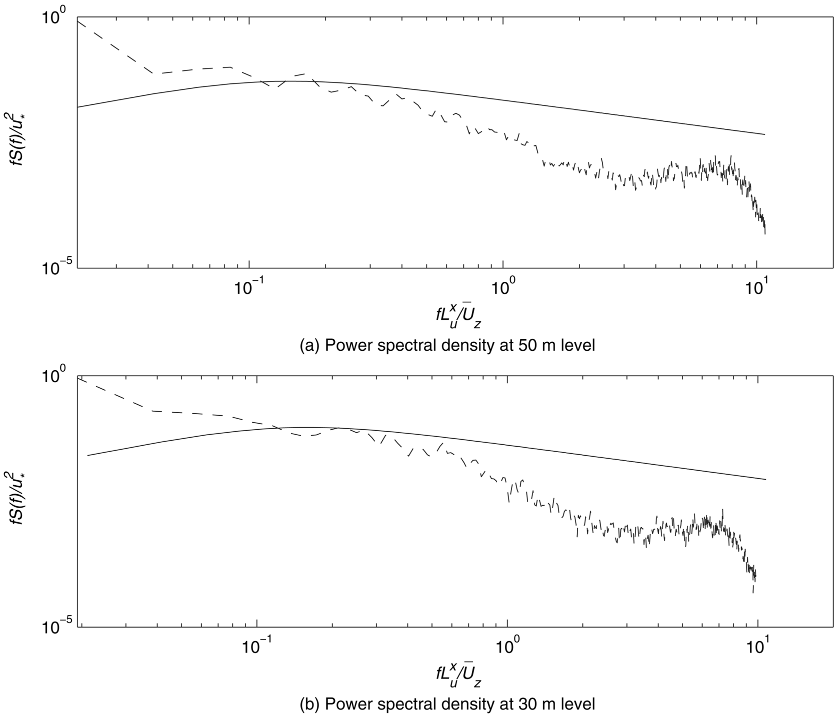


Fig. 5(b) Power spectral density of weak wind at 30 m and 50 m levels (—— von Karman, - - - measured)

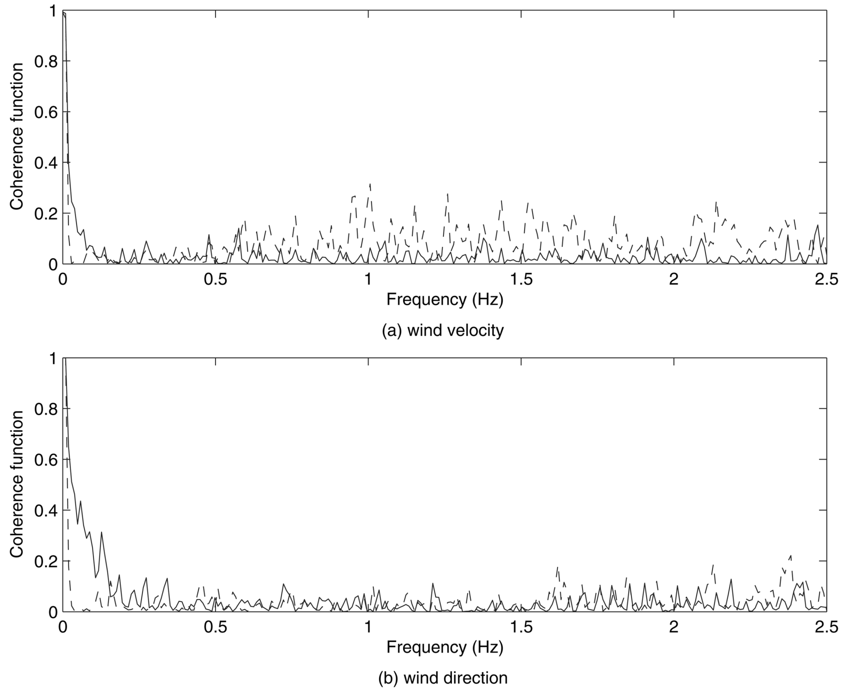


Fig. 6(a) Coherence between wind speed and direction at 30 m and 50 m levels (—— typhoon, - - - weak wind)

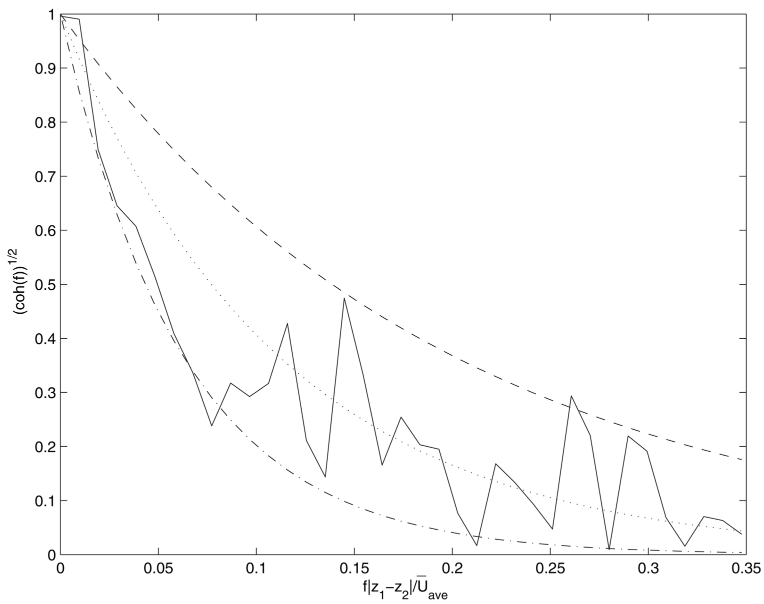


Fig. 6(b) Davenport's coherence between wind speed at 30 m and 50 m levels (—— measured, - - -$C_z = 5$, ···· $C_z = 8$, -·-· $C_z = 15$)

typhoon and weak wind conditions is calculated from the auto-spectrum and cross-spectrum and it is plotted in Fig. 6(a).

In the low frequency region less than 0.05 Hz, the coherence function is very large and is close to unity, and when the frequency reaches 0.2 Hz, the values begin to fluctuate. In the low frequency region (0-0.2 Hz), the coherence function from typhoon is larger or equal to that from weak wind, but in high frequency region, the pattern is reversed. The same conclusion can be obtained for the wind direction variation.

Fig. 6(b) gives another plot on the coherence function based on Davenport's (1968) method to fit the square root of the coherence with an exponential function as

$$\sqrt{\mathrm{coh}(f)} = \exp\left[-C_z\left(\frac{f\,|z_1 - z_2|}{\bar{U}_{ave}}\right)\right] \tag{3}$$

where f is the frequency in Hz, and $\bar{U}_{ave} = [\bar{U}(z_1) + \bar{U}(z_2)]/2$. z_1 and z_2 equal to 30 m and 50 m respectively. C_z is the exponential decay coefficient, the value of which can be obtained by fitting the curve of coherence function, and is found to be in the range of 5-15 with an average value of 10. The suggested experimental decay coefficient $C_z = 8$ for wind in the horizontal direction (Liu 1991) matches the curve very well except in the low frequency region of 0.0 to 0.1 Hz.

4. Conclusions

This paper presents the wind characteristics of Typhoon Dujuan at the location of a 50 m guyed mast in Hong Kong. The von Karman model compares well with the measured power spectral density at the two measurement levels indicating a uniform turbulence condition in the wind speed close to ground. The coherence function on the wind speed between the two levels is found to match the Davenport's prediction very well with an experimental decay coefficient of $C_z = 8$.

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