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Measurement of wind field characteristics at a long-span suspension bridge

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Abstract: In order to provide a reliable basis for wind resistant evaluation of a long-span suspension bridge, a structural health monitoring system is installed on a bridge in the East China Sea and the simultaneous wind data at the bridge deck and at the top of the bridge tower are recorded. The average wind speeds and directions, variations of wind speeds with height, turbulent characteristics, spatial correlation and characteristics of wind flow around the bridge deck are analyzed by using statistical methods and spectral analysis. It is found that the average wind speeds along the bridge girder are almost identical; however, the mean wind directions vary greatly at different locations. The dimensionless exponent decreases as the average wind speed increases. The measured turbulence intensities are greater than the recommended values, and the turbulence power spectrum can well fit the standard spectrum. However, the measured spectral values are considerably smaller in low frequency ranges. The mean wind speed of the wake flow decreases and the turbulence intensity increases significantly, and the spectral characteristics of the wake flow change obviously while the feature frequency of vortex shedding has not yet been observed.

Key words: suspension bridge; wind field; structural health monitoring system; field measurement

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With the rapid increase of cable-supported bridge spans over the years in combination with the low damping, the bridges become more and more flexible and are especially more sensitive to wind action[1]. At present, the bridge flutter can generally be avoided by optimizing the section shape; however, the wind-induced buffeting becomes an important issue, the monitoring of wind field environments and buffeting responses have become one of the research focuses in wind engineering.

Field observation is one of the main research methods in wind engineering. In recent years, researchers have mainly focused on typhoon wind field measurements. Miyata et al. [2] measured Typhoons 9807 and 9918 by the anemometers installed in Akashi Kaikyo suspension bridge in Japan, and the power spectrum density and spatial correlation of the typhoons were discussed. Li et al. [3] observed the typhoon Rananim by the anemometers installed on Shanghai Jinmao Tower and the wind characteristics were discussed. Amano et al. [4] observed Typhoons 9426, 9503 and 9612 in Okinawa by the Doppler sodar. Xu et al. [5] observed Typhoon Sam by the wind and structural health monitoring system of Hong Kong's Tsing Ma suspension bridge. Li et al. [6–7] discussed the wind characteristics of Typhoon Matsa by the measured data of the structural health monitoring system of the Runyang Suspension Bridge. However, the structure not only suffers from typhoons during the operation, but the daily strong winds especially the monsoon also cannot be underestimated, and the observations of daily strong winds are rarely reported.

Although structural health monitoring systems (SHMS) including anemometers and vibration sensors have been installed in long span bridges in China[8–10], the wind field measurement researches are still not enough. In this paper, the wind speed records are collected based on the SHMS of a suspension bridge in the East China Sea and the characteristics of wind field and wind flow around the bridge deck are analyzed.

1 Structural Health Monitoring System of Long-Span Suspension Bridge

A long-span suspension bridge in the East China Sea is analyzed in this paper. The bridge, with a main span of 1 650 m and a side span of 578 m, is the longest steel box girder bridge in the world at present. The cross-section of the stiffening girder is twin-box with an overall width of 36 m and a height of 3. 15 m, the tower is 211 m high and the hanger spacing is 18 m. The climate of the bridge site is complex and there are many disastrous weather conditions including strong winds, storms, thunderstorms, etc.

In order to achieve measurement wind data and to provide a reliable basis for wind resistance evaluations for the bridge, two kinds of anemometers are installed, namely the propeller anemometer and the three-dimensional sonic anemometer. Two propeller anemometers (AN1, AN2) are installed at the top of the north tower and the south tower (downstream) about 257. 6 m above the ground respectively and six 3-D sonic anemometers (UA1 to UA6) are installed in the 1/4, 1/2 and 3/4 main span cross-sections (downstream and upstream) about 62. 6 m above the ground respectively (see Fig. 1). Also the photos of anemometers installed are shown in Fig. 2.

2 Analysis of Wind Field Measurement

2. 1 Average wind speeds and directions

The sonic anemometers at the bridge deck record three wind speed components, namely, u_x of the bridge's transverse direction, u_y of the bridge's longitudinal direction and

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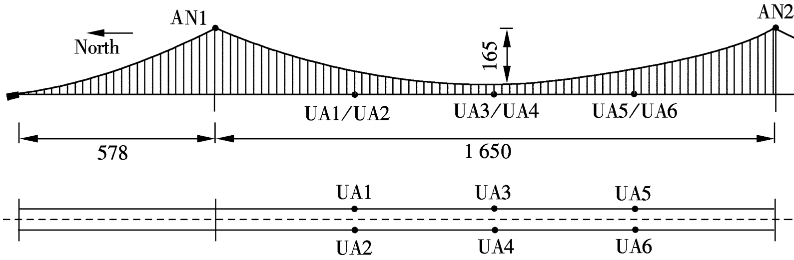

Fig. 1 The arrangement of anemometers in a suspension bridge (unit: m)

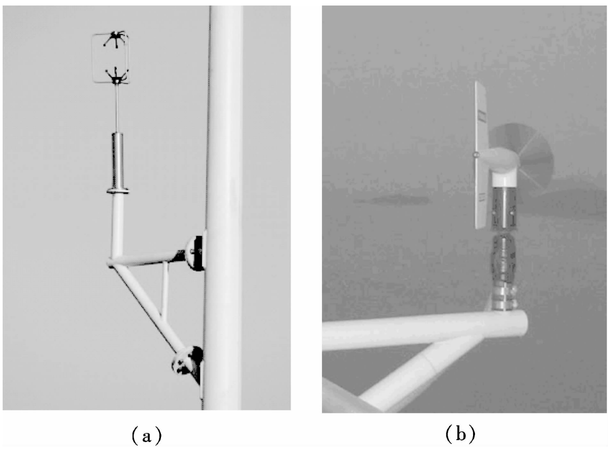

Fig. 2 Anemometers installed in SHMS. (a) 3-D sonic anemometer (UA1-UA6); (b) Propeller anemometer (AN1-AN2)

u_z of the vertical direction, and their sampling frequencies are 32 Hz. The propeller anemometers at the tower record horizontal wind speeds and directions, their sampling frequencies are 1 Hz. The anemometers have collected a mass of wind speed data since being in operation, taking 10 min as a basic time interval. The average wind speeds and directions of the inflow wind of the UA2, UA4 and UA6 anemometers can be derived and the 14 h strong wind records are shown in Fig. 3.

The sample results indicate that the wind speeds gradually decrease during the observed period and the maximum mean wind speed is about 12 m/s. The wind directions become relatively unstable during the last few hours, which is maybe because of the low wind speeds. Also the measured wind speeds at the bridge deck indicate that the average wind speeds of different sensors (UA2, UA4, UA6) are almost identical, and it can be assumed that the average wind speeds are same at the deck height. However, the differences in the mean wind directions among UA2, UA4 and UA6 sensors are obvious, indicating that the mean wind directions are different along the bridge, and their effect on wind induced vibration is a matter of concern.

2.2 Variation of wind speed with height

In the boundary layer, the wind speed increases gradually from the surface upward. Many researchers have proposed a variety of wind profile expressions based on theoretical derivation and experience. In China, the exponential expression is adopted in the wind resistant design specifications for highway bridges [11], namely,

$$\frac{U_2}{U_1}=\left(\frac{Z_2}{Z_1}\right)^{\alpha} \tag{1}$$

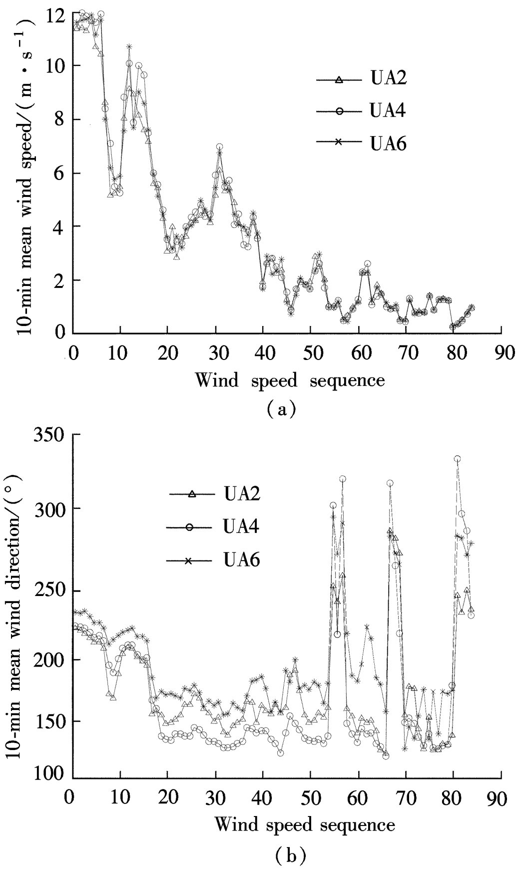

Fig. 3 The sample of 14 h strong wind records at bridge deck. (a) Measured mean wind speeds; (b) Measured mean wind directions

where U_1 and U_2 are the mean wind speeds at Z_1 and Z_2 height, respectively; α is the dimensionless exponent considering surface roughness.

The sample of 14 h strong wind records at the bridge tower of AN1 and AN2 sensors are shown in Fig. 4. Based on

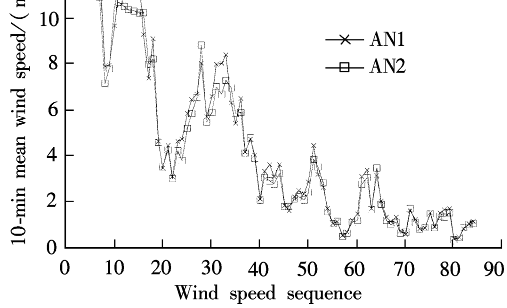

Fig. 4 Measured wind speeds at bridge tower

the measured mean wind speeds at bridge deck height and bridge tower height, the dimensionless exponent α can be derived and the relationships of measured α with the mean wind speeds at the bridge deck are shown in Fig. 5.

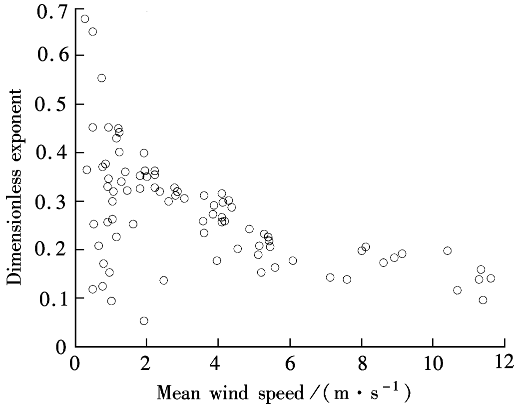

Fig. 5 Measured dimensionless exponent

The measured results indicate that α decreases as the average wind speed increases. It is apparently different from the specification where α is given a fixed value of 0.12 in the sea environment. The measured results have obvious random characteristics and are greater than the specified value especially at low wind speeds.

2.3 Turbulence intensities

The wind turbulent motion is very irregular, so the wind engineering usually decomposes the wind into the mean wind and the fluctuating wind. Turbulence intensities I_u, I_v, I_w are defined as the ratios of σ_u, σ_v, σ_w to the mean wind speed U. The turbulence intensities of along wind, cross wind and vertical directions based on the measured data of the UA2 anemometer are shown in Fig. 6.

The measured results indicate that the measured turbulence intensity decreases as the wind speed increases. It is also different from the specification where I_u is given a fixed value of 0.11 at bridge deck height. The measured I_u is obviously greater than the recommended value especially at low wind speeds. Also, the average values of measured I_u, I_v and I_w are 0.262, 0.200 and 0.114, respectively, and their ratio is 1∶0.766∶0.436, which is close to the ratio of $I_v = 0.88\ I_u$, $I_w = 0.50\ I_u$ that the specification recommends.

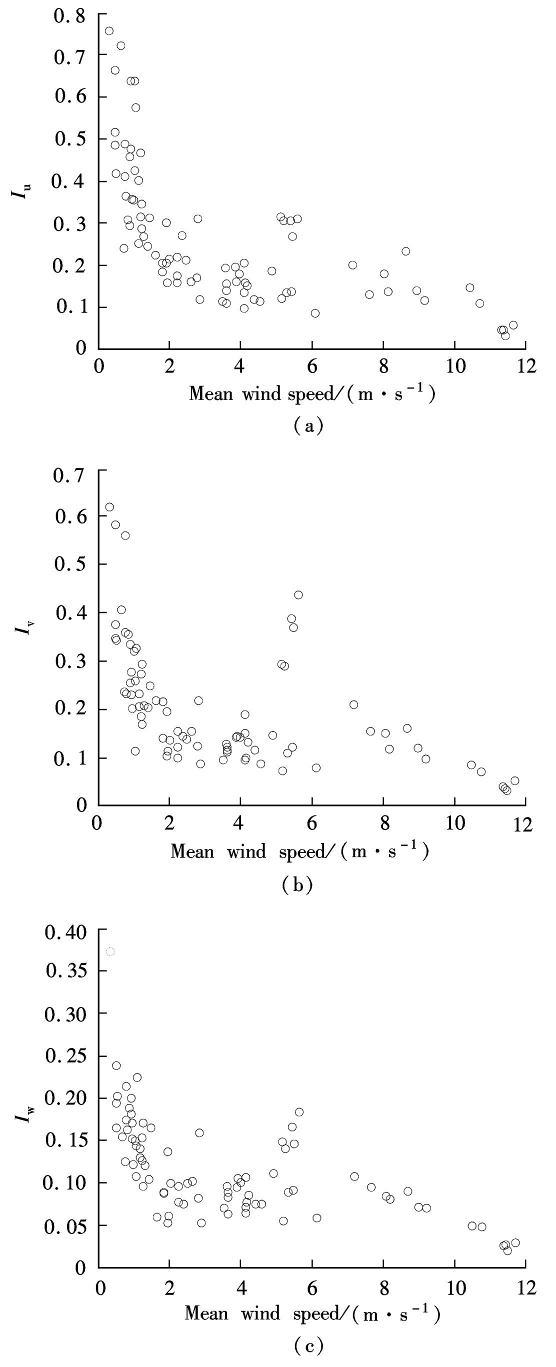

Fig. 6 Measured turbulence intensity. (a) Along wind direction; (b) Cross wind direction; (c) Vertical direction

2.4 Turbulence integral length and power spectrum density of the fluctuating wind

Based on the Taylor hypothesis, the turbulence integral length of along wind direction can be written as

$$L_u^x = \frac{U}{\sigma_u^2}\int_0^\infty R_u(\tau)\,d\tau \tag{2}$$

where $R(\tau)$ is the autocorrelation function of fluctuating velocity. The measured data are divided into separate samples by 10-min intervals and the turbulence integral lengths of along wind direction L_u^x, cross wind direction L_u^y and vertical direction L_u^z are calculated. The statistical results are shown in Fig. 7.

The results indicate that the turbulence integral lengths at the bridge site are of great randomness. During the observed period, the average, maximum and minimum integral length values of L_u^x are 73.8, 222 and 10.1 m; L_u^y are 59.9, 177.4 and 5.5 m; and L_u^z are 27.1, 88.4 and 3.1 m, respectively.

Turbulence power spectral density can accurately describe the contributions of each frequency component of fluctuating winds. The Kaimal spectrum and Panofsky spectrum are adopted for horizontal and vertical wind, respectively, in Chinese wind resistant design specifications of highway bridges. Based on the actual measurement data of wind speeds, the horizontal power spectrum and the vertical power spectrum of wind speeds are deduced in this paper by applying the fast Fourier transformation and the deduced

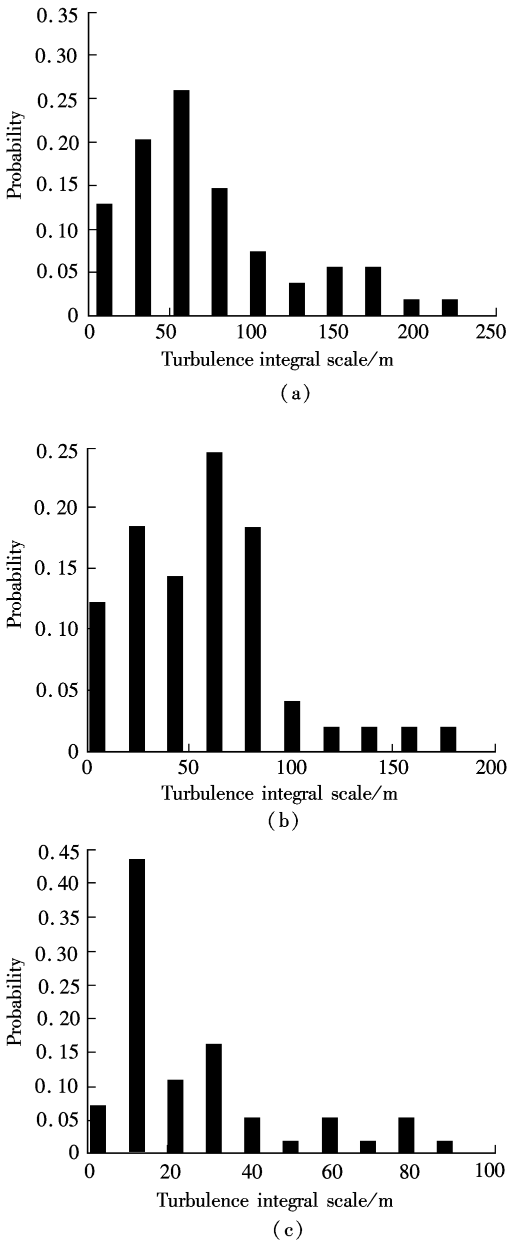

Fig. 7 Measured turbulence integral length. (a) Along wind direction; (b) Cross wind direction; (c) Vertical direction

results are compared with the Kaimal spectrum and the Panofsky spectrum, respectively (see Fig. 8).

The comparisons indicate that the measured spectrum of along wind direction is generally consistent with the Kaimal spectrum; however, the measured values are obviously smaller in low frequency ranges of less than 0.01 Hz. The measured vertical wind spectrum have some difference from the Panofsky spectrum, and the measured values are lower in low frequency ranges of less than 0.1 Hz and are higher in high frequency ranges of more than 1 Hz.

2.5 Spatial correlation of wind field

The spatial correlation is an important factor for the buffeting response. In this paper, the synchronous data from the UA2 anemometer (1/4 main span) and the UA4 anemometer (1/2 main span) are analyzed and their measured cross spectra of the along wind and the vertical directions are shown in Fig. 9.

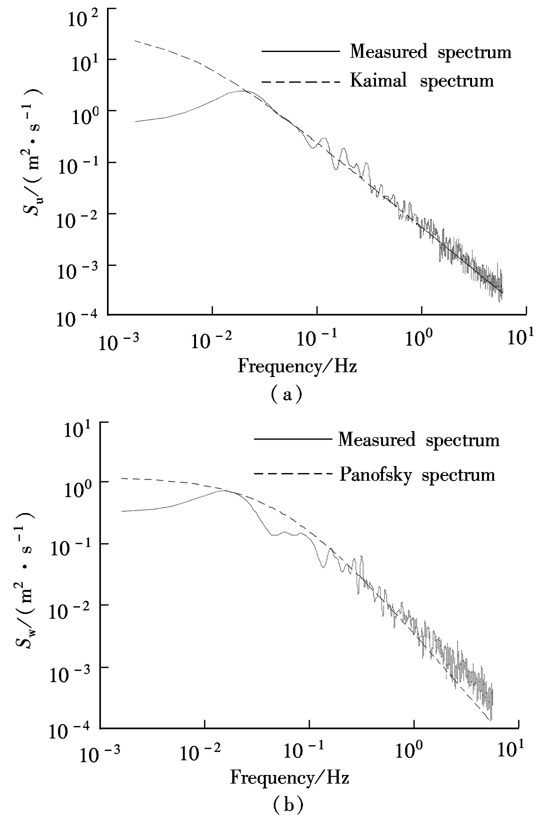

Fig. 8 Comparisons of measured spectra with standard spectra. (a) Along wind direction; (b) Vertical direction

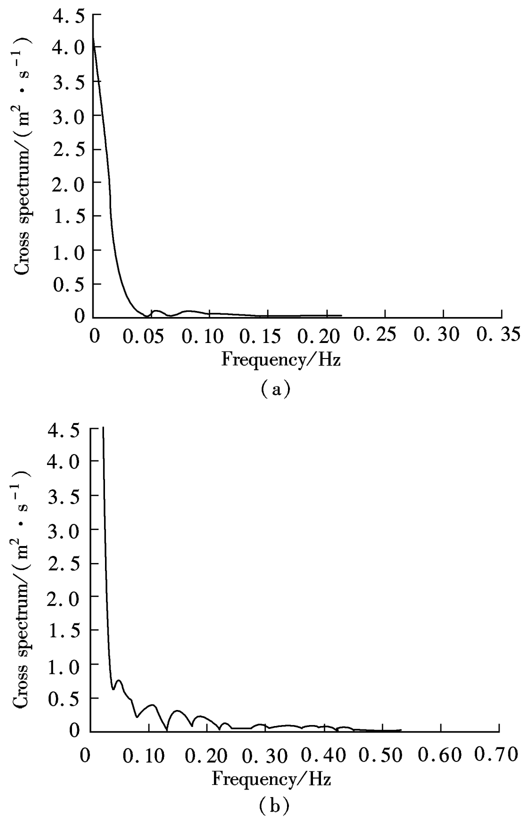

Fig. 9 Measured cross spectra of UA2 and UA4. (a) Along wind direction; (b) Vertical direction

The measured cross spectra of UA2 and UA4 indicate that the correlations between the two are small, and the cross spectra have only small values at very low frequency ranges and rapidly decay to zero. Also the attenuation of the along wind direction is faster than that of the vertical direction. This little correlation is mainly because of the large distance between UA2 and UA4 (412.5 m), which is much longer than the turbulence integral length measured above. This also indicates that the correlation of the wind field constantly decreases along the bridge axial. The correlation attenuation law with distance is not discussed because the anemometers are relatively few and the space between them is too large. This needs to be further discussed.

3 Measured Characteristics of Wind Flow Around Bridge Deck

The flow field will change when the air passes through the bridge deck, and it may even cause vortex shedding near the section and produces periodic excitation to the bridge. To measure and analyze the characteristics of the wake flow can not only determine whether the periodic vortex shedding frequency exists but also can verify the correctness of numerical wind tunnel results. The measured data from the UA2 and UA1 anemometers of the 1/4 section of the main span are analyzed in this paper.

3.1 Average wind speeds of wake flow

The average wind speeds of the wake flow will decrease because of the obstruction of the bridge deck to the airflow. The comparisons of the measured average wind speeds of the inflow and the wake flows are shown in Fig. 10, and the relationships between the reduction ratio (speed reduction/inflow wind speed) and the inflow wind velocity are shown in Fig. 11.

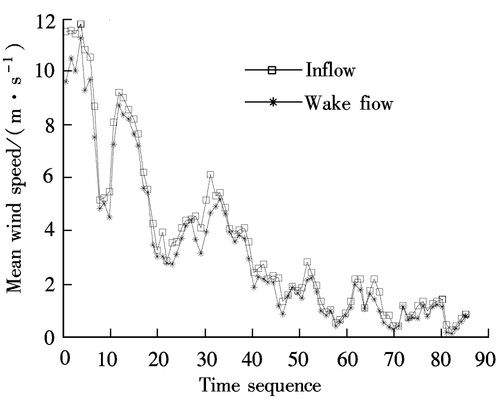

Fig. 10 Average wind speeds of inflow and wake flow

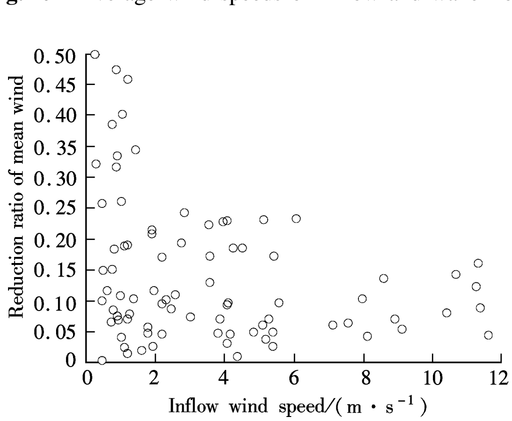

Fig. 11 Reduction ratios of average wind speeds

The results indicate that the average wind speeds of the wake flow are lower than those of the inflow winds and the average wind speed reduction ratio observed is 13.8%. The reduction ratio is very random, which is mainly due to the random factors of wind direction and wind attack angle.

3.2 Turbulent characteristics of wake flow

The turbulent characteristics of the wake flow are analyzed and the comparisons of turbulence intensities of inflow and wake flow are shown in Fig. 12.

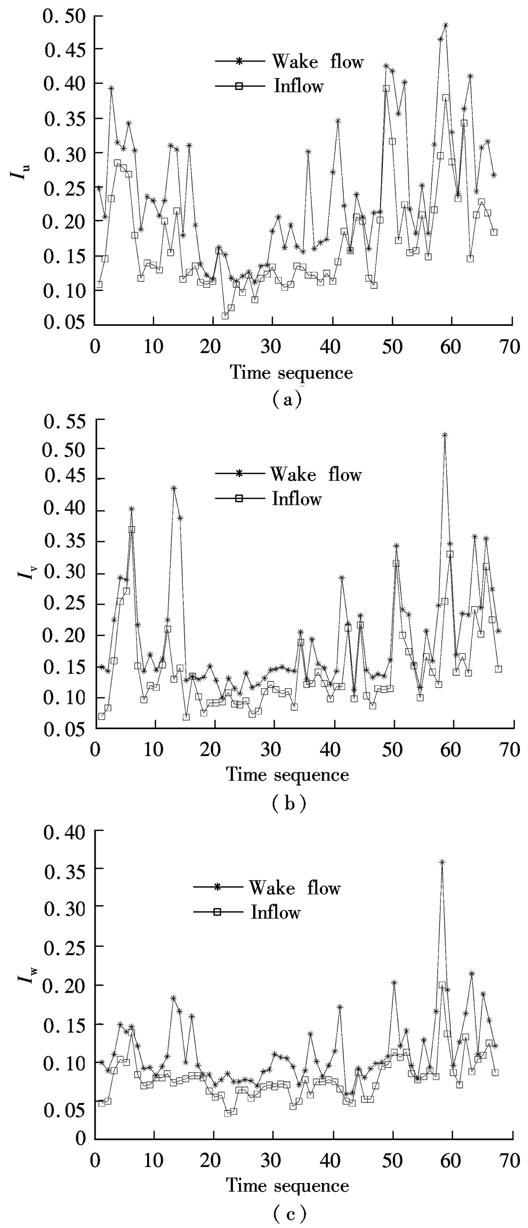

Fig. 12 Turbulence intensities of inflow and wake flow. (a) Along wind direction; (b) Cross wind direction; (c) Vertical direction

The results of Fig. 12 indicate that the turbulence intensity of the wake flow increases significantly. During the observed period, the turbulence intensities of the wake flow of along wind, cross wind and vertical directions increase 1.474, 1.397 and 1.478 times on average compared with those of the inflow wind, and these indicate that the fluid movements become more irregular after passing the section. The significant change in wake flow turbulence characteristics cannot be ignored, especially for twin-deck bridges and the other structures constructed not far from the downstream of the bridge. Also the spectral characteristics of the wake flow are analyzed by FFT spectrum analysis; the comparisons of wake flow's horizontal and vertical spectra with Kaimal and Panofsky spectra are shown in Fig. 13.

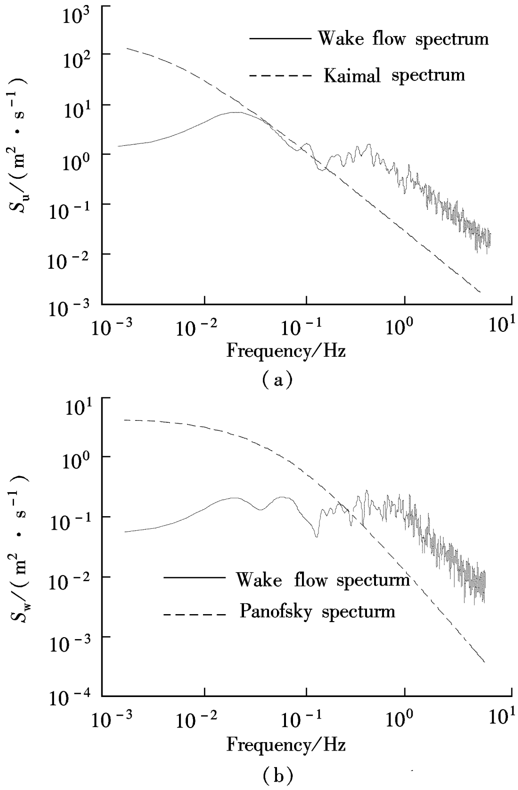

Fig. 13 Observed spectra of wake flow. (a) Horizontal spectrum; (b) Vertical spectrum

The comparisons between Fig. 13 and Fig. 8 indicate that the spectra of the wake flow change significantly, and the spectral values of the wake flow are obviously greater than those of the inflow wind at high frequency ranges, indicating that the kinetic energy distribution of the wake flow's turbulence shifts to higher frequencies. Also the significant frequency features of vortex shedding have not yet been observed. This is maybe due to the fact that the aerodynamic deflector measures can effectively eliminate the vortex shedding, and this is also maybe because the anemometer is located too close to the box, and the whirlpool has not yet been formed.

4 Conclusions

Based on the measurement data of the structural health monitoring system installed on a suspension bridge of the East China Sea, the wind field characteristics are analyzed in this paper and the main conclusions are as follows:

1) The average wind speeds along the bridge deck are almost identical; however, the differences of mean wind directions along the bridge are obvious, and its effect on wind induced vibration is a matter of concern.

2) The measured dimensionless exponent index decreases when the average wind speed increases, and it is greater than the recommended value especially at low wind speeds.

3) The measured turbulence intensity decreases when the wind speed increases and the measured I_u is obviously greater than the specified value at low wind speeds. The turbulence integral length at the bridge site is of great randomness. During the observed period, the average integral length values of along wind, cross wind and vertical directions are 73.8, 59.9, and 27.1 m, respectively. The measured turbulence power spectra can basically fit the Kaimal and Panofsky spectra; however, the measured spectral values are considerably smaller in low frequency ranges. The correlation between UA2 and UA4 is rather small, and their cross spectra have only small values at very low frequency ranges and rapidly decay to zero. The attenuation of the along wind direction is faster than that of the vertical direction.

4) The mean wind speed of the wake flow decreases and the turbulence intensity increases significantly. The spectral characteristics of the wake flow change obviously but the feature frequency of vortex shedding has not yet been observed.

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基于现场实测的某大跨度悬索桥桥址区风场特性

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摘要:为了对大桥抗风评估提供可靠依据,结合东海某大跨度悬索桥的健康监测系统,同步实测了桥面及桥塔处的风速,采用统计及频谱分析方法对桥面平均风速和风向、风速随高度变化、风速的脉动特性、相关性以及桥面风场的绕流特性等进行了分析.结果表明:加劲梁纵向不同位置处平均风速大小接近,但平均风向差别较大;无量纲幂指数随风速增大呈明显减小的趋势;实测的湍流强度比规范偏大,水平及竖向风谱与规范吻合较好,但实测谱值在低频段偏低;风场流过桥梁断面后平均风速减少而湍流强度显著增大,尾流的频谱特性发生明显改变同时尚未观测到规则的漩涡脱落特征频率.

关键词:悬索桥;风场;结构健康监测系统;现场实测
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