Measurement of Turbulence Properties and Spectral Behaviors of Strong Winds at Keelung Coastal Area

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ABSTRACT

Turbulence properties (mean wind velocity, turbulence intensity, integral scale, probability density function, Reynolds stress and heat flux) and spectral behaviors of strong winds at Keelung coastal area are investigated. Gusty winds due to a skite typhoon were recorded with an ultra sonic anemometer. Analysis of the probability density function (pdf) for three components of wind speed and temperature shown that they are close to Gaussian distributions. Events of outward and inward interaction were dominant for the contribution to Reynolds stress, while that of burst and gust was dominant for the contribution to heat flux. The observed time series of wind speed fluctuations were calculated by Fast Fourier Transform (FFT) to obtain the wind spectrum. The observed spectrum of longitudinal wind speed are found to be in agreement with Karman's spectrum theoretical values.

1.Introduction

The probabilistic analysis of wind speed at a site forms the essential premise for dealing with physics, engineering and architecture. There was a dual phase approach proposed by G. Solari (1996). In the first phase all the meteorological stations able to provide data inherent to the problem under consideration are initially identified; the data recorded are later corrected and transformed in order to assemble a homogeneous data base for each station. In the second phase, the individual data bases are subjected to a statistical analysis with the object of evaluating the probability distribution of wind speed at the instrumented sites. In the context of certain classes of problems, especially those relating to the study of structural safety, the treatment is further developed at a third level aimed at appraising, at the individual sites, the probability distribution of the maximum wind speed over a fixed period of time. The collection of the statistical data is then elaborated from a local point of view, according to the problem under consideration.
To obtain further information about the instantaneous features of the velocity and temperature fields that contribute to shear stress or heat flux, quadrant analysis using the conditional sampling technique has been introduced by Fazu Chen in a very rough natural mallee bushland (1990), in which the contributions to \( u'w' \) or \( \theta'w' \) are sorted into four groups depending upon the quadrant of the \( u'w' \) or \( \theta'w' \) plane in which the correlation occurs.

It will increase the occurrence of turbulent flow if the value of \( \theta'w' \) is positive while decrease the occurrence of turbulent flow if the value of \( \theta'w' \) is negative; the boundary layer is unstable when the value of \( u'w'/\theta'w' \) is negative and the boundary layer is stable when the value of \( u'w'/\theta'w' \) is positive, suggested by Holten (1992).

The observed velocity spectra of strong wind near the ground were calculated by FFT. The lateral theoretical velocity spectra were obtained by J. Maeda and M. Makino (1988) according to Karman's longitudinal power spectrum and the theory of isotropic turbulence. The observed spectrum of longitudinal wind speed agreed well with Karman's theoretical spectrum; the observed spectra of lateral ones did not agree with the theoretical spectra developed by isotropic theory but agreed well with Karman's theoretical spectra developed by Maeda etc...

2. In-situ Measurement and Data Processing

2.1 Instrumentation

Wind observation was carried out in Keelung coastland for three days when the typhoon (Babs) passed by, actually passed through Taiwan straight from south to north during Oct. 25-27, 1998. Wind data were obtained by an ultra sonic anemometer (Kajo TJ61B) with three sensors, for 3-D wind velocities and temperature simultaneously, was set up on the top of a five-leveled building. Output signals of three sensors were recorded in an analogue data recorder. The analogue data were converted to digital form in a sampling frequency 20 Hz. After determination of the mean wind direction in each run of the observation the digital data were recomposed into three components of wind speed, \( u,v \) and \( w \), by coordinate transformation since directions of the three sensors of the anemometer were fixed. There are 12288 sets of digital data in a run and the mean wind direction was equal to the mean of 12288 \( \theta \) components. The observation was carried out continuously for 72 hours but 14 data runs for ten minutes were provided for the investigation.

2.2 Coordinate Transformation

Coordinate transformation is necessary for wind velocity analysis. Data of the new wind velocity is transformed from that of the original one obtained from ultra sonic anemometer.

\[
\begin{align*}
    v_j &= -x_j \cos \varphi_j + y_j \sin \varphi_j \\
    u_j &= x_j \sin \varphi_j + y_j \cos \varphi_j \\
    \varphi_j &= \tan^{-1} \left( \frac{\sum x_i}{\sum y_i} \right) + \theta
\end{align*}
\]

where \( x_j,y_j \) represents \( x,y \) components of wind speed respectively; \( \theta=0 \), when \( \Sigma x \) and \( \Sigma y \) are both less than zero ; \( \theta=\pi \), when \( \Sigma y \) is greater than zero; \( \theta=2\pi \), when \( \Sigma x \) is less than zero and \( \Sigma y \) is greater than zero.

\[
\begin{align*}
    u_i &= x_i \sin \varphi_i + y_i \cos \varphi_i \\
    v_i &= -x_i \cos \varphi_i + y_i \sin \varphi_i
\end{align*}
\]

where \( u_i,v_i \) represents \( u,v \) components of new wind speed respectively.

2.3 Concentration Rate of Wind Direction

There are 12288 wind directions in a run, however they are almost different from one another. It can be considered to be in the same direction if the azimuths of wind direction are in the range of \( \varphi_j \pm \)
11.25°) with the concept of the Wind Rose Diagram. The concentration rate of wind direction, \( R_c \), in a run can be expressed as followed:

\[
R_c = \frac{N}{m} (4)
\]

Where \( m \) represents the number of wind directions in a run and is equal to 12288, \( N \) represents the number of wind directions that are in the same direction with the mean wind direction \( \phi_i \).

3. Quadrant Analysis.

3.1 Reynolds Stress

The contributions of \( u'w' \) are sorted into 4 groups of quadrant as shown as followed:

S1 (\( u'>0, w'>0 \)), the first quadrant: represents event of outward interaction and the fluid flows outward in high speed.

S2 (\( u'<0, w'>0 \)), the second quadrant: represents event of burst and the fluid flows outward in low speed.

S3 (\( u'<0, w'<0 \)), the third quadrant: represents event of inward interaction and the fluid flows inward in low speed.

S4 (\( u'>0, w'<0 \)), the fourth quadrant: represents event of gust and the fluid flows inward in high speed.

3.2 Heat Flux

The contributions of \( \theta'w' \) are sorted into 4 groups of quadrant as shown as followed:

S1 (\( \theta'>0, w'>0 \)), the first quadrant: represents event of burst.

S2 (\( \theta'<0, w'>0 \)), the second quadrant: represents event of outward interaction.

S3 (\( \theta'<0, w'<0 \)), the third quadrant: represents event of gust.

S4 (\( \theta'>0, w'<0 \)), the fourth quadrant: represents event of inward interaction.

4 Theoretical Expressions of Power Spectra

Power spectra of three components of wind speeds are investigated from the standpoint of the theory of isotropic turbulence. According to the theory of isotropic turbulence the power spectra of the \( v \) and \( w \) components of gusty wind, \( S_v(n) \) and \( S_w(n) \), relate with that of the \( u \) component, \( S_u(n) \), as follows:

\[
S_u(n) = \frac{1}{2} \left[ S_u(n) \cdot \frac{n dS_u(n)}{dn} \right] (5)
\]

Karmán's power spectrum of the \( u \) component may be given by the following equation:

\[
S_u(n) = \frac{2u'^2 L^u_x}{U \left[ 1 + (2cnL^u_x/U)^2 \right]^{3/2}} (6)
\]

Where \( U \) is the mean wind speed, \( L^u_x \) is the longitudinal scale of turbulence of the \( u \) component, \( U' \) is the variance of the \( u \) component, and \( c=4.2065 \) proposed by J. Maeda... By setting \( v'^2 = w'^2 = u'^2 \), \( L^v_x = L^w_x = L^u_x \) and substituting Eq.(6) into Eq.(5) the following equations are obtained:

\[
S_v(n) = \frac{v'^2 L^v_x}{U \left[ 1 + (2cnL^v_x/U)^2 \right]^{3/2}} (7)
\]

\[
S_w(n) = \frac{w'^2 L^w_x}{U \left[ 1 + (2cnL^w_x/U)^2 \right]^{3/2}} (8)
\]

where \( L^v_x \) and \( L^w_x \) is the longitudinal scale of turbulence of the \( v \) and \( w \) components respectively, \( v'^2 \) and \( w'^2 \) is the variance of the \( v \) and \( w \) component. The autocorrelation coefficient of the \( u \) component gives the longitudinal scale of turbulence, \( L^u_x \). Those of the \( v \) and \( w \) components give the lateral ones, \( L^v_x \) and \( L^w_x \), respectively. The relationships \( L^v_x = L^w_x = 0.5 L^u_x \) hold in the field of isotropic turbulence. Therefore Eq.(7) and Eq.(8) are rewritten by the following equation having \( L^v_x \) and \( L^w_x \) for taking the place of \( L^u_x \) and \( L^v_x \) respectively:

\[
S_v(n) = \frac{2v'^2 L^v_x}{U \left[ 1 + (4cnL^v_x/U)^2 \right]^{3/2}} (9)
\]

\[
S_w(n) = \frac{2w'^2 L^w_x}{U \left[ 1 + (4cnL^w_x/U)^2 \right]^{3/2}} (10)
\]

If \( u \) component of Eq.(6) was replaced by \( v \) and \( w \) components respectively ( except the mean wind velocity \( U \) ) suggested by Maeda, i.e.

\[
v'^2 = w'^2 = u'^2 \quad \text{and} \quad L^u_x = L^v_x = L^w_x
\]

Maeda power spectra of \( v \) and \( w \) component can be given by the following equation:

\[
S_v(n) = \frac{2v'^2 L^v_x}{U \left[ 1 + (2cnL^v_x/U)^2 \right]^{3/2}} (11)
\]
5. Results and Discussion

5.1 Turbulence Characteristics

The accurate date and time period of the run number is shown in Table 1, also the wind direction and the concentration rate of wind direction for each run are included. The wind direction was always in the WNW during the typhoon, and the concentration rate for wind direction was 71% around.

Table 2 shows mean and maximum of wind velocity and the turbulence intensity for each run. That the mean wind velocity of \( v \) component was equal to zero implied that the coordinate transformation be correct. The maximum value of \( I_u \) was 38% and the maximum value of \( U_{\text{max}} \) was 20.1 m/s for Run 14; the maximum value of \( I_v \) was 22% and the maximum value of \( V_{\text{max}} \) was 11.7 m/s for Run 10; the maximum value of \( I_w \) was 17% and the maximum value of \( W_{\text{max}} \) was 9 m/s for Run 10. It can be concluded that max turbulence intensity is related to max wind speed at the same place.

Table 3 shows time and length integral scale. The time integral scale of the \( u \) component was the largest among the three components as shown in the Table 3. The similar results were obtained about the integral scales of turbulence of the three components: the longitudinal scale of turbulence of the \( u \) component and the lateral ones of the \( v \) and \( w \) components were in the ratios about 12:3:4, and the result were different from that of Maeda’s.

Table 1 Time and direction of each run

<table>
<thead>
<tr>
<th>Run No</th>
<th>Date</th>
<th>Begin hr:min</th>
<th>End hr:min</th>
<th>Wind direction</th>
<th>Concentration %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>981025</td>
<td>00:10</td>
<td>00:20</td>
<td>WNW</td>
<td>0.85</td>
</tr>
<tr>
<td>2</td>
<td>981025</td>
<td>01:40</td>
<td>01:50</td>
<td>WNW</td>
<td>0.89</td>
</tr>
<tr>
<td>3</td>
<td>981026</td>
<td>00:20</td>
<td>00:30</td>
<td>WNW</td>
<td>0.73</td>
</tr>
<tr>
<td>4</td>
<td>981026</td>
<td>00:30</td>
<td>00:40</td>
<td>WNW</td>
<td>0.67</td>
</tr>
<tr>
<td>5</td>
<td>981026</td>
<td>00:40</td>
<td>00:50</td>
<td>WNW</td>
<td>0.73</td>
</tr>
<tr>
<td>6</td>
<td>981026</td>
<td>01:00</td>
<td>01:10</td>
<td>WNW</td>
<td>0.81</td>
</tr>
<tr>
<td>7</td>
<td>981026</td>
<td>01:10</td>
<td>01:20</td>
<td>WNW</td>
<td>0.66</td>
</tr>
<tr>
<td>8</td>
<td>981026</td>
<td>01:20</td>
<td>01:30</td>
<td>WNW</td>
<td>0.78</td>
</tr>
<tr>
<td>9</td>
<td>981026</td>
<td>01:30</td>
<td>01:40</td>
<td>WNW</td>
<td>0.68</td>
</tr>
<tr>
<td>10</td>
<td>981027</td>
<td>02:20</td>
<td>02:30</td>
<td>WNW</td>
<td>0.57</td>
</tr>
<tr>
<td>11</td>
<td>981027</td>
<td>02:40</td>
<td>02:50</td>
<td>WNW</td>
<td>0.63</td>
</tr>
</tbody>
</table>

5.2 Probability Density Function

Analysis of the probability density function (pdf) of longitudinal, transverse and vertical wind speed are close to Gaussian distributions shown in Fig. 2. Pdf of temperature seems to be worse than the former ones.
and is shown in Fig 3.

5.3 Reynolds Stress and Heat Flux

The contributions of Reynolds stress for Run 12 appear that S1 and S3 are bigger than S2 and S4 shown in Fig 4, i.e. events of outward and inward interaction were occurred more than that of burst and gust. The contributions of heat flux for Run 12 appear that S1 and S3 are bigger than S2 and S4 shown in Fig 5, i.e. events of burst and gust were occurred more than that of outward and inward interaction. The boundary layer was supposed to be stable and would increase the turbulence.
5.4 Power spectra

The average power spectra, including run3, run5, run6, run7, run8, were shown in Fig 6. \( nL^u/U \), \( nL^v/U \) and \( nL^w/U \) is the unit of \( x \) coordinate for Fig 6 (a), (b) and (c) respectively,

\[
\frac{US_u}{u^2L^u_x}, \quad \frac{US_v}{v^2L^v_x} \quad \frac{US_w}{w^2L^w_x}
\]

is the unit of \( y \) coordinate for Fig 6 (a), (b) and (c) respectively. The longitudinal observed spectrum agreed well with Karman’s spectrum, and the constant \( C \) was equal to 2.5. The transverse observed spectrum agreed well with isotropic and Maeda's theoretical power spectra in the inertial subrange, and the constant \( C \) was equal to 2. The vertical spectra was almost in the same condition as the \( v \) component shown in Fig 6, and the constant \( C \) was equal to 1.5.

The longitudinal observed spectrum agreed well with Karman’s spectrum for run7; the lateral observed spectrum agreed well with isotropic and Maeda’s theoretical power spectra in the inertial subrange shown in Fig 7 for run7; the constant \( C \) was equal to 2.5 all the time.

6. Conclusion

The wind was always in the same direction during Typhoon Babs; the appearance of max wind speed was accompanied with max turbulence intensity, and the ratio of \( u, v \) and \( w \) component for integral scale was 12:3:4. PdF of wind speed seemed to be normal distribution, however that of temperature behaved worse. Reynolds stress was governed by outward and inward interaction events, while heat flux was governed by burst and gust events. The boundary layer was stable and would increase turbulence flow. The observed power spectrum of \( u \) component agreed well with Karman’s spectrum. The observed power spectra of \( v \) and \( w \) component agreed with isotropic and Maeda’s spectra for the inertial subrange only.

Fig 5 Heat flux contributions for Run 12

5.4 Power spectra

The average power spectra, including run3, run5, run6, run7, run8, were shown in Fig 6. \( nL^u/U \), \( nL^v/U \) and \( nL^w/U \) is the unit of \( x \) coordinate for Fig 6 (a), (b) and (c) respectively,

\[
\frac{US_u}{u^2L^u_x}, \quad \frac{US_v}{v^2L^v_x} \quad \frac{US_w}{w^2L^w_x}
\]

Fig 6 (a), (b), (c) Nondimensional wind spectra of \( u, v, w \) components respectively. (average)
References


Fig 7 (a), (b), (c) Nondimensional wind spectra of u, v, w components respectively for Run 7.