Property of a Typical Urban Thunderstorm Outflow Relevant to Wind Load on Structures

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Abstract. Extreme wind, thunderstorm, occurs throughout the world, even in the polar regions. At any given time approximately 2,000 thunderstorms are occurring on Earth. Many structural damages induced by them have been recorded around the world. Study of thunderstorm outflows and their effects on structures already becomes a key topic in modern wind engineering. This paper analysed the main properties of a typical thunderstorm outflow event occurred in Beijing based on the measured data detected by 9 ultrasonic anemometers mounted on the 325 m high Beijing meteorological tower. It is fundamental and crucial to learn the phenomena in urban area and study the structural response to thunderstorm outflows.

1. Introduction
Thunderstorm outflows are transient phenomena at the mesoscale \cite{1} that occur in convective conditions with “nose” velocity profiles \cite{2} totally different from those that are typical of the atmospheric boundary layer. Several studies show that the design wind velocity is often linked with thunderstorm events \cite{3-5}. Recently, some studies have been performed in wind engineering with reference to extracting their parameters of major interest for evaluating the wind loading and response of structures to thunderstorm outflows \cite{6} based on data detected. Despite these and many other analyses, the understanding, representation and modelling of thunderstorm outflows are still full of uncertainties and problems to be clarified due to the physical complexity of these atmospheric phenomena, the short duration and small size making very limited the available data. The 325 m meteorological tower in Beijing provides a unique opportunity to learn the phenomena and analyses the parameters interesting in wind load on structures.

2. Measurement Site and Observations
The 325m high meteorological tower, as shown in figure 1 (a), is located at 39°58'N, 116°2'E, which is a guyed tower with regular triangle cross section, is situated in north central Beijing, and was set up nearly three decades ago \cite{7}. The site around the tower can be regarded as terrain C (an urban area) according to the Chinese National Load Code (GB50009-2001). Eleven three-channel ultrasonic anemometers with a sampling rate of 10 Hz were installed on the tower at nine levels along the tower, which are 8 m, 16 m, 32 m (2), 47 m, 64 m (2), 80 m, 140 m, 200 m, and 280 m respectively. Only 9 anemometers (one for each height) in the north are used for this paper. The anemometric data of the
database is stored in terms of three instantaneous wind speed components \((V_x, V_y, V_z)\) for the three-axial ultrasonic anemometers according to the geophysical coordinate system, where \(V_x\) is directed from East to West, \(V_y\) from South to North, and \(V_z\) is vertical and positive upwards, respectively as illustrated in figure 1 (b). The meteorological tower is the best observation station to study the urban boundary layer and urban intense storm of Beijing city at present.

![Figure 1. Picture of the 325 m high Beijing meteorological tower (a) and ultrasonic anemometer (b).](image)

3. A typical thunderstorm outflow event
Thanks to the high resolution measured data, a number of thunderstorm outflow records are recorded and extracted, in which a typical thunderstorm event occurred on September 7, 2016 is used for the analyse herein. Figure 2 presents the 1-h time history record registered by the 280 m anemometer corresponding to the thunderstorm outflow. The pictures (a) and (b) show the time-series of the horizontal wind speed and direction (North = 0°, East = 90°) raw data, respectively, and they also provide their mean values over 1-h, \(U_{m60}\) and \(\alpha_{m60}\) (solid lines), and 10-min periods, \(U_{m10}\) and \(\alpha_{m10}\) (dotted lines). In pictures (a), the 1-s peak wind speed \(\bar{U}\) (red circle) and maximum value (pink square) of 30 s moving average velocity (cyan line) [8-9] are also shown, which are obviously smaller than the instantaneous peak. The maximum value of the slowly-varying mean wind velocity is 27.92 m/s. The picture (c) shows the time-series of the temperature and their mean values over 10-min and 1-h periods.

The intense jump of velocity is a universal property for thunderstorm outflow [10]. It is obvious that the velocity increases suddenly, decreases a little bit and then increases to the peak value and finally decreases relatively slowly. The direction changes almost 90 degrees when the velocity increases. It is worth noting that the temperature decreases suddenly for 10 °C, after the event it returns to original level, which further confirms occurrence of the thunderstorm outflow.

![Figure 2. Thunderstorm outflow recorded on 07 September 2016 by the 280 m anemometer: (a) 1-h wind speed time-series; (b) 1-h wind direction time-series; (c) 1-h temperature time-series.](image)

4. Signal decomposition and analyses of the parameters related to wind load on structures
In order to inspect the properties of the component parts of the thunderstorm outflow record, the horizontal component of their wind speed is expressed by classical decomposition rule [8-10]. In which, the horizontal resultant velocity $U(t)$ of $V_x$ and $V_y$ is decomposed by a rather classic moving average filter with a moving average period $T = 30$ s [8-11] into a slowly-varying mean velocity $\bar{U}(t)$ and a residual fluctuation $U'(t)$ that is later expressed as the product of the slowly-varying standard deviation $\sigma_U(t)$ by a reduced turbulent fluctuation $U''(t)$ dealt with as a rapidly-varying stationary Gaussian random process with zero mean and unit standard deviation; $t \in [0, \Delta T]$ is the time being $\Delta T = 10$ min. So, the wind velocity $U$ is expressed as:

$$U(t) = \bar{U}(t) + U'(t) = \bar{U}(t) + \sigma_U(t)U''(t) = \bar{U}(t)[1 + I_U(t)U''(t)]$$

(1)

where $I_U(t) = \sigma_U(t)/\bar{U}(t)$ is the slowly-varying turbulence intensity. The time-varying direction $\alpha(t) \in [0:360]$ of the thunderstorm outflows is the direction of the vector $U(t)$ according to the geographical notation (North = 0°, East = 90°, South = 180°, West = 270°).

### 4.1 Mean wind velocity and wind speed profile

Figure 3 (a) shows the ensemble of the diagrams of the moving average velocity with period of 30s relevant to the 9 different heights for the thunderstorm record. They have the typical smoothed shape of the horizontal instantaneous wind speed. The obvious jump can be found for all the heights. This figure confirms what was already discussed in [9]: due to the great variability of $\bar{U}(t)$ they can be regarded as samples of a non-stationary random process. Studies are still in progress to define quantitative criteria aiming to model the peak duration and qualitatively classify the different shapes of moving average velocity.

The time-varying mean wind speed vertical profiles at selected instants in the 30 min from 18:20 to 18:50 for the event are shown in figure 3 (b), which presents the continue variation with the time. It is apparent that the mean wind speed firstly decreases and then increases slightly with height before the event. While the wind speed increases rapidly until 64m and then keeps almost constant with height at the start of the event. Especially at the 800s, the whole mean speed decreases a little bit, while the obvious increasing firstly, decreasing then increasing variation again can be found for the lower height. Then the mean velocity reduces greatly, while presents clearly small at the bottom and big for the top at the end of the event. There is no doubt that the property of time varying and complex are very apparent for thunderstorm. The statistical model of the mean speed profile for thunderstorm is worthy of the further study.

![Figure 3. The 1-h time history of moving average velocity (a) and mean wind speed profiles (b).](image)

### 4.2 Turbulence intensity
Figure 4 shows the signals of $U'$ (a) and $\sigma_U$ (b) of the above thunderstorm record based on the classical decomposition. According to the time varying standard deviation and moving average velocity, the slowly-varying turbulence intensity is easy derived and shown in figure 5 (a) and their mean value varying with the heights are presented in figure 5 (b). It is clear that the turbulence fluctuation is nonstationary process and presents a zigzag trend. This remark confirms that it makes quite questionable the usual position, $\mu = \mu_0 = 1$, adopted in some literatures. Besides, the abnormal large values before and after the event are clear due to the small moving average velocity trending to zero which will influence the analyses of the turbulent intensity relevant to the thunderstorm outflow. In the following and further analyses, the ignoring of them is necessary to improve the precision of analysis for thunderstorm outflows.

4.3 Reduced turbulent fluctuations
The feature of the reduced turbulent fluctuations $\overline{U}'$ of the thunderstorm outflow is illustrated in figure 6 (a), which denotes a stationary behaviour and no significant change of the harmonic content along the time. For the thunderstorm record, the reduced turbulent fluctuation has zero mean and unit standard deviation; its skewness is 0.02 whereas its kurtoses is 2.81 for $T=30$ s. Accordingly, Figure 6 points out the good agreement between the probability density function (pdf) of $\overline{U}'$ and the reference Gaussian pdf, confirming that they reasonably constitute a stationary Gaussian random process with zero mean and unit standard deviation, as widely shared in literature [9].
4.4 Turbulence integral length scales and power spectral density

The turbulence integral length scales $L_u$ are determined from the auto-correlation function of $\tilde{U}'$ [10]. The values as a function of height are shown in figure 7 (a). It is obvious that the turbulence integral length scale increases with the height firstly and then keeps almost constant from 64m to 80m, after decreases with the height increasing, and finally increases again. This result seems to coincide with the general nose shape of the vertical velocity for thunderstorm outflow, which is interesting for the further study about the property of this phenomenon.

The parameterization of the power spectral density (PSD) of $\tilde{U}'$ as a function of the reduced frequency $f = nL_u/\tilde{U}_{max}$ is shown in figure 7 (b) for the thunderstorm outflow records related to 9 heights, in which $\tilde{U}_{max}$ is related to the maximum value of the slowly-varying mean wind velocity. It exhibits almost one dominant peak position for the anemometers located at different heights, while the peak values presents increasing first but then dropping. The black full line is the mean value of all the records detected by the 9 anemometers, which is crucial for the refined model of the PSD for thunderstorm outflow.

5. Conclusions

Based upon the thunderstorm outflow detected by the anemometers mounted on the 325m high Beijing meteorological tower, analyses are carried out in order to extract the parameters of major interest for
evaluating the wind actions on structures. Firstly of all, the wind velocity of thunderstorms is decomposed into the sum of a slowly-varying mean part plus a residual fluctuation dealt with as a non-stationary random process. The fluctuation, in turn, is expressed as the product of its slowly-varying standard deviation by a reduced turbulence component dealt with as a rapidly-varying stationary Gaussian random process with zero mean and unit standard deviation. The extraction of the mean part of the wind velocity is carried out through a moving average filter with the period of 30s, which is found to be appropriate for this thunderstorm data. Among other aspects, special attention is given to the mean wind speed profile, the turbulence intensity, the turbulence integral length scale and the power spectral density. The correlation of these quantities with respect to the height above ground of the sensor are also considered, which confirms the complex of the thunderstorm outflow. Studies are still in progress with reference to furnishing a comprehensive statistical characterization of the huge amount of thunderstorm outflows recorded by the tower.

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