Directional decomposition and properties of thunderstorm outflows relevant to wind engineering

Giovanni Solari(1), Shi Zhang*(1) (2) (3), Massimiliano Burlando(1), Qingshan Yang(4) (3)

1) Department of Civil, Chemical and Environmental Engineering, University of Genoa, Italy
2) School of Civil Engineering, Beijing Jiaotong University, Beijing, China
3) Beijing's Key Laboratory of Structural Wind Engineering and Urban Wind Environment, China
4) School of Civil Engineering, Chongqing University, Chongqing, China
**) Shi Zhang, 10231097@bjtu.edu.cn*

ABSTRACT

The analysis of thunderstorm outflows is usually carried out by decomposing their horizontal resultant velocity into a slowly-varying mean part and a residual fluctuation. This is incoherent with the traditional analysis of synoptic wind speeds, where the mean velocity and direction are determined, and the fluctuations are decomposed in terms of longitudinal and lateral turbulence components. A novel directional decomposition strategy is thus formulated that makes the study of thunderstorm outflows and synoptic winds fully coherent. The classic and novel decomposition methods are compared and elucidated with reference to a real thunderstorm record. This analysis is preliminary to its repetition with regard to a wide dataset of thunderstorm signals, to study their properties in a statistical environment coherent with that traditionally used for synoptic winds.

1 INTRODUCTION

In wind engineering, the wind speed is traditionally separated into its mean and fluctuating parts. This is functional to separate the structural response into a mean static part, due to the mean wind speed, and into a dynamic part, due to the fluctuating wind speed.

In the case of synoptic winds, this separation is usually carried out by determining first the mean wind speed and direction. Then, the fluctuations are decomposed in terms of longitudinal and lateral turbulence components. This facilitates the classic study of the structural behaviour in terms of alongwind and crosswind response.

The study of thunderstorm outflows has followed a rather different approach (Chen and Letchford 2004, Holmes et al 2008, Solari et al 2015), according to which the horizontal resultant velocity is decomposed into a slowly varying mean part and a residual turbulent fluctuation. In this way, the wind direction is often regarded only from a qualitative viewpoint and the structural response is implicitly assumed in the alongwind direction. This framework is easy to apply and very diffused in wind engineering. However, this precludes a parallel treatment and a robust comparison of the wind speed and of the structural response for thunderstorm outflows and synoptic winds.

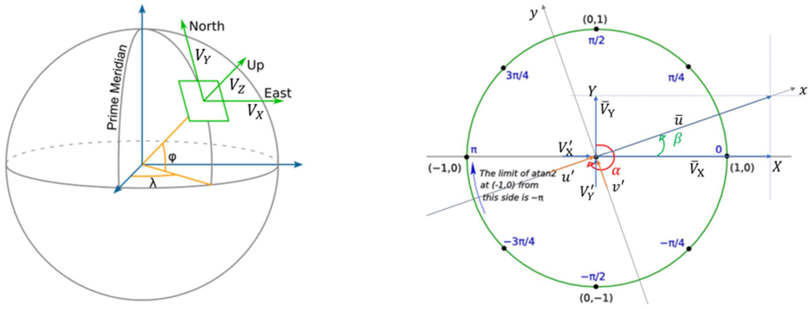
To overcome this shortcoming, a novel directional decomposition strategy of the wind speed is herein formulated that opens the doors to a robust comparison between thunderstorm outflows and synoptic winds in terms of wind speed, of wind loading and of dynamic structural response. In this framework, the classical and the novel decomposition methods are compared and elucidated with reference to a real thunderstorm record. This analysis is preliminary to its repetition with regard to a wide dataset of thunderstorm outflow signals (Zhang et al 2017) aiming to study their properties in a statistical environment coherent with that traditionally used for synoptic winds.

2 CLASSICAL DECOMPOSITION

The anemometric data of the thunderstorm outflow database (Solari et al 2015, Zhang et al 2017) is stored in terms of components $(V_\mathrm{X}, V_\mathrm{Y})$ for bi-axial anemometers or $(V_\mathrm{X}, V_\mathrm{Y}, V_\mathrm{Z})$ for three-axial anemometers according to the geophysical coordinate system (Figure 1a), where V_X is directed from West to East, V_Y from South to North, and V_Z is vertical and positive upwards. Following the classical approach, 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 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 $\tilde{U}'(t)$ 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 ΔT = 10 min. So, the wind velocity U is expressed as:

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

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°).



(a) *(b)*

Figure 1: (a) Geophysical coordinate system of the anemometric data; (b) directional decomposition.

3 DIRECTIONAL DECOMPOSITION

Based upon the new directional decomposition strategy, each horizontal velocity component $(V_\mathrm{X}, V_\mathrm{Y})$ is decomposed into a slowly-varying mean speed $(\bar{V}_\mathrm{X}, \bar{V}_\mathrm{Y})$, evaluated by a moving average filter with period $T = 30$ s, and a residual fluctuation (V'_X, V'_Y) (Figure 1b). The slowly-varying horizontal mean wind velocity vector is defined in terms of wind speed and direction as:

$$\bar{u}(t) = \sqrt{\bar{V}_\mathrm{X}^2(t) + \bar{V}_\mathrm{Y}^2(t)},\, \bar{\alpha}(t) = 270 - \mathrm{atan2}\left(\bar{V}_\mathrm{Y}(t)/\bar{V}_\mathrm{X}(t)\right) \tag{2}$$

where $\bar{\alpha} \in [0{:}360]$ according to the geographical notation.

The residual fluctuations are then projected onto a new Cartesian reference system (*x*,*y*), where the *x*-axis coincides with $\bar{u}(t)$ and is rotated $\beta(t)$ (Figure 1b) with respect to the fixed *X*-axis. Thus:

$$\begin{gathered} u'(t) = -V'_\mathrm{X}(t)\sin\bar{\alpha}(t) - V'_\mathrm{Y}(t)\cos\bar{\alpha}(t) \\ v'(t) = V'_\mathrm{X}(t)\cos\bar{\alpha}(t) - V'_\mathrm{Y}(t)\sin\bar{\alpha}(t) \end{gathered} \tag{3}$$

where u' and v' are referred to as the longitudinal and lateral turbulent fluctuations. They are re-written as the product of their slowly-varying standard deviations ($\sigma_{u'}$,$\sigma_{v'}$) by a couple of reduced longitudinal and lateral turbulent fluctuations $(\tilde{u}', \tilde{v}')$:

$$u'(t) = \sigma_u(t)\tilde{u}'(t), v'(t) = \sigma_v(t)\tilde{v}'(t) \tag{4}$$

Accordingly, the longitudinal and lateral components of the wind velocity may be expressed as:

$$\begin{gathered} u(t) = \bar{u}(t) + u'(t) = \bar{u}(t) + \sigma_u(t)\tilde{u}'(t) = \bar{u}(t)[1 + I_u(t)\tilde{u}'(t)] \\ v(t) = v'(t) = \sigma_v(t)\tilde{v}'(t) = \bar{u}(t)I_v(t)\tilde{v}'(t) \end{gathered} \tag{5}$$

where $I_u(t) = \sigma_u(t)/\bar{u}(t)$ and $I_v(t) = \sigma_v(t)/\bar{u}(t)$ are the longitudinal and lateral turbulence intensities, respectively.

4 APPLICATIONS AND DISCUSSION

To illustrate the new decomposition strategy and to compare it with the classical one, a typical thunderstorm outflow record is analysed by these two approaches. Figure 2 shows the 10-min horizontal velocity components V_{X} and V_{Y}, according to the geophysical coordinate system, and the direction α of the thunderstorm record detected on October 25, 2011 by the anemometer 03 of the Port of La Spezia; the 1s peak wind velocity is 33.98 m/s (Zhang et al 2018). It is apparent a sudden ramp-up for both the wind velocity components. In correspondence of such a jump, the wind direction changes of about 90 degrees.

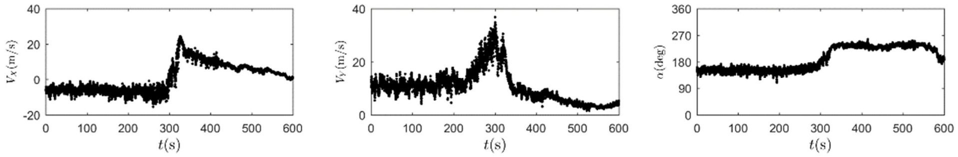


Figure 2: 10-min velocity components (a, b) and direction (c) of a thunderstorm outflow record.

Figure 3 shows the wind velocity classical decomposition of the above thunderstorm record, reporting $U, \bar{U}, U', \sigma_U, I_U, \tilde{U}'$. The slowly-varying mean wind velocity has the typical smoothed shape of the horizontal instantaneous wind speed. The maximum value of the slowly-varying mean wind velocity is 26.86 m/s. The slowly-varying turbulence intensity has a mean value 0.121; it shows a quite unusual decreasing trend. The reduced turbulent fluctuation has zero mean and unit standard deviation; its skewness is -0.120 whereas its kurtoses is 2.895.

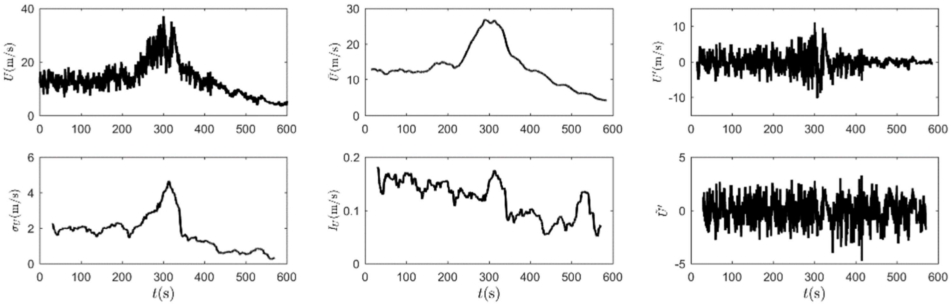


Figure 3: Wind velocity classical decomposition of a thunderstorm outflow record.

Figure 4 illustrates the results provided by the directional decomposition of the same thunderstorm outflow record. The slowly-varying mean wind velocity is very similar to the previous one and has a maximum value of 26.39 m/s; the slowly-varying mean wind direction exhibits a regular rotation of about 90 degrees. The longitudinal turbulent fluctuation replicates rather closely the resultant fluctuation of the classical non-directional decomposition method. The mean values of the longitudinal and lateral turbulence intensities are 0.123 and 0.104, respectively. The reduced longitudinal and lateral turbulent fluctuations have zero mean and unit standard deviation; the former has skewness -0.129 and kurtosis is 2.924; the latter has skewness 0.129 and kurtosis 2.996; the cross-correlation coefficient is -0.152.

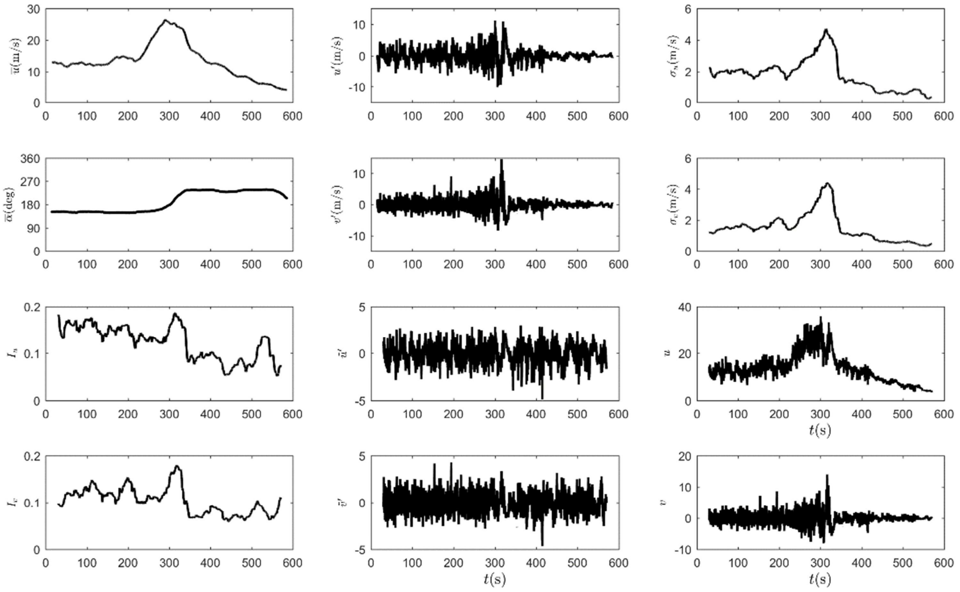


Figure 4: Wind velocity directional decomposition of a thunderstorm outflow record.

5 CONCUSIONS AND PROSPECTIVES

A novel directional decomposition rule for thunderstorm outflows is proposed that represents an advancement respect to the classic non-directional decomposition rule. It establishes a robust parallelism with the classical representation of synoptic winds. Studies are in progress concerning the spectral content of the new component signals and a systematic investigation of their statistical properties with regard to an extensive dataset of thunderstorm outflow records. Authors maintain that the extraction of the slowly-varying mean wind velocity and direction is a fundamental step towards the reconstruction of thunderstorm properties based on single or multiple thunderstorm records. Besides, the extraction of the longitudinal and lateral turbulence components as functions of the slowly-varying mean wind direction is strategic for the directional analysis of the dynamic behaviour of structures and for its expression in terms of alongwind and crosswind response.

Acknowledgements

This research is funded by European Research Council under the European Union's Horizon 2020 research and innovation program (grant agreement No. 741273) for the project THUNDERR - Detection, simulation, modelling and loading of thunderstorm outflows to design wind safer and cost-efficient structures – through an Advanced Grant 2016, and by 111 Project supported by Chinese Ministry of Education. The data was recorded by the monitoring network set up as part of the European Projects "Winds and Ports" (grant No. B87E09000000007) and "Wind, Ports and Sea" (grant No. B82F13000100005), funded by the European Territorial Cooperation Objective, Cross-border program Italy-France Maritime 2007–2013.

References

Chen, L., Letchford, C.W. (2004). A deterministic-stochastic hybrid model of downbursts and its impact on a cantilevered structure. Eng. Struct., 26, 619-629.

Holmes J.D., Hangan H.M., Schroeder J.L., Letchford C.W., Orwig K.D. (2008) A forensic study of the Lubbock-Reese downdraft of 2002, Wind Struct., 11, p19–39.

Solari, G., Burlando, M., De Gaetano, P., Repetto, M.P. (2015). Characteristics of thunderstorms relevant to the wind loading of structures, Wind Struct., 20, p763-791.

Zhang, S., Solari, G., De Gaetano, P., Burlando, M., Repetto, M.P. (2017). A refined analysis of thunderstorm outflow characteristics relevant to the wind loading of structures. Prob. Eng. Mech., DOI:10.1016/j.probengmech. 2017.06.003.