Journal of Physics: Conference
Series

# Alongwind dynamic response of slender vertical structures: thunderstorm outflows vs extra-tropical cyclones

To cite this article: L Roncallo *et al* 2024 *J. Phys.: Conf. Ser.* **2647** 242003

# Alongwind dynamic response of slender vertical structures: thunderstorm outflows vs extra-tropical cyclones

**L Roncallo**[a], **F Tubino**[b] **and M Gimondo**[c]

Department of Civil, Chemical and Environmental Engineering (DICCA), Polytechnic School, University of Genoa, Via Montallegro 1, 16145 Genoa, Italy

E-mail: [a]`luca.roncallo@edu.unige.it`, [b]`federica.tubino@unige.it`, [c]`s4082178@studenti.unige.it`

**Abstract.** This paper studies the maximum dynamic response of a slender vertical structure subjected to thunderstorm outflows and provides a comparison with synoptic events. A reinforced concrete telecommunication tower is considered as case study. The thunderstorm wind speed is modelled as sum of a slowly-varying mean and nonstationary turbulent fluctuations with a vertical nose profile, while for synoptic wind the Italian CNR Guideline is adopted. A reference wind speed with 50 years return period is considered for both the thunderstorm and synoptic events, based statistical analyses carried out on in previous studies. In view of the results outlined for the considered structure, the thunderstorm wind loading, which is currently not accounted by codes and standards, can be more demanding than synoptic events.

## 1. Introduction

Thunderstorms and extra-tropical cyclones provide significantly different wind conditions: extra-tropical cyclones, commonly referred to as Atmospheric Boundary Layer (ABL) winds, provide stationary wind conditions over time intervals of 10 minutes-1 hour and a wind velocity profile increasing with the height; instead, thunderstorms are responsible for nonstationary wind conditions and are characterized by a nose-shaped velocity profile. Furthermore, the two phenomena are characterized by different extreme distributions and high return period thunderstorm wind speeds can be higher than those corresponding to extra-tropical cyclones. Despite these remarkable differences, a shared model for the estimate of the maximum dynamic response and wind loading on structures provided by thunderstorms is, to date, not available. Starting from an Evolutionary Power Spectral Density (EPSD) model of the thunderstorm wind speed [1], the authors proposed a formulation generalized to thunderstorms of the gust response factor from Davenport for Single-Degree-Of-Freedom (SDOF) systems [2; 3]. The objective of the present paper is to extend the approach to slender vertical structures and compare the effects of thunderstorm outflows and extra-tropical cyclones in terms of maximum alongwind dynamic response. A reinforced concrete telecommunication tower is considered as case study. In order to ensure consistency in the comparison, different reference wind speeds with 50 years return period are adopted for thunderstorm and ABL winds, based on the results of a statistical analysis carried out on wind speed data collected by an anemometer located in the port of Livorno [4]. The typical nose-shaped vertical mean wind speed profile for thunderstorm is fixed according to a model from the literature, considering four different heights of the nose tip. The wind speed associated with the ABL wind is modelled through a logarithmic vertical profile assuming five different values of the roughness length. The gust response factor associated with the ABL wind is derived through the Davenport formulation, while for thunderstorms the generalized gust response factor is adopted [2; 3]. Finally, the comparison is reported in terms of ratio between the maximum responses estimated for the two events. Overall, thunderstorms mostly provide a greater response, especially when the tip of the nose-shaped profile is close to the top of the structure.

## 2. Analytical formulation

Let us consider a slender vertical structure schematized as a linear elastic continuous system with width $b(z)$, height $H$ and drag coefficient $c_D(z)$, with $z$ the vertical space coordinate. Assuming the dynamic response is dominated by the first mode of vibration, the alongwind displacement can be expressed as:

$$x(z,t) = \psi_1(z)p_1(t) \tag{1}$$

where $\psi_1(z)$ is the first modal shape and $p_1(t)$ the first principal coordinate, solution of the equation of motion:

$$\ddot{p}_1(t) + 2\omega_1\xi_1\dot{p}_1(t) + \omega_1^2 p_1(t) = \frac{1}{m_1}f_1(t) \tag{2}$$

where $\omega_1 = 2\pi n_1$ is the first circular natural frequency, $m_1$ is the first modal mass, $\xi_1$ the related damping ratio and $f_1(t)$ the first modal force [5]. For thunderstorm outflows, adopting the model proposed by [5], the slowly-varying mean part of the modal force reads:

$$\bar{f}_1(t) = \frac{1}{2}\rho\bar{v}_{max}^2(h)\gamma^2(t)a_1 \tag{3}$$

where $\rho$ is the air density, $\bar{v}_{max}$ is the maximum value of the slowly-varying mean speed of the thunderstorm outflow assigned at reference height $h$, $\gamma(t)$ is the modulating function of the slowly-varying mean speed [6] and $a_1$ can be interpreted as the area perceived by the wind on the first mode and it has the dimension of an area. It is defined as follows [5]:

$$a_1 = \int_0^H \alpha^2(z)b(z)c_D(z)\psi_1(z)dz \tag{4}$$

where $\alpha(z)$ is the non-dimensional vertical profile of the thunderstorm mean speed. The mean part of the response is assumed as the static response to the slowly-varying mean part of the loading $\bar{f}_1(t)$ (Eq. 3):

$$\bar{p}_1(t) = \frac{1}{2m_1(2\pi n_1)^2}\rho\bar{v}_{max}^2(h)\gamma^2(t)a_1 \tag{5}$$

The maximum response is estimated through the generalized gust response factor for thunderstorm outflows and reads:

$$x_{max}(z) = \bar{x}_{max}(z)G_x \tag{6}$$

where $\bar{x}_{max}(z)$ is the maximum value of the mean part of the response (Eqs. 1 and 5) and $G_x$ the generalized gust response factor [3]. They are defined as follows:

$$\bar{x}_{max}(z) = \frac{\psi_1(z)}{2m_1(2\pi n_1)^2}\rho\bar{v}_{max}^2(h)a_1 \tag{7}$$

$$G_x = 1 + 2g_x(\tilde{\nu}_x \tilde{T}_{eq}) \bar{I}_v(z_{eq}) \mathcal{C} \sqrt{B^2 + R^2} \tag{8}$$

where $g_x$ is the Davenport peak factor [7], $\bar{I}_v(z_{eq})$ is the average value of the turbulence intensity over time estimated at the equivalent height $z_{eq} = 0.6H$ [8] and $B$, $R$ and $\tilde{\nu}_x$ are estimated as for the synoptic wind and given by [9; 10]:

$$B^2 = \frac{1}{1 + 0.9\left[\dfrac{b+H}{L_v(z_{eq})}\right]^{0.63}} \tag{9}$$

$$R^2 = \frac{\pi}{4\xi_1} S_{\tilde{v}'}(z_{eq}, n_1) \mathrm{C}_H(\eta_H) \mathrm{C}_b(\eta_b) \tag{10}$$

$$\mathrm{C}_d(\eta_d) = \frac{1}{\eta_d} - \frac{1}{2\eta_d^2}\left(1 - e^{-2\eta_d}\right) \tag{11}$$

$$\eta_d = \frac{4n_1 d}{\bar{v}_{max}(z_{eq})} \tag{12}$$

$$\tilde{\nu}_x = \sqrt{\frac{R^2}{B^2 + R^2}} \tag{13}$$

where $d = H, b$ and $L_v$ is the integral length scale. In Eq. (8) $\mathcal{C}$ and $\tilde{T}_{eq}$ are equivalent parameters derived employing the closed-form solution in [11]. For the synoptic wind Eqs. (8)-(13) are adopted with $\mathcal{C} = 1$ and $\tilde{T}_{eq} = T_{max} n_1$ where $T_{max} = 600$ s [3].

## 3. Structure case study

In this study a reinforced concrete telecommunication tower is considered as example of real slender vertical structure. The tower is reported in Fig. 1 along with its width along the height. The tower is 98 m high and it is composed by three superimposed shafts. The first shaft, up to 3.90 m above the ground, is made up of two concentric tubular circular sections linked by six radial walls. The second one, from 3.90 to 80.50 m, has circular tubular section with outer diameter 6.50 m and thickness 0.50 m; in its upper part, from 59.50 to 80.50 m, there are seven steel platforms with constant distance 3.50 m that carry transmission parabolas. The third shaft, from 80.50 m to 98 m, has circular tubular section with outer diameter 3 m and thickness 0.25 m; its outer surface carries four tubular steel uprights that support other parabolas. The first natural frequency is $n_1 = 0.494$ Hz and the corresponding modal damping ratio $\xi_1 = 0.005$.

## 4. Wind speed modelling and mean wind loading

The wind speed is defined at a certain reference height, fixing a return period and a vertical mean wind profile. The maximum mean wind speed for thunderstorm outflow and mean wind speed for synoptic event are fixed with a mean return period of 50 years from statistical analyses carried out by [4] on full-scale anemometer data. In particular, the wind velocity collected from an anemometer in the port of Livorno is considered, located at 20 m above the ground. Table 1 summarises the main properties the wind velocity data of both thunderstorm outflow (T) and synoptic event (S). The mean wind speeds with return period of 50 years are obtained, respectively, from the peak wind velocities as $\bar{v}_{max} = \hat{v}_{max}/G_{v,T}$ and $\bar{v}_S = \hat{v}_S/G_{v,S}$, where $G_{v,T}$ and $G_{v,S}$ are respectively the gust factor of the thunderstorm and synoptic wind velocities [4]. It can be noticed that the maximum mean wind speed due to thunderstorm is significantly greater than the one related to synoptic events.

The modulating function of the mean wind speed of the thunderstorm outflow $\gamma(t)$ is defined by fixing the parameters $\gamma^* = 0.54$ and $T = 169.81$ s according to model III in [3]. Concerning

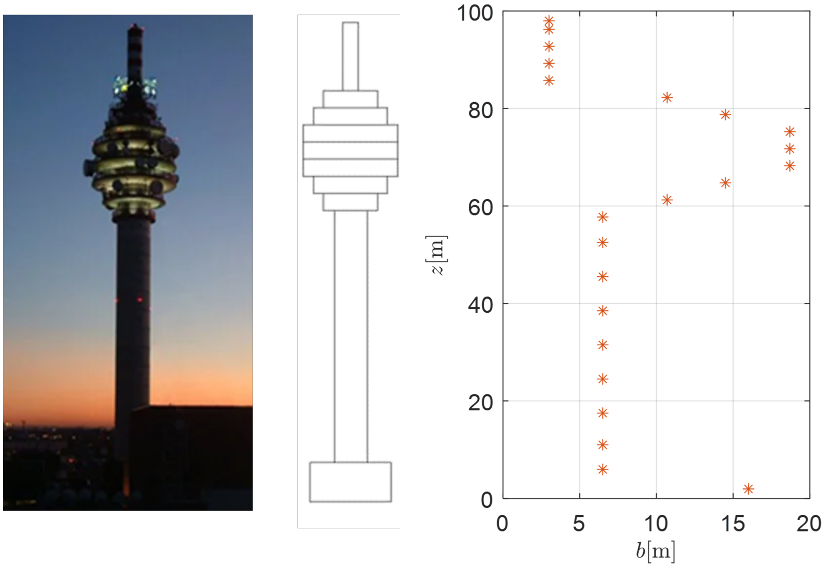

**Figure 1.** Telecommunication tower: width $b$ along the height $z$

**Table 1.** Reference wind speeds and gust factors of the thunderstorm (T) and synoptic event (S).

| $h$ [m] | $\hat{v}_{max}(h)$ | $\hat{v}_S(h)$ | $G_{v,T}$ | $G_{v,S}$ | $\bar{v}_{max}(h)$ | $\bar{v}_S(h)$ | $[\bar{v}_{max}(h)/\bar{v}_S(h)]^2$ |
|---|---|---|---|---|---|---|---|
| 20 | 38.33 | 33.85 | 1.140 | 1.471 | 33.62 | 23.01 | 2.135 |

the modelling of the vertical profile of the mean wind velocity associated to the thunderstorm outflow, the model provided by [12] is employed and the function $\alpha(z)$ is given by [5]:

$$\alpha(z) = \left(\frac{z}{h}\right)^{1/6} \frac{1 - erf\left(0.7\dfrac{z}{z^*}\right)}{1 - erf\left(0.7\dfrac{z}{h}\right)} \tag{14}$$

where $erf(z)$ is the error function, $z^* = 6z_m$ is the height for which $\bar{v}_{max} = 0.5\bar{v}_m$ with $\bar{v}_m$ the maximum value of $\bar{v}_{max}$ along $z$ and $z_m$ is the height for which $\bar{v}_{max} = \bar{v}_m$. Moreover, $\alpha(h) = 1$. The vertical profile adopted for the synoptic winds is the logarithmic law defined in [9]:

$$\alpha_S(z) = \frac{ln\left(\dfrac{z}{z_0}\right)}{ln\left(\dfrac{h}{z_0}\right)} \tag{15}$$

$$\bar{v}_S z = \bar{v}_S(h)\alpha_S(z) \tag{16}$$

with $z_0$ the roughness length. The analyses are carried out for different values of the nose height and roughness length, respectively $z_m = 25, 50, 75, 100$ m and $z_0 = 0.01, 0.05, 0.10, 0.30, 0.70$

m. The profiles of the mean wind speed are plotted in Fig. 2: It can be observed that the nose-shape profile is detectable especially for lower values of $z_m$ and that the synoptic profile provides larger values except nearby the base.
The drag coefficient is evaluated according to the Italian CNR Guideline [9] and plotted in Fig. 3 as a function the height $z$. Since the tower presents a circular section, the drag coefficients is dependent on the Reynolds number and hence on the vertical profile of the wind velocity. Finally, the parameter $a_1$ can be estimated according to Eq. (4).

## 5. Maximum response

The maximum response is estimated according to Eq. (6) by calculating the gust response factor (Eq. 8), for which the closed-form solution by [11] is adopted. The derivation of the parameters $B$ and $R$, respectively in Eqs. 9-10, requires the estimation of the integral length scale. Recent studies suggest that the relations adopted for classic synoptic winds may be adopted also for thunderstorm outflows [4]. Hence in the study the following relation is employed [9; 13]:

$$L_v(z) = \bar{L}\left(\frac{z}{\bar{z}}\right)^{\upsilon} \tag{17}$$

with $\upsilon = 0.67 + 0.05ln(z_0)$, $\bar{L} = 300$ m and $\bar{z} = 200$ m. Concerning the turbulence intensity, its dependence on the height above the ground and roughness length for the case of thunderstorms is weak [6; 14] and thus, also with aim of simplify the analyses, it is assumed constant [5], taking as reference value its average from the thunderstorm set available $\bar{I}_v(h) = 0.12$ [1]. For the synoptic case the relation provided by [9] is adopted:

$$I_v(z) = \frac{1}{ln\left(\dfrac{z}{z_0}\right)} \tag{18}$$

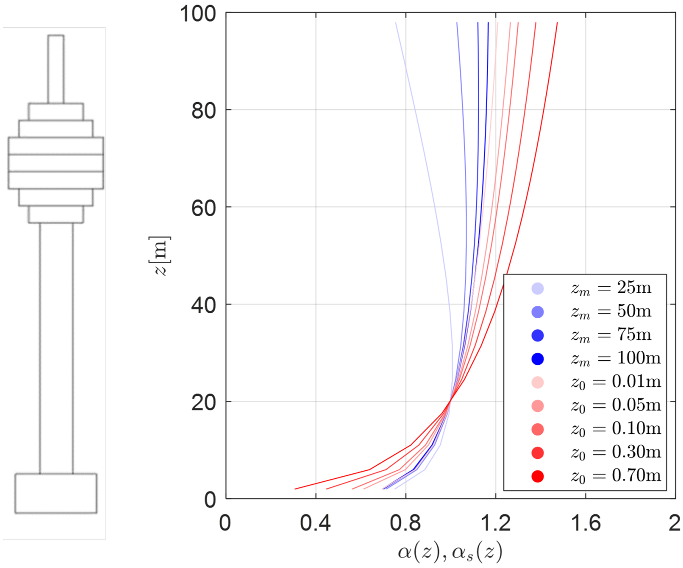

**Figure 2.** Telecommunication tower: wind velocity profiles of thunderstorm (blue lines) and synoptic event (red lines)

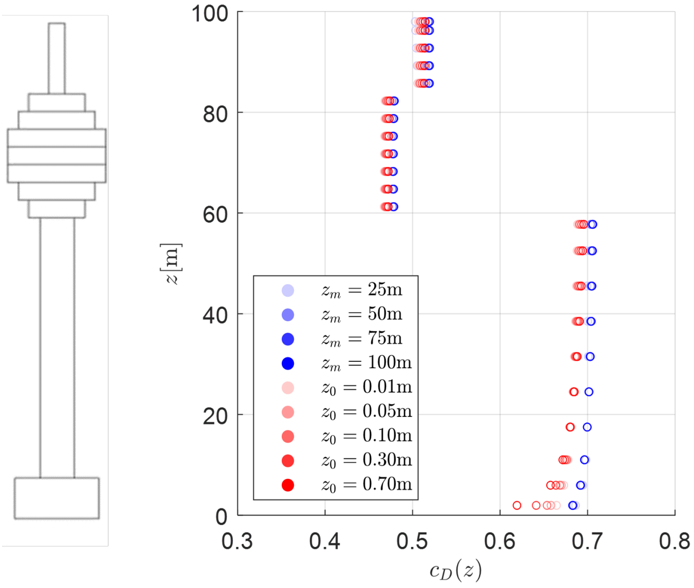

**Figure 3.** Telecommunication tower: drag coefficient $c_D$ along the height $z$

The ratio between the maximum response induced by the thunderstorm ($x_{max,T}$) and the one induced by the ABL wind ($x_{max,S}$) is plotted in Fig. 4 on varying $z_m$ and $z_0$. It can be observed that the dependence on the parameter $z_m$ is more significant the more $z_0$ reduces and for $z_m = 25$ m the synoptic wind causes a greater maximum response than the thunderstorm except for $z_0 = 0.01$ m. This result is due to the fact that the 'nose' of the vertical profile of the thunderstorm impacts mainly the lower part of the structure. On increasing $z_m$ however

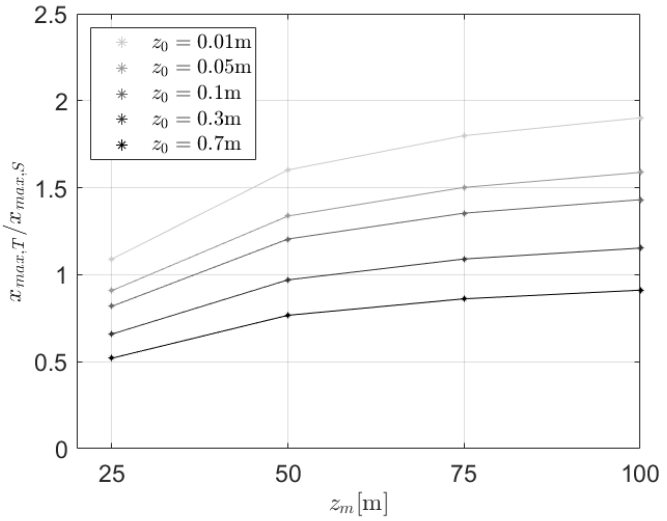

**Figure 4.** Telecommunication tower: ratio between the maximum response evaluated for the thunderstorm and synoptic event.

the thunderstorm returns to give greater values except for $z_0 = 0.7$ m. These results are in accordance with the profiles in Fig. 2 and they confirm that when the ratio $H/z_m$ is sufficiently high the structure is weakly sensitive to the action of thunderstorm outflows. On the other hand for $z_m = 100$ m, hence when the nose of the profile is almost in correspondence of the top, the structure experiences the greater response which for the thunderstorm case can be almost twice the one provided by the ABL wind. It is worth to notice that while changing the profiles of the ABL wind with $z_0$, the associated reference wind speed does not change accordingly, as recommended in [9]. This is because of consistency with the thunderstorm case, for which models that can relate the maximum mean wind speed with $z_0$ are not available. Finally, it is important to observe that the wind velocities employed for the synoptic event are much smaller than the one furnished by [9] i.e. 28 m/s. Hence, it is reasonable to expect that the usage of said wind velocity may provide maximum responses due to synoptic events greater than the one given by thunderstorms, even for low values of $z_0$ and higher values of $z_m$.

## 6. Conclusions

The present paper studied the dynamic response of a slender vertical structure subjected to thunderstorm outflows by carrying out a comparison with the case of a stationary wind such as extra-tropical cyclones. The thunderstorm gust response factor approach previously developed for SDOF systems was adopted to estimate the maximum response of a telecommunication tower considered as case study. The comparison between the thunderstorm and extra-tropical cyclone cases was carried out following the procedure from the Italian CNR Guideline with the aim of furnishing a practical approach and investigate the potential differences between the two wind loading cases. A reference wind speed was chosen with 50 years return period for both the events on the basis of statistical analyses from previous studies. It was shown that the two reference wind speeds are different from each other and the one related to the thunderstorm is greater than the one associated with the synoptic event. The comparison showed that the position of the nose profile of the thunderstorm is crucial for the maximum response. In particular, it is observed that the ABL wind provides the design conditions only if the nose-shaped profile of the thunderstorm outflow is at its lowest height. For the other cases investigated the thunderstorm loading condition provides a higher response that can be almost twice the one observed for the ABL case. In view of these results, for the structure considered it is important to account for the thunderstorm wind loading since it can be more demanding than the synoptic event.

## Acknowledgments

This research is funded by the European Research Council (ERC) 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 - supported by an Advanced Grant 2016.
The data used for this research 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

[1] Roncallo L and Solari G 2020 *J. Wind Eng. Ind. Aerodyn.* **203** 104204
[2] Roncallo L, Solari G, Muscolino G and Tubino F 2022 *J. Wind Eng. Ind. Aerodyn.* **224** 104978
[3] Roncallo L and Tubino F 2023 *J. Wind Eng. Ind. Aerodyn.* **236** 105376
[4] Zhang S, Solari G, Yang Q and Repetto M P 2018 *J. Wind Eng. Ind. Aerodyn.* **176** 239–253

[5] Solari G 2016 *Eng. Struct.* **108** 28–46

[6] Solari G, Burlando M, De Gaetano P and Repetto M P 2015 *Wind Struct. An Int. J.* **20** 763–791

[7] Davenport A G 1964 *Proc. Inst. Civ. Eng.* **28** 187–196

[8] Solari G 1983 *J. Wind Eng. Ind. Aerodyn.* **14** 467–477

[9] CNR 2018 Guide for the Assessment of Wind Actions and Effects on Structures CNR-DT 207 R1/2018, National Research Council, Rome, Italy

[10] Solari G 1988 *J. Struct. Eng.* **114** 1303–1323

[11] Roncallo L 2022 *Evolutionary Spectral Model for Thunderstorm Outflows and Application to the Analysis of the Dynamic Response of Structures* Ph.D. Thesis (University of Genoa)

[12] Wood G S and Kwok K C S 1998 An empirically derived estimate for the mean velocity profile of a thunderstorm downburst *7th Australian Wind Engineering Society Workshop (Auckland)*

[13] Solari G and Piccardo G 2001 *Probabilistic Eng. Mech.* **16** 73–86

[14] Zhang S, Solari G, De Gaetano P, Burlando M and Repetto M P 2018 *Probabilistic Eng. Mech.* **54** 9–24