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Equivalent Synoptic Wind to reproduce non-synoptic wind effects on vertical slender structures

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SUMMARY:
Starting from an ongoing full-scale monitoring campaign over two lighting towers, this paper proposes the idea of defining an Equivalent Synoptic Wind (ESW) as a tool to interpret and discuss the non-synoptic wind-induced effects on vertical slender structures. The dynamic response of the monitored structures is recorded by accelerometers and strain gauges; simultaneous measurements of the wind field are supplied by ultrasonic anemometers installed on top of the poles, providing the structural behaviour under different wind phenomena, namely extra-tropical cyclones, thunderstorms and gust fronts. For each measured non-synoptic record, an ESW is defined as the synoptic wind that produces the measured structural effect, starting from a well-established analytical model. The statistical parameters of the ESW events are presented and compared with real synoptic wind records.

Keywords: Non-synoptic wind, Structural Monitoring, Vertical slender structures

1. INTRODUCTION

The European wind climate, like that of many other parts of the world, can be defined as a mixed climate, a climatologic condition in which wind phenomena of different nature exist (Gomes and Vickery, 1978). Extra-tropical cyclones are the most typical events that strike mid-latitude areas; they generate synoptic winds, characterized by stationary and Gaussian behaviour over 10 min - 1 h time intervals. Since the pioneering research of Davenport (1968), well-established methods have been proposed and codified, to model synoptic wind fields and their effect on structures. On the other hand, non-synoptic meteorological phenomena of limited spatial and time scales but very intense wind velocity can occur; they exhibit rapid changes during a short period, characterized by non-stationary non-Gaussian wind fluctuations. Conventional analysis frameworks, such as the gust loading factor approach, may not be appropriate to evaluate non-synoptic effects. Despite extensive research arose along several research lines (e.g. Choi and Hidayat, 2002; Kwon and Kareem, 2013, Solari et al, 2020), the understanding and the representation of non-synoptic winds and their effect on structures still poses several unsolved problems. It is still unclear whether non-synoptic events constitute the most critical scenarios for structural safety, from the point of views of statistical distribution, aerodynamic behavior and dynamic amplification.

Working in this field, the research group of the University of Genoa set a wide monitoring network to obtain robust full-scale measurements of wind velocity (Burlando et al., 2018) and structural response parameters (Orlando, 2021). In particular, the dynamic response of two lighting towers located in Ligurian port areas is currently monitored by accelerometers and strain gauges; simultaneous measurements of the wind field are supplied by ultrasonic anemometers installed on top of the poles, providing the structural behavior under different wind phenomena. Applying a separation algorithm (De Gaetano et al., 2014), the recorded data have been divided into three categories: (i) synoptic winds, related to extra-tropical cyclones, characterized by stationary and Gaussian records; (ii) non synoptic winds related to thunderstorm outflows, characterized by non-stationary non-Gaussian records and (iii) intermediate events, related to gust fronts, characterized by stationary non-Gaussian records.

This paper proposes a novel idea to investigate and compare the wind-induced response under different wind phenomena using the outcomes of the structural monitoring activity. With this aim, for each full-scale record, an Equivalent Synoptic Wind (ESW) is defined as the synoptic wind that produces the structural effect measured by the sensors during that record. The ESW parameters are retrieved with a numerical inverse procedure based on a well-established analytical model for synoptic wind-induced response of slender vertical structures (Pagnini and Solari, 1999). The statistical parameters characterizing the ESW of non-synoptic records are presented and discussed, in comparison with the ones of real synoptic records.

2. FULL-SCALE MONITORING AND DATASET

Two lighting towers, respectively 16.6 m and 35 m high, and located in the Harbours of La Spezia and Genoa, Italy, have been equipped with a monitoring system including wind speed and structural response sensors (Fig. 1). A three-axial ultrasonic anemometer installed at the top records the wind speed with a sampling rate of 10 Hz; the structural response is recorded at 200 Hz by two biaxial accelerometers (placed at the top of the shaft and at an intermediate level) and by eight uniaxial strain gauges (placed at the base of the shaft). Data from the sensors have been recorded continuously since February 2019 for the tower in La Spezia and since October 2022 for the tower in Genoa.

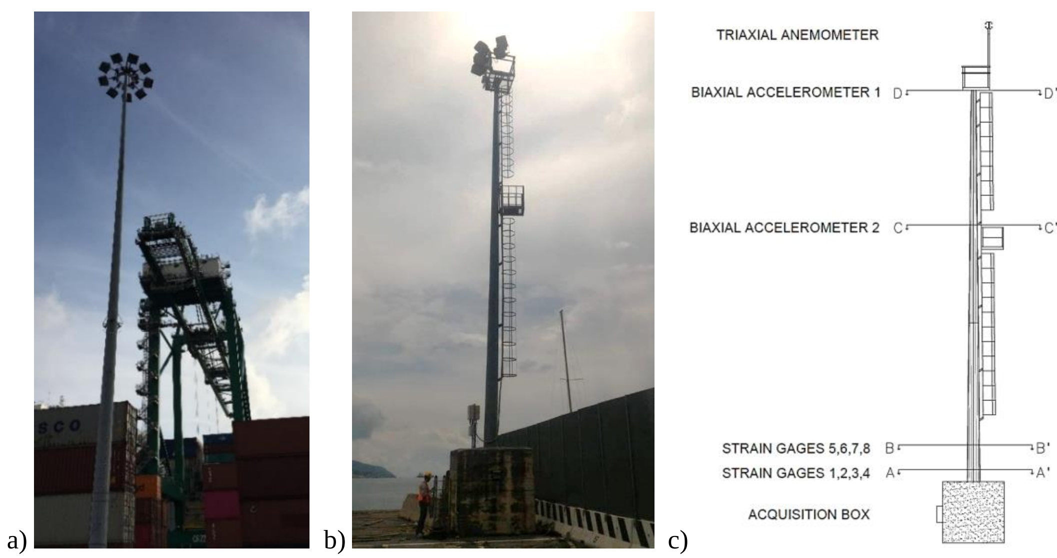

Figure 1. The monitored lighting towers in Genoa (a), La Spezia (b) and their monitoring equipment (c).

Wind velocity records have been analyzed identifying and separating synoptic extra-tropical cyclones, thunderstorm outflows and intermediate events, following a semi-automatic procedure (De Gaetano et al., 2014). The intense records with peak wind velocity greater than 15 m/s associated to the three categories are collected into as many datasets.

3. EQUIVALENT SYNOPTIC WIND EVENT

The Equivalent Synoptic Wind (ESW) event is defined as the synoptic wind that produces the structural effect (e.g., the maximum top displacement) detected by the real full-scale record. In order to define the ESW, the analytical model proposed by Solari and Pagnini (1999) for the calculation of wind-induced effects on poles and monotubular towers is adopted. The model applies the 3-D gust factor technique, modelling the structure as a vertical cantilever beam with localized masses, reproducing the aerodynamic effects of equipment along the shaft. The model has been validated in a previous research (Orlando, 2021), comparing analytical estimates with full-scale records of synoptic wind-induced response.

According to the model, the maximum displacement in along wind and crosswind direction, α=x, y, in the time interval T=10 minutes, is given by:

$$\alpha_{\max}(z) = G_\alpha(z)\bar{\alpha}^x(z) \;,\; G_x = 1 + 2g_x I_x \sqrt{Q^2{}_x + R^2{}_x} \;,\; G_y = g_y I_y \left(\left| \bar{C}_D + \bar{C}'_L \right| / \bar{C}_D \right) \sqrt{Q^2{}_y + R^2{}_y} \qquad (1)$$

where $\bar{a}^x$ is the static displacement due to the application of the mean aerodynamic force $\bar{F}_x$ in direction α, G_α is the gust response factor, g_α and I_α are peak coefficient and turbulence intensity, $\bar{C}_D$ is mean drag coefficient and $\bar{C}'_L$ is the prime angular derivative of lift coefficient, Q_α and R_α are non-dimensional quantities associated to the quasi-static and resonant response.

In this formulation, assuming a classical synoptic wind field model and once the aerodynamic and dynamic structural parameters are defined, the structural effects depend only on the mean wind velocity and on the terrain roughness, in turns governing the turbulence fluctuating components. Thus, a numerical procedure has been established, able to retrieve those wind-related parameters from the measured maximum displacement. The synoptic wind characterized by the obtained mean wind speed and turbulence components is defined as the Equivalent Synoptic Wind event.

As an example, Figure 2 (a) shows a thunderstorm wind velocity record and the corresponding mean and standard deviation of the ESW event. Figure 2 (b) show the thunderstorm-induced top displacement record and the corresponding maximum displacement adopted in Eq. (1) to retrieve the ESW parameters. It is worth noticing that the ESW, evaluated for non-synoptic wind-induced response records, has no physical or meteorological meanings, rather it is an engineering tool to trace back the non-synoptic structural effects to conventional well-known parameters.

The comparison between the distribution of the mean wind speed related to the ESW events and the synoptic events may provide a criterion for dealing with non-synoptic winds according to an equivalent design wind velocity. Applying the procedure to different response quantities, namely the mean top displacement, the maximum stress at the bottom and the mean stress at the bottom, may provide an indirect measure to evaluate how the non-synoptic winds trigger the different structural effects compared to the synoptic ones.

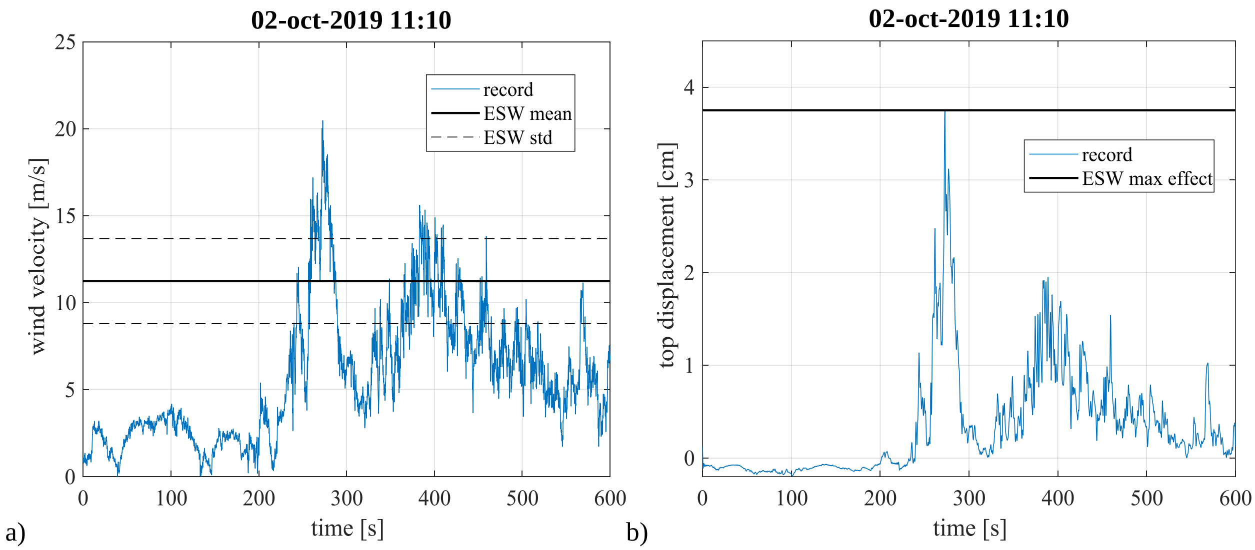

Figure 2. Thunderstorm recorded in La Spezia and relevant ESW (a); simultaneous displacement record (b).

3. CONCLUSIONS AND PERSPECTIVES

The final paper describes the proposed algorithm adopted for the definition of the ESW and reports the ESW events evaluated for the non-synoptic records available from the full-scale monitoring databases, discussing the structural effects induced by each wind phenomena identified and the statistical analysis of the wind related parameters of the ESW events and of the measured synoptic events.

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