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Dynamic response of structures to thunderstorm outflows taking directionality effects into account

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ABSTRACT: Due to the combinate effect of the background wind, the translation of the downburst and the radial nature of the jet after the touchdown, a peculiar characteristic of a signal associated to a thunderstorm outflow measured by an anemometer is the potential variation of direction during the life of the event. Despite this situation, the study of the dynamic response of structures to thunderstorm outflows has traditionally neglected the angle of attack and the effects induced by that, implicitly assuming the response as alongwind. This paper proposes two methods to consider the role of the direction and its possible variation into the evaluation of dynamic response of structures subjected to Aeolian events. In particular, the second one is based on a decomposition method of the wind speed which constitutes a generalization of what historically defined for stationary events. Thus, it allows to establish a robust parallelism between the dynamic response due to synoptic winds and thunderstorm outflows.

KEYWORDS: Directional response, Dynamic response, Thunderstorm outflows.

1 INTRODUCTION

The study of the dynamic response of a structure subjected to a wind event usually regards the evaluation of the displacement and the definition of its maximum probability density function, without considering the potential change of direction. To neglect the role played by the direction is justified because of the nature of the events traditionally studied, which are defined under the hypotheses of stationary phenomena at the synoptic scale. The study of thunderstorm outflows has inherited this setting without having the necessary properties. The result is a research line where the variation of the direction, which is an essential property of thunderstorm outflows, has been ignored [1]. To overcome this shortcoming, a novel directional decomposition strategy of the wind speed has been formulated by Solari et al. [2] which opens the doors to a robust comparison and parallel analyses of thunderstorm outflows and synoptic wind in terms of wind speed, wind loading and structural response. This paper focuses on the effect of the change of direction into the evaluation of the dynamic response to thunderstorm outflows in the time domain.

2 TEST CASES

Two real slender vertical structures with comparable heights are examined as reference test cases: a steel telecommunication antenna mast located in the port of La Spezia (hereinafter called as S1) and the Endless Column (hereinafter called as S2) conceived by Costantin Brâncuși. As far as the wind events are concerned, ten thunderstorm outflows (WE1-WE10) have been selected among the ones present in “Wind and Ports” and “Wind, Ports and Sea” projects database. The pilot event WE1, recorded on January 30th, 2015 by the anemometer 02 in Port of La Spezia, is herein described by plotting its components along *X*- and *Y*- axis (Figure 1).

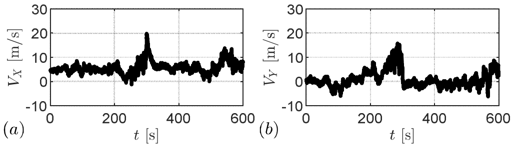

Figure 1. WE1, wind velocity time-histories: (a) *X*- component (b) *Y*- component.

3 WIND SPEED DECOMPOSITION

3.1 *Classical decomposition*

This approach [1] consists of decomposing the horizontal resultant velocity $U(t)$ into a slowly-varying mean velocity $\bar{U}(t)$ and a 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 characterized by a zero mean and a unit standard deviation. So, the horizontal resultant velocity may be expressed as (Figure 2a):

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

where $I_U(t) = \sigma_U(t)/\bar{U}(t)$ is the slowly-varying turbulent intensity. The slowly-varying quantities are determined through a moving average filter with a moving average period *T*=30 s.

The time-varying direction of the velocity vector $U(t)$ is indicated here by the angle $\alpha(t) \in [0{,}360]$ according to the geographical notation, or by the angle $\gamma(t) = 270 - \alpha(t)$, referred to the fixed Cartesian reference system (*X*, *Y*).

3.2 *New directional decomposition*

This approach [2] consists of decomposing separately the wind components into a slowly-varying mean speed $(\bar{V}_X(t), \bar{V}_Y(t))$, evaluated by a moving average filter with period *T*=30 s, and a residual fluctuation $(V_X'(t), V_Y'(t))$. The slowly-varying mean wind velocity vector is given by the vectorial component of $\bar{V}_X(t)$ and $\bar{V}_Y(t)$ and its slowly-varying time direction is indicated by the angle $\bar{\beta}(t)$. The definition of the slowly-varying mean wind velocity vector allows to identify a new cartesian reference system *(x,y)* along which the residual fluctuations are projected, obtaining thus $u'(t)$ and $v'(t)$, respectively the longitudinal and lateral turbulence components. They are later expressed as the product of their slowly-varying standard deviation (σ_u, σ_v) by a couple of longitudinal and lateral reduced turbulent fluctuations $(\tilde{u}', \tilde{v}')$, rapidly-varying stationary Gaussian random processes characterized by a zero mean and a unit standard deviation. Thus, the longitudinal and the lateral components of the wind velocity may be expressed as (Figure 2b):

$$u(t) = \bar{u}(t) + u'(t) = \bar{u}(t)\left[1 + I_u(t)\,\tilde{u}'(t)\right] \tag{2}$$

$$v(t) = v'(t) = I_v(t)\,\tilde{v}'(t) \tag{3}$$

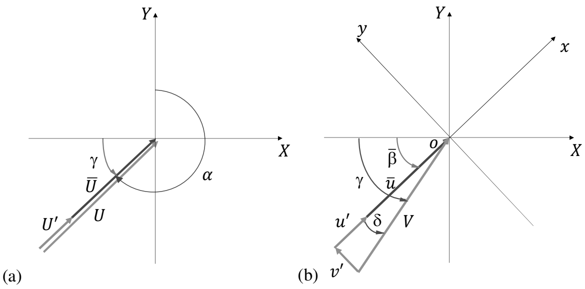

Figure 2. Decomposition methods: (a) classical decomposition, (b) new directional method.

4 WIND FIELD MODEL

To evaluate the aerodynamic wind loading on slender vertical structures, the Equations (1), (2) and (3) are extended along the *Z*-coordinate. As far as the mean wind speed is concerned, the model proposed by Wood & Kwok in [3] is utilized. While the variation with the height of the turbulence intensity is neglected, the multi-variate random processes associated to $\tilde{U}'$, $\tilde{u}'$ and $\tilde{v}'$ (function of *Z* and *t*) are transformed into equivalent mono-variate processes which consider the aerodynamic admittance of the structures and are function of the time only by the application of the Equivalent Wind Spectrum Technique [4, 5].

5 AERODYNAMIC WIND LOADING

Considering the signal decompositions presented in Section 3, for each of the two methods the analytical assessment of the aerodynamic wind loading for a slender vertical structure characterized by a given cross-section is evaluated through quasi-steady theory, neglecting the effect of transient aerodynamics.

The method based on the classical decomposition is called Method 1, whereas the new directional method gives rise to Method 2. Because of the compactness and torsional stiffness of the cross-section of the studied structures, the torsional moment per unit length is neglected and only the forces per unit length are studied. Moreover, Method 2 is extended with the hypothesis of small turbulence (Method 3). Finally, the classical adirectional method traditionally used in literature to study the alongwind response is considered and applied (Method 0).

The different formulations so defined are applied to S1 and S2 in order to evaluate the wind aerodynamic loading, assuming that the wind direction does not change along the height of the test structures and considering an appropriate variation of the aerodynamic coefficients (functions, in general terms, of the angle of attack and of the Reynolds number).

6 DYNAMIC RESPONSE

The structures are considered as characterized by linear elastic behavior, their natural frequencies are well-separated and the damping is small and proportional. Aerodynamic damping is neglected. Thus, the *X*- and *Y*- components of the time varying displacements at quote *Z* are evaluated as decoupled of each other with a classic modal analysis in the time-domain. In the spirit of buffeting analyses, only the contribution of the first mode of vibration is considered in the analysis. For sake of comparison and homogeneity, all the thunderstorm outflows signals have been scaled to the same peak wind velocity equal to 36.5 (m/s).

The maximum displacements exhibited by S2 subjected to WE1 according to the different four methods are presented in Table 1.

$q_{t,max}$ (m) - Method 0	$q_{t,max}$ (m) - Method 1	$q_{t,max}$ (m) - Method 2	$q_{t,max}$ (m) - Method 3
0.50	0.54	0.64	0.59

Table 1. Maximum displacements exhibited by S2 subjected to WE1 according to the different four methods.

Analyzing the time histories of the displacements in the two principal directions, it is possible to evaluate the direction of the response for each step and to generate polar plots which well-represent the spread of the response of the top of the structure in a horizontal plan (Figure 3).

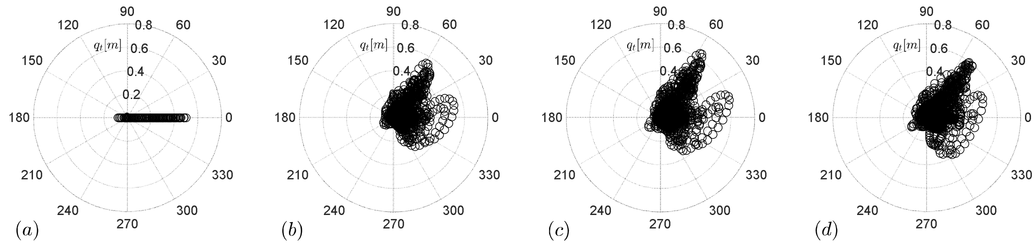

Figure 3. Polar plots reporting the dynamic response at the top of S2 subjected to WE1, evaluated with different methods: (a) Method 0, (b) Method 1, (c) Method 2, (d) Method 3.

7 CONCLUSIONS

The analysis of the results obtained for S2 under the entire set of ten thunderstorm outflows reveals strong differences – in terms of maximum response – between the evaluation through the methods which take into account the direction of the event and Method 0, in particular for events in which the direction presents an irregular variation, with either continuous or sudden change of the angle of attack. Furthermore, differences between the different directional methods are found: Method 2 always leads to more conservative results if compared with Method 1. The hypothesis of small turbulence usually conducts to limited approximations if compared with Method 2 (not exceeding 5 %), except for two cases. On the other hand, there are three cases in which Method 3 leads to higher maximum displacements than the ones evaluated through Method 2. The discrepancies between the different methods are mitigated for S1, due to the polar symmetry of the cross-section, but however remain not negligible. Details will be presented in the final paper.

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