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Dynamic response of structures to thunderstorm outflows: Response spectrum technique vs time-domain analysis

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ABSTRACT

Thunderstorms are transient events. Design wind velocity and wind-induced damage are often related to them. Despite this, research on thunderstorm loading of structures is still fragmentary and uncertain due to their complexity, short duration and small size. These issues make it difficult to set physically realistic and simple models as well as to gather real data. This favoured the implementation of refined methods based on limited measurements. The European Projects "Wind and Ports" and "Wind, Ports and Sea" realised an extensive monitoring network from which many thunderstorm outflow records were extracted. They were analysed to inspect their characteristics and to formulate methods coherent with measurements. Firstly, the response spectrum technique conceived for earthquakes was extended to thunderstorms. Then, a hybrid simulation strategy was proposed and time-domain integrations of the structural response were applied. This paper provides a joint calibration and advancement of these two methods, leading to results that substantially agree, especially faced with their conceptual and operative diversities. This confirms the potential of the response spectrum technique to become a suitable tool for calculating the thunderstorm loading of structures and the efficiency of hybrid simulations and time-domain analyses to investigate, with a limited computational burden, advanced structural issues.

1. Introduction

The study of thunderstorm outflows and their loading of structures is a dominant topic of modern wind engineering [1,2]. This mainly depends on the fact that methods currently applied to determine the wind-excited response of structures are still mostly based on models related to the synoptic phenomena that evolve in about 3 days on around 1000 km on the horizontal. They give rise to nearly stationary wind fields (Fig. 1a) that occur in almost neutral atmospheric conditions, with velocity profiles in equilibrium with the atmospheric boundary layer (ABL) [3].

Thunderstorms are mesoscale atmospheric phenomena that consist of a set of cells that evolve in about 30 min on a few kilometres on the horizontal [4]. They give rise to intense transient downdrafts (Fig. 1b) that impact the earth's surface followed by radial outflows with a typical "nose" profile [5,6] and horizontal ring vortices (Fig. 2). The ensemble of these air movements is called "downburst" and is divided into macroburst and microburst depending on whether its size is greater or smaller than 4 km [7]. The design wind velocity is often related to strong microbursts that may occur individually or along squall-lines. Such events are usually embedded into more or less intense background synoptic phenomena and the damage caused by wind at the mid-latitudes is often due to these situations.

Despite the extensive research carried out on thunderstorm loading and response of structures in the last decades, the knowledge of this matter is still fragmentary and full of uncertainties [2]. This depends, on the one hand, on the complexity of one of the most spectacular and impressive phenomena that nature produces, and, on the other hand, on its short duration and small size. The first issue makes it difficult the formulation of engineering models physically realistic and simple to apply as for cyclonic synoptic events [3]. The second makes the available measurements very limited.

The literature is rich in contributions to determine the dynamic response of Single-Degree-Of-Freedom (SDOF) systems, N-DOF (NDOF) systems and slender beams to thunderstorm outflows. It exhibits a wide panorama of procedures whose complexity matches the complexity of these phenomena.

This research pathway started in 2002, when Choi and Hidayat [8] studied the time-domain response of a SDOF system to thunderstorm outflows identically coherent in space, to generalize the classic gust factor technique introduced by Davenport [3] in 1961 with reference to cyclonic synoptic events. This approach was developed by Chen and

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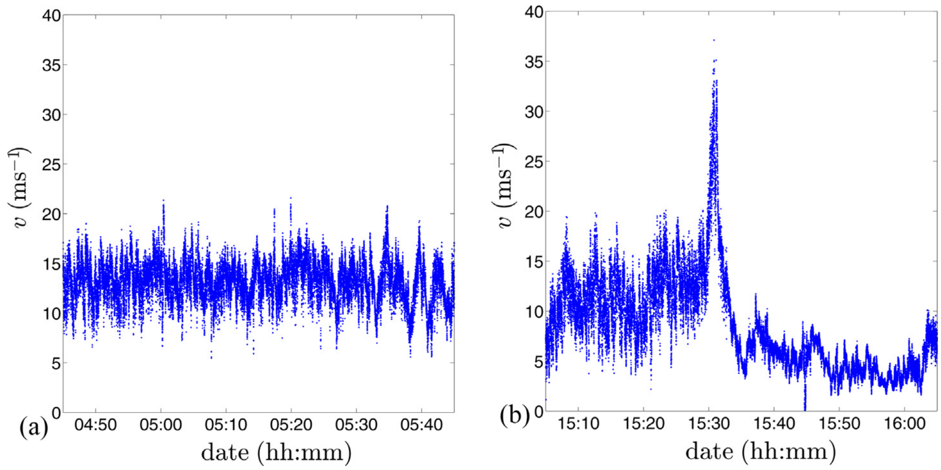

Fig. 1. Wind velocity records *v* detected in the Port of La Spezia: (a) synoptic extra-tropical cyclone recorded on 7 October 2011; (b) thunderstorm outflow recorded on 25 October 2011.

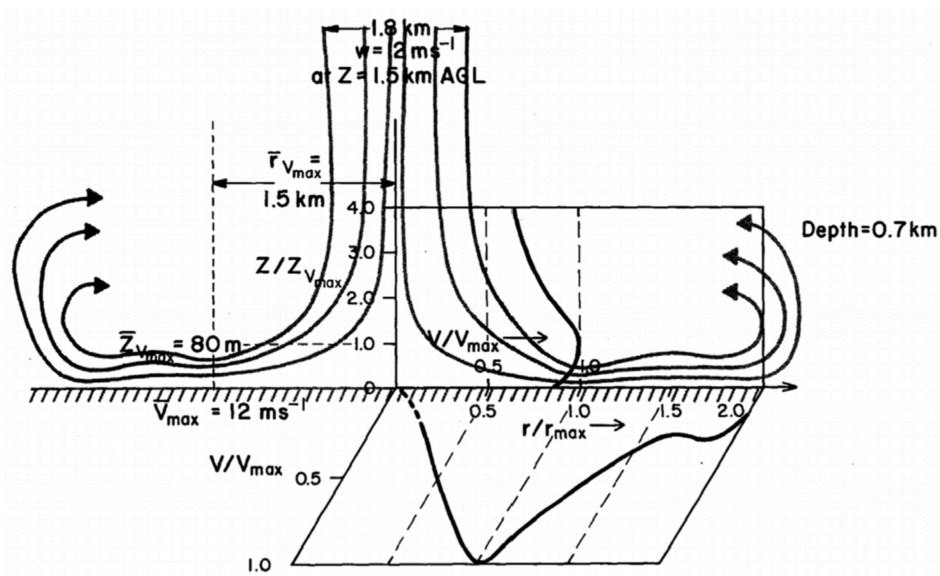

Fig. 2. Thunderstorm downburst and nose velocity profile in the radial outflow [6].

Letchford [9], who analysed a SDOF system by means of a so-called Maximum Dynamic Magnification Factor, given by the ratio between the maximum value of the dynamic response and the static response to the peak loading, by Holmes et al. [10], who used Duhamel's integral to calculate the response of structures to thunderstorm winds, and by Chay et al. [11], who applied a time-domain approach based on ARMA simulations. Chen [12] studied the dynamic response of a building to a transient wind field modelled by an evolutionary power spectral density (EPSD). Kwon and Kareem [13] proposed a gust front factor framework where the original gust response factor technique [3] was generalized from stationary to non-stationary wind actions by an EPSD approach. Le and Caracoglia [14] used the Wavelet-Galerkin method to evaluate the non-linear and/or non-stationary response of SDOF and NDOF systems. They also proposed (2018) [15] a computer model of the transient dynamic response of a tall building subjected to a digitally simulated thunderstorm wind field coherent with an EPSD representation.

Many other papers did not reach the evaluation of the wind-induced response, but provided propaedeutic methods to represent transient wind fields. For instance, Wang et al. [16] conceived a data-driven approach to simulate full-scale downburst wind speeds by Hilbert transform, stationary wavelet transform, and Proper Orthogonal Decomposition (POD). Huang et al. [17] applied the discrete wavelet transform and the kernel regression method to infer the time-varying mean and variance of non-stationary extreme wind speeds, respectively; then, based on the estimated EPSD, they examined the transient features of non-stationary winds. Peng et al. [18] simulated multivariate non-stationary wind fields along lines with uniformly distributed nodes, based on the application of hybrid stochastic waves and POD factorization.

A dominant aspect of most of these contributions is the striking contrast between the formulation of highly refined advanced procedures and the poorness of the experimental measurements used to support theory. In some cases authors acknowledge that methods proposed are theoretical models waiting for real data to make them explicit. In other cases the formulations and applications are based on an inadequate number of measurements in order to ensure the robustness and physical sense of analyses. Sometimes, the use of sophisticated methods faced with the almost total lack of data seems to be quite questionable, especially when analyses are carried out in a probabilistic framework.

The European Projects "Wind and Ports" [19] and "Wind, Ports and Sea" [20] offered authors and the Windyn Research Group (www.windyn.org) a unique opportunity to follow a different pathway according to which novel methods robustly coherent with real data