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Thunderstorm response spectrum technique: Theory and applications

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ABSTRACT

This paper is part of a research project that started from the consideration that thunderstorms are transient phenomena with short duration and the structural response to transient phenomena, most notably to earthquakes, is traditionally evaluated by the response spectrum technique. Based on this consideration, a “new” method is formulated that generalizes the “old” response spectrum technique from earthquakes to thunderstorms. A previous paper addressed this problem for ideal point-like Single-Degree-Of-Freedom systems subjected to wind actions perfectly coherent over the exposed structural surface. The present paper generalizes this formulation to real space Multi-Degree-Of-Freedom systems subjected to partially coherent wind fields with assigned velocity profile and turbulence properties; for sake of simplicity, in this stage of the research, the structure is modeled as a continuous slender vertical cantilever beam. Analyses are carried out by making recourse to the equivalent wind spectrum technique, a method developed for synoptic stationary winds, the use of which is extended here to non-synoptic non-stationary conditions. In spite of a rather complex formulation, the application of the thunderstorm response spectrum technique is straightforward: the equivalent static force is the product of the peak wind loading by a non-dimensional quantity, the equivalent response spectrum, given by a simple diagram. Its derivation represents one of the most typical features of this method: it is based on the joint numerical processing of a set of measured thunderstorm records and an analytical model that conceptually reconstructs the complete wind field around the measured data. In virtue of its characteristics, the thunderstorm response spectrum technique is particularly suitable for rapid engineering calculations and simple code applications.

1. Introduction

Extra-tropical cyclones are synoptic-scale atmospheric phenomena that strike the areas in mid-latitudes, developing on a few thousand kilometers on the horizontal, with frequency and duration of a few days. Their genesis, life-cycle and properties have been explained by the polar front theory formulated by Bjerknes and Solberg in 1922 [1].

The study of the wind actions and effects on structures due to extra-tropical cyclones is traditionally inspired by the principles introduced by Davenport in 1961 [2]. In such a framework the mean wind velocity, usually considered as horizontal, is characterized by a vertical profile in equilibrium with an atmospheric boundary layer whose depth is in the order of 1–3 km; here, within time intervals between 10 min and 1 h, the turbulent fluctuations are dealt with as stationary and Gaussian. The wind velocity is transformed into an aerodynamic loading by assuming that the turbulence is small and neglecting the quadratic term of the fluctuations; so, like the wind velocity, also the aerodynamic loading is Gaussian. Thus, dealing with structures with elastic linear behavior, also their response is Gaussian. In addition, the maximum response is modeled through a distribution function obtained assuming that the up-crossings of a suitably high response threshold are rare and independent events [3]. In this way, the probability density function of the maximum response is narrow and sharp, and its mean value may be considered as representative of the maximum response. This favored the formulation of the gust response factor technique [2,4], and the derivation of closed form solutions for rapid engineering calculations [5–7] and code applications [8]. In spite of a huge literature aiming to generalize and improve this method in several ways [9–13], the analysis of the wind-excited response of structures subjected to extra-tropical is still mainly based on the original Davenport’s method [2].

Thunderstorms are meso-scale atmospheric phenomena that strike most areas of Earth, developing in a few kilometers on the horizontal. As explained by Byers and Braham in 1949 [14], they consist of a set of cells that evolves through three subsequent stages in about 30 min: in the cumulus stage a convective updraft of warm air gives rise to a large size cumulus; in the mature stage

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the cumulus becomes a cumulonimbus and a downdraft of cold air occurs; in the dissipating stage the thunderstorm is first dominated by the downdraft, then it disappears. In the '70s and in the '80s Fujita showed that the downdraft that impinges over the ground produces intense radial outflows; he called downburst the whole of these air movements [15]. On the one hand, these findings gave rise to a fervour of research in atmospheric sciences, which focused on the causes, morphology and life-cycle of thunderstorms [16]. On the other hand, they revealed that design wind actions and effects on structures are often due to thunderstorms, so they have a focal role on the structural safety; this caused a striking research in wind engineering [17,18], where two main lines have been followed.

The first line is based on the simulation of the thunderstorm wind field by wind tunnel tests [17,19–22], CFD codes [20,23–26] and advanced analytical models [27–30]. The use of wind tunnel tests allows to derive the structural loading and possibly the dynamic response in the course of the experiments. The use of CFD codes and analytical models calls for the transformation of the wind field into aerodynamic wind actions subsequently applied on the structure to evaluate its dynamic response, for instance by finite element models of structural systems such as transmission lines [31–33]. These methods allow the representation of the three-dimensional thunderstorm wind field, namely the radial, circumferential and vertical components of the wind velocity as a function of space and time. However, there is still a number of uncertainties associated with the simulation of turbulence [25], the choice of parameters [28,34], and the rules to scale real conditions [35]. In addition, these analyses are burdensome and their results depend on the specific structure dealt with, its position with reference to the centreline of the downdraft, and its orientation; their use in the engineering practice is therefore still rather limited.

The second line, to which this paper belongs, gives up a complete description of the thunderstorm wind field and focuses on the simplified modeling of the most dangerous velocity components for the structure dealt with. In this way, it aims at developing methods for calculating the response of reference models, for instance Single-Degree-Of-Freedom (SDOF) systems and vertical cantilever beams, similar to those formulated for extra-tropical cyclones [2,4–13], so oriented to engineering applications. In this framework, the horizontal component of the wind velocity in the thunderstorm outflows is usually expressed as the sum of a slowly-varying mean part plus a residual zero mean fluctuation dealt with as a non-stationary random process [36–39]. The slowly-varying mean wind velocity is characterized by a vertical "nose" profile that increases up to 50–100 m height, then decreases above; the fluctuation is given by the product of its slowly-varying standard deviation by a rapidly-varying stationary Gaussian random process with zero mean and unit standard deviation. Based on these assumptions, Choi and Hidayat [36] studied first the dynamic response of a point-like SDOF system subjected to a wind velocity field perfectly coherent in space. This study was developed later in [40–42], where the behavior of SDOF systems was analyzed by one parameter, called maximum dynamic magnification factor or dynamic response factor, given by the ratio between the maximum dynamic response and the static response due to the peak wind loading. Kwon and Kareem [43,44] developed a gust front factor framework in which the original gust response factor technique was generalized from stationary to non-stationary wind actions; they provided also a robust interpretation of the conceptual behavior of the structural response. Other authors [45–47] applied advanced techniques using evolutionary spectral densities, wavelet transforms, Galerkin expansions and time-series simulations.

Despite this impressive amount of research, however, there is not yet a model of thunderstorms and their actions on structures that led to a convergence of ideas between scholars and engineers, similar to that which occurred when Davenport formulated his famous model of the dynamic response of structures to synoptic winds. This happens because, on the one hand, the complexity of thunderstorms makes it difficult to formulate physically realistic and simple theories, and, on the other hand, their short duration and small size make the available measurements still rather limited. It follows that wind actions on structures are still almost exclusively determined by the extra-tropical cyclone model that dates back over half a century ago [48], at the most taking the occurrence of thunderstorms into account, if data are available, in the statistical evaluation of the design wind velocity [49,50]. This is not enough, since extra-tropical cyclones and thunderstorms are different phenomena that need separate assessments [18].

This paper is part of a research project that started [18] from the remark that thunderstorms are transient phenomena characterized by short duration, and the structural response to transient phenomena, most notably to earthquakes, is traditionally evaluated by the response spectrum (RS) technique [51,52]. Based on these considerations, a "new" method is here formulated, the Thunderstorm Response Spectrum Technique (TRST), which generalizes the "old" RS technique from earthquakes to thunderstorms. The prospect that this method, though deeply revised and modified, is so very well-known by engineers as to favor its rapid use in both the research and design fields seems to be very attractive.

A previous paper [53] addressed the problem of the thunderstorm response of ideal point-like SDOF systems subjected to wind actions perfectly coherent over the exposed structural surface. The generalization of this method to the thunderstorm response of real space Multi-Degree-Of-Freedom (MDOF) systems involves a crucial aspect. The traditional use of the RS technique is based on the classical model according to which earthquakes give rise to perfectly coherent ground motions at the structural base, and their actions mainly depend on the distribution of the structural masses, namely a property of the mechanical system. Instead, thunderstorms cause partially coherent wind fields that determine wind actions strictly dependent on the wind velocity profile and on the space–time correlation of the fluctuations. Taking a cue from a previous paper by author [54], this major obstacle is overcome by making recourse to the Equivalent Wind Spectrum Technique (EWST) [55,56], a method developed for synoptic stationary winds, the use of which is extended here to non-synoptic non-stationary conditions.

Section 2 develops the wind velocity model subsequently adopted to evaluate the structural response to thunderstorm outflows. Section 3 introduces the basic equations of the dynamic alongwind response of structures to the non-stationary wind velocity model discussed in Section 2; for sake of simplicity, in this stage of the research, they are expressed with reference to a continuous slender vertical cantilever beam, whose response is dominated by the first mode of vibration. Section 4 recalls the fundamentals of the EWST [55,56], and generalizes its use from stationary extra-tropical cyclones to non-stationary thunderstorm outflows. Section 5 formulates the TRST with reference to MDOF systems subjected to partially coherent wind fields; this aim is pursued by introducing the concept of Equivalent RS (ERS), a quantity that multiplied by the peak wind loading furnishes the equivalent static force. Section 6 provides two noteworthy limit solutions that represent upper and lower bounds of the ERS, corresponding to ideal structures with infinitely small and infinitely large surfaces exposed to wind, respectively; it is demonstrated that in these cases the ERS coincides, respectively, with the RS and the base RS (BRS) for SDOF systems developed in [53]. Section 7