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Peak factor statistics of wind effects for hyperbolic paraboloid roofs

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ABSTRACT

This paper investigates the statistics of the pressure coefficients and their peak factors in hyperbolic paraboloid roofs that are commonly used in tensile structures. The experimental peak factor statistics, estimated using pressure coefficient time histories experimentally measured in wind tunnel tests, were compared with the corresponding peak factor statistics estimated through the use of six analytical models available in the literature, namely the Davenport, classical Hermite, revised Hermite, modified Hermite, Translated-Peak-Process (TPP), and Liu's models. The basic assumption of the TPP model, i.e., that the pressure coefficient local peaks follow a Weibull distribution, was validated and was used to estimate analytically the peak factors' quantiles. Different time history durations and different error measures were also considered. The non-Gaussian properties of the pressure coefficient processes were characterized at different roof locations for different wind angles of attack. It was found that: (1) the region of non-Gaussianity is significantly affected by the wind angle; (2) as expected, the Davenport model underestimates the peak factor mean and standard deviation in regions of high non-Gaussianity; (3) the modified Hermite model provides the best estimates overall of the peak factor mean; and (4) the TPP model provides the best estimates overall of the peak factor standard deviation. In addition, the modified root mean squared error was found to provide the most reliable assessment of the analytical models' accuracy among the different error measures considered in this study.

1. Introduction

Tensile structures are widely used for hyperbolic paraboloid roofs (HPRs). This structural typology is frequently used for multi-functional buildings that require large interior open spaces [1], since they allow covering extremely large spans (up to 150 m, as for example The Khan Shatyr Entertainment Centre in Kazakhstan, completed in 2010) without intermediate pillars in a cost-effective manner. In addition, they are lighter than other structural typologies for similar spans and, thus, permit a wider selection of design solutions.

These structures present the unique feature that their load-bearing elements (i.e., cables and membranes) sustain pure tension and, thus, resist very efficiently external loads [2–4]). These load-bearing elements are very flexible and generally experience large deflections. Thus, the initial structural equilibrium configuration needs to be optimized through the appropriate distribution of permanent loads and a careful selection of the geometric shape. The most commonly used shape for tensile structures is the hyperbolic paraboloid, which has been employed in many structures around the world, e.g., the Olympiastadion in Munich, Germany (designed by Otto Frei and completed in 1968) and the Denver Union Station roof in Denver, CO (USA) (completed in 2013). The hyperbolic paraboloid is an elementary double curvature surface, nowadays usually realized by means of two series of parallel cables, one series oriented upward and the other downward. For load combinations controlled by gravity loads (e.g., self-weight, dead and snow loads), the upward cables act as load-bearing cables, whereas the downward cables are stabilizing cables. However, under suction due to wind loads, the upward cables provide the stabilizing action, whereas the downward cables resist the wind loads.

Because of their lightness and deformability, the stability of tensile structures and in particular of hyperbolic paraboloid cable nets is extremely sensitive to their aerodynamic and aeroelastic response under wind actions. However, knowledge of these aerodynamic and aeroelastic behaviors is limited [2]. In addition, existing technical codes provide design guidelines only for static loading conditions and/or temporary structures [5–7]. These code prescriptions are backed up by several manuals of practice, which examine in depth several aspects related to the design of tensioned fabric roofs [8,9]. In this context, the European Network for Membrane Structures "TensiNet" developed the TensiNet Design Guide [10], which is widely considered the state-of-the-art guide for the design of tensile structures and also provides a few

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examples of aerodynamic wind actions on tensile structures [4].

It is noted here that HPRs have been used in the past also for low-flexibility shell structures made of light reinforced concrete (e.g., the Olympic Saddledome in Calgary and several buildings designed by Mexican architect Felix Candela [11]), and for medium-flexibility lattice structures constructed with plywood [12]. For these stiffer structural typologies, the aerodynamic behavior is predominant, whereas the aeroelastic behavior has a smaller influence on the structural design. For flexible HPRs consisting of tensile structures, both aerodynamic and aeroelastic behaviors are equally important and their characterization for design purposes requires an iterative two-phase approach in which the results of two separate analyses (performed numerically or experimentally in wind tunnels) are interdependent [13]. However, the pressure coefficients can be accurately estimated using rigid models in wind tunnel tests even for flexible HPRs, since the deflections of well-designed structures need to satisfy code requirements and are generally too small to affect the pressure coefficients [14].

The importance of the aerodynamic behavior of HPRs has been recognized in a few recent studies that investigated the dynamic behavior [14–18] and the distribution of pressure coefficients on different geometries [19–26]. It is noteworthy that peak pressure coefficients (usually expressed in terms of peak factors) are crucial to estimate peak loads [27], which for this type of structure could be related to local and global critical conditions. In addition, modern performance-based reliability design approaches require the accurate estimation of extreme wind loads and their distribution [28–30].

In principle, the peak factor's distribution can be obtained based on the classical extreme value theory [31]. If the process is Gaussian, the Davenport equations provide satisfactory estimates of the mean and standard deviation of the peak factor [32,33]. If the process is non-Gaussian, no exact solution exists to predict mean and standard deviation of the peak factors. In general, using a Gaussian approximation yields non-conservative peak factor values when applied to non-Gaussian processes [34,35].

Several analytical models have been proposed in the scientific literature to predict non-Gaussian load effects. Kareem and Zhao [34] proposed an analytical expression for the mean of non-Gaussian peak factors using a moment-based model [31] based on the concept of non-Gaussian translation process [36] with a cubic Hermite polynomial transformation. Winterstein et al. [37] proposed a modification of the Davenport equation for the non-Gaussian peak factor mean by including the effects of clustering. Sadek and Simiu [38] proposed an automated mapping procedure to estimate the peak distribution of wind-induced non-Gaussian internal forces on low-rise buildings by using a database-assisted design software. This mapping procedure requires identifying an analytical marginal probability distribution for the time series of interest through numerical fitting of the distribution parameters. However, the Sadek–Simiu method has been applied only to non-Gaussian processes with an underlying marginal gamma distribution [39–43].

Kwon and Kareem [27] derived an analytical solution for the non-Gaussian peak factor standard deviation based on the Hermite model and proposed a revised Hermite model and a modified Hermite model for estimating the mean and standard deviation of non-Gaussian peak factors. The revised Hermite model is based on the optimal parameters of a four-moment cubic Hermite polynomial transformation [44]; however, this model has some validity limitation regarding the specific ranges of the skewness and kurtosis of the process. The modified Hermite model is based on an equivalent statistical cubicization procedure [45,33] and requires solving of a system of coupled nonlinear equations that depend on the skewness and kurtosis of the process. Huang et al. [42] proposed the Translated-Peak-Process (TPP) model to estimate the local peak distribution, peak factors, and quantiles of peak extremes. The TPP model is a modification of the Sadek-Simiu point-to-point mapping procedure, which assumes a Weibull distribution for the local peaks of non-Gaussian process' time histories. The TPP model was validated by comparing the analytical estimates with wind-tunnel pressure experimental results for a tall building. Ma and Xu [46] proposed a moment-based Johnson transformation method in conjunction with a Gumbel distribution assumption to estimate the statistics of wind pressure peak factors. The results of this method were validated through a comparison with the peak factors obtained from long-duration pressure records measured in wind-tunnel tests on the model surfaces of a high-rise building. It is noted here that, while there is an agreement in the literature that the Davenport model tends to underestimate (sometimes significantly) the mean value of the peak factors, there is no agreement on a single best model for all structures, with different versions of the Hermite model that seem to perform better for roof of low-rise buildings [27,42,47], and other approaches that seem to be preferable for the vertical sides of tall buildings [42,46].

Validation of the peak statistics' estimation models available in the literature is extremely limited for HPRs. Ding and Chen [21] compared the accuracy of various methods for extreme value analysis, (i.e., the peaks-over-threshold method, the average conditional exceedance rate method, and the translation process method with various translation models, including the Hermite model) for select pressure taps' recordings obtained from a wind tunnel test on a saddle-type HPR. Liu et al. [23] investigated different statistics of dynamic pressures on a saddle-type HPR, as well as the dependence of these statistics on different turbulence profiles. They observed that the peak factors in the flow separation regions presented a significant non-Gaussian behavior and that moment-based Hermite estimates were accurate only for mild non-Gaussianity. Liu et al. [24] proposed a new version of the Hermite model, in which modified moments of the original process are used to estimate separately the means of positive and negative peak factors. This model (referred to as the Liu's model hereafter) was verified through a comparison with the peak factors of wind pressures measured in wind tunnel tests on a large-span saddle-type roof. It is noteworthy that the roof considered in [23,24] is representative only of HPRs with linear edges (i.e., inclined at 45° with respect to the sagging and hogging directions of the roof). The extreme values of the pressure coefficients on HPRs are significantly affected by turbulence [23] and roof shape [19,20]. However, information on appropriate ranges and/or models for HPRs is lacking in current technical standards and design codes [48–56]. In addition, there is a need for a detailed comparison of the different analytical models available in the literature in terms of their accuracy in estimating the statistics of wind pressure peak factors for HPRs. It is also noted that, while many studies available in the literature investigate the accuracy of analytical models for individual wind pressure recordings (i.e., single pressure tap and single duration), only few of them investigate the overall accuracy of these models for a given surface, e.g., [42,46] for the vertical sides of tall buildings, and [47] for the roof of low-rise buildings. Moreover, in these investigations different types of errors have been used to quantify the accuracy of different models, and it is not immediately apparent how the results obtained using different error definitions can be compared. Finally, the authors of the present paper were not able to identify studies that take into consideration the effects of different durations of the wind pressure recordings.

Based on an extensive wind-tunnel experimental campaign, the research presented in this paper investigates in detail the statistics of the peak factors in HPRs, as well as the non-Gaussian properties of the peak factors as functions of the position on a square HPR and the relative direction of the wind. This study also investigates the overall relative accuracy of different analytical models for the estimation of peak factor statistics when compared with experimental wind tunnel measurements on a scaled model of a building with a square HPR. This accuracy is investigated for different lengths of the pressure time histories and for different definitions of error.