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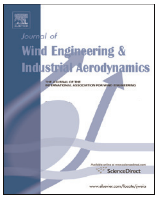

Assessing probabilistic wind load effects via a multivariate extreme wind speed model: A unified framework to consider directionality and uncertainty

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ABSTRACT

This study presents a new approach of estimating wind load effects (responses) for various mean recurrence intervals (MRIs) with consideration of both directionality and uncertainty of wind speed and wind load effects. The joint probability distribution model of directional extreme wind speeds is established based on extreme wind speed data using multivariate extreme value theory with Gaussian Copula. The distribution of yearly maximum wind load effect is then calculated through the exceeding probability of directional wind speeds over the corresponding levels. The uncertainty of extreme response conditional on wind speed and direction is further considered using the theorem of conditional probability. The proposed analytical framework can be considered as an analytical formulation of the existing approach based on historical directional wind speed data, but with an additional capability of accounting for the uncertainty of extreme response conditional on wind speed and direction. It can also be regarded as an extension of the existing fully probabilistic methods with an additional capability of accounting for directionality. Applications of the proposed approach are presented and the results are compared with those from the existing approach to demonstrate its accuracy. The characteristics of directionality factor for wind load effects are discussed. Finally, the influence of uncertainty of extreme response conditional on wind speed and direction is further examined.

1. Introduction

The importance of considering wind directionality effect in estimating probabilistic wind load effects of structures has been well recognized. As the most unfavorable direction which produces the largest wind load and structural response under given wind speed does not necessarily align with the direction of the strongest wind, considerations of directionality effect of wind, aerodynamics and structural characteristics result in a reduction of response as compared to the analysis regardless of direction, i.e., the consideration of the worst case scenario. A directionality factor is often introduced to model this reduction effect (Simiu and Heckert, 1998; Rigato et al., 2001; Laboy-Rodríguez et al., 2014). In ASCE 7-10 (ASCE, 2010), a directionality factor of 0.85 is specified for buildings. This factor is only applicable to the load specified in code for which calibrations have been made.

Project-specific wind engineering studies usually take advantage of wind tunnel studies for a more accurate definition of wind loads, which is then combined with the use of state-of-the-art approaches for consideration of directionality effect. Several approaches have been developed in literature, some of which are based on parent distribution and the others on yearly extreme value distribution of mean wind speed. Previous studies have shown that the discrepancies of predictions from these approaches are often significant (e.g., ASCE, 1999; Sadek, 2005). The lack of specificity in the use of approaches for combining wind tunnel data with directional wind speed statistics has been discussed in a recent critique of ASCE 7 procedure (Simiu et al., 2013).

The random process crossing rate approach initially introduced by Davenport (1977) remains one of the popular methods in North America. Wen (1983, 1984) carried out an extensive study of directionality effect using this crossing rate approach. An alternative formulation for the crossing rate analysis was presented by Lepage and Irwin (1985) with a consideration of the derivative of direction variable of wind speed. The accuracy of predictions from this approach can be affected by the inadequate description of the extreme wind statistics with the commonly used Weibull

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distribution as the parent distribution of directional wind speed (Simiu and Scanlan, 1996; Irwin et al., 2005; Isyumov et al., 2014). A bi-modal Weibull distribution was proposed for an improved modeling of the parent distribution of mean wind speed (Xu et al., 2008; Isyumov et al., 2014).

Another approach estimates distribution of extreme wind effect using historical directional yearly maximum wind speed data (Simiu and Filliben, 1981; Simiu and Heckert, 1998). Because this method is implemented based on observation data series rather than an analytical formulation, it is not very convenient for a parametric study to gain fundamental understanding on how directional characteristics affect the reduction of response. The storm passage method introduced in Isyumov et al. (2003) follows a similar scheme but directly uses the time series of mean wind speed and direction during storm passages instead of directional yearly maximum wind speed data. This method is also not convenient to carry out parameter studies as it is not formulated in an analytical form.

The sector-by-sector method is also often used due to its simplicity (Simiu and Filliben, 2005; Irwin et al., 2005). It determines the extreme response for a target mean recurrence interval (MRI) directly from the extreme wind speeds at different directions. Two variants of this approach are adopted in practice: (1) The wind speeds at various directions (sectors) with a target MRI of *R* years are firstly determined. The corresponding extreme responses are quantified and their maximum over all sectors is considered as the response for MRI of *R* years; (2) The cumulative distribution functions (CDFs) of annual maximum responses at different sectors are determined from the yearly extreme value distributions of directional wind speeds. The CDF of annual maximum response over all sectors is then estimated as a product of these CDFs of directional extremes under the assumption that extremes of directional wind speeds are mutually independent. Both predictions can be less accurate than the predictions that take the statistical dependence of extremes of directional wind speeds into consideration. It is noted that all these approaches for directionality effect treat the extreme response conditional on wind speed and direction as a deterministic quantity rather than a random variable. Therefore, these approaches are unable to account for the uncertainty and directionality in a unified framework.

It is reported that during a storm passage, the wind direction may vary about 200° (e.g., Cook, 1982). Therefore, the extreme wind speeds in neighboring sectors often have certain level of correlation. A slightly different method of using directional extreme winds in mixed wind climates (typhoon and non-typhoon winds) was introduced in Matsui and Tamura (2005), where the storm correlation between directions was also not taken full account. Itoi and Kanda (2002) extended the Gumbel's bivariate distribution, equivalent to Gumbel copula, to four directional extreme wind speeds with dependence structures given empirically by assuming an identical slope for all marginal Type I distributions. Estimations of direction-free wind speed were made and compared based on such models for directional maximum wind speeds.

The first fully probabilistic method that accounts for uncertainties of wind speed and wind load effect conditional on wind speed was given by Cook and Mayne (1979, 1980) for extreme wind load effects of rigid structures. This method is referred to as the first-order method as it neglects the possibility of larger wind load effects produced by second and higher-order strongest winds in a year (Gumley and Wood, 1982; Harris, 1982). A full-order method was proposed by Harris (1982, 2005). Chen and Huang (2010) introduced a refined full-order method, which is capable of dealing with any type of asymptotic extreme value distribution, and can be used for both rigid and flexible structures. It should be emphasized that these fully probabilistic methods are incapable of further accounting for the effect of directionality. The probabilistic wind load effects have also been addressed in literature from different perspectives where Monte Carlo simulations are often required for the estimations (Kareem, 1987, 1988; Bashor and Kareem, 2009; Diniz et al., 2004; Diniz and Simiu, 2005; Hanzlik et al., 2005).

With the motivation to diminish the difference in predictions among existing methods and to permit parametric study with analytical formulations, a new unified framework to include both directionality and uncertainty is proposed in this study for estimating wind load effects for various MRIs. In this study, the directional extreme wind speed data are used to model joint probability distribution of directional extreme wind speeds based on multivariate extreme value theory with application of Gaussian copula (Mikosch, 2006). Copula has been a popular approach in multivariate extreme value analysis (Renard and Lang, 2007; Cherubini et al., 2004), while its applications to wind engineering has not been fully explored (Itoi and Kanda, 2002; Schoelzel and Friederichs, 2008). The Gaussian copula, as one of the copula models, can be regarded as identical to the classic multivariate Gaussian translation model in formulation (Grigoriu, 2009). However, the introduction of copula with the concept of standardizing correlated variables into uniform distribution margins enables the potential use of a variety of existing models for the wind directionality studies. The multivariate extreme wind speed models determined from wind speed and wind velocity pressures are compared. With the multivariate extreme model of directional wind speeds, the probability of exceeding a certain wind effect level is then calculated through the probabilities of exceeding directional wind speeds over corresponding levels. The uncertainty of extreme response conditional on wind speed and direction is further considered using the theorem of conditional probability. The proposed analytical framework can be considered as an analytical formulation of the existing approach based on historical directional wind speed data (Simiu and Filliben, 1981; Simiu and Heckert, 1998), but with an additional capability of accounting for the uncertainty of extreme response conditional on wind speed and direction. It can also be regarded as an extension of the fully probability methods (Cook and Mayne, 1979; Harris, 2005; Chen and Huang, 2010) with an additional capability of accounting for directionality. Applications of the proposed approach are presented and the results are compared with those from the existing approach that is based on historical extreme wind data in order to demonstrate its accuracy. The characteristics of directionality factor for wind load effects as function of MRI are discussed. Finally, the influence of uncertainty of extreme wind response conditional on wind speed and direction is further examined.

2. Methodology of the proposed approach

2.1. Modeling of extreme wind speed at each sector

To model the joint distribution of directional extreme wind speeds with multivariate extreme value theory, the first step is to determine the extreme value distribution of wind speed in each sector. Extensive literatures are available for modeling the distribution of univariate extreme wind speed. The methods used include a direct use of univariate extreme value theory based on extreme wind speed data (e.g., Cook and Mayne, 1979, 1980; Harris, 1999), Peaks-Over-Thresholds (POT) method (e.g., Holmes and Moriarty, 1999; Simiu and Heckert, 1996; An and Pandey, 2005) and average conditional mean exceedance (ACER) method (Naess and Gaidai, 2009) which used wind speed data over a selected high threshold, and the approach based on crossing rate of random wind speed process (e.g. ASCE, 1999), and others.