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A comparison of methods to estimate peak wind loads on buildings

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ABSTRACT

The most appropriate statistical technique to estimate a peak pressure coefficient from wind tunnel data is not a settled issue. The lack of a standard acceptable method can lead to inconsistent definitions and interpretations of peak pressure coefficients, particularly since time constraints associated with wind tunnel tests necessitate relatively short test durations. A Gumbel model is commonly used to represent the peak distribution, where parameters are determined using observed peaks. Recent papers have proposed several variations of a peak estimation procedure using the entire time history and a translation from a Gaussian peak distribution model to non-Gaussian. It is shown that, in the case of mildly non-Gaussian data, translation methods achieve accuracy comparable to the Gumbel method. It is also shown that translation methods lose accuracy when the record deviates significantly from Gaussian, while the Gumbel model maintains stable accuracy and precision. This paper presents two new translation-based peak pressure coefficient estimation schemes that offer accurate and stable performance for strongly non-Gaussian data. Very long duration wind tunnel data provide empirical peak distributions with which to compare the relative performance of the Gumbel, existing translation and proposed new translation methods. One of the new methods slightly outperforms the Gumbel method.

1. Introduction

An important outcome from wind tunnel testing of low-rise buildings is a statistical assessment of peak pressure coefficients (C_{p_peak}), typically defined as a chosen fractile from a peak probability model whose parameters are determined from the observed data. The accuracy and precision (uncertainty) of this approach depend upon the form of the chosen peak probability model, the method used to identify its parameters, and the quantity of data available. In order to obtain an adequate tap resolution, large model scales are desirable for low-rise buildings. This leads to a decreased time scale and long data records to achieve the desired full-scale equivalent time. Thus, there is a trade-off between the uncertainty of the estimated C_{p_peak} and the desire to minimize data record lengths to limit the time and cost of wind tunnel experiments.

Many techniques for estimating C_{p_peak} have been proposed in the literature (Davenport, 1964; Gioffrè et al., 2000; Huang et al., 2013; ISO, 2009; Kwon and Kareem, 2011; Lieblein, 1974; Peterka, 1983; Sadek and Simiu, 2002; Stathopoulos, 1983; Tieleman et al., 2006). Each of them has unique advantages and disadvantages. This study concerns those methods that fall into one of two approaches: (1) determining C_{p_peak} from observed peaks (observed peak methods); and (2) mapping the peak distribution of a Gaussian process to a non-Gaussian peak cumulative distribution function (CDF) via the translation process (translation methods).

Observed peak methods include: a single observed peak value recorded during a sampling period (Stathopoulos, 1979), the mean of several observed maxima (Holmes et al., 1989), and a value corresponding to a chosen fractile from a probability distribution (commonly Gumbel) fitted to observed maxima (Cook and Mayne, 1980; Ho et al., 2005; St. Pierre et al., 2005). The last method (Gumbel method) is the most flexible among the three, offering a statistical quantification of the peak at a selected fractile rather than a single observed peak or simple average.

The perceived data length requirement of the Gumbel method has led to the development of alternative methods for the estimation of C_{p_peak} from short records. The complete time series is used to estimate a peak CDF from an underlying Gaussian process, and a translation maps this CDF to the peak CDF of the assigned non-Gaussian time series (translation methods). Kareem and Zhao (1994) used the moment-based Hermite polynomial to define the translation between the Gaussian and non-Gaussian processes. Kwon and Kareem (2011) employed an updated and more robust Hermite polynomial model (Winterstein and Kashef, 2000). Sadek and Simiu (2002) modeled the non-Gaussian time

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series by using gamma and Gaussian distributions to fit the long and short tails, respectively. The parameters in the fitted distributions were re-evaluated by using the theoretical moment estimators in Tieleman et al. (2006). Ben Ayed et al. (2011) employed a translation model to full scale pressure data and compared results with values in ASCE 7. Huang et al. (2013) established the mapping relationship between the non-Gaussian CDF and its underlying Gaussian CDF based on a probabilistic model using the kernel smoothing technique.

The minimum wind tunnel testing time interval necessary to estimate C_{p_peak} should be selected within the context of acceptable uncertainty. Sadek et al. (2004) used wind tunnel data to quantify fluctuating internal forces and Monte Carlo simulations of additional time histories to evaluate the sampling error of C_{p_peak} using a translation method. Gavanski et al. (2013) determined the uncertainty of C_{p_peak} estimates produced by the Gumbel method in terms of the time series duration and the number of subsets used to observe the peaks, providing guidance regarding the trade-off between time series duration and C_{p_peak} uncertainty. The current study expands the Gavanski et al. (2013) peak wind pressure estimation uncertainty analysis to include four existing and two new translation methods. This provides a common framework by which to compare the relative strengths and weaknesses of the methods with regard to: (1) time series duration necessary to achieve similar precision and (2) accuracy when applied to mildly and strongly non-Gaussian time series.

It is shown that: (1) the Gumbel method maintains similar accuracy in both mildly and strongly non-Gaussian time series; (2) for mildly non-Gaussian data, the existing translation methods require less data to achieve accuracy comparable to the Gumbel method; (3) for strongly non-Gaussian data, the existing translation methods lose accuracy; and (4) the new translation methods maintain a short data duration requirement, robust accuracy and precision for mildly and strongly non-Gaussian data.

Section 2 provides details of the Gumbel method (observed peak method). Section 3 presents three existing and two new translation methods. Section 4 presents the wind tunnel dataset and comparative performance studies, and Section 5 concludes.

2. Gumbel method

The Gumbel distribution is often used to fit the distribution of peak wind pressure coefficients

$$F_{X_{PK}}(x;t) = \exp\{-\exp[-\alpha_t(x-U_t)]\} \quad (1)$$

where α_t and U_t are the coefficients determined from a series of observed peaks, x is the pressure coefficient, and t is the duration in which a single peak is observed (reference duration). α_t and U_t are determined based upon N observed peaks using one of a number of available methods, as listed in the schematic in Fig. 1. This method requires a total record duration of $t_{total}=Nt$. The resultant cumulative distribution function (CDF) corresponds to the reference duration of t. For example, C_{p_peak} representing a 22% probability of exceedance (POE) within a ten minute reference duration could be estimated by dividing a 160 min record into 16 ten minute segments, observing the largest peak in each segment, estimating the Gumbel parameters using these peaks, and identifying the 22% POE from the Gumbel CDF model.

Cook and Mayne (1980) presented a procedure to convert the Gumbel parameters between different reference durations. This allows the estimation of α_t and U_t using a sufficient N within a relatively short data record, followed by a conversion to the desired longer reference duration T. For the two time reference duration values (t, T, $t<T$), the conversion is (Cook and Mayne, 1980)

$$\alpha_T = \alpha_t \quad (2)$$

$$U_T = U_t + 1/\alpha_t \ln(T/t) \quad (3)$$

C_{p_peak} is then identified as x_{pk} at a chosen fractile in $F_{X_{PK}}$. A subsequent study by Cook (1982) calibrated this method to assess the peak factor and quasi-static approaches to assess wind loads. The accuracy and precision (uncertainty) associated with the Gumbel method with this conversion will be compared with the uncertainties of translations methods in Section 4. Gavanski et al. (2013) showed that the Gumbel method as defined above yields almost identical results to the observed peaks methodology proposed in the ISO (2009) standard.

Kasperski (2003) and Holmes and Cochran (2003) applied the Type III Extreme Value Distribution and three-parameter Generalized Extreme Value Distribution to fit the peak wind pressure coefficients, respectively. Holmes and Cochran (2003) recommended the Gumbel model for its simplicity.

3. Translation methods

A series of studies have presented an alternative methodology for the estimation of the C_{p_peak}. Rather than fitting an extreme value distribution to observed peaks, these methods utilize the entire time series to produce an estimate of C_{p_peak} (Ben Ayed et al., 2011; Kwon and Kareem, 2011; Sadek and Simiu, 2002; Tieleman et al., 2006).

3.1. Translation method concept

Fig. 2 illustrates the translation method to estimate C_{p_peak}. Consider a standardized non-Gaussian record x. This record can be expressed as a translation of a standardized Gaussian process u, and the relation inverted to express u in terms of x

$$x = g(u) \text{ and } u = g^{-1}(x) \quad (4)$$

in which $g(\bullet)$ represents the translation function.

For the underlying Gaussian process u, the CDF of its peak within reference duration t, $F_{U_{PK}}(x;t)$, is (Rice, 1945)

$$F_{U_{PK}}(u;t) = \exp[-\nu_0 t \exp(-u^2/2)] \quad (5)$$

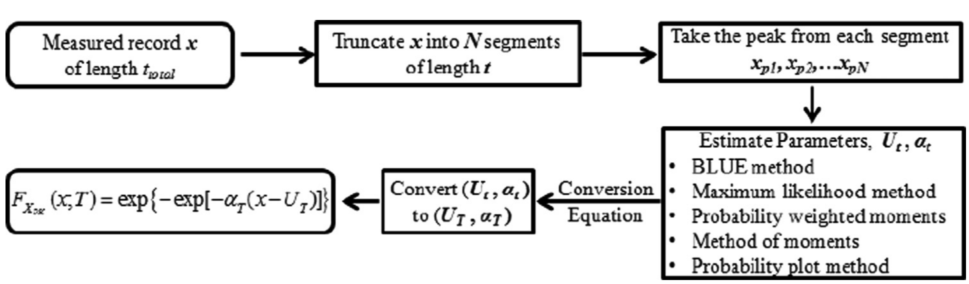

Fig. 1. Observed peak method (Gumbel method).