Practical issues for pedestrian wind comfort prediction: comfort criteria

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Abstract

New pedestrian comfort criteria are proposed based on the expected number of times that an appropriate size of gust exceeds a threshold speed. A gust size of 20 m is suggested, though a 3 second gust could be used for historical consistency. The gust speeds would be directly measured with appropriate instrumentation and filtering, and extreme value statistics would be applied to a sufficient number of gusts to ensure a robust conclusion. The thresholds are to be based on observed discomfort.

1 Introduction

Over the past 35 years, many authors have addressed the question of pedestrian wind comfort. Blocken and Carmeliet [1] provide a comprehensive review of over one hundred papers related to the topic, while several other authors [2-4] have compared the published criteria. Many cities require that pedestrian wind speeds be considered as part of the planning for a new building, often using criteria from these studies as the basis for acceptance.

Such criteria typically specify a mean and/or gust speed not to be exceeded some threshold percentage of the time. (In some studies, the influence of temperature also considered [5], though this is not considered in this paper.) This threshold percentage varies a good deal from one criterion to the next. In some cases, a high wind speed not to be exceeded more than once per year is used. This type of infrequent event is often though of as a safety-related threshold. In other criteria, a weekly or even daily wind speed threshold is specified. For these more common events, a lower wind speed is specified, and such criteria are considered to be comfort-based.

In some climates, an absence of safety issues implies a good comfort rating as well. In a generally calm climate with occasional strong winds, however, a location can be rated as generally comfortable, while also failing the safety test for occasional dangerously high winds. As a result, the various criteria often produce substantially different ratings for the same location [2, 4].

Since both comfort and safety are of concern, there is a general consensus in many criteria currently in commercial use [6, 7] that there should be one high threshold for safety (typically wind speeds exceeded 0.1% of the time or less) and another low threshold for comfort (using wind speeds exceeded 5% to 20% of the time.)

Much experimental effort has gone into measuring *wind effects*, as the literature describes the wind speeds at which clothing flaps or umbrellas invert or walking becomes difficult. The most ubiquitous such study is probably the modified Beaufort scale [8]. But how often will paper plates be blown about before the elevated terrace is no longer used for receptions? How often will employees stumble on the way to the parking lot before mitigation is implemented? Bottema makes the valuable distinction between such wind effects and *wind discomfort*, defining discomfort as “acting to avoid the wind effects”. [9]

We believe that current techniques for measuring pedestrian level winds and combining this data with meteorological record can predict with adequate accuracy how often a given wind effect can be expected at a given location. More details on instrumentation and the use of meteorological record is provided in companion papers [10, 11]. In this paper, we discuss the direct measurement of peak wind speeds in the wind tunnel, which we consider of paramount importance. We also propose the generation of a database to quantify wind discomfort.

2 Just measure the gusts

Studies have shown that a gust can have a greater effect on a pedestrian than a steady wind of the same speed [1]. While some of the published comfort criteria disregard gusts, or conversely used gust

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speeds exclusively, criteria currently in commercial use rightly consider both mean and gust wind speeds.

In most criteria the gust speed is defined from the mean and standard deviation as

$$U_G = \overline{U} + \lambda \sigma_U \quad (1)$$

The peak factor λ varies a good deal from one criterion to the next, ranging from 1.0 to 3.5. We will refer to U_G as a "statistical gust".

As Bottema [9] points out, at high values of longitudinal turbulence intensity (T_u > 35%), T_u is underestimated due to the signal being rectified by the wind tunnel sensors. T_u is defined as

$$T_u = \sigma_U/U \quad (2)$$

where σ_U is the standard deviation of the longitudinal wind velocity, and U is the mean local wind velocity. A rectified signal will overestimate the mean wind velocity and underestimate the standard deviation, a double reduction in T_u.

He suggests, based on a comparison of T_u and mean velocity values estimated from numerical simulations (presumably a coarse RANS CFD simulation), that an assumption of constant value of σ_U is preferable to the large errors inherent in high T_u values from rectified measurements. This assumption has been used to justify the use of steady state CFD calculations to estimate gust speeds for pedestrian comfort [12].

This justification is questionable. Figure 1 presents hot film velocity data for several points around a building in Florida. The approach flow turbulence and velocity profiles were identical for all wind directions. We have excluded data where the turbulence intensity is above 35 %, as indicated by the solid line providing an upper bound to the data. We see that σ_u varies from under 5% to over 20% of the reference velocity, which is measured upstream at a full-scale height of 500 ft. above the surface. The variations exist not only between points, but also for a single point at different wind directions.

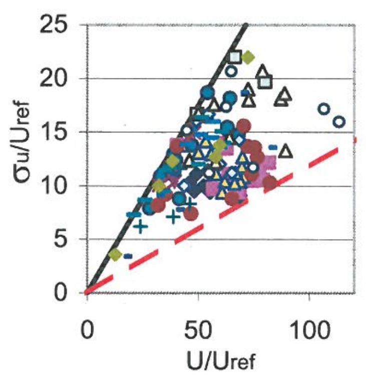

Figure 1: Standard deviation vs. mean wind speed from a pedestrian wind level tests at CPP. The solid line indicates T_u = 35%. The dashed line is T_u = 12%.

Given the importance of gust speeds to pedestrian comfort we do not believe that the assumption of constant turbulence intensity is justified, and as a result, steady state CFD simulations cannot be expected to reliably predict pedestrian comfort until a reliable method of deriving peak gust wind speeds from steady state calculations is found [13].

This discussion of T_u is something of a red herring, however. The inability of velocity rectifying probes to accurately measure longitudinal turbulence intensity in highly turbulent areas, such as the recirculation zones so common around buildings, is not really a problem. While wind direction information is valuable for mitigation design, what is needed for comfort assessments are mean speeds (irrespective of direction), rather than mean velocities. More importantly, we want to know the largest gusts speeds, also irrespective of the local flow direction, and these are correctly indicated even when the signal is rectified [14]. The inaccuracy in σ_U is only an issue if Equation (1) is used.

It is likely that those who proposed criteria based on Equation (1) were looking for a robust statistic to characterize the gustiness of a location. In practice, σ_U is not as robust a statistic as it seems, due to the rectification issue discussed above. More importantly, while the σ_U is a much more robust statistic than a single peak, it is not an accurate indicator of the worst gusts because no assumptions can be made about the underlying probability distribution function (pdf). The use of extreme value statistics to characterize the peak gusts, as is routinely done with peak pressures in wind tunnel cladding studies, provides a more robust peak estimate that Equation (1).

3 What size of peaks should be measured?

A gust lasting 3 seconds is often cited as the target [7]. A 3-second gust at 23 m/s is probably unnecessarily big, stretching over 69 m. A more intuitive approach to the target gust size for safety might be to think of a gust large enough to envelope the pedestrian and unbalance him or her. We suggest that a gust length of roughly 10 times a person's size (20 m) is sufficient to produce the same effect as a longer gust. Bottema [9] estimates that a gust length of 6 m would be sufficient to knock a person out of balance, though this is admittedly not a precise calculation.

Bottema [2] also lists gust speeds and durations producing various wind effects. We can calculate that the gust sizes in these studies varied from 20 m to 180 m. The use of 3 seconds as the shortest gust duration in these studies is possibly a historical legacy of instrumentation, since it corresponds to the frequency response of typical cup anemometers.

4 How can these peaks be measured?

The duration of a gust in the wind tunnel depends on the time scaling of the wind-tunnel study, which in turn is controlled by the model scale and the wind speed:

$$t_m = \frac{\overline{U}_f}{\overline{U}_m} \cdot \frac{t_f}{R} \tag{3}$$

where the subscript m indicates model scale, and f indicates full scale. $\overline{U}$ is the mean wind speed, t is the time, and R is the physical model scale ratio, $R=L_f/L_m$. Gust of shorter than 3 seconds or smaller than 20 m would be removed from the wind tunnel data by low-pass filtering the time series. The filter cutoff frequency f would be

$f_{3\sec} = \dfrac{R}{3\sec} \cdot \dfrac{\overline{U}_m^{ref}}{\overline{U}_f^{ref}}$ for the 3 second gust, and $f_{20m} = \overline{U}_m^{ref} \cdot X^n \cdot \dfrac{R}{20m}$ for the 20 m gust,

where X is the ratio of the local mean wind speed to the reference wind speed, $X = \overline{U}^n / \overline{U}^{ref}$. The superscript n is a number identifying the pedestrian point in question. For typical sites and wind tunnel test conditions, f is slightly lower for the 20 m gust.

For both the 3 second gust and the 20 m gust, the cutoff frequency at which the signal would be low-pass filtered is between 40 Hz and 100 Hz. This would require sampling at 250 Hz, which is common practice. However, in some cases sampling at up to 500 Hz may be needed. It is worth wondering whether or not any information even exists in the tunnel at this frequency, but if it does, the hot wire is the only one of these probes with a sufficiently high frequency response to measure it. Typically, the frequency response of the tubing connecting a surface mounted pressure probe to the transducer can be expected to damp out information above 200 Hz [15]. Rather than pushing the instruments to this speed, it is hoped that a trend analysis of the extreme value statistics will allow the 3 second or 20 m gust to be estimated.

It may be more common for wind tunnel labs that do directly measure the peaks to select a sample rate, omit the filtering, and simply average the 5 or 10 highest speeds measured over some sample period T. How inaccurate this might be depends on the specifics of the study.

5 What's too gusty? Looking for criteria.

Rather than directly assess whether or not the peak gust speed exceeds some criteria, it is common to divide the measured gust speed by a number close to 1.85 to calculate a "gust equivalent mean" (GEM). For example, Durgin derived this factor from averaging hundreds of pedestrian wind speed measurements from wind tunnel tests of developments in the Boston area. [3] The average ratio of the measured peaks to the means in these tests was 1.875. (Is this accurate for more open environments?)

In typical criteria, if the GEM is higher than the mean, then the location is considered dominated by gusts, and this higher number is compared to the mean speed comfort criteria [7]. It is not clear why only locations that are gustier than average would be considered as potentially too gusty. It would seem preferable to directly compare the gusts to some gust criteria. Unfortunately, there is little observed data on gust related discomfort. Only a few of the criteria [8, 16] are actually based on discomfort data at all, as opposed to educated conjecture about how often people might accept certain wind effects.

Fortunately, we have a ready supply of locations where the wind conditions have been deemed uncomfortable. Every client who calls a wind lab to ask for a wind tunnel study to mitigate winds is experiencing wind discomfort (as defined in the introduction), and the first step in every one of these studies is to quantify the existing conditions, so that the relative performance of mitigation measures can be assessed. A database of such cases is being assembled at CPP, with wind gusts measured as described above. Unfortunately, much of the legacy data from past studies is of limited value, as only mean and standard deviations have been recorded.

It is common to assume that some level of habituation to wind conditions exists, and that this acclimatization colours people's perception of wind comfort. If the discomfort database were world wide, and so covered a wide range of wind conditions, it should reveal whether or not habituation should be incorporated into the criteria.

6 Conclusions and recommendations

An assessment of wind gusts is crucial to pedestrian wind comfort evaluation. The gusts can be characterized by recording and analyzing wind speed time histories from wind tunnel tests. This type of direct measurement of gusts is simpler, more intuitive, and more accurate than the use of statistical gusts. To be done correctly, direct gust measurement requires appropriate low pass filtering of time series.

These measured gusts are currently compared to existing comfort and safety criteria, in some cases by using a Gust Equivalent Mean (GEM) method. However, in light of instrumentation advances since many of these criteria were written, a re-examination of the convoluted combination of arbitrary thresholds, statistical gusts, pdf fits to meteorological data, and GEM adjustments is warranted. For this purpose a database of conditions at locations that have required pedestrian wind mitigation is being compiled, and other labs are encouraged to contribute relevant data to be shared in the public domain.

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