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Relationship in gust and peak factors and evaluation duration of turbulent approaching flow

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SUMMARY:
Predicting rare strong wind speeds has been an important research question for wind environmental assessments. To quantify such strong wind speeds, the gust and peak factors are commonly used. The peak values are usually defined based on the maximum value of the instantaneous wind speeds averaged in an evaluation duration. Although the period has the critical impact on the peak, yielding to variations in the gust and peak factors, the influence of the ratio between the evaluation period and turbulent time scale has not been studied. Therefore, this study investigates the relationship between the gust and peak factors and evaluation duration of the turbulent approach flow generated using a large-eddy simulation reproducing the entire approaching section of a wind-tunnel experiment. The result shows that both the gust and peak factors attenuate by increasing the evaluation duration because of the elimination of the contribution to the gusty events of the small-scale eddies. Although this is the first step to understand the effect of the evaluation periods, this study helps us establish a stochastic model for predicting instantaneous wind speeds and resulting peak values.

Keywords: Gust factor, Peak factor, Evaluation duration

1. INTRODUCTION

Predicting low-occurrence strong wind speeds has been a long-term research topic in the fields of wind and structural engineering. In addition, infrequent high-impact wind events at pedestrian levels are also recognized as a key issue for wind environmental assessments in built environment. To evaluate the peak wind speeds based on statistics, the gust factor defined as the ratio between the peak wind speed to the mean, and the peak factor expressed by the difference between the peak and mean scaled by the standard deviation, are commonly used indices. The peak values in these indices are defined as the maximum value of the time series data averaged out in an evaluation duration for a sampling period (e.g., 3 s for the evaluation duration and 10 min for the sampling period are used at Japan Meteorological Agency, Japan). In contrast, recent studies dealing with the probability density functions (PDFs) of the wind speeds and velocity components proposed modelling the PDFs of the wind speeds at the pedestrian level around buildings based on scaled model experiments and computational fluid dynamics (Hirose et al., 2022; Wang et al., 2022). They employed the percentile values based on the cumulative PDFs to evaluate the strong wind events. Determining the peak or percentile values of the wind speeds, the evaluation duration is an influential parameter because the relative period of the turbulent time scale and evaluation duration affects the occurrence frequency of the extreme values in the sampling period. A fundamental study is required to understand the effect of the evaluation duration on the stochastic nature of the turbulent flow, gust and peak factors, for establishing the probabilistic model of the wind speed and velocity components. Therefore, this study investigates the relationship between gust and peak factors and evaluation duration of the turbulent approaching flow generated using a large-eddy simulation (LES) reproducing the entire approaching section of a wind-tunnel experiment.

2. METHODOLOGY

2.1. Turbulent approaching flow

A turbulent approaching flow adopted in this study is based on the database of the Architectural Institute of Japan CFD guideline (AIJ, 2016). The guideline website provides open-access experimental datasets as well as instantaneous turbulent approaching flow calculated by an LES for further LES benchmark simulations. The flow was numerically simulated using the LES with the wall-adapting local eddy-viscosity model by reproducing the entire approaching section of a wind tunnel including a barrier, spires, and roughness elements at Tokyo Polytechnic University (Okaze et al., 2021). The inflow data were also used as boundary conditions for the further various following studies (Ikegaya et al., 2019; Wang et al., 2022).

The time series data of the streamwise, spanwise and vertical velocity components, denoted as u, v, and w for 60 s were extracted from the database at the spanwise centre of $y = 0$ at 21 vertical positions from $z/h = 0.005$ to 3.0. Here, h (=0.2m) represents the standard block height used in the benchmark simulations. Although we do not consider a building, we use it as the representative length scale to maintain the consistency of the analyses with the previous studies. The sampling frequency is 1000 Hz. Figure 1 (a, b) shows the comparisons of $\overline{u}$ and standard deviation σ between the LES and experiments. They agree well with each other. Since the velocity components were provided as instantaneous values, we determined the turbulent integral time scales τ based on the autocorrelation function R defined as the area where $R >$ 0.1. Below $z/h = 0.4$, the integral scales change vertically; however, mostly they showed the constant values above the height. The magnitudes of τ in the streamwise velocity component is

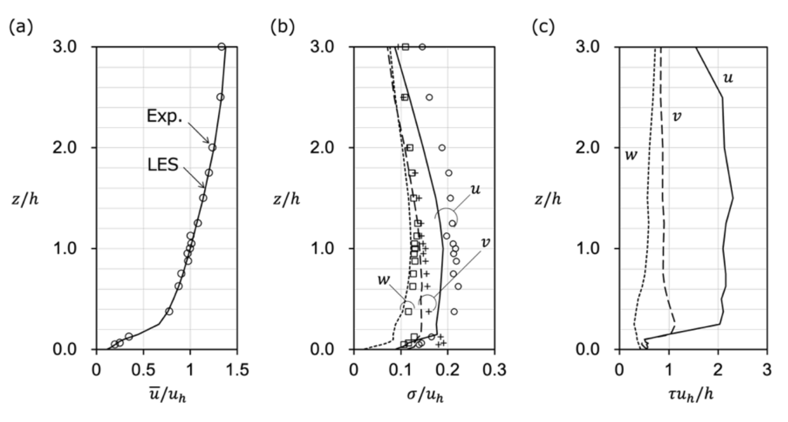

Figure 1. Vertical profiles of (a) mean streamwise velocity component $\overline{u}$, (b) standard deviations σ, and (c) integral time scales τ of the turbulent approaching flow in AIJ guideline (2016). The markers in the figures represent the data obtained by wind-tunnel experiments. u_h is the streamwise velocity component at the block height h (=0.2m). The data in (a,b) were adopted from Okaze et al. (2021) and Ikegaya et al. (2019).

the largest, and those of the spanwise and vertical velocity components follow as we can expected. The values of τ are used to scale the evaluation durations.

2.2. Filtering operation based on integral time scale

To investigate the effect of the evaluation duration T [s] on the peak and gust factors, we consider the durations standardized by the integral length scale as $T = n\tau$, where n is from 0 to 16.0. Since T is defined as the period taking the moving average of the time-series data, it corresponds to the low-pass filter operation with the cut-off frequency $f_c = 1/n\tau$ [Hz]. It is known that the power spectral density S of turbulent flow with the integral time scale τ and standard deviation σ is approximately expressed by von Karman spectrum. It gives the peak frequency of S as $f_p \cong 0.15/\tau$ or $T_p = 1/f_p \cong 6.9\tau$, implying that we adopted filtering periods based on f_p. Although it is not necessary for the velocity components at all the locations follow the von Karman spectrum, τ can be a standardized duration.

3. RESULTS

Figure 2 shows the vertical profiles of the standard deviation σ^T, skewness s_k^T and kurtosis k_t^T with the evaluation period of T for u. The suffix T indicate that the statistics are determined by the filtered time-series data with T. Because the change in T corresponds to reducing the turbulent contribution to σ in the frequency over f_c, it is plausible to see the decreasing tendency of σ_u^T as explained in Weiner-Khinchin theorem. In contrast, the difference in s_k^T and k_t^T are marginal in $0.1 < z/h < 1.5$ when $T \leq 4\tau$. Above $z/h = 1.5$, T becomes more sensitive to determine s_k^T and k_t^T. When $T = 16\tau$, s_k^T and k_t^T approaches to 0 and 3, respectively, implying the PDFs are probably expressed by the Gaussian distributions. Since T was selected based on τ at each position, the reduction tendency of the standard deviation is monotonic regardless of the height. In contrast, the skewness and kurtosis showed the height-dependent reduction to the evaluation period. These results imply that the power spectral

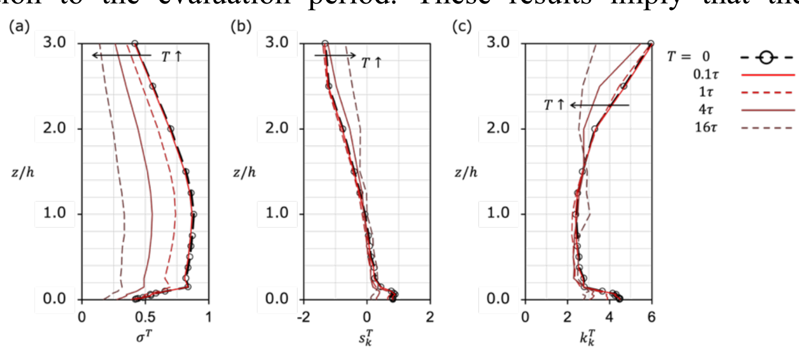

Figure 2. Vertical profiles of turbulent statistics for filtered streamwise velocity component. (a) standard deviation σ, (b) skewness s_k^T, and (c) kurtosis k_t^T. The suffix T indicates the evaluation duration.

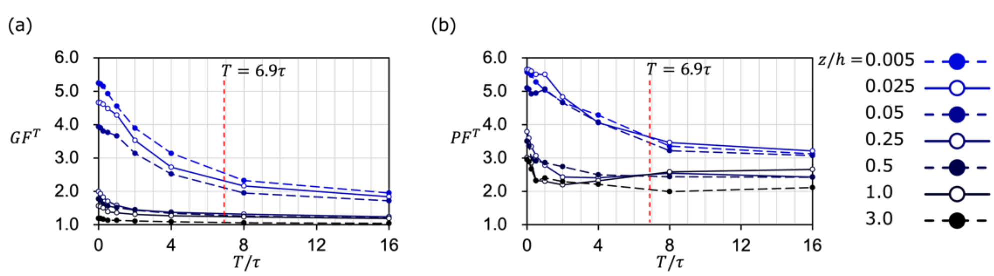

Figure 3. Relationship between the evaluation duration T/τ. (a) Gust factor GF^T, and (b) peak factor PF^T.

densities at each position are characterized by τ, and therefore, the reduction of the filtered statistics are similar at each height due to the elimination of the contribution of the eddies with the frequency higher than f_c. In contrast, the turbulent eddies smaller than f_c do not equally contribute to the higher-order statistics, indicating the rarely occurring strong or weak velocity values might be related to the large-scale eddies with the frequency smaller than f_c.

To quantify the effect of the evaluation period on the indices for the gust event of the gust factor GF^T and peak factor PF^T, Figure 3 shows these statistics for T/τ at several selected heights. When $z/h \leq 0.05$, both GF^T and PF^T gradually decreases with T/τ, and approach to 2.0 and 3.0, respectively. In contrast, those above $z/h = 0.1$ are not affected by T/τ except for the range of $T/\tau < 1.0$. The reduction of the indices means that the magnitude of the infrequent gust events is also attributed from the small-scale turbulence probably because of the superimposition of these eddies on the large-scale fluctuations. Therefore, increasing T, meaning the elimination of the small-scale turbulence, causes the reduction of the GF and PF. Interestingly, this is not always true when $z/h \geq 0.1$ probably because of the larger contribution of the large-scale eddies.

4. CONCLUSION

We investigate the relationship between the gust and peak factors and evaluation duration of the turbulent approaching flow generated using an LES reproducing the entire approaching section of a wind-tunnel experiment. The result shows that both the gust and peak factors attenuate by increasing the evaluation period because of the elimination of the contribution to the gusty events of the small-scale eddies. Although this is the first step to understand the effect of the evaluation periods, this study helps us establish a stochastic model for predicting instantaneous wind speeds and resulting peak values.

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