Large-Eddy Simulation On The Gust Probability In Urban Pedestrian Spaces

Y. Ikeda¹,², A. Hagishima¹, N. Ikegaya¹, and J. Tanimoto¹

¹ Interdisciplinary Graduate School of Engineering Science, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan

ABSTRACT
Large-eddy simulation (LES) on the airflow in pedestrian spaces of cubic block canopy is performed to investigate the influence of gust events on urban pedestrian safety. The authors analyzed spatio-temporal fluctuation of wind speed recorded with the frequency of 1Hz for 4000 seconds, and examined convergence of turbulence statistics to find the appropriate solution under the trade off of limited data storage and the accuracy of statistics. In addition, the duration of the gust events in pedestrian spaces is investigated. Based on them, it is revealed that 1) convergence of kurtosis can be a parameter to estimate statistically steady state in the analysis of gust events, and that 2) the difference of wind speed between 1st and 5th percentile is around 24 %; thus, determining criteria based on the percentile should be carefully done.

KEYWORDS
Pedestrian wind environment, Gust, Statistical analysis

INTRODUCTION
The airflow within a canopy layer is an important factor in terms of the thermal comfort and safety; thus, numerous researchers have investigated the flow in urban pedestrian spaces. For example, Kubota et al. (2000) performed the multi-point measurements of the wind speed at a pedestrian level of miniature models of existing urban districts located in Japan by means of a wind-tunnel experiment (WTE) and clarified that the area-averaged mean wind speed ratio decreases linearly with the increase of gross building coverage ratio (same with plan area ratio, \( \lambda_p \), a ratio of plan area of buildings to district area). Yoshie et al. (2008) also conducted a series of WTEs to investigate the ventilation and thermal environment in a built-up area with closely-packed high-rise buildings, and revealed that the height variation of buildings was quite effective for improving the air ventilation and the thermal environment in such a dense area.

* Corresponding author email: 2es13150r@s.kyushu-u.ac.jp
Nowadays, the rapid development of computer resources has enabled the numerical simulation based on the computational fluid dynamics (CFD) techniques and has greatly contributed to analyze 3D turbulent flow field around buildings which is difficult to be measured by WTEs. For example, Razak et al. (2013) implemented the large eddy simulation (LES) on the airflow over various types of block arrays and showed that the spatially averaged mean wind speed ratio at a pedestrian level can be described universally by a simple exponential function of frontal area ratio \((\lambda_f\), a ratio of frontal area of a block to unit district area). These researches are useful to predict urban ventilation; however, considering the facts that the airflow near the ground surface is highly heterogeneous in urban areas (see Coceal et al. 2007) and instantaneous strong wind often exceeds several times of the average as reported by Yoshie et al. (2007), the knowledge about spatio-temporal variation of wind speed is needed for the assessment of the pedestrian safety.

To reproduce the rare and strong wind events in pedestrian spaces, statistically sufficiently large sampling period is necessary. In addition, considering the fact that the size of turbulence organized structure at the block height \((H)\) exceeds several times of block scale (e.g., Inagaki et al. 2012), sufficiently large computational domain might be also required. Although the LES technique can predict spatio-temporal flow fluctuation with high resolution, it needs huge calculation cost and data storage to record calculated turbulent flow field of a large domain for a long time sequence; therefore, there is a few researches dealing with the urban pedestrian gust characteristics using LES. To reconcile the accuracy of the gust analysis with the limitation of computation, it would be informative if the acceptable criteria of minimum sampling time or spatial scale for the gust analysis are available. Although the criteria for averaging time \(200T\) \((T=L/\bar{u}_*)\) established by Coceal et al. (2006) is widely used in researches on the airflow over urban canopy, it is unclear whether the criteria can be applied to the gust analysis or not.

Under these circumstances, the authors performed the LES on the airflow over cube arrays and analyzed two dimensional instantaneous flow fields at a pedestrian level.

**RESEARCH METHODS**

Parallelized Large Eddy Simulation Model (PALM) developed by Raasch et al. (2001) is used in the current study. PALM consists of the continuity equation, incompressible Bussinesq equation with the 1.5th-order turbulent closure model proposed by Deardoff (1999), and the transport equation of subgrid-scale turbulence kinetic energy.

In this research, the authors adopted the data of instantaneous flow field in the cubic blocks arranged in the staggered layout with \(\lambda_p = 16.0\%\).

The computational domain of the LES is shown in Figure 1. The coordinate \((x, y, z)\) and flow component \((u, v, w)\) are defined as the streamwise, spanwise, and vertical direction. 2x2 blocks are arranged in a domain with a height of \(4h\) \((h=25m\): building height). The grid resolution for \(x, y, z\) direction is fixed to \(h / 64\). The cyclic condition
is employed for streamwise and lateral boundaries; thus, an infinite uniform urban
district is reproduced, and the flow is driven by constant pressure gradient determined
by the experimental result of Hagishima et al. (2009). In contrast, the free-slip
condition is used on an upper boundary, and the logarithmic law \( z_o = 0.01 \text{m} \) is applied
for wall surfaces. The wind speed is recorded with a frequency of 1Hz for 4000
seconds.

Meanwhile, the computational domain is subdivided into four unit districts in the
analysis; the authors calculated statistics under 15 cases of target area (A, B, C, D,
A+B, A+C, A+D, B+C, B+D, C+D, A+B+C, A+B+D, A+C+D, B+C+D, A+B+C+D)
to investigate how convergence of statistics varies with target area size.

**RESULTS**

1. The influence of sampling period and area on the convergence of statistics
The authors calculated spatio-temporally averaged scalar wind speed \( \mu \), standard
deviation \( \sigma \), skewness \( Sk \), and kurtosis \( Ku \) under the conditions of various target
areas and sampling periods. Figure 2 shows how these statistics of each condition
differ from those of the reference condition (case A+B+C+D, 4000s).

Mean wind speed gradually converges with the increase of both the number of target
districts and the sampling periods. For the cases of unit district (A, B, C, and D),
however, the value is oscillating even though the sampling period is longer than 3000
seconds; it indicates the number of samples is insufficient for statistical convergence.

On the other hand, the values of standard deviation seem to depend strongly on the
size of target districts; the differences between the values of the cases comprise three
units and the reference value are less than 1% for the condition of sampling time
period more than 500 seconds. In contrast, skewness and kurtosis for all the
conditions exhibit larger fluctuation with the sampling time period. The difference
among the cases is especially large for kurtosis, and it is reasonable because kurtosis
is the largest order moment among the four. According to Figure 2(d), \( |1-Ku/Ku_{ref}| \) at
the sampling time sequence of 3000s is 5.4%, and that at 3500s is 2.7%; hence, the
authors assume that kurtosis converges after the sampling period of 3000s of all the
four unit (case A+B+C+D), and use the case of A+B+C+D, 4000s for the following analysis.

2. The relation between statistics and the probability density function
To make the meaning of turbulence statistics more clear, the distribution of probability density function (PDF) is analyzed. The result is shown in Figure 3. The difference between them seems to be small at the lower part of PDFs, while it is slightly large at the upper part.

Mean wind speed is correlated to the wind speed of the largest probability density, and skewness represents the balance of positive and negative strain from normal distribution; thus, these two statistics are affected by total sample number and probability distribution of positive and negative perturbation.

Standard deviation represents the average width of PDF and it is less sensitive to the total sample number than mean wind speed or skewness because only the absolute value of wind speed fluctuation has influence on it. In addition, the value of kurtosis indicates the extent of bottom part of PDF; thus, this value is influenced by rare event. These values are less affected by the probability of positive and negative oscillation.

Figure 2. Statistics calculated under various sampling periods

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3. Duration of the gust event

For the wind safety assessment, not only the amplitude but also the duration or frequency of gust events are of importance; thus, the authors checked whether instantaneous wind speed at each grid point exceeds the 1st percentile ($V_{1%}$) or not for every time steps. If the event "$V>V_{1%}$" occurs in succession, we defined it the duration of gust event ($T_g$). Figure 4 shows the longest duration of gust event ($T_{gmax}$) at each grid point normalized by sampling time sequence ($T_s$=4000s). The map clearly shows that the gust duration is longer at the block corners and downstream of them; one possibility is that high momentum fluid is swept from above the canopy layer and it is accelerated by channel effect. Figure 5 describes time series of gust event at the point of (P), (Q), and (R); the black lines indicate gust events. Occasionally the gust event like a pulse signal appears at (P). On the other hand, the gust period and relatively calm period turns up mutually at (Q), and the more complex temporal variation can be observed at (R) due to the interaction between the flow around neighboring districts.
DISCUSSION: ON DETERMINING GUST CRITERIA

Cumulative distribution function (CDF) is calculated in whole the data of target area and sampling period to evaluate the probability of gust event at a pedestrian level explicitly. The authors defined CDF for gust analysis as following equation:

\[ F(\Phi) = \int_{\Phi}^{\infty} f(\varphi) d\varphi , \]

where \( \Phi \) is a threshold, \( F(\Phi) \) is CDF, and \( f(\varphi) \) is the probability distribution function (PDF) for a variable \( \varphi \). The result for two cases of target area and sampling period are shown in Figure 6: one is district A+B+C with 500 seconds, and the other is district A+B+C+D with 4000 seconds (i.e., the case of largest sample number). Generally, it is believed that when the sampling time sequence increases, the amplitude of rare and strong wind event becomes larger because low frequency oscillation of the flow is resolved; however, the graph indicates the case A+B+C, 500s shows larger wind speed over all the range of cumulative distribution. This is because the gust event appears at early moment during the time steps in the case of A+B+C, 500s, and it causes such a probability distribution of entirely larger wind speed. This indicates that, if the total sampling number is statistically insufficient, probability distribution of wind speed can easily change depending on at which moment the sampling is started. Actually, the maximum level wind speed of the case A+B+C+D, 4000s is larger than the other, although this tendency appears only in the range of considerably low cumulative frequency, as shown in Figure 6(b).

Meanwhile, determining the criteria should be carefully done because the wind speed varies drastically at less than around 10th percentile due to the steep slope of CDF; for example, the difference between 1st and 5th percentile is around 24%, whereas that between 10th and 15th percentile is only about 9% for the case of A+B+C+D, 4000s.
CONCLUSIONS
The LES database of the instantaneous wind speed within the uniform staggered block arrays with $\lambda_p=16\%$ is analyzed to assess the criteria of statistics for gust analysis in a pedestrian space. Based on the results, following things are clarified:

1) Among the turbulence statistics of mean value, standard deviation, the convergence of skewness and kurtosis are strongly affected by the sampling period. Especially, kurtosis requires the longest sampling period; thus, the convergence of kurtosis can be one of the statistical criteria for gust analysis.

2) The difference of wind speed between 1st and 5th percentile is around 24 %, whereas that between 10th and 15th percentile is only about 6%; thus, defining criteria with the idea of percentile should be carefully done.

In addition, the fundamental research on pedestrian gust characteristics is performed. The authors calculated gust duration for each grid point. As a result, we revealed that gust duration is relatively large at the block corner and it seems that there is some characteristic frequency for gust events; it should be analyzed in future work.

ACKNOWLEDGEMENTS
This research was financially supported by JSPS KAKENHI Grant Number - 22360238, 25820282.

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of Architecture, Environmental Engineering, Vol.73, No.627, pp.661-667