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Consistency of mean wind speed in pedestrian wind environment analyses: Mathematical consideration and a case study using large-eddy simulation

Hideki Kikumoto[a,*], Ryozo Ooka[a], Mengtao Han[b], Keigo Nakajima[b]

[a] *Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*
[b] *Graduate School of Engineering, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*

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ABSTRACT

When analyzing pedestrian wind environments, the evaluated mean wind speed sometimes varies in its definition depending on the method used, such as in wind tunnel experiments (WTEs) and in computational fluid dynamics (CFD) simulations. First, this study defined three types of mean wind speed (mean-vector speed, mean speed, and effective speed) and investigated their interrelations mathematically. Second, discrepancies between the three mean wind speeds were predicted quantitatively by conducting a large-eddy simulation of flow around a single building model in an urban boundary layer. Near the ground surface, the differences between the mean wind speeds became larger in the recirculation flow near the building's windward corners and in its wake. However, in the region where the maximum wind speeds occurred, all the mean wind speeds were similar. Finally, we presented a method to estimate mean speed, which is commonly evaluated in WTEs, using information that can be obtained from CFD using turbulence models based on Reynolds-averaged Navier–Stokes equations. By modeling the probability distribution of the instantaneous velocity in a multivariate Gaussian distribution, we demonstrated its ability to estimate mean speed with high accuracy.

1. Introduction

Construction of high-rise buildings can increase the local wind speed at pedestrian level. Gusty wind near the ground can cause discomfort for pedestrians by impeding their walking and causing chilling (Hunt et al., 1976; Murakami and Deguchi, 1981), as well as increasing safety problems in extreme cases in relation to the scattering of objects (Blocken and Stathopoulos, 2013). However, excessive concentration of buildings can reduce wind speed at pedestrian level. This means that heat and airborne pollutants remain longer in the urban space causing problems concerning the urban thermal environment and air quality (Blocken et al., 2013). It is therefore necessary to create a pedestrian wind environment (PWE) that maintains a moderate wind speed range.

Conventionally, wind tunnel experiments (WTEs) have been used for the analysis of PWEs. However, given the recent enhancement of available computing power, many analyses using computational fluid dynamics (CFD) have been undertaken. For example, Blocken et al. (2016) provided an extensive review on WTE and CFD methods for pedestrian-level wind. In WTEs, various techniques are used to measure wind velocity. Among the various point measurement techniques, hot-wire anemometry and laser Doppler velocimetry have rapid temporal response to wind velocity change, making it possible to measure not only the mean flow but also to derive turbulence statistics (Blocken et al., 2016). Recently, particle image velocimetry has also been used to measure the spatial distribution of wind velocity at high density (e.g. Allegrini et al., 2013).

In the analysis of a PWE in an urban area with complicated geometry, it is common to use an omnidirectional anemometer typified by a thermistor anemometer and the Irwin probe (e.g. Irwin, 1981; Kamei and Maruta, 1979; Yoshie et al., 2007; Zahid Iqbal and Chan, 2016). However, such anemometers are insensitive to changes in wind direction, and the thermistor anemometer in particular has slow temporal response and it measures only mean wind speed. Nevertheless, because it is necessary to evaluate wind speed at multiple points for many wind directions in practical PWE analyses, omnidirectional anemometers are preferred for their high robustness, low cost, and freedom from requiring angular adjustment for each wind direction.

Many studies using CFD have incorporated large-eddy simulation (LES) in their analyses, including unsteady turbulent flow fields (e.g. Gousseau et al., 2013; He and Song, 1999; Hertwig et al., 2017; Murakami et al., 1987). However, LES is very expensive computationally and it remains impractical for PWE evaluations that require simulations for

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[*] Corresponding author.
E-mail address: kkmt@iis.u-tokyo.ac.jp (H. Kikumoto).

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Nomenclature

Variables

f	probability density function of instantaneous wind velocity
f_g	multivariate Gaussian distribution
H	height of building model
k	turbulence kinetic energy
K	kinetic energy of mean flow
M	number of dimensions of space
N	number of samples of ensemble average
N_p	total number of data points
R_{sk}	ratio of variance of speed to doubled turbulence kinetic energy
s	instantaneous wind speed
$\mathbf{u}$	instantaneous wind velocity
U_{ref}	mean inflow velocity at height of building model
V_{es}	effective speed
V_{ms}	mean speed
$V_{\mathrm{ms.g}}$	estimate of mean speed
V_{mv}	mean-vector speed
$\boldsymbol{\mu}$	mean vector for multivariate Gaussian distribution
Ω	space where instantaneous wind velocity is defined
Σ	covariance matrix for multivariate Gaussian distribution

Acronyms, abbreviations

AIJ	Architectural Institute of Japan
CFD	computational fluid dynamics
LES	large-eddy simulation
MB	mean bias
MNGE	mean normalized gross error
MR	mean ratio
PWE	pedestrian wind environment
RANS	Reynolds-averaged Navier–Stokes equation
RMS	root mean square
WTE	wind tunnel experiment

Operators, superscripts

$\langle a \rangle$	Reynolds average
a'	deviation from Reynolds average
$\lvert A \rvert$	determinant of a matrix or absolute value of a scalar
$\lVert \mathbf{a} \rVert$	square norm of a vector
$\mathbf{a}^{\mathrm{T}}$	transpose of a vector

All bold characters in the manuscript denote a vector

multiple wind directions. Therefore, it is common to predict the wind velocity in complex urban areas using turbulence models based on the Reynolds-averaged Navier–Stokes (RANS) equations, which might have inferior accuracy compared with LESs but are faster in terms of calculation speed (e.g. Blocken and Persoon, 2009; Hertwig et al., 2012; Zahid Iqbal and Chan, 2016; Zhang et al., 2005).

In both WTEs using omnidirectional anemometers and CFD simulations using RANS models (CFD-RANS), the "mean wind speed" is used as an indicator in the PWE analysis. However, the definitions of the mean wind speed are not strictly consistent between WTEs and CFD simulations (Tominaga et al., 2004). Generally, WTEs take the mean value of wind speed (scalar velocity) as the mean wind speed, whereas the magnitude of the mean vector is taken as the mean wind speed in CFD simulations. Because of different error factors in the WTEs and CFD simulations, the results of one will not necessarily agree perfectly with the other. However, it is undesirable that bias will occur in the evaluation of a PWE depending on the analysis method used.

The results of CFD simulations are commonly validated by WTEs. Thus, because of the different definitions of mean wind speed, it is difficult to determine whether any disagreement between the two is due to modeling error of the physical phenomenon or inaccuracy in the definition of the evaluation index. For example, Yoshie et al. (2007) and Blocken and Carmeliet (2008) reported that results obtained using CFD-RANS models agreed well with experimentally derived values in the region of high wind speed around a building; however, CFD underestimated the wind speed in the building wake (Blocken and Carmeliet, 2008; Yoshie et al., 2007). Steady RANS models do not reproduce large-scale unsteady fluctuations, such as vortex shedding, which cannot necessarily be modeled as turbulent components (Tominaga, 2015; Tominaga et al., 2008). This means there is a limit to the reproducibility of the flow of CFD-RANS models. However, in addition, there is a possibility that the prediction accuracy of CFD-RANS models is unduly low because of the inconsistency in the evaluation index of the mean wind speed.

In this study, we first defined mean wind speed using three different definitions, which can be used in PWE analyses, and we investigated their interrelations mathematically. Then, we investigated the discrepancies between those wind speeds quantitatively by conducting a LES for flow around a single building model in an urban boundary layer. Finally, using the results of the LES, we studied methods to estimate the mean wind speed obtained by omnidirectional anemometers using statistics obtainable from CFD-RANS model results.

2. Mathematical discussion on mean wind speeds

2.1. Definitions of mean wind speed

The instantaneous wind velocity in three-dimensional space is represented by $\mathbf{u}$. The Reynolds average and deviation from the mean of a quantity are denoted by $\langle a \rangle$ and a' respectively, i.e., $\mathbf{u} = \langle \mathbf{u} \rangle + \mathbf{u}'$. The square norm of a vector is expressed by $\lVert \mathbf{a} \rVert$. This defines the instantaneous wind speed as $s \equiv \lVert \mathbf{u} \rVert = (\mathbf{u}^{\mathrm{T}}\mathbf{u})^{0.5}$. Here, T of the vector right shoulder means the transpose of the vector.

We define three types of mean wind speed: mean-vector speed V_{mv}, mean speed V_{ms}, and effective speed V_{es}, as follows:

$$V_{\mathrm{mv}} \equiv \lVert \langle \mathbf{u} \rangle \rVert = \left(\langle \mathbf{u} \rangle^{\mathrm{T}} \langle \mathbf{u} \rangle \right)^{0.5} = (2K)^{0.5} \tag{1a}$$

$$V_{\mathrm{ms}} \equiv \langle \lVert \mathbf{u} \rVert \rangle = \langle s \rangle \tag{1b}$$

$$V_{\mathrm{es}} \equiv \langle \lVert \mathbf{u} \rVert^2 \rangle^{0.5} = \langle s^2 \rangle^{0.5} = (2K + 2k)^{0.5} \tag{1c}$$

where K and k are the kinetic energies of the mean flow and turbulence, respectively.

An omnidirectional anemometer in WTEs measures s as instantaneous speed data. Although it is usual that the measured value is temporally filtered by such as the thermal inertia of the sensor probe, the mean wind speed resulting from the time-averaged data is the same as V_{ms}. In the

Table 1
Analysis methods and mean wind speeds to be evaluated. * With omnidirectional anemometer; ** Approximated value because of the spatial filtering of small-scale turbulence in the LES.

Method	V_{mv}	V_{ms}	V_{es}
WTE*		✓	
CFD-RANS	✓		✓
CFD-LES	✓	✓	✓**