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Equivalent wind incidence angle method: A new technique to integrate the effects of twisted wind flows to AVA

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ABSTRACT

This paper presents a novel and cost-effective method to replicate modified pedestrian level wind (PLW) fields in twisted winds using a conventional wind profile with similar wind speeds and turbulent intensities. The novel method, namely the Equivalent Wind Incidence Angle (ϕ_{Eq}) method was developed using data of PLW fields near five isolated buildings with aspect ratio (height:width) ranging from 4:1 to 0.5:1 subjected to two twisted wind profiles with the maximum clockwise yaw angles of 13° and 22°. The magnitude of ϕ_{Eq} was found to be 6° and 14° for the two twisted wind profiles with maximum yaw angles of 13° and 22° and for any clockwise wind incidence angle ϕ, ϕ_{Eq} is $\phi + 6°$, and $\phi + 14°$. The ϕ_{Eq} method was applied for an Air Ventilation Assessment (AVA) done for an urban site in Hong Kong, and the outcomes were compared with two similar AVAs conducted using the two twisted wind profiles and a conventional wind profile without ϕ_{Eq}. The comparison revealed that velocity ratios (*VRs*) and wind speeds with a 50% probability of exceedance are similar or slightly different from those in twisted winds if the conventional wind profile is combined with the ϕ_{Eq} method.

1. Introduction

Knowledge on the urban wind field and its dependence on environmental factors is essential for evaluating pedestrian wind comfort, estimating air pollution dispersion, maintaining outdoor thermal comfort, estimating the potential of natural ventilation of buildings, assessing the damages from wind-driven rains, quantifying the budget of wind-energy production in urban areas, and preventing quick spread of airborne pathogens in cities. In particular, any urban wind field is strongly correlated to the properties of oncoming wind including its ambient wind speed [1], turbulence intensity [2], and incident wind direction [3]. Given the importance of oncoming wind profiles on the urban wind field, many researchers have devoted significant efforts on replicating accurately the atmospheric boundary layer (ABL) and associated environmental conditions in controlled environments such as in a boundary layer wind tunnel (BLWT) [4–11].

The simulation of twisted wind profiles in BLWT is driven by the same motive for accurate simulation of ABL wind flows for wind tunnel tests. Twisted wind profiles, which have varying wind directions along the profile's height, were first employed for studying the aerodynamic performance of yacht sails [12–15] and later used for pedestrian-level wind tunnel tests by the authors of this paper [16–19]. Advantages of using twisted wind profiles for testing yachts' sails were reported by Flay and Vuletich [20], and for evaluating the pedestrian-level wind (PLW) fields near isolated buildings, arrays of buildings, and in a real urban area were demonstrated by Tse et al. [16–18] and Weerasuriya et al. [19]. Tse et al. [17,18] found noticeable flow modifications at the pedestrian level including asymmetric corner streams, and the deviation of building far wakes from the centre line of isolated buildings and dissimilar wind speeds in the passages between an array of buildings. The study of Weerasuriya et al. [19] indicates significant variations in pedestrian-level wind conditions in urban areas with the magnitude and direction of wind twist, where those flow features are outright in pedestrian-level wind fields in conventional winds with zero wind twist.

Motivated by the previous studies, Weerasuriya et al. [21] have integrated twisted wind profiles into the Air Ventilation Assessment (AVA) following the established guidelines for AVA. The AVA conducted using twisted wind flows had more than 60% differences in wind speeds at locations directly exposed to incoming winds and more than 50% differences in wind speeds near buildings compared to the outcomes of AVA obtained using a conventional wind flow with similar wind speeds and turbulence intensities. Interestingly, they found that the correction methods that are used to account the effect of twisted winds on the outcomes of AVA cannot accurately adjust the results of

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AVA in the postprocessing stage but continuously overpredict the indicators in AVA compared with those obtained using twisted wind flows. Based on the results, Weerasuriya et al. [21] have suggested employing twisted wind profiles for AVA to improve its accuracy similar to the previous studies that proposed integrating different atmospheric stabilities [22,23], heterogeneous urban morphology and surface roughness [24,25], and precise modelling of the surrounding complex terrain [26] for AVA. However, they rightly predicted that cost, time and technical difficulties can be all significant constraints when simulating twisted wind profiles for AVA in a BLWT. Such constraints are inevitable results of the extremely laborious process of simulating twisted wind profiles in a BLWT, which requires specific knowledge on design, manufacturing, and calibrating vane systems [16,17]. In addition, twisted-flow wind tunnels, which are specifically designed to simulate twisted wind profiles, are currently rare; and constructing a new twisted flow wind tunnel or upgrading an existing BLWT is costly, time-consuming and technically challenging. By considering all these facts, Weerasuriya et al. [21] suggested inventing a novel, cost-effective method to replicate the influence of twisted wind profiles on the outcomes of AVA.

Following the suggestion of Weerasuriya et al. [21], this study proposes a novel, cost-effective method, namely the Equivalent Wind Incidence Angle method (the ϕ_{Eq} method) to employ conventional wind profiles to replicate similar impacts of twisted wind profiles on the outcomes of AVA. The main advantage of this method is its ability to use the conventional wind profiles with adjusted wind incidence angles, where the two components are common in any general wind tunnel test. The proposed method is presented in Section 2: the first half of that section describes the experimental setup of wind tunnel tests including approaching wind profiles, used building models, and measurement techniques that produced the data for the derivation of the ϕ_{Eq} method; the derivation and evaluation of the equivalent wind incidence angle (ϕ_{Eq}) for two twisted wind flows are presented in the second half of Section 2. Section 3 demonstrates the application of the ϕ_{Eq} method in an AVA done for an urban site in Hong Kong. Section 4 provides a comparison of the results of AVA obtained with twisted wind profiles applied and conventional wind profiles with and without using ϕ_{Eq}. Section 5 discusses the limitations of this study, and Section 6 presents some concluding remarks to close the paper.

2. Methodology

2.1. Background

In wind engineering applications, the pedestrian level is considered as a two-dimensional (2-D) horizontal plane that exists at a height of 1.5 m–2 m above the local ground level [27–31]. The idea of the 2-D horizontal plane simplifies the 3-D flow field near a building to a 2-D flow field of interest, where the flow features are dependent on flow properties (i.e., wind speed, turbulence intensity, wind incidence angle, yaw angle, and pitch angle) of the approaching wind flow at the pedestrian level. This simplification allows two or more PLW fields to be compared with respect to similarities or differences in flow properties of the approaching winds. An example in previous studies [16–19] related the flow modifications in PLW fields with twisted wind flows to the difference in yaw angles associated with the oncoming twisted wind profiles.

These previous studies [16–19] attempted to establish a relationship between the degree of flow modifications in PLW fields near buildings and the magnitude and direction of yaw angle in a twisted wind profile at the pedestrian level. For example, Tse et al. [18] assumed that these flow modifications are correlated with the effective wind incidence angle (ϕ_{eff}) of the oncoming twisted wind, where ϕ_{eff} is estimated as the vector summation of the incident wind direction of the twisted wind profile far upstream of a building (ϕ) and the yaw angle (θ) at the pedestrian level. The yaw angle (θ) here referred is the angle between the longitudinal velocity component, u, and the lateral velocity component, v (i.e., $\theta = \tan^{-1}(v/u)$). Later Weerasuriya et al. [32] used ϕ_{eff} as incident wind direction for a conventional wind flow to simulate PLW fields near isolated buildings in Computational Fluid Dynamic (CFD) simulation. Their study showed that combining the conventional wind profile with the ϕ_{eff} angle is insufficient still to reproduce the flow modifications in a PLW field with twisted wind flows. However, Weerasuriya et al. [32] predicted another possible set of incident wind direction that can be combined with a conventional wind flow to replicate a PLW field with twisted wind flow. The following sections explore this postulation by presenting the equivalent wind incidence angle (ϕ_{Eq}) method.

2.2. Experimental setup

The derivation of ϕ_{Eq} is based on the data obtained from a series of wind tunnels conducted in the boundary layer wind tunnel (BLWT) at the CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong

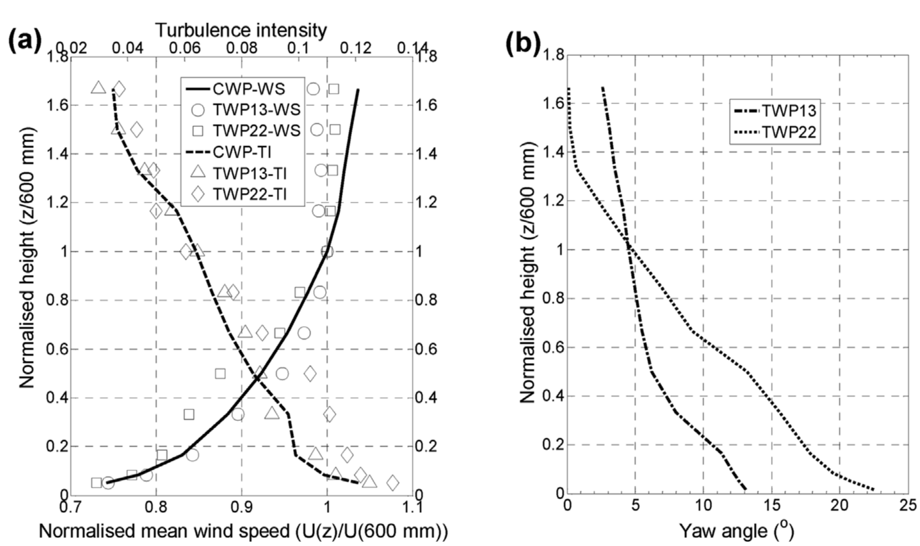

Fig. 1. (a) Normalised profiles of wind speed and turbulence intensity; (b) yaw angle profiles as measured at the centre of the turntable.