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A wind tunnel study of effects of twisted wind flows on the pedestrian-level wind field in an urban environment

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ABSTRACT

The influence of twisted wind flows on the pedestrian-level wind (PLW) field of an urban area was evaluated by testing a typical urban site (Tsuen Wan, Hong Kong) in a boundary layer wind tunnel. Four twisted wind profiles with different magnitudes and directions of yaw angles were employed to investigate variations in wind speed with the properties of the twisted wind flows at the pedestrian level. An additional conventional wind profile with similar wind speeds and turbulence intensities to the twisted winds but with zero yaw angles was simulated for comparisons. The mean wind speeds at 77 locations including the perimeter, roadsides, and groups of high-rise buildings were analysed for the conventional and the four twisted wind flows. The comparisons show a tendency of twisted winds to generate higher wind speeds at the pedestrian level than the conventional wind profile. The wind speeds of the twisted winds have a strong dependence on the magnitude and direction of the yaw angles, particularly at locations where the densities of buildings in the neighbourhood are low and hence local wind circulations are significantly modified by the twisted winds.

1. Introduction

The properties of an approaching wind such as its wind speed, turbulence intensity, and direction are important for evaluating the pedestrian-level wind (PLW) field in an urban area. For example, when a wind flow with high ambient speed strikes a building, it tends to generate windy areas around it near the ground, causing discomfort to pedestrians [1]. Highly intense turbulence, on the other hand, has its advantages: for example, it increases the velocity of the horizontal wind component near the roof of a building, strengthening the street-canyon vortex, facilitating the removal of air pollutants from a street canyon [2]. Kastner-Klein and Plate [3] have demonstrated how pollutant concentration in a street canyon decreases with a change in wind direction from the perpendicular to the oblique and concluded that the effects of wind direction are of practical concern. Given that the properties of the approaching wind are important in assessing the wind environment in a built-up area, researchers have devoted significant time and effort on simulating the atmospheric boundary layer (ABL) wind flows in a boundary layer wind tunnel (BLWT) [4–6] and on computational fluid dynamics (CFD) simulations [7–10].

Wind speed profiles simulated in BLWT and CFD generally conform to an empirical model with logarithmic or power-law relations, even though the ABL wind flows are more complex and deviate considerably from the empirical models. Particularly in an urban area, the accuracy of empirical models becomes low because of the complex morphology. For instance, the shape of the power-law wind model can become distorted because of Urban Heat Island (UHI) effect [11] and the development of an internal boundary layer [12]. Similarly, the assumption of the constant wind direction along the profiles' height is doubtful in the urban wind field [13,14]. Compared to wind speed and turbulence, the variation in wind directions has not received much attention even though several researchers, such as Kikumoto et al. [14] have emphasised that the deviation in wind directions should be replicated accurately in both physical and numerical simulations to obtain precise results when studying urban wind fields.

The vertical variation in wind directions is a topic that has been insensitively studied in the field of yacht sail's aerodynamic [15–17]. Conversely, directional variations in a wind flow have not been systematically investigated in the field of wind engineering until very recent when Tse et al. [18–20] conducted a series of wind tunnel tests using twisted wind profiles. Tse et al. [18] first simulated twisted wind profiles, which have varying wind directions along the profile's height, in a BLWT and then used them for the wind tunnel tests to show the ways that twisted wind flows modify the PLW field near isolated buildings and arrays of buildings [19,20]. Although these wind tunnel tests are indicative of the impact of twisted winds on the PLW field near

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generic buildings, it is not yet fully understood whether twisted wind profiles have similar importance in assessing the PLW field in an urban area. This uncertainty arises from the inherited characteristics of an urban area, including its inhomogeneous land use, irregular building arrangement, and non-uniform dimensions, shapes, and forms of buildings; all of them are vastly different from the generic buildings that were previously tested in twisted wind flows. Therefore, it is a timely need to conduct a comprehensive study on the urban PLW field under the influence of twisted winds to expand the existing knowledge. Moreover, such a study would be beneficial in fine-tuning the testing procedures of the urban PLW field such as the Air Ventilation Assessment (AVA) [21].

In this study, five wind flows with and without directional deviations are employed to test a typical urban site in Hong Kong. The wind speeds at the pedestrian level are measured at different locations at the site to evaluate the variations in the PLW field with the properties of approaching winds. The PLW fields at the site perimeter, along main highways, and near a group of high-rise buildings are analysed comprehensively to determine whether the twisted wind flows have significant impacts on the urban PLW field. These three test locations are indicative of the PLW fields under unobstructed wind flows (at the perimeter), wind penetration along main breezeways (along the highways), and wind conditions near buildings (the group of high-rise buildings) resulted in twisted wind flows and the variations in PLW fields with the properties of approaching wind flows.

After the introduction, Section 2 introduces the characteristics of the twisted wind profiles and their existence in Hong Kong. Section 3 presents the experimental setup of this study, the technique for simulating the twisted wind profile in a wind-tunnel test, and the details of the selected urban site. Section 4 compares the pedestrian-level wind fields in twisted and conventional wind flows at different locations including the perimeter, roadside, and near a group of high-rise buildings to demonstrate the overall differences in PLW fields under the influence of the conventional and twisted wind profiles. Section 5 discusses some limitations of the study and Section 6 concludes the paper.

2. Twisted wind profiles and their existence in Hong Kong

In the ABL, the wind profiles often have different flow directions at different heights, as confirmed by mathematical models [22,23] and field observations [13,14,24]. The vertical variation in flow directions is a result of the combined effects of Earth's rotation, friction between the wind and Earth's surface, and the pressure gradient force between high- and low-pressure zones [13]. The resulting wind profile is shaped like a spiral commonly known as the Ekman Spiral. The variation in wind direction within the Ekman Spiral is about 20° on average but can vary from 10° to 30° between the heights in the range of 1–1.5 km in the ABL [25]. However, deviations in wind direction observed in field measurement campaigns are larger than the average deviation in wind direction of the Ekman Spiral and are confined to the lower altitudes in the ABL (as opposed to all along its height). For example, Wind-Lidar measurements taken by Peña et al. [13] reveal 25°-45° deviations in wind direction under the neutral and stable atmospheric conditions while Kikumoto et al. [14] report about 70° of the deviations in wind direction for the heights in between 67.5 m and 500 m from SODAR-Lidar measurements.

There is no field measurement campaign ever conducted in Hong Kong to verify the existence of twisted wind profiles nevertheless almost every topographical wind tunnel tests conducted in Hong Kong affirm the twisted wind profiles' existence. Since the topographical wind tunnel tests reproduce the field conditions under neutral atmospheric stability, it is reasonable to assume that the twisted wind profiles very likely exist in Hong Kong. In fact, Tse et al. [18] confirmed the existence of twisted wind profiles in Hong Kong by analysing 256 wind profiles obtained from topographical wind tunnel tests. Their analysis reveals that the absolute difference in wind directions between the full-scale measurement heights of 25 m and 500 m can be as large as 40° irrespective to wind speeds, in which the yaw angles were measured. Apparently, the wind directional deviations observed from the wind tunnel tests are smaller than those reported by Peña et al. [13] and Kikumoto et al. [14]. Nevertheless, the deviation can still be considered as significant when considering that its magnitude is larger than that of the Ekman Spiral and the deviation is confined to the lower 500 m of the ABL. Based on the results of the wind tunnel tests and CFD simulations carried out by Weerasuriya et al. [26] and Li et al. [27], Tse et al. [18] conjecture that the hilly terrain of Hong Kong may generate large wind direction deviations in the lower part of the ABL. Consequently, the influence of the hilly terrain on the wind direction field should be included in the evaluation of the PLW field in Hong Kong for finding solutions for many wind-related issues, including outdoor thermal discomfort [28], degradation of air quality [29], increase of UHI effect [30], and favourable conditions for spreading airborne pathogens such as the SARS (Severe Acute Respiratory Syndrome) virus [31]. Although the twisted wind profiles observed in Hong Kong are dependent of the underlying hilly terrain, atmospheric stability conditions, in particular, the stable atmospheric stability, can alter the properties of topography-induced twisted wind profiles such as the magnitude of yaw angle [32].

3. Experimental setup

3.1. Simulation of twisted wind profiles

All wind tunnel tests described in this study were carried out in the CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology (HKUST). The wind tunnel in the WWTF is a closed-return type BLWT, which has two test sections, referred to as the high-speed section (maximum operating wind speed is 25 m s^{-1}) and the low-speed section (maximum operating wind speed is 10 m s^{-1}) according to their operating wind speeds. The wind tunnel tests in this study were conducted in the low-speed section because of its large dimensions (5 m in width and 4 m in height) under its maximum operating wind speed of 10 m s^{-1} at 1 m height. The large dimensions of the test section are advantageous for simulating twisted wind profiles because flow reflections from the sidewalls of the wind tunnel are of a considerable concern.

Fig. 1 shows the experimental setup arranged in the low-speed section of the wind tunnel. A wooden vane system, which had 5 individual vanes as shown in Fig. 2, was installed 4 m upstream from the centre of the turntable to generate twisted wind flows. Each vane was 1.5 m tall and was fabricated using laminated wooden strips. The maximum guide angles of the vane systems were 15° and 30°, and strips were rotated in either clockwise or counter-clockwise direction, as shown in Fig. 2(a) and (b). In other words, there were four types of vanes employed to simulate twisted wind profiles in this study. The previous publications of the authors [18–20] provide more details of the vane system.

The simulated wind profiles were measured at five points in the low-speed section to evaluate the consistency of mean wind speeds, turbulence intensities, and yaw angles. A TFI® Series100 Cobra probe fixed into a one-dimensional traverse system was used for the measurements. The Cobra probe can measure fluctuating wind speeds in three orthogonal directions, a range of from 2 m s^{-1} to 100 m s^{-1} with an accuracy of ± 0.5 m s^{-1}, and pitch and yaw angles with an accuracy of ± 1°. The one-dimensional traverse system sets the heights for the Cobra probe to take measurements with an accuracy of ± 1 mm.

Fig. 3 shows the wind profiles measured at 5 points in the low-speed section: at the centre of the turntable (A), moving laterally away from the centre of the turntable (B and D) by 2 m, along the centreline at a 2 m distance upstream and downstream from the centre of the turntable (C and E). At each point, mean wind speeds, turbulence intensities, and yaw angles were measured at 12 discrete heights from 10 mm to