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Simulation of twisted wind flows in a boundary layer wind tunnel for pedestrian-level wind tunnel tests

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ABSTRACT

Topography-induced twisted wind profiles are frequently observed in Hong Kong due to the abundance existence of mountains. Observed twisted wind profiles are with larger wind twist angles and are confined to the lower 500 m of the atmosphere, thus may impose significant effects on both structures and near-ground wind conditions. In order to investigate the influences of twisted wind flows on the pedestrian-level wind environment, two twisted wind profiles were simulated in a boundary layer wind tunnel by using 1.5 m tall wooden vanes. The maximum guide angles of vanes were 15° and 30° at the ground level to represent two nominal yaw angles of ‘high’ and ‘extreme’ twisted wind flows. Simulated twisted wind profiles followed the power-law profile and have acceptable longitudinal and lateral turbulence power spectra similar to conventional wind flows. The yaw angle profiles were exponentially decayed with the height but had smaller maximum yaw angles than of the guide vanes. The evaluation of wind conditions near an isolated building and a row of buildings in twisted wind flows has displayed substantially modified flow features such as asymmetric wind speed distributions about the building centre line and reduced wind speeds in the passages between buildings.

1. Introduction

Approaching winds control both the responses of structures and wind conditions in a built-up area. Properties of a wind flow such as wind shear and turbulence, on the other hand, depend on a number of factors including roughness heights, their distributions, the stability of the atmosphere, and significant topographic features of the terrains upstream of built-up areas. It is essential that upstream terrain features and their effects are modelled accurately in order to successfully simulate atmospheric wind flows for wind tunnel tests. However, limited wind tunnel dimensions and constraints of simulation techniques have created some difficulties when replicating atmospheric boundary layer (ABL) wind flows. In response, a number of studies on simulating ABL wind flows in a boundary layer wind tunnel (BLWT) have been carried out.

Simulation techniques and evaluation of similarity between field observations and simulated ABL wind flows have been two main focuses of previous studies. For an example, Lawson (1968) has listed four different techniques including gauzes and honeycombs, rods, flat plates, and obstructions that can be employed to model a turbulent boundary layer in a BLWT. The invention of ‘elliptical wedges’ by Counihan (1969) has become a successful method for replicating ABL wind flows in a BLWT that has a shorter development section. The elliptical wedges have been shown to be effective in simulating wind profiles corresponding to ‘rural’ terrain category and simulated flow properties are comparable with the field measurements of mean wind speeds and turbulent intensities, and turbulence power spectra (Counihan, 1969). Later this method has extended to simulate an urban boundary layer by replicating mean wind speed and turbulence intensity profiles with an acceptable accuracy (Counihan, 1973). However, in some cases, part of the ABL was simulated for wind tunnel tests when test section’s dimensions are not adequate to simulate the ABL fully. Cook (1971) employed a partially simulated ABL for wind tunnel tests and has concluded that modelling of the lower 1/3 of ABL is sufficient for the most of the wind engineering applications. Other than modelling of wind shear and turbulence, the vertical temperature gradient is another important factor to be considered in wind tunnel tests. Although the majority of wind tunnel tests have been conducted under neutral stability, researchers have occasionally simulated both stable and unstable atmospheric stabilities in thermally stratified wind tunnel facilities (Meroney and Melbourne, 1992; Fedorovich et al., 1996; Ohyá, 2001). Furthermore, several researchers (Cermak, 1971; Snyder, 1972; Meroney, 1990) have proposed a set of non-dimensional parameters to satisfy similarity...
criteria in micro, small, and meso scales for a comprehensive simulation of ABL wind flows for wind tunnel tests.

When attempting to replicate the ABL, all of the studies described above have assumed wind direction to be constant along the height of the layer. However, as confirmed by mathematical models (Taylor, 1916; Rossby and Montgomery, 1935) and field observations (Mendenhall, 1967; Peña et al., 2014) natural wind flows vary in directions within the ABL height. This Variation in wind directions is primarily attributed to the combined effects of Earth’s rotation, the friction of the Earth surface, and pressure gradient force (Peña et al., 2014) and, in fact, leads to a spiral-shaped wind profile in the ABL commonly known as the Ekman spiral. The average deviation in wind direction of the Ekman spiral is about 20° but can vary between 10 and 30° under certain conditions within the boundary layer, which usually has a height of 1–1.5 km (Dyrbye and Hansen, 1996). Several other factors, including atmospheric stability, change in terrain roughness, and baroclinity can also cause the wind flows to vary their wind directions at different altitudes (Peña et al., 2014). These changes of wind directions in a wind profile are commonly referred to as the turning of winds (Peña et al., 2014), wind veering (Mendenhall, 1967) or wind twist (Flay, 1996). Although the wind twist is an inherent characteristic of the natural ABL wind flows, they have been ignored in general wind engineering applications due to their relatively smaller directional deviations over the common structural heights of 3–100 m. However, these deviations in wind direction cannot be ignored any longer in designing super tall buildings or gigantic wind turbines as spiral-shaped wind profiles may impose significant asymmetrical loadings on structures (Peña et al., 2014).

Despite the existence of twisted wind flows were confirmed by field observations, fewer attempts have been made to simulate twisted winds in a BLWT. One of the first attempts of employing twisted wind flows in a BLWT is a series of wind tunnel tests done by Professor Richard Flay and his yacht research group from the University of Auckland to evaluate the performance of downwind yacht sail (Flay, 1996). To simulate twisted wind flows, they converted a boundary layer wind tunnel to a twisted flow wind tunnel by installing a set of plastic vanes downstream of the development section of the wind tunnel. The vanes had 600 mm wide chords and spanned from floor to roof of the wind tunnel. The vane system consisted of a number of individual vanes, which were installed in 300 mm spacing across the width of the test section. Desired wind twists were achieved by adjusting the tension of installed horizontal wires at the trailing edges of the vanes. Measured wind flows at different heights indicated some effects from the vane system such as high turbulence intensities and dips of mean wind speeds at regular height intervals (Flay, 1996). These observations suggest the importance of a properly designed vane system and evaluation of flow properties when simulating twisted wind flows in a BLWT. In spite of difficulties that were encountered, promising test results were obtained for evaluating the performance of downwind yacht sails, which also well agreed with numerical simulation data and field measurements (Hedges et al., 1996). The success of use of twisted wind flows in evaluating sail performances lead to construct a couple of twisted flow wind tunnels in Politecnico di Milano, Italy (Viola and Fossati, 2008), and University of Applied Sciences Kiel, Germany (Graf and Muller, 2009) and encourage to conduct comprehensive studies on sail aerodynamics (Izaguirre Alza, 2012).

Encouraging results of the aforementioned studies suggest employing twisted wind flows for wind tunnel tests if twisted winds exist in field conditions. Although twisted wind flows have not been used as a boundary condition, they are frequently observed in topographical wind tunnel tests done in Hong Kong. Those measured wind profiles have displayed different degrees of wind twist ranging from zero to about 40° as shown in Fig. 1. The exceedance probabilities shown in Fig. 1 were calculated from 256 wind profiles extracted from 13 previous topographical wind tunnel tests, which modelled 13 different locations in Hong Kong. The details of tested sites, model descriptions, testing procedures and test results can be found on the official website of the Planning Department, Hong Kong (http://www.pland.gov.hk/pland_en/info_serv/site_wind/index.html). The total wind twist angle (θ_total) employed in Fig. 1 is calculated as the absolute difference between yaw angles measured at the highest and lowest measurement points of a wind profile (Eq. (1)). The yaw angle(θ), which is analogous to wind twist is defined as the angle between the lateral and longitudinal wind speed components as expressed in Eq. (2).

\[ \theta_{\text{total}} = |\theta_{v,\text{low}} - \theta_{v,\text{high}}| \]  
\[ \theta = \tan^{-1} \left( \frac{v}{u} \right) \]  

where, θ_v,low and θ_v,high are measured yaw angles at the lowest and highest measurement points of a wind profile respectively. v and u are the lateral and longitudinal mean wind speed components.

As it can be seen from Fig. 1, total wind twist angles (θ_total) can be as large as 40°, which is approximately the highest wind twist observed in the Ekman spiral. Moreover, about 10% of the measured wind profiles have θ_total values larger than 20° and this percentage increases to 30% when θ_v,low value is limited to 10°. It should be noted that these deviations in wind direction were observed between the lowest and highest measurement points of 25 m and 500 m respectively in the full scale. Larger θ_total values found at lower altitudes suggest that these deviations in wind direction may influence a wind environment more significantly than by the Ekman spiral in the ABL. Moreover, the maximum wind twist angles that were observed near the ground, may have considerable effects on the ‘habitat layer’, where people live and structures reside. The evaluation of influences of twisted wind flows on the habitat layer has a particular importance in Hong Kong, where thousands of tall buildings exist and the near-ground wind environment is a vital concern in urban planning.

Despite the existence of twisted wind profiles in Hong Kong are affirmed by topographical wind tunnel tests, causes and impacts of them have yet to be studied systematically. Particularly the common causes of wind twist such as effects of the Earth’s rotation, roughness of terrain, atmospheric stability, and baroclinity are insufficient to explain observed twisted wind flows in topographical wind tunnel studies because of experiments were conducted (1) in fixed wind tunnel facilities, (2) under the neutral stability condition, and (3) locations where measurements were taken from in different terrains. Therefore, the following section scrutinises the possible causes for observed larger
deviations in wind directions and some issues arisen from the existence of twisted winds on wind engineering applications in Hong Kong.

2. Origin of twisted wind flows and its impacts in Hong Kong

2.1. Topography induced twisted wind flows

Hong Kong’s land, totalling approximately 1000 km² ensembles of a number of small islands and a land mass connects to the Asian continent. An estimated 60% of this land area is covered by mountainous terrain. Due to the scarcity of suitable land for settlement, most of the town centres with numerous high-rise buildings, where most of Hong Kong citizens live, are located near mountains. Wind environments of these towns are subjected wind flows that are modified by the neighbouring mountains. The study done by Cham and Kwok (2011) has demonstrated the influences of mountains on Hong Kong’s wind conditions by the use of data from a number of topographical wind tunnel tests. According to their study, modified profiles of mean wind speed and turbulence intensity were detected even several kilometres downstream from mountain regions. The findings of their study are tallied with previous topographical studies that have revealed that wind flows are modified considerably when passing over mountains (Mickle et al., 1988; Mason and King, 1985; Mason, 1986). It is also true that mountains redirect the wind flow both vertically and horizontally according to how they shaped geometrically. These redirected wind flows are sustained their modified wind directions a considerable distance downstream from topography features (Weerasuriya et al., 2016; Li et al., 2016). Therefore, it is reasonable to assume that commonly found complex terrain is the main cause of the existence of twisted wind flows in Hong Kong rather than other possible sources listed before.

The assumption of topography-induced twisted wind flows in Hong Kong can be further validated by topographical wind tunnel tests’ measurements taken in the vicinities of mountainous areas. Fig. 2 displays such measurements taken at three sites in Sheung Wan, Central Water Front, and Causeway Bay on Hong Kong Island, which are bound by mountains to the south. For ease of reference, measured wind twists are expressed as $\theta_{\text{total}}$ values and are divided into four groups according to the magnitudes. The calculated values of $\theta_{\text{total}}$ are marked by arrows of different colours; a black arrow indicates $0-2^\circ$, red $2-8^\circ$, blue $8-14^\circ$, and green $14-40^\circ$.

As evident from Fig. 2, smaller values of $\theta_{\text{total}}$ ($0-2^\circ$) were observed in the north-east and northwest directions where the wind blew over longer sea fetches. Slightly higher values of $\theta_{\text{total}}$ ($2-8^\circ$) were reported for winds over built-up areas such as over the Kowloon Peninsula in the north. However, in the north, the modified wind directions by buildings may recover partially it’s original flow directions as winds blow over a shorter sea fetch between Kowloon Peninsula and Hong Kong Island (Fig. 2). The most striking feature of Fig. 2 is that significantly larger $\theta_{\text{total}}$ values ($8-40^\circ$) observed for winds approaching from the south where it is mountainous and include several high peaks such as Victoria Peak (552 m), Mount Kellett (501 m), and Mount Gough (479 m). This mountainous region, which detours the wind flows considerably, is the probable reason that highly twisted wind profiles measured at three sites in Central Water Front, Causeway Bay, and Sheng Wan. Most of Hong Kong’s other town centres may also be under the similar influence of topography-induced twisted wind flows as they are located near mountains.

2.2. Problems caused by existence of twisted wind flows

Topography-induced twisted wind flows have significant effects on both structural and environmental wind engineering applications in Hong Kong. For example, twisted wind flows impose asymmetrical wind loads on tall buildings, which have a considerable susceptibility to torsional loading. More significant complications have arisen in environmental wind engineering applications such as assessing pedestrian-level wind conditions or modelling air pollution dispersion in built-up areas. Particularly, wind environmental issues are critical in Hong Kong such as reported undesirable low wind speeds and deteriorating air quality levels in urban areas, which are necessary to be addressed properly (Yim et al., 2009). Wind tunnel tests, which replicate prevailing field conditions, are indispensable in evaluating the aforementioned environmental issues and designing remedial measures. However, the existence of twisted wind flows has introduced several uncertainties to environmental wind engineering applications such as some problems encountered in Air Ventilation Assessment (AVA).

The AVA has established its main objectives as to evaluate possible impacts of new developments on existing wind environments and preserve acceptable near-ground wind conditions in built-up areas (Ng, 2009). The AVA was initiated after the Severe Acute Respiratory Syndrome (SARS) epidemic in 2003, which caused the loss of about 300 lives of Hong Kong citizens. Inadequate ventilation and poor air quality in urban areas were blamed for rapid spreading of SARS and worsening the epidemic in highly populated residential areas (Niu and Tung, 2008). The AVA procedure has been designed to target this specifically; to assure adequate rate of ventilation is available in urban areas by assessing near-ground wind conditions. In order to evaluate near-ground wind conditions, the AVA systematically integrates pedestrian-level wind speeds and wind climate data of Hong Kong. However, the existence of twisted wind flows creates uncertainties of both wind speed measurements and the way combine wind climate data in Hong Kong, thus leading to less accurate test results.

In general, two major uncertainties exist in AVA as a result of twisted wind flows. An issue arises due to varying wind directions of twisted wind flows, which impedes determining approaching wind directions precisely. For an AVA, accurate details of approaching wind directions are essential in calculating the probability of occurrence of winds by the use of wind climate data of Hong Kong. Varying wind directions of twisted wind profiles create dilemmas in determining approaching wind directions, which may subsequently lead to inaccurate calculations of the probability of occurrence of winds. Another uncertainty is caused by the use of conventional wind profiles instead of employing twisted wind flows as a boundary condition for wind tunnel tests. Because a wind environment depends on properties of an approaching wind, a false boundary condition, such as the use of conventional wind flow, may lead to erroneous wind conditions at the site of interest. These false wind conditions may be a source of inaccurate wind speed measurements at the pedestrian level, which

Fig. 2. Total wind direction changes at three sites of Sheng Wan, Central Water Front, and Wan Chai.
in turn cause the AVA to make erroneous predictions. It should be noted that, over the years, researchers have identified these problems that are associated with the AVA and have proposed some remedial measures. One of such correctional methods is to modify the probability of occurrence of winds according to the yaw angle of an approaching wind flow by using statistical methods in the post-analysis. Therefore, the modified probability of occurrence of wind includes the effects of twisted wind profiles on the wind climate data but are unable to account for the direct influence of twisted winds on the near-ground wind speed measurements. The influence of twisted winds on the near-ground wind speeds can only be replicated by the use of twisted wind flows as a boundary condition for pedestrian-level wind tunnel tests. To the authors’ best knowledge, no previous pedestrian-level wind tunnel tests have employed twisted wind flows as their boundary conditions. Therefore, the main objective of the current study is to simulate realistic twisted wind flows in a BLWT that can be adopted for pedestrian-level wind tunnel tests.

This paper demonstrates the simulation of twisted wind profiles in a BLWT, their flow properties, and the use of twisted wind flows to evaluate pedestrian-level wind environments in the vicinities of one of two generic building configurations; an isolated building, and buildings that form a row. Specific details of the employed vane system include its dimensions, the design of its guide vanes including the selected maximum angles are presented in Section 3. Measured flow properties of simulated twisted wind flows are discussed in Section 4 with special references to vertical profiles of mean wind speed, turbulence intensity, and yaw angles. A comparison of turbulence power spectrum and length scales between twisted wind profiles and a conventional wind profile with similar mean wind speeds and turbulence intensities are also presented in Section 4. Section 5 demonstrates altered wind environments near a single building and a row of buildings subjected to twisted wind flows. A number of concluding remarks are presented in Section 6 together with possible future work to scrutinise the altered wind environments resulted from twisted winds and the importance of employing twisted wind flows for wind engineering applications.

3. Simulation of twisted wind profiles in a BLWT

One of the main requirements of simulated twisted wind flows in this study is their similarity to twisted wind profiles that were observed in previous topographical wind tunnel tests. Two features of measured wind profiles: maximum yaw angle and the shape of the vertical profile are employed to simulate realistic twisted wind flows in the current study. In order to understand features of topography-induced twisted wind flows, measured wind profiles in previous topographical wind tunnel tests were analysed comprehensively. These wind tunnel tests were performed at 13 different locations in Hong Kong using a 1:2000 topographic model as a part of AVA tests. At each location, wind profiles were measured in 16 wind directions by using a TFI* series 100 Cobra probe at 9 discrete points in the vertical direction with the lowest and highest measurement heights of 25 m and 500 m in full scale. Measured mean wind speed, turbulence intensity, yaw angle, and pitch angle profiles are presented in graphical and tabular forms in reports that are available on the official website of Hong Kong Government’s Planning Department for public reference (http://www.pland.gov.hk/pland_en/info_serv/site_wind/index.html). For the current study, measured yaw angles profiles were extracted and divided into four groups according to calculated magnitudes of \( \theta_{\text{total}} \) as shown in Fig. 3. These groups were defined to represent ‘negligible’ (0–2°), ‘slight’ (4–8°), ‘high’ (8–16°), and ‘extreme’ (16–32°) wind twist conditions. Moreover, only wind profiles with positive yaw angles were selected for convenience of analysis. It should be noted that negative yaw angles have a similar variation with the height as for the positive yaw angles. Using the curve fitting technique, yaw angle profiles in each group were approximated by a function to represent the vertical variation of yaw angle with height.

As it can be seen from Fig. 3, measured yaw angle profiles (grey lines) have their maximum angles near the ground level and they monotonically decay with the height. Despite different vertical variations of the four groups, measured yaw angle profiles are successfully approximated by exponential functions (black lines) with satisfactory accuracies except for the ‘negligible’ group (0–2°). The exponential function, which estimates the yaw angle at a given height (\( z \)) is defined by Eq. (3);

\[
\theta(z) = \theta_0 \exp(\alpha z/z_0) \tag{3}
\]

where, \( \theta_0 \) is the yaw angle measured at the lowest measurement height \( (z_0) \), and \( \alpha \) is a constant.

According to curve fitting data, the \( \alpha \) value varies from \(-0.058\) to \(-0.181\) for the four wind twist groups. Nevertheless, \( \alpha \) value approximately remains constant at \(-0.10\) for larger \( \theta_{\text{total}} \) values (8–32°) belonging to ‘high’ and ‘extreme’ wind twist conditions. Compared to higher correlation coefficient \( R^2 \) of fitted curves in groups with larger \( \theta_{\text{total}} \) values, the calculated \( R^2 \) value is smaller for wind profiles with \( \theta_{\text{total}} \) less than 4°. The lower \( R^2 \) value of ‘negligible’ wind twist group is not a significant drawback of the exponential function approximation because smaller \( \theta_{\text{total}} \) values indicate a relatively constant wind direction with the height that is similar to as in conventional wind profiles. The success of approximation of exponential function in estimating the vertical variation of yaw angle with the height leads adopt a similar exponential function to design profiles of guide vanes for the current study.

Fig. 4 shows the wooden vanes employed for the current study. The vanes are 1.5 m tall and were fabricated using 1 m long and 0.3 m wide laminated wooden strips. The guide vanes were created such that the wooden strips were glued together with small offsets to each other. The leading edge of a vane is straight and the trailing edge is curving to form guide angles as displayed in Fig. 5. The shapes of guide vane follow an exponential function similar to Eq. (3) with two \( \theta_0 \) values of 15° and 30° and an \( \alpha \) value of \(-0.05\). The maximum guide angles of 15° and 30° were selected to represent ‘high’ and ‘extreme’ wind twist conditions as observed in topographical wind tunnel tests. The guide angle is maximum at the ground level and gradually decreases to 0° at 1 m height. The rest of the 0.5 m height consists of a straight wooden board, which is used to prevent unwanted eddies created by edges of vanes reaching to the test area on the turntable.

The manufactured vanes were installed in the Wind and Wave Tunnel Facility (WWTF) of the Hong Kong University of Science and Technology (HKUST) to simulate twisted wind flows. The WWTF is a state-of-art-closed circuit type wind tunnel with two test sections named ‘high-speed’ and ‘low-speed’ based on operating wind speeds ranges. The ‘high-speed’ section, which is 29.2 m long with a cross section of 3×2 m², can operate under the maximum wind speed of 25 ms\(^{-1}\). The ‘low-speed’ section has larger test section dimensions of 41×5×4 m³ for length, width and height respectively. Maximum operating wind speed in the low-speed section is about 10 ms\(^{-1}\). The ‘low-speed’ section was selected to conduct all wind tunnel tests described in this paper due to its larger test sections dimensions. The larger test section may reduce flow reflections from the side walls of wind tunnel after installing the vane system.

Fig. 6 displays the installed vane system 4 m upstream of the centre of the turntable in the ‘low-speed’ section (TB1). The vane system consists of five individual vanes fixed in a row across the width of the test section with 0.75 m spacing between two adjacent vanes. The 1 m×1 m grid as shown in Fig. 6 (marked with dashed lines) was used to evaluate flow consistency of simulated twisted wind flows because (1) the vanes may affect the wind flow by reducing wind speeds and/or increasing turbulence levels, and (2) flow properties can vary in both the longitudinal and lateral directions in the test section. Another purpose of flow property assessment was to select an area with consistent flow properties to conduct pedestrian-level wind tunnel tests later. In order to assess simulated wind flows, wind profiles were
measured at each grid point of the 1 m×1 m grid by using a TFI® Series 100 Cobra probe. The Cobra probe is a dynamic multi-hole pressure probe, which is capable of measuring three components of mean and fluctuating wind speeds including turbulent intensities and static pressure. The frequency response of this instrument is 0–2000 Hz and can measure wind speeds from 2 ms⁻¹ to 100 ms⁻¹ with an accuracy of ± 0.5 ms⁻¹, which is sufficient for measuring turbulent flows inside a BLWT. Additionally, a Cobra probe can measure yaw and pitch angles of wind flows approaching within angles of ± 45° and have a measurement accuracy of ± 1°. At each grid point, mean wind speed, turbulence intensity, and yaw angle were measured at 12 discrete points in the vertical direction. The discrete points at heights of 10, 30, 50, 100, 150, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 mm were pre-set by using a 1-dimensional traverse system, which has an accuracy of ± 1 mm at any given height. For the evaluation process, measurements were taken for 130 s at a frequency of 2000 Hz at each height. The measurements in the wind tunnel replicated the wind speeds recorded over an hour in the field condition.

4. Flow properties of simulated twisted wind profiles

Mean wind speeds, turbulence intensities, and yaw angles at each grid points were compared with corresponding measurements at neighbouring grid points to assess the consistency of flow property. It was found that flow properties initially varied in both longitudinal and lateral directions until they have reached a state of uniformity in the vicinity of the centre of the turntable. Specifically, measured wind profiles within an area of 2×2.5 m², whose centre is 0.75 m downstream of the centre of the turntable (shown as a shaded area in Fig. 6)
had consistent flow properties, which are also suitable under to conduct wind tunnel tests. The measured vertical profiles of mean wind speed, turbulence intensity, and yaw angles at 5 different locations on the longitudinal and lateral axis of the turntable are shown in Figs. 7 and 8 for the vanes with maximum guide angles of 15° and 30°, respectively. Those five points are at the centre of the turntable (Point-A), 1 m left of the centre of the turntable (Point-B), 1 m upstream of the centre of the turntable (Point-C), 1 m right of the centre of the turntable (Point-D), and 2 m downstream of the centre of the turntable (Point-E).

According to Figs. 7(a) and 8(a), it is clear that the measured mean wind speed and turbulence intensity profiles are approximately similar at five points except minor deviations observed at two locations in the lateral directions. However, yaw angle profiles moderately deviated at five locations as seen from Figs. 7(b) and 8(b). In general, there is a slight decay of magnitude of yaw angles along the longitudinal direction while larger deviations can be observed in the lateral direction. Furthermore, the deviations in yaw angle are increased with the maximum guide angle of vanes such that relatively larger yaw angle differences are observed for a vane system with maximum guide angle of 30° compared to that for vane system with maximum guide angle of 15°. Another noticeable difference in the measured yaw angle profiles is their smaller maximum angles compared to the maximum guide angles of vanes. The maximum measured yaw angles are 13° and 22° for the vanes with maximum guide angles of 15° and 30° respectively.

In spite of different profile shapes and maximum yaw angles, simulated twisted wind flows have similar flow characteristics to twisted wind profiles that were observed in previous studies. As shown in Fig. 9, a linear relationship between the longitudinal ($u$) and lateral ($v$) mean wind speed components has been identified from the simulated twisted wind profiles similar to that was recognized by Weerasuriya et al. (2016), Li et al. (2016) for topography-induced twisted wind flows. The negative gradient of the linear relationships of $v/u$ with the normalized height ($z/z_0$) implies smaller magnitudes of $v$ compared to larger $u$ values at higher altitudes. Because $\tan^{-1}(v/u)$ values are analogous to yaw angles, smaller $v$ and larger $u$ values indicate decay of yaw angles with the height, which is also tallied with the observations from previous topographic wind tunnel tests.

The measured wind profiles at the centre of the turntable were selected as representative profiles for twisted wind flows generated by two sets of vanes. Despite the differences of yaw angle profiles, both twisted wind profiles had similar wind speed and turbulence intensity profiles at the centre of the turntable. Fig. 10(a) shows one set of normalized wind speed and turbulence intensity profiles of simulated twisted wind flows. For the purpose of comparison, a conventional wind profile was simulated with similar mean wind speed and turbulence intensity properties to twisted wind profiles. To replicate similar flow properties for the conventional wind flow, roughness blocks were arranged upstream of the turntable. The simulated conventional wind profile has followed the power-law wind profile model with the power-law exponent of 0.11 as shown in Fig. 10(a). Measured mean wind speed and turbulence intensity at the normalized height of 600 mm are about 7.9 ms$^{-1}$ and 5.7% respectively. Measured yaw angle profiles at the centre of the turntable are shown in Fig. 10(b). For reference, the two twisted wind profiles are named as TWP13 and TWP22 according to maximum yaw angles of 13° and 22° measured at the centre of the turntable. Similarly, the conventional wind profile with zero wind twist is referred to as CWP.

Apart from mean wind speed and turbulence intensity profiles, turbulence power spectra have been frequently used to evaluate simulated wind profiles in a BLWT (Armit and Counihan, 1968; Counihan, 1973; Cook, 1973). Since the energy distributions of wind flows have significant influences on structural responses, it is necessary
to assess turbulence power spectra of simulated twisted wind flows before them adopted for wind tunnel tests. Fig. 11 shows the non-dimensional along-wind turbulence power spectra calculated for the three simulated wind flows. The along-wind turbulence power spectrum ($R_n(n)$) was calculated according to Eq. (4) using the along-wind turbulent wind speed measurements ($U$) taken for 130 s at a height of 600 mm at the centre of the turntable.

$$R_n(n) = \frac{nS_u(n)}{\sigma^2_u(n)}$$

where, $n$ is the frequency in hertz, and $S_u(n)$ is the power spectrum for the along-wind turbulent component and $\sigma_u$ is the fluctuating wind speed in the along-wind direction.

The calculated along-wind power spectra were compared with the Von-Karman spectrum model and found a better agreement for all three wind flows. However, the peak of the power spectrum slightly moved to a higher frequency for twisted wind profiles, particularly for TWP22. The shifted peaks of twisted winds may have resulted from distorted flow fields due to the installation of vane systems upstream of the turntable. The length scales ($L_n$) were moderately decreased with the maximum wind twist angle such that the calculated $L_n$ value was 0.27 m for CWP but it reduced to 0.25 m and 0.21 m for TWP13 and TWP22 respectively. Similarly, across-wind turbulence power spectra were calculated for both conventional and twisted wind flows as shown in Fig. 8. The peak of across-wind turbulence power spectra has also shifted to higher frequencies in twisted wind flows similar to the along-.
5. Pedestrian-level wind environments in twisted wind flow

The simulated twisted winds were employed to evaluate the pedestrian-level wind environments around an isolated building and a row of buildings. These generic building models were selected as two fundamental studies because of (1) wind conditions near a single building and a building array have been studied for a long time and well documented, and (2) altered flow features resulted from twisted wind flows are easy to identify from less complex flow fields around generic buildings. Therefore, in order to demonstrate the modified flow features in twisted wind flows, pedestrian-level wind environments around a building and a row of buildings are presented in the following section.

The selected models represent tall buildings with dimensions of 120×30×20 m$^3$ (height×width×depth) in full scale. The fabricated building models according to the 1:200 length ratio have dimensions of 600×150×100 mm$^3$ in model scale. The building array consists three similar buildings located 50 mm apart from each other to replicate 10 m wide passages between buildings in full scale. All models were tested in three approaching wind flows; TWP13, TWP22, and CWP. The resultant pedestrian-level wind environments were assessed by the measured mean wind speed at 10 mm height, which represents 2 m measurement height in full scale according to the 1:200 length ratio. Mean wind speeds were measured by installing about 200 Irwin sensors surrounding building models. The wind speeds were recorded for 130 s in the wind tunnel tests, which was comparable to one hour measurement time in field conditions. It was found that the wind speed measurements of Irwin sensors had mean and maximum differences of ± 0.12 ms$^{-1}$ and ± 0.27 ms$^{-1}$ with respect to the simultaneous wind speed measurements of a hot-wire anemometer for a wide range of wind speeds and turbulence intensities. For the analysis, measured mean wind speeds were first converted to the normalized
mean wind speed ratio (K) (Eq. (5)) and then constructed contours by connecting similar K values by using the cubic interpolation method. Figs. 13 and 14 display the contour (hereafter referred to as K-contours), which cover measurement points within distances of 375 mm upstream, 1425 mm downstream, 600 mm in the lateral directions from the centre of the turntable (TB2).

\[ K = \frac{V_{10\text{mm},x,y}}{V_{10\text{mm},x,y,\text{ambient}}} \]  

(5)

where, \(V_{10\text{mm},x,y}\) is the mean wind speed measured at 10 mm height at location \((x, y)\), and \(V_{10\text{mm},x,y,\text{ambient}}\) is the mean wind speed at the same location but in the absence of the building. The ambient mean wind speed was about 5.92 m\(s^{-1}\) with \(\pm\) 15% difference in any location of the measurement area.

Fig. 13 displays K-contours around the isolated building for conventional and two twisted wind profiles. Red arrows shown at the upstream edge of figures indicate the direction of approaching wind flows as measured at 10 mm height. All the distance shown in contour figures are normalized with respect to the building depth (20 m) and centre of the building is considered as the origin. There are several modified flow features that can be identified from K-contours in twisted winds (Fig. 13(b) and (c)) compared to K-contours of CWP (Fig. 13(a)). The asymmetric distributions of K value are the most noticeable flow modification in twisted winds compared to the symmetric K-contours.

Fig. 13. The distributions of K around a 120×30×20 m\(^3\) building in (a) CWP, (b) TWP13, and (c) TWP22.

Fig. 14. The distributions of K around a row of buildings with three 120×30×20 m\(^3\) buildings and 10 m wide passages in (a) CWP, (b) TWP13, and (c) TWP22.
in CWP about the building centre line. The asymmetric distribution of K value was attributed to a number modified flow features in twisted winds such as (1) the deviation of Downstream Far Field Low Wind Speed (DFLWS) zone from the building centre line, (2) dissimilar Corner Streams (CS) with a stronger left side corner stream compared to the right side corner stream, and (3) inclination of the Upstream Near Field Low Wind Speed (UNFLWS) zone to the direction of the approaching wind. Moreover, it is clear from Fig. 13 that these flow differences were intensified with the wind twist angle of approaching wind flows such as a larger deviation of the DFLWS zone was observed for TWP22 than for TWP13. These altered flow features are important in evaluating pedestrian-level wind environments in built-up areas, where the existence of twisted wind flows is evidenced. For example, less strong corner streams in twisted wind flows may reduce the risk of occurrence of unpleasant or dangerous wind conditions near building corners and subsequently lower the requirement of remedial measures than predicted by CWP for larger high-speed wind zones.

Fig. 14 displays mean wind speed distributions near a 120 m tall building array, which has two 10 m passages among buildings. Compared to the symmetric wind environment in CWP, the distributions of K values were asymmetric near the building array in twisted winds. As for the isolated building, the surrounding wind environment of the building array had modified flow features, which were intensified with the wind twist angle. For example, the DFLWS zone deviated from the centre line of the building array such that the higher deviation was observed for TWP22 than for TWP13. Similar flow modifications observed in Figs. 13 and 14 depict that the similar influences of twisted wind flows are on the pedestrian-level wind environment regardless of the type of building configuration. The reduced wind speeds in passages are another striking feature can be identified from Fig. 14 for twisted wind flows. The wind speeds in passages are important in evaluating wind conditions within a building array as passages are notorious to create high-speed wind jets at the pedestrian level. Therefore, more accurate wind speed data on the surrounding of a building array can be obtained from a wind tunnel test by the use of twisted wind profiles than employing conventional wind profiles.

6. Concluding remarks

Two twisted wind profiles were simulated by using a novel vane system in a BLWT to conduct pedestrian-level wind tunnel tests. The vane system consisted of 5 individual 1.5 m height wooden vanes. The guide angles of vanes were designed to replicate the observed yaw angle profiles in previous topographical wind tunnel experiments. The profiles of guide angles followed an exponential function with height and had the maximum guide angle at the ground level. Two maximum angle guides of 15° and 30° were selected to represent wind twist conditions of ‘high’ and ‘extreme’.

The simulated twisted wind profiles were measured at a 1 m × 1 m grid to assess the consistency of flow properties. The assessment confirmed similar profiles of mean wind speed and turbulence intensity at grid points but yaw angles displayed some deviations in two orthogonal wind axes. The differences of measured yaw angles were insignificant in the longitudinal direction and were moderate in the lateral direction of the wind tunnel test section. Based on the assessment, an area of 2 × 2.5 m² around the centre of the turntable had relatively consistent flow properties and selected as the measurement area for pedestrian-level wind tunnel tests. The wind profiles measured at the centre of the turntable were selected as representative wind profiles for the simulated twisted wind flows. All representative wind profiles followed the power-law wind profile model with the power-law exponent of 0.11. The measured turbulence intensity profile has the maximum value about 16% at 10 mm height. The measured maximum yaw angles at the centre of the turntable were 13° and 22° at 10 mm height for the vanes with maximum guide angles of 15° and 30°, respectively. The along-wind and across-wind turbulence power spectra of twisted wind flows well agreed with the simulated conventional wind profile with similar mean wind speeds and turbulence intensities.

Simulated twisted wind flows were employed to assess the surrounding wind environments of an isolated building and a row of buildings. The wind environments in twisted wind flows were asymmetric due to the significant flow feature differences such as the deviation of DFLWS zone from the building centre line, dissimilar corner streams, and reduced wind speeds in the passages between buildings. Those flow modifications were completely absence in the wind environments in the conventional wind flow and thus the wind distribution was symmetric about the building centre line. In order to understand the effects of twisted winds on the pedestrian-level wind environments, it is proposed to conduct a series of wind tunnel tests on generic building configurations such as isolated buildings and rows of buildings using twisted wind profiles.

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