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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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A B S T R A C T

Topography-induced twisted wind flows 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; Ohya, 2001). Furthermore, several researchers (Cermak, 1971; Snyder, 1972; Meroney, 1990) have proposed a set of non-dimensional parameters to satisfy similarity

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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 inherited 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 attempt 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). Notably, most of the wind profiles had their maximum yaw angle at the lowest measurement point near the ground surface and minimum yaw angle at the highest measurement altitude. Few measured wind profiles displayed maximum yaw angles in the middle of the wind profile.

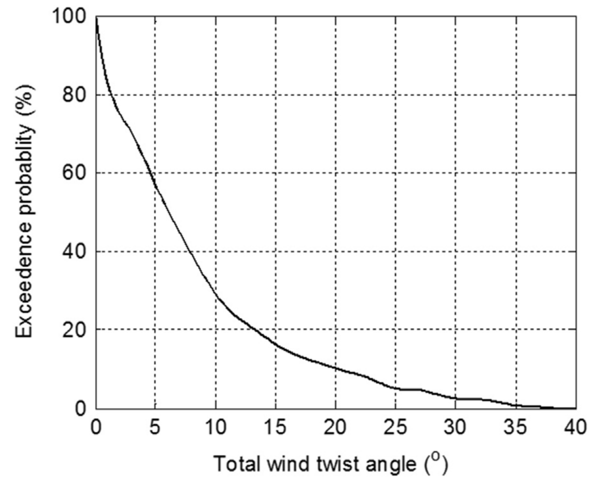

Fig. 1. Exceedance probability of total wind twist angle of 256 measured wind profiles.

$$\theta_{total} = |\theta_{z,low} - \theta_{z,high}| \quad (1)$$

$$\theta = \tan^{-1}\left(\frac{v}{u}\right) \quad (2)$$

where, $\theta_{z,low}$ and $\theta_{z,high}$ 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_{total} 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