Skewed Wind Flows and the Performance of Wind Energy Devices on Rooftops: A Review

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Abstract—**Currently the development of wind energy devices, either the horizontal or vertical axis wind turbines, are mainly focused on the use of orthogonal wind flows to generate on-site power. However, in an urban environment, the vertical axis wind turbine is thought to be better suited for building integrated applications due to its durability and better performance in skewed and turbulent flows compared to the more common horizontal axis wind turbine. Application of wind turbines in skewed flow is a subject of increasing interest due to the improved power output of turbines in this wind condition. Skewed flow in the built environment can be referred to as the deflected wind vector at a roof that is not horizontal. Therefore, there exists a potential for better diffusion of renewable energy in the urban built environment, especially in the implementation of vertical axis wind turbines on rooftops. This study provides a critical review of the skewed wind flow phenomena, the physical characteristics of the interaction between the skewed flow with the vertical rotor, and the state-of-the-art studies of wind energy devices in skewed flow, especially in the built environment.**

Keywords—Wind energy; Urban energy; On-site power generation

I. INTRODUCTION

Developments on small wind turbines in urban areas have gained much attention due to the rising concern in global energy issues. Wind energy is recognised as a potential source of free, clean and inexhaustible energy, especially for use in urban cities where it is urged to place wind turbines closer to populated areas due to the decreasing number of economic sites [1]. A wind turbine is a device that converts energy from the wind into electrical power that can be used for various applications. Wind farms use large horizontal axis wind turbines (HAWTs) with long blades. These larger wind turbines generate noise and vibration that are not suitable for urban use. In recent years, small vertical axis wind turbines (VAWTs) have been employed in urban areas for local off-grid applications.

It is widely known that the lower efficiency of the VAWT compared to the HAWT is due to the highly unsteady operating conditions of the VAWT at all wind speeds caused by the periodic variation of the rotor and the direction of the apparent

wind velocity perceived by the blades [2]. Moreover, as the VAWT rotates, the interactions between wakes shed by the blades rotating in the upwind and downwind regions of the rotor causes dynamic and reliability issues in which the blades have to go through a dynamic stall in every revolution [3], [4]. Intrinsically, the understanding of the aerodynamic phenomena manifested in VAWTs presents challenging tasks for researchers to thoroughly understand the complex fluid mechanics of such devices to estimate their performances [5]–[8]. Furthermore, new concepts of vertical axis wind energy devices are being introduced to overcome the disadvantages of the conventional design of VAWTs. Some of these wind turbine concepts are being adopted in the design of the building [9], [10] or mounted on top of a building for maximum exploitation of wind energy [11].

The complex nature of urban winds requires wind turbines that are designed to receive the wind from various directions. Moreover, urban winds are erratic, insubstantial and inconsistent due to the many obstacles (e.g. buildings and other obstructions), creating blockages that can reduce wind turbine performances [12]. Hence, necessitating wind turbines with excellent self-starting characteristics [13]. For a wind energy generation system to be installed in urban areas, several factors need to be considered, i.e. blade failures, noise levels, visual impacts, structural issues, and electromagnetic interference [14]–[16]. Recent investigations on Darrieus vertical axis wind turbines, however, showed that in some cases the behavior of the rotors performed better than a horizontal axis wind turbine in misaligned flow conditions (airflow parallel to the vertical axis of the rotor), though this varies on the design and geometry of the turbine rotor [17]–[20].

II. SKEWED WIND FLOW OVER BUILDINGS

Diffusion of wind energy technology, in particular, small vertical axis wind turbines can effectively be exploited for on-site power generation in the built environment. Theoretically, small wind turbines can be placed on top of buildings to harness a larger potential of wind energy due to the higher zone of wind profile, which is usually exploited by a large horizontal axis wind turbine (Fig. 1). The atmospheric boundary layer is the lowest part of the atmosphere that contains most atmospheric gases and humidity [21]. From a climatological viewpoint, the urban atmosphere has been considered as a boundary layer over a fully rough wall which consists of

several layers, including a roughness sublayer and an inertial sublayer [22]. Within the inertial sublayer, vertical profiles of environmental variables such as velocity have been known to satisfy the similarity theory characterised by several aerodynamic parameters including the roughness length and displacement height, which depend on urban geometry [23]. The accurate estimation of aerodynamic parameters of rough urban surfaces, roughness length and displacement height is important for prediction of airflow, dispersion of pollutants, and other atmospheric phenomena [24]. These parameters directly affect the wind flow patterns in the respective area, which alter the surrounding wind environment. The wind profile in the internal boundary layer of urban locations is, in fact, different from the classical profile as shown in Fig. 1 [25]. This figure shows how buildings as the solid bodies slow the wind near to the ground and increase the turbulence in the wind.
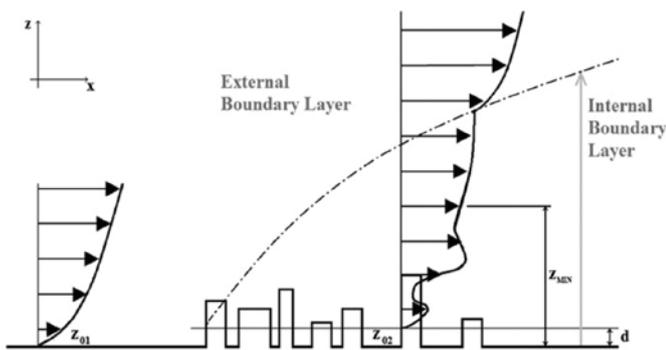

Fig. 1. Wind profile visualisation in the internal boundary layer of a built environment [25].
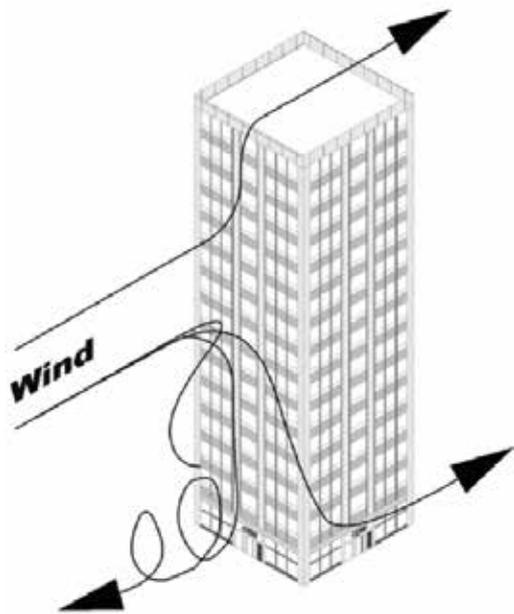

Fig. 2. Simplified sketch of wind flow around a tall building [26].

The boundary layer separates at the windward edge of the building, and the flow forms a separation bubble on the outer surface below the streamlines above the surface [17]. Approaching a solid obstacle, the separation bubble makes an angle to the velocity vector with the building's surface (Fig. 2). This angle is subsequently referred to as the skew angle. The wind is either rising flow up vertical surfaces or toward the prevailing wind direction on building corners or ridges.

Several studies have shown that the Darrieus type VAWT's power output increases while operating in skewed flow condition [18], [19]. This is mainly due to the possibility of increased projected swept area based on the cosine angle of the skewed flow. However, further investigations must be carried out to determine the exact parameters and variables related to the performance of a VAWT in skewed wind flow, i.e. airfoil profile, geometric ratios, turbine design structure, etc.

III. APPLICATION OF WIND ENERGY DEVICES IN SKEWED FLOW

The lift and drag coefficient of an airfoil blade are the major parameters that determine its aerodynamic performance. These coefficients vary with every angle of attack (AOA) of the airfoil blade. The AOA is a term used in wind turbine design to describe the angle between the chord line of an airfoil and the oncoming wind flow. Lift coefficient, C_L is the factor that contributes to the elevation of the blade (lift is always perpendicular to the wind flow). Drag coefficient, C_D is used to quantify the drag, i.e. the resistance of an object in the air. These dimensionless units are expressed in the following equations:

$$C_L = F_L/(0.5\rho A V^2)$$
$$C_D = F_D/(0.5\rho A V^2)$$

where F_L and F_D is the lift and drag force respectively. Fig. 3 shows the pressure distribution on an airfoil. The AOA of an airfoil controls the distribution of pressure above and below it. An airfoil at positive AOA develops negative pressure on its upper surface and positive pressure below it. The result of this pressure difference creates lift. Whereas, an airfoil at negative AOA develops negative pressure on the upper and lower surfaces of the airfoil, and positive pressure at its leading edge. This leads to the separation of flow at its trailing edge resulting in higher resistance or drag. Aerodynamic performance is fundamental for efficient rotor design. The lift-to-drag ratio is the amount of lift generated by the airfoil over the aerodynamic drag that it creates while moving through the air. A higher value of C_L/C_D ratio is more favourable as the higher lift with lower drag leads to a better performance of wind turbine. Traditionally, the airfoil is tested experimentally with tables correlating lift and drag at given AOA and Reynolds numbers. Wind turbine airfoil designs have been adapted from aircraft technologies with similar Reynolds numbers and section thicknesses that are suitable for conditions at the blade tip. However, due to the differences in operating conditions and mechanical loads, special considerations should be made for the design of wind turbine specific profiles and in low Reynolds number regime.
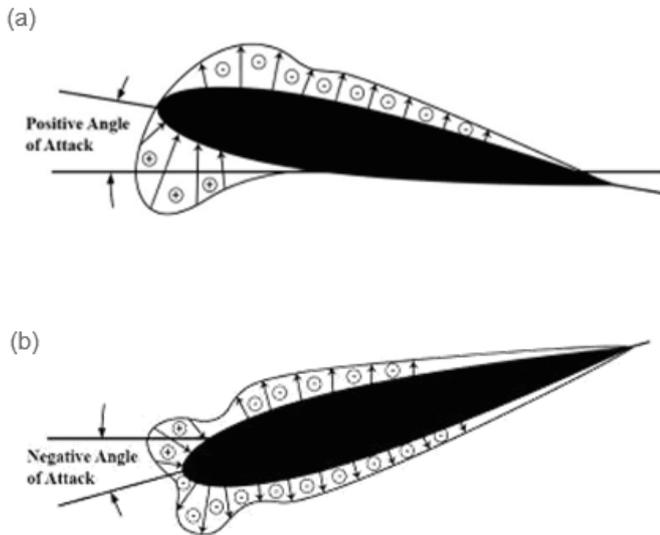
Fig. 3. (a) An airfoil at positive angle of attack, (b) at negative angle of attack.

Fig. 4. Wake characteristics during aligned (normal) flow [29].

Fig. 5. Wake characteristics during skewed flow [29].

During the rotational movement of airfoils, the passing airfoils will encounter the wake of the previous passing airfoils as they move to the downwind region of the wind turbine rotor (azimuth angle between 180° to 360°). In an aligned flow, the whole length of each airfoil is exposed to the wake of the turbine in the downwind region of the rotor (see Fig. 4). In misaligned flow, the convection of the wake follows the skew angles of the oncoming flow (as shown in Fig. 5), therefore allowing the undisturbed portion of the skewed flow to interact with some parts of the downwind airfoil blades. The resultant effect, and in comparison, between these two flows, are in the tangential force produced by each of the airfoil blades.

In normal flow, the interaction between the wake and the blades in the downwind region suppresses the potential torque due to the turbulent and low Reynolds number condition of the downwind wake. Therefore, the airfoil blades in the upwind region of the rotor produce much of the torque output. In skewed flow, however, the undisturbed portion of the downwind wake that interacts with each of the airfoil blades contributes to the overall increase of rotor power output. Hence, the skewed flow condition presents a significant impact on the overall performance of the turbine.

IV. WIND ENERGY DEVICES ON ROOFTOPS

Recent studies have shown that the progress of vertical axis wind turbine (VAWT) should be focused on optimisation of the struts' shape and configuration, as the supporting structures can influence the performance of wind turbine rotors, particularly in small wind turbines [27]. Airfoil-shaped struts can reduce the parasitic drag commonly found in normal struts and produce additional torque from the lift force of the airfoil struts. Some suggest that the airfoil struts in skewed flow conditions can further increase the performance of the wind turbine [28]. However, many of the current research work only deal with the conventional wind turbine in skewed wind flow conditions.
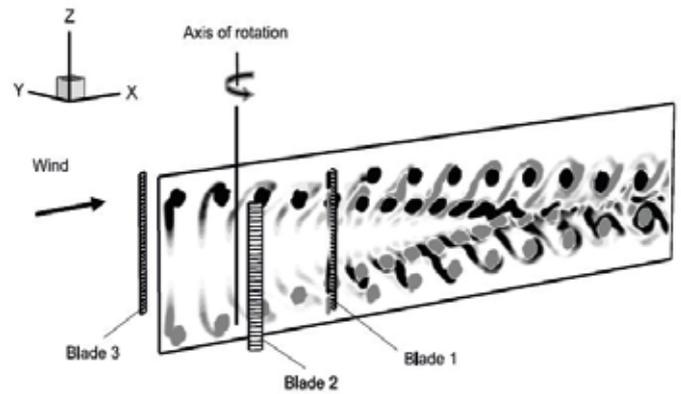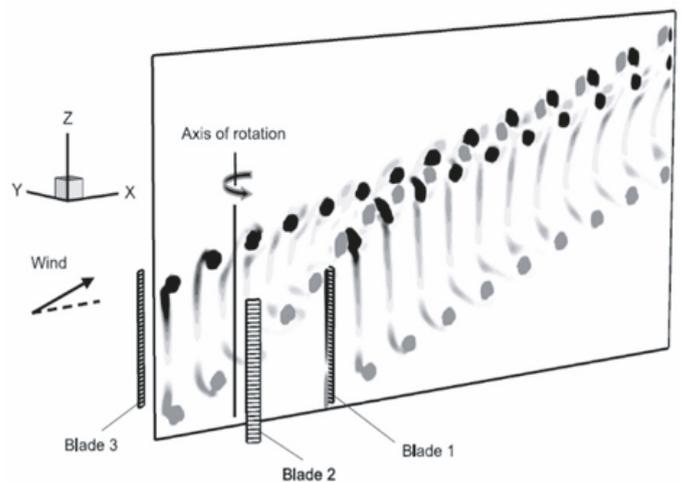
Ferreira [20] showed that with normal flow, the characteristics of the flow in and around the rotor, and in the wake, are mostly influenced by the upwind passage of the blades. Therefore, the downwind region of the VAWT operates in the wake of the upwind half of the rotor which results in reduced energy potential. The stronger vorticity in the upwind area of the VAWT (due to higher lateral wind loading) generates wake and alters the downwind stream which saw the loss of energy potential in the downstream position [30]. Similar observations were made by Balduzzi et al. [31] who carried out computational fluid dynamics (CFD) studies on different roof shapes with different geometrical proportions. The results showed that the power output from the VAWT increased by up to 12% for skew angles between 15° to 30°. In another study, Orlandi et al. [32] developed an unsteady RANS 3D approach to predict the performance of an H-rotor VAWT in skewed flow conditions. Comparable observations were made, in which the improvement of power potential produced by the VAWT in skewed flows are due to the reduced disturbance in the wake generated during the upwind phase.

In the urban context, wind turbines operate close to the wakes induced by buildings that may cause skewed flow conditions. In investigating the performance of an H-Darrieus performance on a roof, Mertens et al. [17] had shown that the rotor power output increased by 30% when the rotor was exposed to 10°-40° skewed angle wind flow. Mertens et al. suggested that in skewed flow conditions, the lift and drag forces generated by the airfoils depend only on the orthogonal component of the oncoming wind velocity, whereas the parallel component contributes to the zero effect on the surface of the airfoils. This is known as the cross-flow principle, which describes the wind speed interacting with the blades of the vertical rotor in skewed flow to become a function of both the induction factor of a stream tube and the skew angle. Lee et al. [33] investigated the influence of the vertical wind and wind direction on the performance of a small VAWT on the rooftop of a building. Their study showed that the vertical wind coming off from the sides of the building greatly influence the power output of the VAWT, in which 90% of the power was generated when the vertical angle is less than or equal to 45°, and when the horizontal wind speed is between 5 m/s and 8 m/s.

In normal flow, a lower height-to-radius (H/R) ratio turbine has a slightly lower aerodynamic efficiency due to the lower aspect ratio (AR) of the blades. This is the fundamental reason for the lower performance of turbines with small AR. From the swept-wing theory [34], the vertical component of the oncoming wind that is parallel to the VAWT axis has no aerodynamic effects on the turbine. Therefore, the performance of the turbine in skewed flow is strictly influenced by the cosine angle of the oncoming velocity, with an increased effective tip speed ratio. Findings from the literature showed that the performance of the VAWT in skewed flow conditions could be further improved. However, this depends on the design and geometry of the rotor, and limited range of skew angles. In a skewed airflow, it was shown that the VAWT with the smallest H/R ratio could generate a higher power output than the other turbines with larger H/R ratios, especially at higher tip speed ratios [29] (see Fig. 6).

The effect of skewed wind flows, and the resultant wakes is more significant in the higher tip speed ratio of the turbine. After the vortex filaments are shed by the blades, a coalescence of vorticity in the immediate surroundings of the blades in the downwind cycle was observed [35]. This coalescence enhanced the influence of the wake to improve the load produced by the blades during their passage downwind of the rotational axis of the turbine. At higher tip speed ratios, the convection of the wake relative to the motion of the blades is slower than at low tip speed ratios and the coalescence of the vorticity is more noticeable. At lower tip speed ratios, the effect of the coalescence did not take place due to the wake being swept away from the rotational trajectory of the blades, therefore reducing the influence of the wake on the loads produced by the blades. Therefore, the improved performance of the VAWT in skewed airflow is due to the wake convection that covers a larger area in the downstream and upstream regions of the rotor.
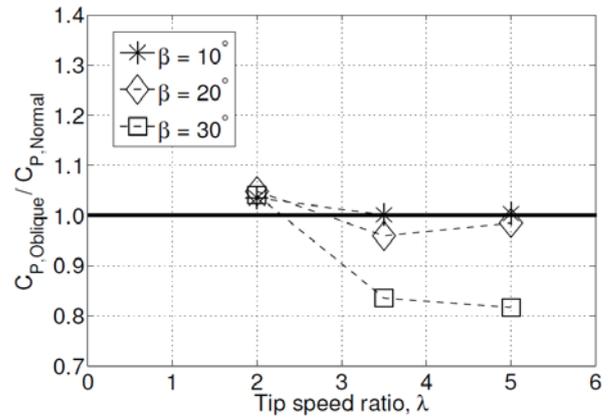
(a) $H/R = 3.0$
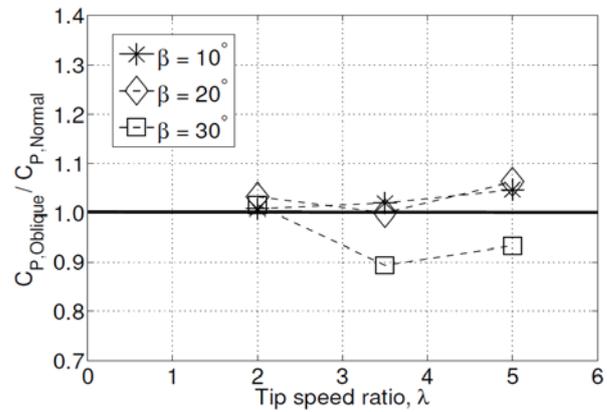
(b) $H/R = 2.1$
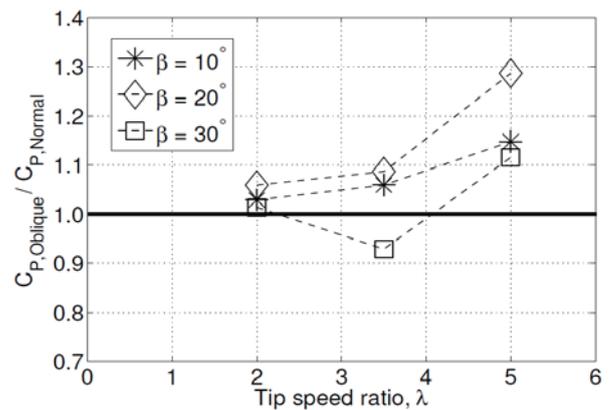
(c) $H/R = 1.2$

Fig. 6. Vorticity Transport Model prediction of VAWT performance with different H/R ratios in various skewed flows[29].

V. CONCLUSION

There is increasing attention to the performance of wind turbines in skewed wind flow. Normally, the expected flow conditions are parallel to the rotor axis of the HAWTs or perpendicular to the VAWTs. Experimental and numerical investigations on VAWTs showed that the power output was increased in skewed flows, depending on the geometrical ratios

of the rotor. In the varying interaction between the blades and the oncoming flow volume, the blades of the vertical rotor describe a cylindrical volume, different from the planar surface generated by the horizontal rotor. Therefore, the total swept area of the vertical rotor is increased, mostly due to the contribution of the skewed flow in the downwind region that balances the decrease of the projected upwind area. Hence, the misaligned flow interacts with an increased available surface area of the rotor. Also, the increased swept area may be due to the expanded airflow in the downwind region of the rotor. If the aspect ratio of the vertical rotor is sufficiently small, the skewed convection of the wake could cover a larger surface area in the downwind and upwind regions of the rotor. Therefore, the interaction between the skewed airflow and the blades of the vertical rotor could potentially generate more lift, hence producing higher torque and better power output. The study has shown that the Darrieus vertical axis wind turbine has the potential for the built environment due to the effect of the skewed wind flows. Evidently, the remarkable outcome of many of the studies has illustrated that the VAWT can generate a higher power output in skewed flow, compared to VAWT in normal flow. To optimise the siting of VAWT on top of rooftops, it is recommended that wind profile studies must be carried out to determine the best placement of VAWT in skewed airflows. This is to ensure that the performance of the VAWT can be maximised, and therefore the diffusion of wind energy technology in the urban environment can be more efficient.

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