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# The influence of flow field and aerodynamic forces on a straight-bladed vertical axis wind turbine

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ABSTRACT

This paper has attempted to compile the assessment of flow field and aerodynamic forces acting on a small straight-bladed vertical axis wind turbine (VAWT). Two dimensional unsteady flows around the VAWT, operating at three different tip speed ratios in a wind tunnel, were investigated through the use of a Laser Doppler Velocimeter (LDV) system. Furthermore, in order to explicate the characteristics of aerodynamic forces, pressures acting on the blade surface were measured during the rotation by a multiport scanner mounted on the hub and pressure signals were transmitted to the stationary system through a wireless LAN. Velocity distribution proved the wind velocity deficit. While, the geometrical angle of attack and resultant flow velocity change periodically due to local wind velocity and direction depending on the azimuth angle. The power coefficient, tangential force, lift and drag which are obtained by pressure distribution are discussed as a function of blade azimuthally position, achieving a numerical quantification of the influence of tip speed ratio on overall rotor performance. As a result, it is clarified that aerodynamic forces show the maximum values when the blade passes through the upstream region.


## 1. Introduction

The wind energy issue, which recognized significant development due to the energy crises experienced in the early 1970s [1,2], still remains important and globally challenging. Most of the wind energy utilization has been achieved through the implementation of two types of wind turbines which are used mainly for electricity generation and pumping water [3–6]: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). The primary turbines for large-scale wind power generation are mainly depending on HAWTs [2,4,7–10].

It is commonly believed in most of the literature that the power coefficient of VAWT is less than that of HAWT. However, as some literature shows, that does not really indicate the truth [11]. VAWT technology is not widely commercialized, not because it has been proved to be inferior to HAWT technology. Rather, it appears to be because relatively a few companies have made the investment required to truly understand and objectively evaluate the VAWTs [12,13].

One of the main advantages of VAWT is that its single moving part (the rotor) where no yaw mechanisms are required [8,10,14–16] can simplify the design configurations significantly. Another advantage is that blades of straight-bladed VAWT may be of uniform section and untwisted, making them relatively easy to fabricate or extrude, unlike the blades of HAWT, which should be twisted and tapered for optimum performance. Furthermore, it can reduce the transmission losses due to proximity to the demand center. There is an urgent demand of this type of wind turbine with high efficiency and low cost in urban areas [17,18]. Therefore, the design research on straight-bladed VAWT became one of the hot spots in recent wind power technology development.

However, the critical disadvantage of VAWT is that the flow field characteristics are very complicated at low tip speed ratio during rotation, because the resultant wind velocity and the angle of attack for the blade are periodically changing [15,19–21]. The complex flow field, associated with a turbulent wake behind the wind turbine, can cause flow separation and vortex shedding from the blade surface. Furthermore, several dynamic effects such as dynamic stall and added mass can affect the aerodynamic loading of the blade [15,17,22–24]. Therefore, it is difficult to analyze and improve the

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**Nomenclature**

| | |
|---|---|
| $a$ | Velocity deficit |
| $A$ | Swept area of wind turbine [m$^2$] |
| $c$ | Airfoil chord length (=0.265) [m] |
| $C_D$ | Drag coefficient ($=F_D/(0.5\rho c U_0^2)$) |
| $C_L$ | Lift coefficient ($=F_L/(0.5\rho\ c U_0^2)$) |
| $C_N$ | Normal force coefficient ($=F_N/(0.5\rho c U_0^2)$) |
| $C_p$ | Pressure coefficient ($=P/(0.5\rho U_0^2)$) |
| $C_{power}$ | Power coefficient ($=Q\omega/(0.5\rho DH\ U_0^3)$) |
| $C_Q$ | Torque coefficient ($=Q/(0.5\rho DHR\ U_0^2)$) |
| $C_{thrust}$ | Thrust coefficient ($=F_x/(0.5\rho DHU_0^2)$) |
| $C_T$ | Tangential force coefficient ($=F_T/(0.5\rho c U_0^2)$) |
| $D$ | Rotor diameter (=2.0) [m] |
| $F_D$ | Drag force per unit length [N/m] |
| $F_L$ | Lift force per unit length [N/m] |
| $F_N$ | Normal force per unit length [N/m] |
| $F_T$ | Tangential force per unit length [N/m] |
| $H$ | Height of rotor blade (=1.2) [m] |
| $i$ | The measurement point position |
| $N$ | Number of blades (=2) |
| $P$ | Pressure acting on the surface of blade [Pa] |
| $P_{ower}$ | Power putout [W] |
| $P_d$ | Power for downstream [W] |
| $P_u$ | Power for upstream [W] |
| $Q$ | Rotor torque [N·m] |
| $R$ | Rotor radius (=1.0) [m] |
| $Re$ | Local Reynolds number ($=Wc/\nu$) |
| $U_0$ | Mainstream wind velocity [m/s] |
| $U_{local}$ | Local wind velocity without wind turbine [m/s] |
| $U'_{local}$ | Local wind velocity with wind turbine [m/s] |
| $u$ | Local wind velocity with wind turbine in the mainstream direction [m/s] |
| $v$ | Local wind velocity with wind turbine in the lateral direction [m/s] |
| $V$ | Tip speed of blade ($=R\omega$) [m/s] |
| $W$ | Resultant flow velocity [m/s] |
| $x$ | Longitudinal coordinate [m] |
| $y$ | Lateral coordinate [m] |
| $\triangle y$ | A minute width in $y$-axis direction [m] |
| $z$ | Vertical coordinate [m] |
| $\alpha$ | Angle of attack [deg] |
| $\beta$ | Blade pitch angle [deg] |
| $\theta$ | Azimuth angle [deg] |
| $\lambda$ | Tip speed ratio ($=R\omega/U_0$) |
| $\nu$ | Kinematic viscosity [m$^2$/s] |
| $\rho$ | Air density [kg/m$^3$] |
| $\varphi$ | Angle of resultant flow velocity [deg] |
| $\omega$ | Angular velocity of rotor [rad/s] |

aerodynamic characteristics of the blades of VAWT operating at low tip speed ratio.

Recently there has been a revival of interests regarding VAWT as several universities and research institutions have carried out extensive research activities and great achievements have been acquired for crossflow wind turbines. There are three main aspects to be considered: developing of theoretical model, computational fluid dynamics (CFD) and wind tunnel experiments.

There exist many different theoretical model methods to theoretically predict wind turbine performance. One of the most successful methods is the multiple-streamtube theory for the performance prediction of wind turbine which was studied by Mays I. et al. [25], Wilson R E [26], as well as Dumitrescu H. et al. [27]. This model indicates that, if an ideal rotor is designed and operated such that the wind velocity at the rotor is 2/3 of the mainstream wind velocity, it would be operating at the point of maximum power production. The maximum achievable value of the power coefficient is known as the Lanchester-Betz limit [28]. The main disadvantage of Multiple-Streamtube model is its inherent inability to distinguish between upstream and downstream of blade revolution, thus forcing an unrealistic symmetry of aerodynamic loads between the two passages of the blade element into the same streamtube. Paraschivoiu [29] in 1981 proposed the double multiple-streamtube model where each strip in the streamtube has two actuator discs, one each for both upstream region and downstream region. With this additional actuator disc, the forces on the blades as they pass the downwind are more accurately assessed due to a secondary velocity induction. These results were similar to investigations in Islam M. et al. [17], Klimas P C [30], Brahimi M T. et al. [31], Masson C. et al. [32], Staelens Y. et al. [33], Beri H. et al. [34] and Wang K. et al. [35]. Moreover, Hara et al. [36] proposed the quadruple-multiple streamtube model, based on the blade element momentum theory, for simulating double blades VAWT performance. From the results of comparisons, it was determined that the effects of the inner rotor on the decrease in upstream velocity must be included.

Castelli M R. et al. [37] and Almohammadi K M. et al. [38] presented a CFD model in 2D for the evaluation of energy performance and aerodynamic forces acting on a straight-bladed vertical-axis Darrieus wind turbine. In the proposed analytical/numerical procedure, the basic principles which were currently applied to BE-M theory for rotor performance prediction were transferred to the CFD code, allowing the correlation between flow geometric characteristics (such as blade angles of attack) and dynamic quantities (such as rotor torque, blade tangential and normal forces). Furthermore, Yao J. et al. [39] simulated the flow characteristics of VAWT by CFD model in 3D. The velocity field, pressure field distribution of different angle were obtained and analyzed. These results showed that simulation of the ambient flow field could reflect the flow conditions of different angles effectively. The effect of dynamic stall was also investigated by Ferreira C S. et al. [40] and Chougule P. et al. [41] with experimentally and numerically, reporting the influence of the turbulence model in the simulation of the vortical structures spread from the blade itself. The obtained results showed that the reduction of blade angles of attack passing from lower to higher tip speed ratio values.

Ferreira C S. et al. [42] focused on the phenomena of dynamic stall and measured the velocity field around the blade of VAWT in wind tunnel with PIV technology. The particle image velocity results of the evolution of dynamic stall for a Darrieus VAWT at low tip speed ratios identify 2D phase locked and random components of the flow field. Wang S. et al. [43] measured the lift and drag coefficients against angle of attacks at different Reynolds numbers and intensities. The effect of increasing turbulence intensity on flow bears similarity to that of increasing Reynolds numbers, albeit with a difference. The flow separation shifts upstream with increasing Reynolds numbers but downstream with increasing turbulence intensity. This work was also performed in Volino R J. et al. [44], Chamorro L P. et al. [45], as well as Maldonado V. et al. [46].

The angle of attack, decided by the local wind velocity and the rotational velocity of the rotor, is one of the most important parameters for rotor aerodynamics [18,24,39–46]. However, in