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The effects of aerofoil profile modification on a vertical axis wind turbine performance

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A R T I C L E I N F O

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A B S T R A C T

This paper investigates the effect of profile-modifications on a NACA-0015 aerofoil used in VAWTs (vertical axis wind turbines). The profile-modifications being investigated consist of a combination of inward semi-circular dimple and Gurney flap at the lower surface of the NACA-0015 aerofoil. Rather than maximize the lift-coefficient or the ratio of the lift to drag coefficients, this paper choose to maximize the average (or effective) torque of the VAWT as this is a much better measure of the power produced. A fully automated optimization using RSA (Response Surface Approximation) is utilized here to maximize the average torque produced by the wind turbine blade. The data-set used in the optimization is generated using CFD (computational fluid dynamics) simulations. In order to ensure reliability, the computational domain and the turbulence model used in the CFD simulations are validated against previous experimental results. The optimized shape of the modified aerofoil is shown to improve the aerodynamics of the wind turbine blade.

1. Introduction

Wind turbines are classified into HAWT (horizontal axis wind turbine) and the VAWT (vertical axis wind turbine) based on their axis of rotation. HAWT are better suited for large scale energy generation while VAWT are easier to install, omni-directional and better suited for small-scale and micro-scale energy generation [1]. With the increasing focus on off-the-grid energy generation and grid supplementation, VAWT will begin to play a major role in wind power. Hence this paper focuses on optimizing VAWT blades.

Sheldahl et al. [2] reported experimental investigations of the aerodynamic characteristics of NACA-0012, NACA-0015, NACA-0018 and NACA-0021 aerofoils for use in VAWT. The aerodynamic performance of the aerofoil blades under dynamic flow condition has been investigated by Gharali et al. [3] and Ahmadi et al. [4]. Researchers working on aerofoil for non-VAWT application have proposed two profile modifications that have been independently shown to enhance aerofoil aerodynamics. The first modification is a vertical flap known as Gurney flap. Gurney flaps have been experimentally shown to improve the lift coefficients of aerofoils [5]. A Gurney flap having a height 1.25% of chord length (c) increases the lift with only a small increase in drag coefficient [5]. The drag coefficient is known to rise rapidly for flap sizes larger than 2%-c [5]. This phenomenon is explained in studies on NACA-0012 [6], NACA-0011 [7] and LA-203A [8] aerofoils which note that the Gurney flap increases the suction of the aerofoil upper surface and pressure on the lower surface which in turn result in increased lift. Similar trends in lift and drag coefficients have been observed in other aerofoil such as race car wings [9,10]. Outward dimples on the upper surface of the aerofoil, the second modification, can act as a vortex generator to improve the lift coefficient of aerofoil [11]. These dimples increase flow turbulence and reduce the wake, thereby reducing the drag coefficient. They help to increase the overall lift at higher angle of attack. The combined aerodynamic effect has also been shown to change the angle of the stall.[1]

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[1] At stall flow separation is dominant any further increases in angle of attack results in a rapid decrease in lift and an increase in drag force [1]. For a wind-turbine, stall results in loss of torque.

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This paper aims to provide a systematic approach to optimizing the blades used in VAWT by studying a NACA-0015 VAWT blade with both inward dimples and a Gurney flap at the lower surface of the blade near the trailing edge. As the angle of attack of the blades in a VAWT changes continuously even when the wind-speed and rotation speed remain constant (refer to Section 3), the paper aims to maximize the effective torque rather than to maximize the lift coefficient at a single angle of attack. The paper will use a RSA (Response Surface Approximation) based optimization. RSA involves evaluating a chosen objective function (in this case the average torque) at discrete points in the parameter space to generate a "response surface" [12]. The optimal distribution of the evaluation points can be achieved using DOE (design of experiment) analysis [13]. Details on RSA can be found in literature on engineering optimization [12–23]. To ensure reliability, the turbulence models used in this paper are validated against the corresponding experimental results published in the literature.

To the best of authors' knowledge, the present paper is the first study to investigate the simultaneous effects of a Gurney flap and a dimple on the aerodynamic performance of VAWT blade. The paper additionally analyzes the results for light dynamic stall cases. It should also be noted that previous studies on RSA based optimization [14,19,20,22] have been applied only to maximize the ratios of the lift to drag coefficients to improve the performance of wind turbine blades. As tangential force is responsible for the power produced by VAWT, this study maximizes the tangential force. The results of the optimized aerofoil are presented for both static and dynamic (oscillating) flow conditions.

2. Simulation model

2.1. Average tangential force

The orientation of the blades relative to the true wind direction is known as the azimuthal angle (θ). The rotation of the VAWT results in a change in the tangential and normal component of the wind (relative to the blade). As a result, the chordal (tangential) velocity (V_c) and normal velocity (V_n) can be written in terms of the induced velocity (U) and tip speed ratio (λ) as [24] (Fig. 1)

$$V_c = U(\lambda + \cos\theta) \quad (1)$$

$$V_n = U\sin\theta \quad (2)$$

where,

$\lambda = \omega R/U_\infty$ is the tip speed ratio

In the absence of flow restrictors, the induced velocity can be assumed equal to the free-stream velocity (U_∞), i.e. $U = U_\infty$. The effective wind velocity (W) and the angle of attack (α) are given as

$$W = \sqrt{V_c^2 + V_n^2} \quad (3)$$

$$\alpha = \tan^{-1}\left(\frac{V_n}{V_c}\right) \quad (4)$$

we define the tangential force coefficient C_T to represent the non-dimensional tangential force in terms of the lift coefficient (C_L) and drag coefficient (C_D) as

$$C_T = C_L\sin\alpha - C_D\cos\alpha \quad (5)$$

The tangential force per unit width of the aerofoil is given by

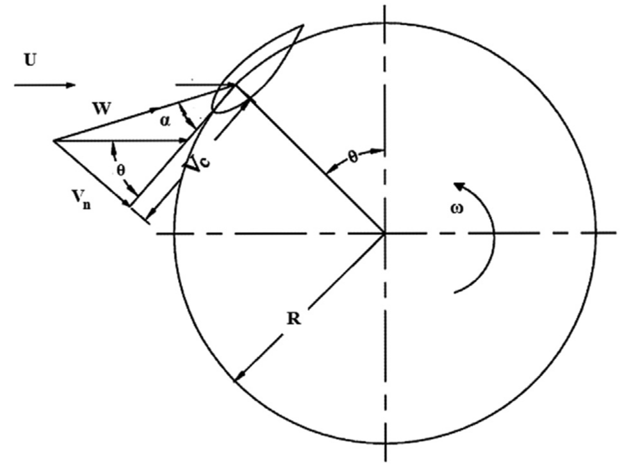

Fig. 1. Force analysis of a vertical axis wind turbine.

Fig. 2. Computational domain having two circular sub domains.

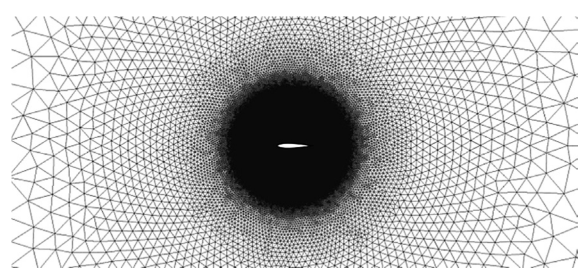

Fig. 3. Mesh view-denser mesh at the pseudo circular domain near the aerofoil.

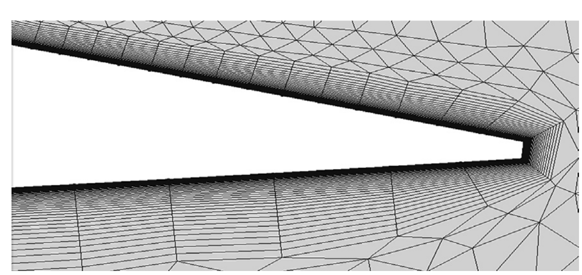

Fig. 4. Boundary layer mesh near the aerofoil surface.