

Computational investigation of flow control by means of tubercles on Darrieus wind turbine blades

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Abstract. This work presents the current status of the computational study of the boundary layer control of a vertical axis wind turbine blade by modifying the blade geometry for use in wind energy conversion. The control method is a passive method which comprises the implementation of the tubercle geometry of a humpback whale flipper onto the leading edge of the blades. The baseline design is an H-type, three-bladed Darrieus turbine with a NACA 0015 cross-section. Finite-volume based software ANSYS Fluent was used in the simulations. Using the optimum control parameters for a NACA 634-021 profile given by Johari et al. (2006), turbine blades were modified. Three dimensional, unsteady, turbulent simulations for the blade were conducted to look for a possible improvement on the performance. The flow structure on the blades was investigated and flow phenomena such as separation and stall were examined to understand their impact on the overall performance. For a tip speed ratio of 2.12, good agreement was obtained in the validation of the baseline model with a relative error in time-averaged power coefficient of 1.05%. Modified turbine simulations with a less expensive but less accurate turbulence model yielded a decrease in power coefficient. Results are shown comparatively.

1. Introduction

Boundary layer control is a major concern in aeronautical research which aims to improve performance and decrease costs in device operation. Mostly, the control is applied to alter the fluid flow on the walls which are the streamlined lifting surfaces. The useful force that is created by the fluid on these walls is heavily influenced by the parameter known as the angle of attack. Each airfoil section has its own critical angle of attack value above which the phenomenon called stall occurs where flow separates from walls and sharp decrease in the useful force is observed. The boundary layer control methods briefly aim to delay stall or increase the critical angle of attack if possible. The methods are classified into two: (1) Passive control methods that don't require any energy input such as vortex generators, fixed slats, leading edge tubercles etc., (2) Active control methods where a certain amount of energy is required in application such as, suction, blowing, synthetic jets, plasma actuators etc. In particular, tubercles (figure 1, 2, 3, 4) take part in vortex generation by the excitation of flow that results in an increase in the lift in the post-stall region [1].





Figure 1. Tubercles on humpback whale flippers [1].

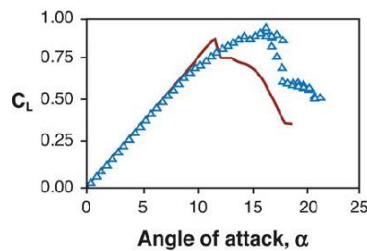


Figure 2. Photographs by W.W. Rossiter Experimental lift curves [2].

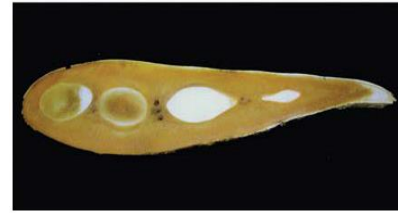


Figure 3. Tubercles on humpback whale flippers [1].



Figure 4. Photographs by W.W. Rossiter Experimental lift curves [2].

Wind turbine performance relies on blade aerodynamics where similar flow characteristics are observed. Modern horizontal axis wind turbines have twisted blades to account for the change in the angle of attack at design conditions. However, turbines often operate at off-design conditions where stall occurs and causes sharp decrease in performance. In order to improve the energy efficiency of the machinery, efforts are made to control the boundary layer on the airfoil cross-section [3, 4, 5]. Flow computations based on numerical methods (finite volume, finite element methods etc.) have become standard tools in turbomachinery design. Howell et al. [6] reported the performance of a vertical axis wind turbine found from computational fluid dynamics simulations. Authors studied the problem in 2D and 3D with a transient sliding mesh model and compared the results with experiments. Trivellato and Castelli [7] presented the influence of the Courant-Friedrichs-Lewy (CFL) number on the computed torque of a 2D vertical axis wind turbine model and proposed a relation for time step selection. In this work, the results of a computational study is reported which investigates the effect of the leading edge tubercles on the performance of a three-bladed, vertical axis wind turbine. Numerical research was conducted using the commercial code ANSYS Fluent 14.5. In order to validate the methodology, a baseline design was modeled and simulated based on the experimental performance testing given by Bravo et al. [8]. The baseline turbine blades had constant cross sections with a NACA 0015 profile. This procedure was followed by the implementation of the leading edge tubercles on the turbine. Geometric parameters of the tubercle geometry were determined by following the experimental research conducted by Johari et al. [9] on a NACA 634-021 profile. Current study focuses on a certain operating point of the turbine with a tip speed ratio of 2.12. Qualitative and quantitative results derived from CFD simulations are shown and discussed.

2. Turbine details

The wind turbine under consideration is a vertical axis, three-bladed Darrieus turbine which is also known as the H-type rotor. The velocity triangle obtained from a two-dimensional analysis at any cross section of the blades is given in figure 5. Here, V is the free stream velocity; U is the circumferential velocity at radius (R) and ω is the relative velocity as seen by an observer moving with the blades. The tip speed ratio of the turbine is defined as

$$\lambda = \frac{|\mathbf{U}|}{|\mathbf{V}|} = \frac{\Omega R}{V} \quad (1)$$

where Ω stands for the angular velocity. From the geometry, the angle of attack (α) is found to be a dependent of the blade azimuthal position (θ) and tip speed ratio as

$$\alpha = \tan^{-1}\left(\frac{\sin \theta}{\cos \theta + \lambda}\right) \quad (2)$$

which indicates that the angle of attack itself is a time-dependent parameter since $\theta = \Omega t$.

Pressure differences between the suction and pressure sides of the blade create the useful moment (M) which is non-dimensionalized as a torque coefficient

$$C_M = \frac{M}{\rho V^2 L R^2} \quad (3)$$

and the power coefficient which reflects the energy efficiency of the blades is defined as

$$C_P = \frac{M\omega}{\rho V^3 L R} \quad (4)$$

For a vertical axis wind turbine, C_M and C_P are both time-dependent parameters. For convenience, their time-averaged values are used to indicate the performance as follows (overbars will be omitted after Eq. 5):

$$\bar{C}_{M,P} = \frac{1}{T} \int_0^T C_{M,P} dt \quad (5)$$

The baseline model in this study has constant NACA 0015 cross-section with a chord (c) of 0.4 m, blade span (L) of 3 m and radius (R) of 1.25 m. figure 5. shows the wind tunnel performance testing results reproduced from Bravo et al. [8] for the case with a free stream velocity of 8 m/s.

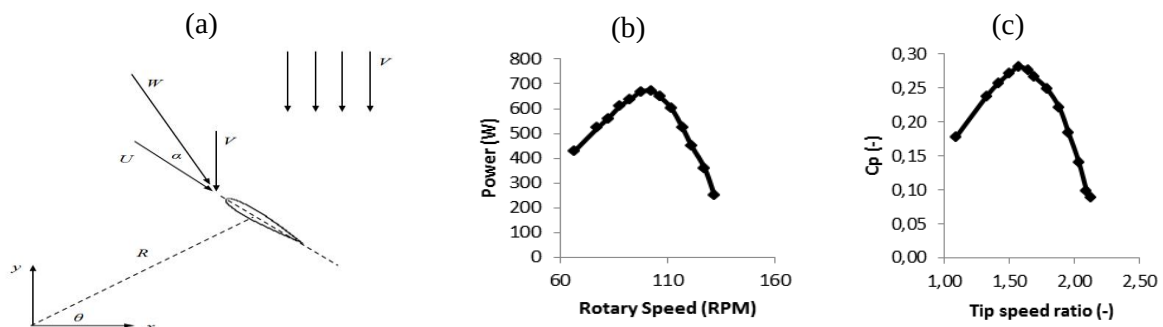


Figure 5. (a) The velocity triangle on a blade cross section (b, c) Baseline turbine performance curves reproduced from Bravo et al. [8].

Minimum and maximum values of the tip speed ratio are estimated from the original plot as 1.09 and 2.12 respectively. For these cases, angle of attack variations based on Equation 2 are plotted in figure

3. Here, dotted lines show the static stall angle as 12° for a NACA 0015 airfoil which clearly demonstrate that the turbine operates in a stalled condition mostly.

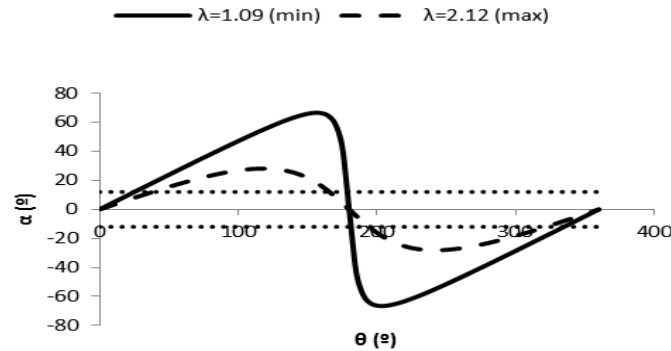


Figure 6. Angle of attack variations for tip speed ratio extrema.

In order to look for a possible improvement of the energy efficiency of this turbine, the influence of the leading edge tubercles is investigated. A suitable geometry is obtained from Johari et al. [9] where authors conducted parametric research of leading edge tubercles on a NACA 634-021 profile. Here, case 8M was chosen since it yielded better lift characteristics in the post-stall region while having almost the same drag compared to other tubercle cases. It should be emphasized that since the airfoil types are essentially different, the exact same post-stall behavior is not expected. Nevertheless, it clearly provides information on geometric parameters and implementation. Figure 7 shows the extruded view of the blades before and after modification.



Figure 7. Extruded view of the blades (a) Baseline model (b) Modified model

3. Computational study

Under the assumptions of three-dimensional, unsteady, viscous and incompressible flow, the velocity and the pressure fields were calculated by using commercial CFD code ANSYS Fluent 14.5. To accelerate convergence, initial fields were calculated using the Multiple Reference Frames Model (MRFM) which is basically a steady-state approach with different reference frames attached to zones that have relative motion with respect to each other. Transient simulations were run using the Sliding Mesh Model (SMM). The governing equations for the SMM are as follows [10]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho(\mathbf{V} - \mathbf{U})) = 0 \quad (6)$$

$$\frac{\partial(\rho \mathbf{V})}{\partial t} + \nabla \cdot [\rho(\mathbf{V} - \mathbf{U})] = -\nabla P + \nabla \cdot \boldsymbol{\tau} + \mathbf{F} \quad (7)$$

Here, ρ is the fluid density, P is the pressure field, $\mathbf{F}$ stands for the body forces and $\boldsymbol{\tau}$ is the stress tensor $\boldsymbol{\tau} = \mu[\nabla \mathbf{V} + (\nabla \mathbf{V})^T - (2/3)\nabla \cdot \mathbf{V}]$. The problem domain was made up of two zones (rotating

and stationary) with overlapping interfaces. The stationary zone represents the wind tunnel having a cross section of 9 m×9 m as in Bravo et al. [8] with extended downstream yielding a total length of 22.5 m. Rotating zone enclosed the three blades of the turbine. Any other parts such as the rotating shaft, connecting elements etc. were excluded in the model.

Standard air properties were used ($\rho=1.225 \text{ kg/m}^3$ and $\mu=1.7894\text{e-}05 \text{ kg/(ms)}$) resulting in a Reynolds number based on chord ($Re_c = \rho Vc/\mu$) of ~ 219000 . Velocity inlet (8 m/s) and pressure outlet (0 Pa gauge static pressure) boundary conditions were defined and no-slip wall boundary condition was assigned on the blades and the tunnel walls. For the validation of the baseline model which is relatively simpler in terms of geometry, $k-\omega$ SST turbulence model was used with default model constants. Hybrid grids were used with inflation layers on solid walls to resolve the boundary layers where the first cell height, growth rate and total number of inflation layers were $\sim 0.1 \text{ mm}$, 1.2 and 18, respectively. Due to the grid quality considerations, baseline grid had approximately 9 million cells. Minimum and average orthogonal qualities were approximately 0.19 and 0.87 for the baseline blade while 0.004 and 0.82 for the modified blades. Using the same grid properties on the modified model yielded an increase in grid size and computation time. For this reason, the turbulence model was switched to $k-\epsilon$ realizable with default model constants. Pressure-based solver was used with the PISO scheme for pressure-velocity coupling. Second-order upwind schemes for momentum, turbulent kinetic energy and specific dissipation rate equations and a second order implicit discretization for transient terms were used. In addition to residual monitoring, the moment coefficient on each blade was monitored and recorded at each time step. Time step size was defined as $1\text{e-}03 \text{ s}$ and calculated fields were recorded once in every 15° turn.

4. Results and discussion

Instantaneous torque on a single blade and total torque on the blades are shown as a function of dimensionless time ($t^*=t/T$) in figure 8 comparative evaluation of curves depict that the baseline model is superior in general.

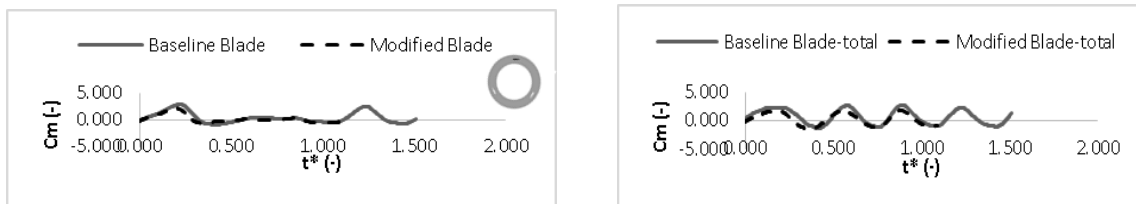


Figure 8. Torque coefficient versus dimensionless time. The initial blade position is shown on the plot.

A closer look on the blade tips are given in figure 9. These figures are also in line with the plot in figure 6 in terms of the angle of attack so that the blade in figure 9a is in the unstalled region.

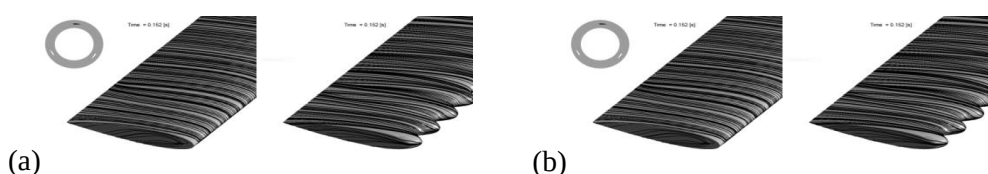


Figure 9. Comparative surface streamlines of two blades. The blade positions are shown on the figures where the flow is from left to right. (a) low angle of attack, (b) high angle of attack.

Time-averaged C_p values for both blade types are presented in table 1 for an overall performance comparison. Results show that, for the investigated tip speed ratio, CFD results are in good agreement with the experiments given by Bravo et al. [8]. However, the turbine with leading edge tubercles

yielded a decrease of 54% in C_p yielding a value of 4.0%. This result is discussed as follows: In the simulations for the baseline geometry, $k-\omega$ SST turbulence model was used. After an iterative mesh refinement study, maximum and average y^+ values obtained on the blades were 10.4 and 2.9 respectively. Aiming for a low y^+ value with the grid quality mentioned above ensued a good estimate for the time-averaged power coefficient. The modified geometry on the other hand was modeled with the $k-\epsilon$ realizable turbulence model where maximum and average y^+ values obtained on the blades were 320.9 and 14.9 respectively. In the recent years $k-\omega$ SST turbulence model gained popularity due to its superiority compared to other one-equation and two-equation models especially for strongly separated airfoil flows. It's believed that more accurate performance estimation would be achieved with $k-\omega$ SST turbulence model for the modified blade. However, due to the grid size, current study exploited the $k-\epsilon$ realizable turbulence model for the modified blade.

Table 1. Power coefficient comparison.

	Bravo et al. [8] Baseline (CFD)		Modified (CFD)
C_p (%)	8.8	8.7	4.0

5. Conclusions

The numerical investigation of the influence of leading edge tubercles on vertical axis wind turbines has been presented in this study. Simulations were run for a single tip speed ratio for the baseline and modified blade forms. Post-processing tools were exploited to gain a better understanding of the flow around the blades. An overall conclusion would be that this turbine type is prone to stalled operation and boundary layer control would be a way to improve performance. Current study is confined in obtaining a solution field for the modified geometry with the $k-\epsilon$ turbulence model. Results for this tip speed ratio yielded a decrease in power coefficient about 54%. Further studies will likely to involve research on the use of $k-\omega$ SST turbulence model, grid sensitivity analysis and performance estimation for several other tip speed ratios.

6. References

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