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PERFORMANCE IMPROVEMENT OF VERTICAL AXIS WIND TURBINE WITH AIRFOIL GEOMETRY

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Abstract:
In this work, an airfoil geometry optimized for vertical-axis wind turbine applications is presented in the present studies, the effects of Gurney flaps on aerodynamic characteristics of a static airfoil and a rotating vertical axis wind turbine are investigated by means of numerical approaches. First, mesh and time step studies are conducted and the results are validated with experimental data in good agreement. Furthermore, mounting a Gurney flap at the trailing edge of the blade increases the power production of the turbine considerably. Increasing the Gurney flap height further increases the power production. The best performance found is obtained for the maximum height used in this study at 6% relative to the chord. This is in contrast to the static airfoil case, which shows no further improvement for a flap height greater than 0.5%c. Increasing the angle of the flap decreases the power production of the turbine slightly but the load fluctuations could be reduced for the small value of the flap height. The present paper demonstrates that the Gurney flap height for high solidity turbines is allowed to be larger than the classical limit of around 2% for lower solidity turbines.
Keywords: aerodynamics; CFD; flow characteristics; gurney flap; wind energy.

1.0 INTRODUCTION

In a world in which living without electricity is almost unconceivable, wind energy represents a power source becoming cheaper and more competitive in the course of time. Nowadays, more than 3% of the world energy consumption is supplied by wind energy. This number is expected to rise above 5%. It is inexhaustible, renewable and non-contaminant. In addition, the use of wind energy helps to reduce the dependence on fossil fuels. For all these reasons, the development of improvements and innovations regarding wind turbines and the aerodynamic airfoils employed to build the blades is a topic of great interest. Wind turbines may be classified with respect to the orientation of the rotor axis in horizontal and vertical axis wind turbines (HAWTs and VAWTs). Although research has been traditionally focused on HAWTs, VAWTs present important advantages, being the main one that they are capable of working independently of the wind direction. In this work, an airfoil shape optimized for vertical-axis wind turbine applications is proposed. Different airfoil shapes have been analysed with a panel method, using the results from the analysis in order to optimize the performance of a new airfoil shape. This airfoil presents a high lift-to-drag ratio and a delayed stall angle with respect to the previously analyzed airfoils, which makes it suitable for vertical-axis wind turbine applications.

2.0 LITERATURE REVIEW

In the early years of the VAWT history, researchers mainly opted for symmetric airfoils since it was believed important that the behaviour was similar in the upwind and downwind part of the rotor and because abundant information was available for symmetric airfoils. Pioneering research in the airfoil design for VAWTs has been performed at Sandia National Laboratories at Tokai University and at Delft University of Technology.[1] At Sandia National Laboratories, Klimas investigated the desired characteristics of VAWT airfoils the maximum power coefficient is found for a rotor loading approaching uniform distribution of normal loading in the upwind half of the rotor and a uniform distribution of normal loading in the downwind half of the rotor. [2] The difference in magnitude between the upwind and downwind distributions defines the non-conservative force field that is responsible for the energy exchange and the generation of the wake. In 2D, this load case results in the same velocity (and wake) field as the 2D actuator line, which represents the 2D actuator disk, and should therefore have the same optimum. [3] The validity of the optimisation results and performance results is limited by the assumptions made and the codes used Firstly, in the derivation of the aerodynamic objective function, an assumption is made that the velocity field is constant. This is not completely true. When changing the rotor loading, the induced velocity field will be affected. [4] However, for a fixed tip-speed ratio, the induced velocity is only a minor portion of the relative velocity at the rotor blades, and therefore, this assumption is expected not to affect the results significantly

Ideally, the optimal pitch schedule should be determined freely, without any constraint on the required loading. [5] However, this causes the code converges to its numerical limits. Therefore, the variable pitch schedule is determined iteratively using an optimisation scheme assuming that the circulation upwind and downwind should be constant.

The optimisation routine performed in this work already considers the aerodynamic and structural needs of airfoils to operate in a VAWT including blade pitching; however, additional requirements could be added. [6] These could include internal blade structure, aeroelastic behaviour, production costs, circulation control, unsteady effects, or turbulent inflow. However, this is out of the scope of this research and irrelevant when analysing the effect of variable blade pitching to airfoil optimisation.

RESEARCH METHODOLOGY

In this section, the analyses carried out for a static air foil employed with a Gurney flap at various configurations are detailed. The studies were conducted for the NACA 4412 air foil, having a relative thickness of about 12%. The Reynolds number was around 1.86 million. Indeed, this value is a little small for modern HAWTs, but VAWTs generally operate at very small rotational speeds. Thus, their Reynolds numbers are also smaller. First, the impacts of spatial and temporal discretization's on the resulting aerodynamic loading under static conditions were investigated on the clean air foil without the Gurney flap. Having obtained a suitable numerical setup, quantitative and qualitative computational data on the performance of the gurney flap on the air foil were carried out. Computations of the air foil equipped with a gurney flap were compared with experimental data in order to determine the effect of Gurney flap parameters on the lift and the drag coefficients.

Mesh Configurations:

In order to discretize the airfoil in space, the O-mesh topology was employed since it offers a high resolution of the flow in the boundary layer and avoids unnecessary cells downstream of the profile. The two-dimensional (2D) mesh was created using an automated script developed at the institute in a grid generator Pointwise. The far field was located at 150 times the chord length. A large far field distance was set to prevent the far field domain from reflecting flow. The high-quality meshes for airfoil and Gurney flap were created independently and combined using the chimera approach. The boundary layer was fully resolved with a non-dimensional y+ near the wall less than unity. Thirty-two-cell layers were located within the boundary layer regime with a growth rate of 1.1. The boundary conditions were set in the mesh as well as around it as shown in Figure.

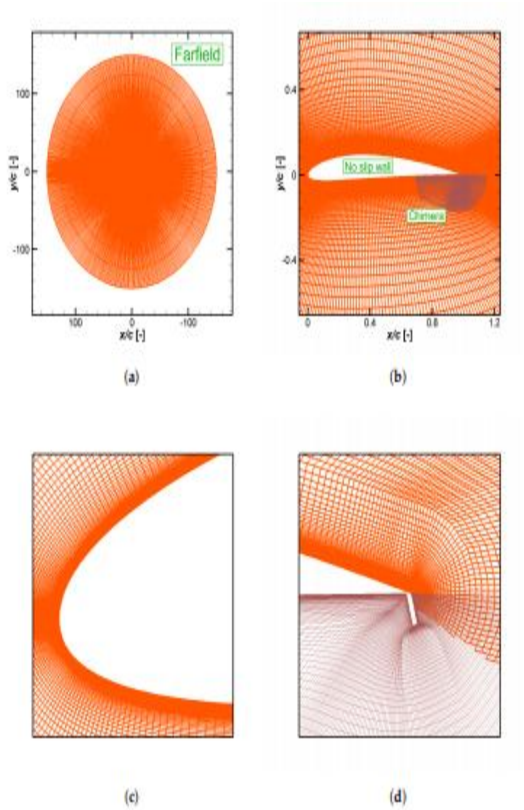

Figure: Computational mesh of the static airfoil and applied boundary conditions. (a) Overall mesh, (b) enlarged views near the airfoil (c) near the leading edge and (d) near the trailing edge.

The far field boundary condition was used for the outer side of the domain, and a non-slip boundary condition was applied around the airfoil with the purpose of simulating the viscous wall of the airfoil assuming a zero-flow velocity. In the following sections, time step studies as well as grid studies were performed to keep the computational costs low while still retaining reasonable accuracy of the flow solutions.

Influence of the Grid Refinement

For the spatial discretization study, the grid along the baseline was refined from 71,680 cells to 97,280 cells. A coarser grid 51,200 cells of cells was also tested. According to the grid convergence index introduced by the grid refinement should be at least by a factor of 1.4. The simulations for the grid studies were performed using the time step size Δt = tc/75 (with tc being the convective time of the fluid flow over the air foil, i.e., c/U∞) at a Reynolds number of 1.86×10^6.

Table: Spatial discretization data for the clean static NACA 4412 air foil

Grid Name	Circumferential	y +	Number of Cells
G1	290	<1.0	51,200
G2	416	<1.0	71,680
G3	576	<1.0	97,280

The variation in the lift coefficient CL versus the angle of attack α. The computed lift coefficient CL of the NACA 4412 airfoil from the simulation for the three different grid resolutions as well as the lift coefficient from the experimental data and CFD reference data are compared. Figure 2b shows the variation in the lift coefficient versus the drag coefficient for the simulated CFD data in comparison with the experimental data. The refinement has a very small impact on the increase in the lift coefficient. Generally, finer grid and time resolutions produce more accurate results than coarser ones, but it is followed by an increase in the computational expenses as a consequence.

4.0 RESULTS AND DISCUSSIONS

In this section, the employed vertical axis wind turbine is described, including its coordinate system. Then, the scenario and strategy for mesh studies are described in detail. Lastly, the simulation results are presented in the last section and discussed considering the dynamic stall phenomena on the performance of the VAWT

Turbine and Operating Conditions:

Computational fluid dynamics (CFD) studies were performed on a straight-two bladed vertical axis wind turbine. The turbine operated at a wind speed of 8 m/s. Measurements of this turbine were conducted for tip speed ratios ranging from λ = 0.50 to λ = 3.0. The investigated turbine had a rotor radius of 1 m, a pitch angle of 6◦, and a chord length of 0.265 m. This turbine employed a NACA 0021 airfoil having a rotor solidity (σ = Nc/R) of 0.53

Table: Characteristics of the investigated vertical axis wind turbine.

Parameters	
Type	H-Darrieus
Airfoil	NACA-0021
Solidity(σ)	0.53
Number of blades	2
Radius(R)	1.0 m
Pitch angle (αp)	6°
Chord length (c	0.265 m
Operating range	0.5 < λ < 3.0

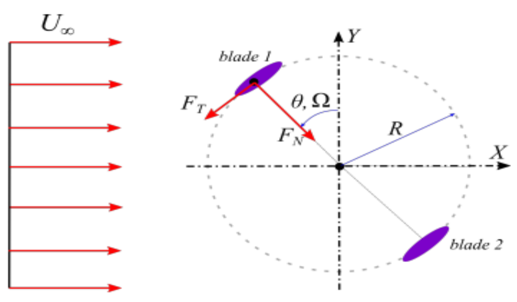

Figure: The employed coordinate system in the study.

Gurney Flap Height and Angle Effects

In this section, unsteady loads over the azimuth angle in the normal and tangential directions are analyzed. Two Gurney flap angles for three different flap heights are considered for the studies. In addition to that, for each case, the flow field at a selected azimuth position is compared to illustrate the source of the load characteristics. the Gurney flap configuration of 0.5%c at two flap angles 90° and 105°. The considered tip speed ratio is λ = 2.13. This is where the turbine is near the optimal position for the baseline case. It can be seen that the normal and tangential force coefficients increase starting from the azimuth angle of θ = 0° until the azimuth angle of θ = 90◦ .

Table: Test cases for the height effect study for the two-bladed rotating vertical axis wind turbine with NACA-0021 airfoil.

Case Nr.	GF Angle	GF Height
1	90°	0.5%c
2	90°	1%c
3	90°	2%c
4	90°	4%c
5	90°	6%c
6	105°	0.5%c
7	105°	1%c
8	105°	2%c

These forces then decrease steadily, reaching zero at about θ = 180°. The normal force then becomes negative as the angle of attack is also negative within the downwind region. A different characteristic is observed for the tangential force. It is shown that, for an azimuth angle larger than 180°, the tangential force in general remains constant around the zero level. This shows that the (negative) lift generated within the downwind phase has only a small contribution to the tangential force component.

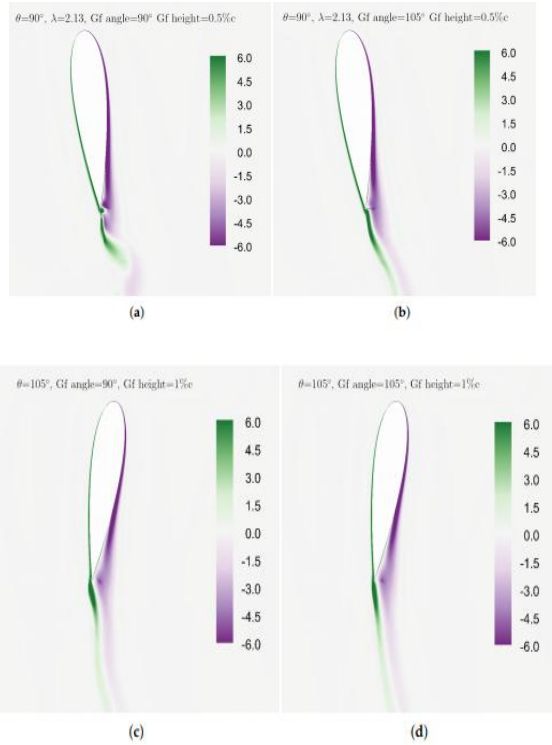

Figure: Spanwise vorticity contour at a tip speed ratio of λ = 2.13. (Top): GF height of 0.5%c in (a,b), (middle): GF height of 1%c in (c,d).

The results for the Gurney flap height of 1%c are presented in Figure c,d. Similar to the observations made for the lower Gurney flap height, the azimuthal loads increase starting from the azimuth angle of θ = 0 ◦ to the azimuth angle of θ = 90◦ . The maximum loads are obtained at an azimuthal angle of 90◦ . A light unsteady behavior is also shown near the maximum load position, which indicates the stall region up to an azimuthal angle of θ = 110◦ . However, it is clearly shown that, now, the fluctuations are much weaker than the shorter flap height.

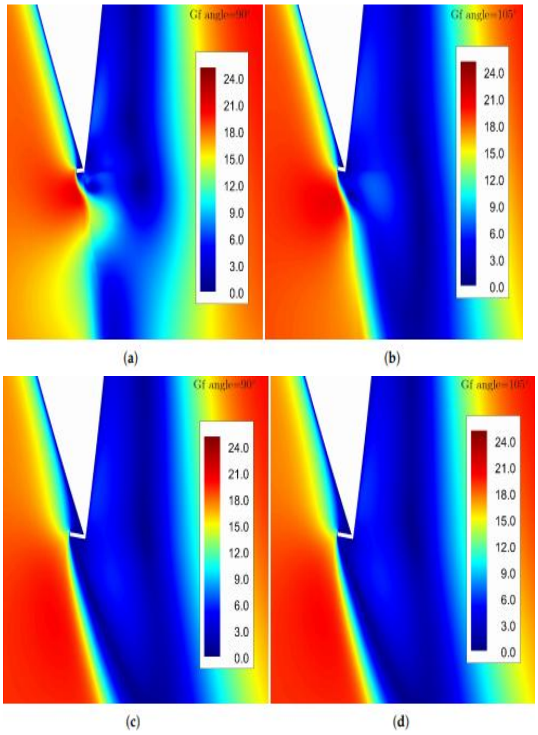

Figure: Total velocity plot (in m/s) in the rotating frame of reference at a tip speed ratio of λ = 2.13. (Top): GF height of 0.5%c in (a,b), (middle): GF height of 1%c in (c,d),

the Gurney flap changes the direction of the wake centerline. This artificially creates an additional camber effect in the fluid flow, which in turn enhances the lift force acting on the rotor blade. This is identified as the main source of performance improvement. However, in contrast with the low solidity rotors considered in past studies, the performance of high solidity rotor is less affected by the drag increase due to Gurney flaps. This allows blade designers to use longer Gurney flaps in their designs. Furthermore, this aspect also modifies the unsteady characteristic of the flow field commonly denoted as dynamic stall. The effect seems to be influenced by the flap and could potentially be controlled. Future studies in this direction are strongly encouraged.

Conclusions:

The present paper delivers a computational study on the flow characteristics of static airfoil and rotating vertical axis wind turbine equipped with Gurney flaps in order to provide quantitative and qualitative data on the aerodynamic performance of this device. The following conclusions can be drawn:

- Increasing the Gurney flap height results in increased lift and drag coefficients for the static air foil case. However, a height of 0.5%c generates a very small increase in drag and provides the highest lift-to-drag ratio compared to the clean air foil.
- The lift improvement is greater for the 90° configuration than the 105° configuration.
- For the rotating VAWT case, the load fluctuations decrease with increasing flap angle at a small value of the flap height. By increasing the flap height, the fluctuations are suppressed and, at the same time, the difference between the flap angles 90° and 105° becomes insignificant Mounting a Gurney flap at the trailing edge of the blade increases the power production of the VAWT remarkably for tip speed ratios between $0.5 < \lambda < 2.5$

The results show that, for this type of turbine, the Gurney flap height can be increased to a larger value, extending the limit of around 2% for the lower solidity turbine.

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