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Performance Assessment of Darrieus Wind Turbines with Symmetric and Cambered Airfoils

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ABSTRACT
During the operation of a Darrieus type Vertical Axis Wind Turbine (VAWT), the blade sections are subjected to different flow velocities and incidences that can be converted to mechanical power with varying efficiency depending on the airfoil. The goal of the present study is to emphasize the advantages and the drawbacks of the use of symmetrical, cambered and laminar airfoil for a typical Darrieus type VAWT. The NACA 0018, FX63-137 and SNLA 18/50 airfoils were selected for this study.

KEYWORDS: Darrieus; Vertical Axis Wind Turbine; airfoil; symmetrical; cambered; laminar.

INTRODUCTION
The combination of the rotation of the blades of a VAWT and the freestream induces on each blade section a non-stationary flow with fluctuating velocity and incidence angle with the azimuthal position of the blade. Considering the non-stationary behavior of the flow, the blades’ airfoil must be chosen with attention since the torque generated by the blades depends on the lift and drag coefficients of the airfoil. Using CFD method, Travis et al. (2012) optimized the both symmetric and cambered NACA 4-series family airfoil cross-section of a vertical-axis wind turbine (VAWT) to maximize the torque while enforcing typical wind turbine design constraints such as tip speed ratio, solidity, and blade profile. They could increase the efficiency of constraint by changing the profile of airfoils. Battisti et al. (2016) compared the effect of the DU 06-W-200 and the NACA 0018 airfoils camber line (comparing symmetrical with asymmetrical profiles) on power and thrusts of a VAWT (in the streamwise direction and in the crosswise one) as a function of blade azimuthal position and TSR. They showed that DU 06-W-200 cambered airfoil increases rotor performance at starting TSRs at low rotor speed, but a limitation in exploiting the wind resource at medium to low wind speeds, which are typical of the urban environment. Foley, S., & Paraschivoiu, M. (2017) analyzed a modified morphing trailing edge NACA0012 SSMA (Synergistic Smart-Morphing Aileron) airfoil for a D-VAWT using CFD. They showed for six different fixed morphed profiles that the most performing airfoil regarding $C_p$ is the symmetric airfoil and the $C_p$ increases by morphing the airfoil outward in the upwind path and inward in the downwind path. Moshfeghi et al. (2017) numerically investigates effects of a passive flow control method on aerodynamic performance of a horizontal axis wind turbines airfoils by splitting and non-splitting its blades along the span. 2-D and 3-D simulations are conducted on S809 airfoil in order to study effects of split width and Reynolds. They showed that an appropriate split for can increase the stall performance of the airfoil and then generated power by the blade increases.

This study presents the advantages and the drawbacks of the use of symmetrical, cambered and laminar airfoil for a typical Darrieus type VAWT and covers an aerodynamic analysis using the design software CARDAAV to predict the flow conditions and the performances of a Darrieus type VAWT for the 3 analyzed airfoils: the NACA 0018 symmetrical airfoil, the FX63-137 cambered airfoil and the SNLA 18/50 symmetrical natural laminar flow airfoil. All 3 airfoils were chosen with similar relative thickness for comparison and are depicted in Figure 1 to Figure 3. For each airfoil, the performance of 3 rotors (5, 17 and 34 meters) is compared with emphasis on the torque yield by each airfoil. The novelty of this work is using the FX63-137 cambered airfoil to increase the performance of VAWT regarding the torque and power coefficient ($C_p$).

CARDAAV
The numerical tool used during this analysis is based on the improved Double-Multiple Streamtube model (DMS) (Paraschivoiu, 1981; Paraschivoiu & Delclaux, 1983). The model consists in dividing the rotor in streamtubes and treating each one of the two blade elements defined by a given
streamtube as an actuator disk. Figure 4 illustrates a streamtube with the different wind velocities achieved during the flow through that streamtube. Disk 1 represents the upwind blade element while the disk 2 represents the downwind blade element.

The actuator disk theory is based on the momentum conservation; therefore, the wind velocities must be known to compute the force acting on the disks. The different velocities \( V, V_e, V' \) depend on the freestream velocity \( V_\infty \) and on the interference factors \( u \) and \( u' \):

\[
V = uV_\infty \\
V_e = (2u-1)V_\infty \\
V' = u'(2u-1)V_\infty
\]

\( u \) is upwind interference factor of the wind velocity in each stream tube. To determine the interference factors, a second set of equations is used. Those equations are derived from the blade element theory (Paraschivoiu, 2002), which equates in each streamtube, the normal forces acting on the upwind and downwind blade elements to the forces acting upon the actuator disks. The normal and tangential forces are computed from the airfoil lift and drag coefficients. The following azimuthal function is then obtained:

\[
u(\theta) = \frac{KK_f}{KK_f + \int_{\theta_1}^{\theta_2} W \left( C_n \cos \theta + C_T \sin \theta \cos \delta \right) d\theta}, \quad K = \frac{8\pi r}{N_c}, \quad K_s = \sin(\theta + \Delta \theta/2) - \sin(\theta - \Delta \theta/2)
\]

\( \theta \) is azimuthal angle of turbine blade, \( C_N \) is normal Aerodynamic load coefficient, \( C_T \) is tangential aerodynamic load coefficient, \( \delta \) is blade slope angle (or meridian angle), \( \eta = r/R \), and \( W \) is relative velocity, \( N_c/r = \) rotor solidity, \( r \) is the local rotor radius, \( R \) = rotor radius of rotation.

A similar set of equations is derived for the downwind interference factor and a unitary interference factor is assumed at the beginning of the iterative process. Once the force given by the blade element theory equates the one given by the actuator disk theory, the convergence is achieved and the upwind and downwind velocities are obtained. Then the torque and the mechanical power are computed. The dynamic stall used for this study was the Berg variation (Berg, 1983) of the Gormont model (Gormont, 1973), as it was giving the best correlation with the experimental studies carried out on similar prototypes as those used in this work.

**SELECTED AIRFOILS AND AERODYNAMIC PROPERTIES**

Three types of airfoil are commonly used in Darrieus type VAWT designs: symmetrical, cambered and laminar. One profile of each type was selected to emphasize the impacts of their different aerodynamic characteristics and dependency to the Reynolds number \( (Re) \).

The first airfoil selected for this study is the symmetrical NACA 0018. The NACA symmetrical airfoils family are predominant in the VAWT development for their good efficiency within a wide range of operating conditions. Figure 5 and Figure 6 illustrate the variation of the NACA 0018 lift and drag coefficients as function of the angle of attack \( (\alpha) \) for different Reynolds numbers. These data were obtained experimentally and numerically by Sheldahl, E., & Klimas, P. C. (1980).

The wind tunnel experiments were carried out at Reynolds number of \( 3.6E5, 7E5, 8.6E5 \) and \( 1.76E6 \) through \( 180 \) degrees of angle of attack. The lift and drag coefficients at extrapolated Reynolds numbers were obtained by combining the predictions of the software PROFILE (Eppler & Somers, 1980) with the experimental values. As observed by Jacobs and Sherman (1937) based on experiments on NACA airfoils, the lift and drag coefficients are relatively constants for different Reynolds numbers at high angles of attack.

Figure 7 and Figure 8 illustrate the variation of the lift and drag coefficients of the FX63-137b cambered airfoil as a function of the angle of attack for different Reynolds numbers. Only the data for a few Reynolds numbers are illustrated for clarity. That high lift airfoil was originally designed for a man-powered aircraft.

The data set is composed of three sources: the values from \(-8^\circ < \alpha < 24^\circ\) for Reynolds numbers up to \( 3E5 \) comes from wind tunnel experimental data from the University of Illinois at Urbana-Champaign (Selig & McGranahan, 2004); the coefficients for the Reynolds numbers from \( 3.6E5 \) to \( 3.6E6 \) were computed with the software XFOIL for a viscous and incompressible flow; wind tunnel experimental data were used to extend the data set on high angles of attack. The airfoil was tested on a range of \(-180^\circ < \alpha < -180^\circ\) at \( Re = 152 \ 000 \).
As observed by Jacobs and Sherman (1937) based on experiments on NACA airfoils, it will be considered that at high absolute values of \( \alpha \), lift and drag coefficients are independent of the Reynolds number. It should be pointed out that for this particular airfoil, the blade element tangential force coefficient will be negative for angles of attack between \( \{\alpha_{\text{ZERO LIFT}}; 0^\circ\} \) because of the positive lift generated by a cambered airfoil at some negative angle of attack. Therefore, it was considered for this study that the cambered airfoil would consist of a variable section, which would change its camber from the upwind to downwind section and switch back from the downwind to the upwind section to operate with positive incidence only (see Figure 9). Hence, in this study, all the simulations were realized considering that the cambered blade section has the same aerodynamic properties in the positive and negative incidence flows.

The last airfoil used for this study is the SNLA 18/50. Its lift and drag coefficients as function of the angle of attack for different Reynolds numbers are illustrated on Figure 10. Those data were obtained in wind tunnel experiments for Reynolds numbers of 2E5, 5E5, 1E6 and 1.5E6 at the Texas A&M University and extrapolated numerically (Klimas, 1984).

In summary, the airfoil coefficients were collected from experimental and numerical data. The main purpose of these collected coefficients is to allow a good comparison between the profiles. The 3 airfoils data sets allow a comparison over a range of Reynolds numbers from 2E5 to 3.6E6 and for all angle of attack.

**MAIN OPERATIONAL PARAMETERS INFLUENCING THE COMPARISON**

The aerodynamic forces produced by a rotating blade section depend on the angle of attack, the local flow velocity and the static stall angle, if dynamic stall effects are accounted. During the operation of a Darrieus type VAWT, the angle of attack of a blade element in a streamtube is given by the following relation:

\[
\alpha = \arcsin \left[ \frac{\cos \theta \cos \delta \cos \alpha_0 - (X - \sin \theta) \sin \alpha_0}{\sqrt{(X - \sin \theta)^2 + \cos^2 \theta \cos^2 \delta}} \right], \quad X = \text{Turbine Tip Speed Ratio} = \frac{R \omega}{V_\infty} \tag{5}
\]

Figure 11 shows the variation of the local angle of attack at the equator as a function of the blade azimuth (\( \theta \)) for different turbine Tip speed ratios (TSRs) by changing free stream velocity (\( V_\infty = 5.5, 10, 17.5 \text{ m/s} \)). The Figure 11 indicates that for the same operating conditions, the three airfoils have slightly different local angles of attack. There are two reasons for this: firstly, the downstream wind speed will be different for each airfoil as they have different influences in the upwind part of the blade circular trajectory; secondly, the dynamic stall model uses the airfoil static stall angles to correct the actual angle of attack. The turbine Reynolds number (\( Re \)) and the blade element Reynolds number (\( Re_c \)) of a blade element tangential to the rotation path (\( \alpha_0 = 0 \)) is given by Equations 6 and 7 respectively.

\[
Re = \frac{R \omega c}{V_\infty} \tag{6}
\]

\[
Re_c = \frac{Re \eta}{X} \sqrt{(X - \sin \theta)^2 + \cos^2 \theta \cos^2 \delta} \tag{7}
\]

Where \( V_\infty \) is kinematic viscosity of the fluid, \( X \) is TSR, \( \omega \) is the rotation speed (rad/s), \( c \) the blade chord length (m), \( \eta \) is the local radius to rotor radius (\( r/R \)) ratio and \( \delta \) the angle between the blade normal ad the equatorial plane. The independent parameters of this study will be chosen so that the variation between \( Re_c \) and \( Re \) is minimized. Thus, the VAWT will be a straight bladed (H-Darrieus) VAWT (with \( \eta = 1 \) and \( \delta = 0 \)). This will ensure that the turbine operates in a narrow range within the selected \( Re \) to emphasize its effects in the comparison. Figure 12 illustrates the variation of \( Re_c \) as a function of \( \theta \) for the analyzed airfoils and different TSRs.

The Table 1 presents the different cases simulated in CARDAAV for this comparison. All 3 wind turbines have a rotor aspect ratio (\( \beta \)) equal to 1 and are 2-bladed H-Darrieus rotors. The rotor solidity (\( \sigma = Nc/D \)) was fixed at a low value of 6.1\% for the 3 rotors to obtain a greater range of operating TSRs. The rotational speeds were selected to obtain turbine Reynolds numbers of different orders. The computations were made for all airfoils without considering the blades' tip loss (finite aspect ratio). The performances were computed for all 3 turbines with each one of the analyzed airfoils, for a total of 9 simulations. Please note that the blades chord length was kept constant for all 9 simulations.
RESULTS AND ANALYSIS

Figure 13 compares the results of CARDAAV software: Power output performance for 3rd case study in Table 1 (Re=3.35E6) with the experiment results of ref. [Berg, Klimas and Stephenson (January 1990)]. There is a good agreement between results. The first series of computations were made to compare the power produced by each of the 3 airfoils at optimal rotation speed i.e. the rotation speed associated with the highest power coefficient. Figure 14 to Figure 16 present the azimuthal distribution of the torque coefficient per blade for each analyzed H-Darrieus at a given TSR.

At the TSR = 2.62, the torque produced by the cambered airfoil is the strongest for the 3 Reynolds numbers as one can see on the Figure 14. The higher static stall angle of the FX63-137 allows the airfoil to perform better at low tip speed ratio. On the other side, the laminar blade section produced the smallest average torque because of its sharp stall.

Figure 15 shows the results at TSR = 4.58. At this TSR, the NACA 0018 leads with its less abrupt stall than the SNLA 18/50, even though they have similar average drag characteristic for those angles of attacks. However, as Re number increased, XFOIL predicted an increase of the low drag zone of the cambered airfoil, which leads to the results of the Figure 15-c where the greatest average torque is obtained with the FX63-137. It should be pointed out that numerical convergence was hard to obtain for this operating condition and this airfoil. Thus, those results for the range of a = {-90; -25} should be taken with reserve.

Figure 16 shows the results at TSR = 8.33 which corresponds to the lowest amplitude of angle of attack during the H-Darrieus operation (|α| < 10°).

Figure 16-b-c shows that the greatest average torque is obtained with the SNLA 18/50. The reason for this is the main characteristic of a laminar airfoil: low drag values which correspond to its drag-bucket. However, Figure 16-a show that the greater average torque is obtained with the NACA 0018. This could be explained by the low Reynolds value of that operating condition where the gain from the drag-bucket of the SNLA 18/50 does not surpass the relative high lift of the NACA 0018. One can also notice that for this high TSR value, the cambered airfoil produces the lowest average torque because of its relative low lift to drag ratio at low angles of attack. However, it can be pointed out that in the downwind zone (90< θ<270 in Figure 16), the cambered airfoil with a reversed camber, produces more torque (see results in Figure 16 for cambered airfoil FX63-137: 90<θ<270 and Figure 9).

Figure 17 summarize the previous results through the power coefficients of the 3 Darrieus rotors. As it is illustrated in Figure 17 a,b, the NACA 0018 airfoil has the greatest maximum efficiency as expected, but not for the full range of operation. One can note that at the smaller TSR values (TSR<3.5 on Figure 17 a and TSR<3.0 on Figure 17 b), the cambered airfoil (FX63-137) has the highest efficiency, although, it offers poor performances for greater TSRs at low Reynolds numbers (Re = 3.6E5, 1.8E6). Regarding Figure 17 c, at Re = 3.35E6, CARDAAV predicts the cambered airfoil to be the most efficient blade section all over the TSR range. As mentioned previously, convergence was hard to achieve at higher TSRs for the cambered airfoil, hence the results from Figure 17-c should be considered with reserve.

Finally, Figure 18 illustrates the mechanical power produced by each airfoil on the 3 VAWTs. The SNLA 18/50 laminar airfoil slightly gives more efficiency than the NACA 0018 at small wind speeds. Very high power output can be achieved with the cambered airfoil, but only at high wind speeds, which are rare and associated with very severe operating conditions.

CONCLUSIONS

The aerodynamic coefficients of the 3 types symmetrical, cambered and laminar airfoils for a typical Darrieus type VAWT (NACA 0018, FX63-137 and SNLA 18/50 airfoils) were collected from wind tunnel experiments data sources and numerical computations. They might not be accurate on their whole range, but are believed to respect the airfoils aerodynamic behavior of the airfoils. Comparing torque coefficients ($C_Q$) of these 3 types airfoils indicates that in the low TSRs (<3) with high free stream speed or low rotational frequency, cambered airfoil shows maximum torque coefficient in upwind and downwind azimuth angle of rotation $\theta$. For the high TSRs in the downwind region, due to reverse cambered airfoil, one can see also the higher values for $C_Q$. In addition, power coefficients ($C_p$) in TSRs<3 show better performance for cambered airfoil. Also, in some cases, maximum power coefficient can be obtained from cambered airfoil (Figure 17 c). The predicted performances can be summarized as follow: the laminar airfoil...
lift to drag ratio at low angle of attack and appropriate Reynolds number gives a better efficiency than a conventional symmetrical airfoil at high TSRs; the high static stall angle of the cambered airfoil allows higher power production than a symmetrical airfoil, but at high wind speeds.

REFERENCES
Table 1: Summary of the simulated cases

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<tr>
<td></td>
<td>3.6E5</td>
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<tr>
<td>Number of blades (N)</td>
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</tr>
<tr>
<td>Rotor height [m]</td>
<td>5</td>
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<tr>
<td>Rotor diameter (D) [m]</td>
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<tr>
<td>Rotor solidity (σ)</td>
<td>6.1%</td>
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<tr>
<td>Chord length (c) [m]</td>
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<tr>
<td>Rotation speed [rpm]</td>
<td>175</td>
</tr>
<tr>
<td>Kinematic viscosity [m²/s]</td>
<td>1.945E-5</td>
</tr>
<tr>
<td>(V_∞) [m/s]</td>
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Figure 1: NACA 0018 airfoil.

Figure 2: FX63-137 airfoil.

Figure 3: SNLA 18/50 airfoil.

Figure 4: Actuator disks in a stream-tube.

Figure 5: NACA 0018 lift coefficients (Sheldahl & Klimas, 1981).

Figure 6: NACA 0018 drag coefficients (Sheldahl & Klimas, 1981).

Figure 7: FX63-137b lift coefficients.

Figure 8: FX63-137b drag coefficients.

Figure 9: Airfoils positions in flow stream.

Figure 10: SNLA 18/50 aerodynamic coefficients (Klimas & Berg, 1983).

Figure 11: Local incidence angle as a function of $\theta$ for different turbine TSRs.

Figure 12: Local Reynolds number as a function of $\theta$ for different turbine TSR.

Figure 13: comparing the results of CARDAAV and Berg, Klimas and Stephenson (January 1990): Sandia 34 meter turbine Power output performance for 3rd case study in Table 1 (Re=3.35E6).

Figure 14: Comparison between the azimuthal torque coefficients at TSR = 2.62.

Figure 15: Comparison between the azimuthal torque coefficients at TSR = 4.58.

Figure 16: Comparison between the azimuthal torque coefficients at TSR = 8.33.

Figure 17: Comparison of the power coefficient of the three prototypes.

Figure 18: Mechanical power in function of the wind velocity.
FX63-137b LIFT COEFFICIENT
SELIG EXPERIMENTAL DATA & XFOIL COMPUTATIONS
LINKED WITH HIGH AOA EXPERIMENTAL DATA

![Diagram showing lift coefficients for different Re values](https://mc06.manuscriptcentral.com/tcsme-pubs)
FX63-137b DRAG COEFFICIENT
SELIg EXPERIMENTAL DATA & XFOIL COMPUTATIONS LINKED WITH HIGH AOA EXPERIMENTAL DATA

Re = 101,700 XP
Re = 202,700 XP
Re = 303,400 XP
Re = 360,000 XFOIL
Re = 720,000 XFOIL
Re = 1,440,000 XFOIL
Re = 2,160,000 XFOIL
Re = 2,880,000 XFOIL
Re = 3,600,000 XFOIL
Cambered Airfoil

Upwind

θ

Downwind

Reversed Cambered Airfoil

$V_\infty$
DOE/SANDIA - 34m
Test bed performance

Power, $P$ (kW)

Equatorial wind speed, $V_{EQ}$ (mph)

- CARDA: 28.0 rpm
- Measured: 28.3 rpm
  - L. E. peeling
  - Measured: 28.3 rpm
  - L. E. sanded
TORQUE COEFFICIENT PER BLADE \( \text{Re} = 3.6 \times 10^5, |\text{ALFA}| < 30^\circ \)
\( 2H = 5 \text{m}, \text{BETA} = 1, c = .1524 \text{ m}, N = 2, \text{RPM} = 175, \text{TSR} = 2.62 \)
TORQUE COEFFICIENT PER BLADE \( Re = 3.35e5, |\alpha| < 15^\circ \)
\( 2H = 5m, \beta = 1, c = .1524 m, N = 2, \text{ RPM} = 175, \text{ TSR} = 4.58 \)

- NACA 0018
- FX63-137
- SNLA 18/50

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(a)

https://mc06.manuscriptcentral.com/tcsme-pubs
TORQUE COEFFICIENT PER BLADE \( Re = 1.8 \times 10^6 \), \( |\alpha| < 15^\circ \)
\( 2H = 17 \text{m}, \beta = 1, c = .5185 \text{m}, N = 2, \text{RPM} = 60, \text{TSR} = 4.58 \)
TORQUE COEFFICIENT PER BLADE  $Re = 3.35 \times 10^6$, $|\text{ALFA}| < 15 \, ^\circ$

$2H = 34m$, $\text{BETA} = 1$, $c = 1.050 \, m$, $N = 2$, $\text{RPM} = 28$, $\text{TSR} = 4.58$
TORQUE COEFFICIENT PER BLADE $Re = 3.6e5$, $|\alpha| < 10^\circ$
$2H = 5m$, $\beta = 1$, $c = .1524 m$, $N = 2$, $RPM = 175$, $TSR = 8.33$

(a)
https://mc06.manuscriptcentral.com/tcsme-pubs
TORQUE COEFFICIENT PER BLADE Re = 1.8e6, |ALFA|< 10 °
2H = 17m, BETA = 1, c = .5185 m, N = 2, RPM = 60, TSR = 8.33
TORQUE COEFFICIENT PER BLADE $Re = 3.35e6$, $|\alpha| < 10^\circ$

$2H = 34m$, $\beta = 1$, $c = 1.050m$, $N = 2$, $RPM = 28$, $TSR = 8.33$
POWER COEFFICIENT IN FUNCTION OF TSR
Re = 3.6e5, 2H = 5m, BETA = 1, c = 0.1524 m, N = 2, RPM = 175

(a)
https://mc06.manuscriptcentral.com/tcsme-pubs
POWER COEFFICIENT IN FUNCTION OF TSR

Re = 1.8e6, 2H = 17m, BETA = 1, c = .5185 m, N = 2, RPM = 60
POWER COEFFICIENT IN FUNCTION OF TSR
Re = 3.35e6, 2H = 34 m, BETA = 1, c = 1.050 m, N = 2, RPM = 28
POWER IN FUNCTION OF WIND SPEED

$Re = 3.6e5$, $2H = 5m$, $\beta = 1$, $c = 0.1524m$, $N = 2$, $RPM = 175$

- NACA 0018
- FX63-137
- SNLA 18/50
POWER IN FUNCTION OF WIND SPEED
Re = $1.8 \times 10^6$, $2H = 17$ m, $BETA = 1$, $c = 0.5185$ m, $N = 2$, $RPM = 60$

(b)

https://mc06.manuscriptcentral.com/tcsme-pubs
POWER IN FUNCTION OF WIND SPEED

\[ \text{Re} = 3.35 \times 10^6, \quad 2H = 34\text{m}, \quad \text{BETA} = 1, \quad c = 1.050\text{m}, \quad N = 2, \quad \text{RPM} = 28 \]