Investigation of the two-element airfoil with flap structure for the vertical axis wind turbine

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Abstract. The aerodynamic performance of Vertical axis wind turbine (VAWT) is not as simple as its structure because of the large changing range of angle of attack. We have designed a new kind of two-element airfoil for VAWT on the basis of NACA0012. CFD calculation has been confirmed to have high accuracy by comparison with the experiment data and Xfoil result. The aerodynamic parameter of two-element airfoil has been acquired by CFD calculation in using the Spalart-Allmaras (S-A) turbulence model and the Simple scheme. The relationship between changings of angle of attack and flap’s tilt angle has been found and quantified. The analysis will lay the foundation for further research on the control method for VAWT.

1. Introduction
Generally, wind turbine consist of vertical axis wind turbine(VAWT) and horizontal axis wind turbine(HAWT). [1] VAWT can be divided into two categories. One is Darrieus wind turbine that driven by the lift forces. The other is Savonius wind turbine that driven by the drug forces. Compare with HAWT, VAWT has a lot of advantages, such as lower blade loading makes it has less fatigue. Lower center of gravity (CG) makes it more stability. Easy for production and installation[1]. But VAWT also has disadvantages, such as poor startup performance and hard to get rid of the dynamic stall effect. The paper has been designed a new kind of two-element airfoil for VAWT on the basis of NACA0012. The aerodynamic performance of the airfoil is acquired through CFD calculation. It is feasible for two-element airfoil to be applied in VAWT theoretically. Meanwhile, it becomes infinite possible to improve the performance, stability and efficient for VAWT with flag structure.

2. Model construst and calculation
2.1. Operation principle of VAWT
The azimuthal angle of lift force driven VAWT could be vary from 0 degree to 360 degree, so it always use the blade that with symmetrical airfoils, such as NACA0012, NACA0015, NACA0018 and so on. Fig.1 shows the operation principle of VAWT.

The $\dot{V}_t$ represents the wind flow velocity, $\dot{V}_a$ represents the airfoil’s tangential velocity, $\dot{V}_w$ represents the resultant velocity, $F_l$ and $F_d$ represents the lift force and drag force, $\alpha$ represents the angle of attack, $\psi$ represents the azimuthal angle, $\omega$ represents the angular velocity, $\lambda$ represents the tip speed ratio and $R$ represents the radius.
The tip speed ratio is defined:

$$\lambda = \frac{\omega R}{V_w}$$  \hspace{1cm} (1)

In VAWT, the relative velocity is the vector of tangential velocity and wind flow velocity. Actually, the angle of attack is not from -360 degree to 360 degree for VAWT. The angle of attack is a function of the tip speed ratio and the azimuthal angle:

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

In Fig 2, the higher tip speed ratio will correspond to the small changing range for angle of attack. The angle of attack changed from the negative angle to the positive angle and distributed in a symmetric way.

In VAWT, lift force provides positive torque in a circle of rotation and is more than the negative torque caused by drag force. This is the operation principle of VAWT. [2]
2.2. Two-element airfoil construct

The flap could optimize aerodynamic performance. In the stall region, the aerodynamic performance could be optimized by changing the lift force and the flap direction. Research by Xu Zhang from ZheJiang University shows that suited airfoil could improve aerodynamic performance and output power of the wind turbine. [3]

![Airfoil with flap.](image)

**Figure 3. Airfoil with flap.**

The airfoil’s main body is constructed on the basis of NACA0015 airfoil showed in Fig.3. The flap could rotate around its center. Its center is apart from the trailing edge for 1/4 chord’s length. The rotate angle is range from negative 30 degree to positive 30 degree. With the need of structure, the width of the inner seam could be 1/30 chord’s length.

The flap is fixed on the airfoil by upper and lower hinged(showed in Fig.4). The flap could rotate around its center. Considering the blade structure, NACA0012 airfoil is used on the upper and lower blade. So the axis of rotation for the flap could be installed easily.

![Three-dimensional model for the blade.](image)

**Figure 4. Three-dimensional model for the blade.**

The largest advantage for the airfoil that has flap is optimized aerodynamic performance. When the VAWT is going to start, the operated condition will very adverse because of the lower tip speed ratio. At the moment we could adjust the flap to maximize the lift forces so it could quickly get started. When the
VAWT is running in the overloaded situation, the flap can also help the turbine to slow down through man-made stall or lower the lift force on the airfoil. The method could decrease the fatigue load on the blade and extend the use age of VAWT.

2.3. Computational domain and meshing
The angle of attack is range from negative 30 degree to positive 30 degree. NACA0012 is symmetrical airfoil, so flap angle $\theta$ is symmetrical about $0^\circ$. $\theta$ could be $10^\circ$, $20^\circ$ and $30^\circ$ in this paper. In the meshing process, the computational domain has been divided into two parts that is near airfoil part and the outer flow part. The import comes nine times of chord length from the blade leading edge; export comes 20 times of chord length from the blade trailing edge; upper and lower surface are 10 times of chord length from the blade. Assuming the outlet pressure is not the atmospheric pressure, suitable outer flow should be defined to get the valid boundary conditions.

The air could be the fluid medium, where $\rho = 1.225 \text{ kg/m}^3$, $\mu = 1.7894 \times 10^{-5} \text{ kg m/s}$, $V = 10 \text{ m/s}$, $Re = 6.85 \times 10^6$ and $Ma = 0.03$. Meshing is the key point in CFD computation. The NACA0012 airfoil with the flap is meshed in structured grid, showed in Fig.5, the first layer of the grid is 0.0001. The value of $y^*$ along the blade surface is between 0.5 and 9.

![Figure 5. Meshing.](image)

2.4. Control equation
Because of the rotation speed is rather slow compare with the wind speed, then the flow around the airfoil could be seemed as incompressible Navier-Stokes equation. The equation could be express as follow when the coordinate axis is put on the blade.

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0$$

$$\left\{ \begin{array}{l}
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} + \omega \frac{\partial X}{\partial Y} + 2\omega \frac{\partial U}{\partial Y} = -\frac{1}{\rho} \frac{\partial p}{\partial X} + \nu \left( \frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right) \\
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} + \omega \frac{\partial Y}{\partial X} + 2\omega \frac{\partial V}{\partial X} = -\frac{1}{\rho} \frac{\partial p}{\partial Y} + \nu \left( \frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} \right)
\end{array} \right.$$  

In the equation: $X$, $Y$, $U$ and $V$ are represents the position and velocity in rotating coordinate system. Their relation in static coordination could be expressed as follow.

$$x = X \cos \theta + Y \sin \theta \quad X = x \cos \theta - y \sin \theta$$

$$y = -X \sin \theta + Y \cos \theta \quad Y = x \sin \theta + y \cos \theta$$

$$u = U \cos \theta + V \sin \theta + \omega y \quad U = u \cos \theta - v \sin \theta - \omega y$$

$$v = -U \sin \theta + V \cos \theta - \omega x \quad V = u \sin \theta + v \cos \theta + \omega x$$

where: $x, y$ represents the position and $u, v$ represents the velocity in static coordinate system.
while $\theta$ represents the rotation angular speed.

3. Result analysis
When $\alpha<12^\circ$, the boundary layer separation haven't happened. The test data of lift and drag coefficient could be consistent, and the error could be under 5%. When $\alpha>12^\circ$, the error could be markedly increased. NACA0012 airfoil stalls when $\alpha>16^\circ$. The airfoil began stalling and separating When $12^\circ<\alpha<16^\circ$, the stall vortex appears alone the leading edge.(Showed in Fig.6)

![Figure 6. Separation of boundary layer and stall vortex.](image)

Because of the errors in CFD calculation data, qualitatively analysis always adopt to the static computation when the airfoil was static stalling. Errors in both CFD calculation data and Xfoil calculation data could under 5% before stalling(Shown in Fig.7). But the errors could changed obviously after stalling. The static stall is the major factor for the misalignment of lift and drag force.

![Figure 7. Lift/drag coefficient (Re = 6.85×10^5).](image)

![Figure 8. Drag coefficient (Re = 6.85×10^5).](image)

The difference of the drag coefficient between CFD calculation data and experimental data is less than 0.3 percent. But the error of the actual calculation data is up to 50%(showed in Fig.8). The reason for the error in the calculation of the drag coefficient should be tested and verified in the further researches.

There is little difference on the lift and drag coefficient between two-element airfoil and NACA0012
airfoil when $\theta = 0^\circ$ (showed in Fig.9). It shows that two-element airfoil could keep the aerodynamic performance of the NACA0012 airfoil when $\theta = 0^\circ$. The physical significance of the offset of the lift coefficient curve is to change the airfoil aerodynamic performance by changing the tilt angle.

![Figure 9. Lift coefficient (Re=6.85×10^5).](image)

![Figure 10. Tilt angle vs. Angle of attack ($C_L = 0$).](image)

In this paper, it shows the changes and relationships between angle of swing and angle of attack when $C_L = 0$. The angle of swing is range from $0^\circ$ to $30^\circ$, and the increment of angle of swing is $5^\circ$. It also provides the basis for controlling of VAWT on high angle of attack (Showed in Fig.10). In other words, the correspondence could establish the change of angle of attack on the static state with the specific angle of swing. The control policy of angle of attack could improve the aerodynamic performance theoretically, but the actual result should be worked out through experimental test.

4. Conclusion

The blade is key technology for VAWT and its airfoil is directly influence it power efficiency. This paper presents the flap trailing edge on the basis of VAWT’s aerodynamic theory. The CFD calculation for airfoil with flap has been made. The result proves the airfoil aerodynamic computational accuracy. The result shows:

1) Both of Xfoil and CFD can get aerodynamic performance of the airfoil accurately before the airfoil stalling. Calculation accuracy are similar. But if the airfoil stalled, no method can accurately get the aerodynamic performance.

2) Because of the surface roughness of the airfoil, the assume of the turbulence model and the round-off error, there are some errors when calculating the drag force. The errors can be ignored for the overall performance of the airfoil.

3) Flap trailing edge partly changes the attack angle of the airfoil. The paper shows the corresponding relationship of the flap’s rotating angle and the attack angle. It will provides the basis for the research of flap controlling scheme.

The work in this article has its meanings in the study for the aerodynamic performance analysis on two-element airfoil for VAWT. It also lays a solid foundation for the research on the flag control.

References

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