Aerodynamics Analysis of a Slotted NACA4412
Wind Turbine Airfoil Leading Edge Using CFD Case One

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Abstract

The static pressure, dynamic pressure and velocity magnitude are important parameters and have a strong influence on airfoil lift force. In this paper a slotted NACA 4412 airfoil profile is considered for analysis by using the commercial code ANSYS 14.5.7 WORKBENCH FLUENT® at an inlet boundary condition of different approaching wind velocities for various airfoil angles of attack in the range 0˚ to 24˚. Renormalized group (RNG) k-ε turbulence model with enhanced wall function is used for the analysis. Variations of static pressure, dynamic pressure and velocity magnitude are plotted in form of contours and / or vectors.

Keywords: computational fluid dynamics, angle of attack (AoA), airfoil, wind velocity, slotted, lift, wind turbine.

1. Introduction

Since the sum of static and dynamic pressures is the total pressure, where the difference on the upper and lower surfaces of the airfoil is the cause of lift. This paper presents an idea of connecting these two sides by slots to predict its effect on the lift and airfoil cut-in speed.

2. Validation

The work was validated against a published technical paper that was referred to in reference (1).

Fig. 1: Typical NACA 4412

Saxena & Agrawal[1] published a technical paper to evaluate the critical angle of attack of NACA4412 by using FLUENT® and they compared their results with the laboratory test results.
They concluded that the airfoil critical angle of attack is 16°. The author used all the physical parameters they applied at AoA15 and found a complete match of the velocity magnitude results.

![Fig. 2: Velocity Magnitude Contours at AoA15 and V=18.4 m/s](image1)

![Fig. 3: Velocity Magnitude Contours at AoA15 and V=18.4 m/s](image2)

Table I: Percentage change of values as calculated from velocity key for Figs. 1 & 2.

| Title / No. | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Percentile | 67.90| 45.50| 53.20| 40.80| 28.80| 36.00| 33.60| 31.20| 28.80| 26.40| 24.00| 21.60| 19.20| 16.80| 14.40| 12.00| 9.60| 7.19| 4.80| 2.40| 0.00|
| % Change   | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00|

According to the velocity comparison in table I above; it is noted that:

1- The validation obtained are the same for (81%) of the results
2- The change in the other values is less than (0.1%).
3- This is (BACK TO BACK) Validation.

The grid independence test of NACA4412 is shown by figure (4); accordingly the critical angle of attack was found to be 20°.

![Fig. 4: NACA 4412 grid convergence chart](image3)

3- Case One General Description

The standard airfoil NACA4412 was modified by making a groove that starts from the airfoil pressure side (at 11.5% of the chord length) and extends toward the airfoil suction side in a curved shape side (at 20% of the chord length). Both groove edges at the inlet (at the pressure side) and outlet (at the groove suction side) remain sharp. This case was named as **Case One**.
Fluid physical properties are (fluid type: air, pressure: 101325Pa, kinematic viscosity: 1.2800E-05 m²/s).
- Pressure based close out model was selected (realizable RNG K-ε Model).
- Monitoring accuracy is set at (1.0e-06) for all parameters.

4- Case One Output Results
This case was computed at the following velocities and angles of attack shown by the table (2) below:

Table II: Simulation points

<table>
<thead>
<tr>
<th>Approaching wind velocity (m/s)</th>
<th>AoA(deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0, 5</td>
</tr>
<tr>
<td>2</td>
<td>0, 5</td>
</tr>
<tr>
<td>3.4</td>
<td>0, 5</td>
</tr>
<tr>
<td>5.5</td>
<td>0, 5</td>
</tr>
<tr>
<td>18.4</td>
<td>0, 5, 10, 16, 17, 18, 20, 21, 22, 23, 24, 25,</td>
</tr>
</tbody>
</table>
5- Stall Angle

Case One showed a change of the stall angle of the attack from (20°) which recorded by the original NACA 4412 airfoil to (23°) in this case, also recorded a lift force of (320.4065 N/m) at this angle in comparison with the NACA 4412 airfoil lift force of (448.11421 N/m) which gives a decrease of (-28.50%) in the lift force value at this angle, as shown by figure(8), the calculations are performed according to reference(2).

The following analysis is for one selected simulation scenario at (AoA23) and inlet velocity of (18.4 m/s).

6- Velocity Magnitude

The velocity magnitude at the airfoil leading edge reaches (45 m/s) and decreases gradually to around (0 m/s) on the pressure side at (5%) of airfoil chord line where the flow separated from the surface. The velocity starts increasing gradually up to (21 m/s) at the airfoil groove inlet edge, the velocity remains in the order of (5 m/s) after the groove back side edge, then it starts increasing after (35%) of the chord length.

On the suction side, the velocity magnitude value is about (47 m/s) at the leading edge of the airfoil; then it decreases sharply to (0 m/s) within a distance equals to (0.17%) of the chord length where the shear force vanishes, then it remains around (2.5 m/s) until about (70%) of the airfoil chord length then rises to (5 m/s) at (90%) of the airfoil chord length, as shown by figures (10 -11).

Case One has a lower lift force and (lift/drag) ratio than NACA 4412 for all approaching wind velocities in the range of (2-5.5 m/s) on Beaufort wind scale for both angles of attack (AoA0) and (AoA5). At the approaching wind velocity of (0.3 m/s), Case One performs better than NACA 4412 at (AoA0) only but at (AoA5) it gives a less lift force than NACA 4412 by a (-45.9%), as shown by figures (12 -15) and table (III).

Vortices start forming gradually as the airfoil angle of attack increases, as shown by figure (18). At AoA23, three vortices are formed on the suction side of the airfoil; two on the trailing edge suction side and the third at the groove outlet at the leading edge side. The flow velocity inside the groove is homogenous and remains at a velocity of order of (15 m/s) and forming two vortices close to the pressure side (groove inlet), as shown by figures (18.H).

At low approaching wind velocities and AoA0, the vortices start disappearing as the wind velocity strength increases, as shown by figure (19 C & D).

Case One shows instability at (AoA0) when the approaching wind speed is (0.3 m/s) despite the positive lift it can provide. This phenomena occurred because of the vortices that formed
inside the groove which in addition to the fluid mixing between that flowing out through the groove (of low energy) and that accelerating on the suction side (of a high energy). This instability disappears when the approaching wind speed reaches (2m/s); at this velocity the forces on both groove sides are balanced. The vortices created inside the groove are completely trapped by the high stream velocity and cancels its effect, as shown by figure (19).

<table>
<thead>
<tr>
<th>Table (III): Variation of Lift Force of Case One with respect to NACA4412 at low angles of attack and low wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of Attack / Wind Velocity</td>
</tr>
<tr>
<td>AoA0</td>
</tr>
<tr>
<td>AoA5</td>
</tr>
</tbody>
</table>

Case One showed lower lift force at all airfoil angles of attack in the range of (0˚-24˚) at approaching wind velocity of 18.4 m/s and it gives a (5.9%) increase in lift force than NACA 4412 at (AoA25), as shown by figures (16 - 17) and table (IV).

<table>
<thead>
<tr>
<th>Table (IV): Variation of Lift Force of Case one with respect to NACA4412 at different airfoil angles of attack and approaching wind speed of 18.4 m/s.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
</tr>
<tr>
<td>Case 1</td>
</tr>
</tbody>
</table>

“The sum of static and dynamic pressure is the total pressure and its difference on the upper and lower surface is the cause of the lift"[4]. The approaching flow splits at the airfoil stagnation point on the leading edge into two streams; first stream travels towards the airfoil upper surface while the other one travels towards the lower one. According to Bernoulli equation; the static pressure will be at its maximum value at the stagnation point where the approaching fluid velocity is zero. The total pressure is constant at every streamline but the only variations are on static and dynamic pressures at every point on it.
7- Conclusions

Comparing Case One characteristic with the original NACA 4412 airfoil; the following can be concluded:

1- Case One has a poor lift force at low approaching wind velocities in the range of (2-5.5 m/s) on Beaufort scale except when the (AoA0) and the wind velocity is (0.3 m/s) showed a higher lift than NACA 4412 by (486%).

2- Case One recorded a new critical angle of attack of (23’) with comparison of the NACA 4412 airfoil angle of attack of (20’) but with a lower lift force by (-28.50%) comparing with NACA 4412 critical angle of attack Lift force when the approaching wind velocity is 18.4 m/s.

3- Static and dynamic pressures (i.e. total pressure) variation on both the lower and upper surfaces of the airfoil are the main cause of the airfoil lift. The total pressure is constant at every streamline but the only variations are on static and dynamic pressures at every point on it.

4- The dynamic pressure on the pressure side is decreasing with the increase of the angle of attack.

5- The dynamic pressure away from the leading edge on the suction side is decreasing as the angle of attack increases.

6- The dynamic pressure is at it’s lowest value inside the slot when the airfoil angle of attack is zero then increased slightly when it increases.

7- The dynamic pressure has the maximum value at the maximum airfoil thickness when the airfoil angle of attack is zero then this point moves towards the leading edge direction.

8- The slot plays the major role in the flow separation from the airfoil upper surface and causing the static pressure to build up tremendously on the whole area the airfoil trailing edge area behind the slot which has a negative impact on the lift.

9- The stagnation point moves towards the trailing edge on the lower surface side of the airfoil as the airfoil angle of attack increased.
Fig. 8: Comparison of lift force and AoA between Case One and NACA 4412

Fig. 9: Case One static pressure

Fig. 10: Velocity magnitude curve

Fig. 11: Wall shear stress

Fig. 12: Comparison of lift force between NACA 4412 and Case One at Low wind speeds and AoA0

Fig. 13: Comparison of lift force between NACA 4412 and Case One at low wind speeds and AoA5
Fig. 14: Comparison of lift/drag ratio between NACA 4412 and Case One at low wind speeds and AoA0.

Fig. 15: Comparison of lift force between NACA 4412 and Case One at low wind speeds and AoA5.

Fig. 16: Comparison of drag force between Case One and NACA 4412 at approaching wind velocity 18.4 m/s.

Fig. 17: Comparison of lift/drag ratio between Case One and NACA 4412 at approaching wind velocity 18.4 m/s.
Fig. A: Velocity Magnitude at AoA0 and 18.4 m/s

Fig. B: Velocity magnitude at AoA10 and 18.4 m/s

Fig. C: Velocity at AoA16 and 18.4 m/s

Fig. D: Velocity at AoA18 and 18.4 m/s
**Fig. E**: Velocity at AoA20 and 18.4 m/s

**Fig. F**: Velocity at AoA21 and 18.4 m/s

**Fig. G**: Velocity at AoA23 and 18.4 m/s

**Fig. H**: Velocity magnitude, streamlines and the vortices at AoA23 and 18.4 m/s

**Fig. 18**: Velocity magnitude at different angles of attack and wind velocity of 18.4 m/s
Velocity magnitude contours

**Fig. A:** AoA0 and 0.3 m/s

Velocity magnitude vectors across the groove

**Fig. 19:** Velocity at AoA0 and low approaching wind velocity
Fig. A: AoA0 and 18.4 m/s

Fig. B: AoA10 and 18.4 m/s

Fig. C: AoA16 and 18.4 m/s

Fig. D: AoA18 and 18.4 m/s

Fig. E: AoA20 and 18.4 m/s

Fig. F: AoA21 and 18.4 m/s

Fig. G: AoA23 and 18.4 m/s

Fig. 20: Static Pressure at different angles of attack and wind velocity of 18.4 m/s
Fig. 21: Dynamic pressure variations at a different angles of attack and wind velocity of 18.4 m/s
References


4- Arvind Prabhakar; “CFD analysis of static pressure and dynamic pressure for NACA 4412”, 2013, IJETT, Volume4; issue8, ISSN: 2231-5381.