Analytical Assessment of the Effects of Blade Cone Angle on the Aerodynamic Performance of the Horizontal Axis Wind Turbine

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Abstract: In this research, the performance of a horizontal axis wind turbine (HAWT) is investigated, considering the cone angle effects. In a HAWT with an ordinary pattern, all blades are located in one plate and the cone angle of the plate is zero. In the design of HAWTs, to prevent contact between the blades and the turbine’s tower and considering the aero elasticity effects, the blades are installed on the shaft of the rotor using a cone angle, which has effects on the turbine’s performance. We investigated the aerodynamic performance of the HAWT according to cone angle deviations, numerically. With a change in the blade’s plate pattern, a cone-shaped volume is created. In this condition, the projected blade’s length gets smaller and the blade’s sections (vertical to the wind) become larger. The geometry of these sections was obtained with AutoCAD software. The performance of the turbine was analysed with Qblade software, and the results compared with each other. The output results of Qblade for the situation, in which the cone angle is considered, equal to the projected blade’s length and the new sections for the projected airfoils within the zero cone angle investigated and compared. This research was carried out for two conditions: a blade with a constant chord and a blade with different chords through the length of the blade. The creation of the cone angle may be suggested as one approach for controlling the wind turbine.

Key Word: Horizontal Axis Wind Turbine, Cone Angle, Qblade, Numerical Analysis.
1. Introduction

Given continually increasing energy costs, the reduction of fossil fuel resources and acute environmental pollution, the pursuit of clean, renewable energies has become inevitable. Wind energy and wind turbines have made a great contribution. Currently, horizontal axis wind turbines (HAWT) have a superior role due to their large size and high electricity generation capacity.

The design and optimization of wind turbines require aerodynamic analysis. In a wind turbine, the direction of turbine control and also the aeroelastic considerations often are applied per blades, and the nacelle assembly is installed with specific angles including the tilt angle, which is the angle between the main turbine axis and the horizontal axis. In larger turbines, the tilt angle may be used as an approach to prevent contact between the turbine blades and the tower. Another use of this angle is to control smaller-sized turbines. In some turbines, curved blades are used to overcome the aeroelasticity effects, and this is shown in Figure 1.

Furthermore, the cone angle is introduced as the angle between the blade’s torsion axis and the rotor plane, and that has been assessed in this research. Several research projects have been conducted in order to study the performance of the turbine as a function of various parameters, and they are referred to in this paper. In the present research, the effect of cone angle as an effective parameter on the performance and optimized blade design of a HAWT, was carried out.

Mohammad Reza Mohaghegh et al.[1] conducted aerodynamic analysis of a wind turbine airfoil motion and its aerodynamic characteristics in a HAWT. With an analysis of the important parameters in the design of a horizontal axis wind turbine’s airfoil, they assessed the effect of each parameter on the airfoil’s, and consequently the wind turbine’s, performance. Mahmoud Mehrdd Shokrie et al. [2] designed and analyzed the blade of a HAWT regarding the applied aerodynamic forces generally. In addition, the analysis and design for a specific blade with a capacity of producing 300 kW was carried out. The aerodynamic of the flow around the blade was analyzed using simple theories such as Betz’s vortex momentum theory. In the next steps, the aerodynamic analysis of the flow was carried out using more advanced theories, such as Stewart’s.

Farid Khalafi et al. [3] numerically analyzed a 20kW wind turbine and investigated the effects of the intense flow turbulence of the rotational wind flow around the blades, and also the effect of atmospheric external flow on the turbine’s performance, using models suitable for the simulation of external turbulence and vortex surrounding flow. That paper included a comparison; various numerical results were obtained and experimental results were found using the required tests on a simplified model of a three-blade horizontal axis wind turbine. Morteza Behbehani Nejad et al.[4] used the finite element method to aerodynamically analyze an unsteady 660 kW VESTAS HAWT with a 3.22 m blade, operating in Binalood Wind Plant.

Mohsen Jahanmeiri et al. [5] evaluated the effects of thickness in some commonly-used 4-digit NACA airfoils on the wind turbine’s performance. The geometries of the blades were modeled and meshed in Gambit software, and Fluent software was used for the solutions, applying the finite volume approach. To numerically solve the unsteady flow around the airfoil, Reynolds-averaged Navier-Stokes (RANS) equations were used. Regarding the results of the simulation and with a comparison with the power coefficient of vertical axis wind turbine (VAWT) in different sections of the blade, the NACA showed the best performance coefficient in the range compared with the assessed tip velocity.
2. Blade Element Momentum Theory (BEM) and the Governing Equations

Blade Element Momentum (BEM) theory methodology is one of the most useful and commonly used in the design of wind turbine blades. It may be used for analysis of an existing wind turbine, or to design one. This approach is widely used by many researchers and craftsmen due to its simple operation, suitable accuracy and perfect speed compared with other methods. This method is used in Qblade software to analyze the wind turbine [7-11]. The summary of the derived relations from momentum equations and blade element momentum are presented in relations 1 and 2 [12, 13]:

\[
\begin{align*}
\frac{dT}{d\theta} &= \sigma \pi \rho \left(1 - \alpha^2\right) \sin(\phi) \frac{C_s}{r} \right) dr \\
\frac{dP}{d\theta} &= \sigma \pi \rho \left(1 - \alpha^2\right) \left(1 + \alpha\right) \sin(\phi) \cos(\phi) \frac{C_t}{r^2} \right) dr \\
\end{align*}
\]

(1)

\[
\begin{align*}
\frac{dT}{d\theta} &= 4\alpha \left(1 - \alpha\right) \rho \pi v_t \Omega r \right) dr \\
\frac{dP}{d\theta} &= 4\alpha \left(1 - \alpha\right) \rho \pi v_t \Omega r \right) dr \\
\end{align*}
\]

(2)

With the equality of the above relations for thrust force and power, we have:

\[
\begin{align*}
\alpha &= \frac{1}{4\sin(\phi)} \frac{C_s}{\sigma C_s} + 1 \\
\alpha &= \frac{1}{4\sin(\phi) \cos(\phi)} \frac{C_t}{\sigma C_t} - 1
\end{align*}
\]

(3)

The above relations are used in the blade-designing process. It should be noted that since the \(C_s\) and \(C_D\) are functions of the angle of attack (AOA), and the induction coefficient of the tangential axis affects the AOA, the above equations should be solved using the trial and error method. Obtaining the above coefficients, external power coefficient of the turbine, could be calculated as:

\[
C_e = \frac{8}{\lambda} \int_{\lambda} \left(1 - \alpha \right) \left[1 - \frac{C_t}{C_s} \tan(\phi) \right] d\lambda
\]

(4)
The BEM method is an analytical–numerical approach, which is based on the simple relations of fluid mechanics. This method has been obtained for infinite number of wind turbines’ blades and needs some corrections to completely model the wind turbine. For example, the effects of limited blade number, modeling the wakes, the effects of Yaw, Tilt and Cone angle, the effects of unsteady flow, tower effects etc, could be taken into account. The corrections related to the cone angle in the WT_Perf software are added to this method [14-16]

3. Blade Geometry and Turbine Characteristics

In this paper, the aerodynamic design of a HAWT’s blade of step angle control type has been carried out to assess the effect of cone angle on the turbine’s performance. For this purpose, two blades with a constant chord and a variable chord were designed and evaluated. The characteristics of the simulated turbine are presented in Table. 1.

| Characteristics             | Quantity       |
|----------------------------|----------------|
| Number of Blades           | 3              |
| The airfoil Type           | NACA4412       |
| Rotor Radius               | 2.132 m        |
| Rated Speed                | 224 rpm        |
| Rated Wind Speed           | 10 m/s         |
| Rated tip Speed Coefficient| 5              |
| Rated Power Coefficient    | 0.40           |
| Rated Power                | 5 kW           |

The airfoil geometry in Qblade software is shown in Figure 3. In addition, Figures. 2 and 3 illustrate the lift and drag coefficient curves of the NACA4412, with regard to AOA.

Figure 2. The geometry of NACA4412 airfoil
In the next step, using the software’s optimization feature, the blade’s characteristics in various radiuses, chord distribution and each airfoil’s pitch were obtained in every blade’s sections. It would also have been possible, knowing the field specifications, to perform blade optimization. This is one of the notable features of Qblade software. The output results of the wind turbine’s design, generated by Qblade software for two blades with constant and variable chords, are presented in Figure 4. The chord values and the twist angle, which is calculated by Qblade, are presented in Figure 5.
In a HAWT with common pattern, all blades are located in one plane and the cone angle of the blades’ plane is considered as zero. In order to prevent the contact between the blades of a HAWT and its tower, and also considering the aeroelasticity effects, the blades are installed on the rotor shaft using a cone angle that affects the turbine’s performance.

With a deviating the pattern in the blades’ plane, a cone-shaped volume is created. In this situation, the length project of the blade gets smaller and the blade’s sections (vertical to the wind) become larger. The geometries of these sections were calculated by AutoCad software in this step [17, 18]. Afterwards, the Qblade-designed blade that has been described was modeled by cone angles of 10, 20, 30 and 40 in AutoCad software, and the blade’s sections were calculated in this condition. Figures 6 and 7 illustrate.
After obtaining the blade’s geometry in AutoCad software, the new sections within every cone angle were considered as an input value of Qblade and thus the performance of the turbine could be analyzed within different cone angles. The output solution of the Qblade for the state that the cone angle is considered equals to projected blade’s length and the new sections for projected airfoils were compared and assessed with the zero cone angle. This research was carried out for two conditions; the blade with a constant length and variable length through the length of the blade.

4. Results and Discussion

Using information from the previous parts of this paper, the created blades will be assessed and analyzed. For this purpose, first with the help of Qblade, the practical parameters of the blades including the coefficients of power (Cp), moment (Cm) and axial force (CT) were calculated and compared with the original state (zero cone angle). The distribution of power coefficient according to tip speed within zero cone angle for the blade with constant chord length and cone angles of 10, 20, 30 and 40 was compared and this is shown in Figure 8.

It is observed that at first, with an increase in the tip speed ratio, the power coefficient increases and decreases after reaching to its maximum value in the optimum tip speed of TSR=5. The behavior of the chart could be analyzed such that with a constant rotational speed and increasing of the wind speed, the AOA of the flow on the airfoils increases. An increase in the AOA leads to stall and eventually the lift coefficient falls and the drag coefficient increases, and consequently the power coefficient falls. Furthermore, the value of tip speed ratio reduces and leads to the power coefficient chart’s development and the slope of the power coefficient variations decreases. The decreased slope of the chart leads to better control conditions for the turbine.
Figure 8. Power coefficient according to the TSR within constant chord length

In Figure 9 the torque coefficient variation, according to the tip speed ratio of the blade with a constant chord and different cone angles, is presented. The values of the optimum tip speed ratio for power and moment ratio differ, which is logical due to the relation between the power and moment (P=Τ*ω). With
an increase in the cone angle, the value of moment coefficient within $TSR < TSROptimum$ has been increased, but for $TSR > TSROptimum$ the moment coefficient has been reduced. This issue leads to amplification of the initial state of the turbine, but low-rated power. With an increase in the cone angle up to 40, the variations become intense.

In Figure 10, the trust coefficient variations, according to the tip speed ratio with constant chord length and different cone angles, are presented. This shows that with increasing the cone angle, the TSR
increases and leads to gradual increase in the thrust coefficient. With more cone angle incensement, the thrust coefficient becomes even higher. This might be due to a reduction in the surface swept by the blades within the cone angle incensement. The thrust coefficient definition ($C_T = \frac{T}{0.5\rho AV^2}$) reveals that the value of thrust coefficient increases.

![Figure 10. The thrust coefficient according to TSR with constant chord length](image-url)
In Figure 11, the coefficients of power, moment and thrust force with constant chord blade within different cone angles are compared in one chart. The behavior of power coefficient, moment and thrust are obvious with regard to cone angle incensement.

![Figure 11. Comparison of blade coefficients with constant chord within different cone angles](image)

Next, we turn to the results related to variable chord length. In Figure 12, the power coefficient differences according to the TSR with variable chord length within different cone angles are presented. It can be observed that the behavior of the blade’s power curve with the chord’s variable length is similar to the same blade with a constant length. The difference is that the intensity of the variations in the variable chord length is less than the other. This shows that the effect of cone angle impacts the constant chord length blade’s performance more.
Figure 12. The power coefficient according to the TSR within variable chord length and different cone angles.

Figure 13 shows the variation of the moment coefficient regarding to TSR within variable chord length and different cone angles.
In Figure 14, the variation of the thrust coefficient according to TSR within variable chord length and different cone angles is presented. It can be observed that with an increase in the cone angle, the thrust coefficient of the blade grows higher.
In Figure 15, the coefficients of power, torque and thrust of the blade within variable length and different cone angles are compared in one chart.
As we have seen, the terms related to cone angle were added to BEM method using WT_Perf software. In order to assess the validity of the results, the above analysis was performed in the software and the output results were compared with the current results. On this basis, the value of maximum calculated power coefficient using the two mentioned methods for cone angles ranging from 0 to 40 within blade’s constant and variable chord length are presented in Table. 2. In the last column of the table, the error of the two methods is calculated. It can be observed that the power coefficient values have a low difference relative to each other and the maximum existing error is 4.56 percent.
Table 2. Comparison of the maximum output power of Qblade and WT_Perf software programs

| cone angle | blade with       | Max. Power Coefficient | maximum existing error percent |
|------------|------------------|-------------------------|--------------------------------|
|            |                  | Qblade | WT_Perf |                  |                          |
| 0 degree   | variable chord   | 0.482 | 0.480  | 0.42             |
|            | constant chord   | 0.473 | 0.459  | 3.05             |
| 10 degree  | variable chord   | 0.473 | 0.477  | -0.84            |
|            | constant chord   | 0.453 | 0.458  | -1.09            |
| 20 degree  | variable chord   | 0.466 | 0.470  | -0.85            |
|            | constant chord   | 0.448 | 0.455  | -1.54            |
| 30 degree  | variable chord   | 0.462 | 0.459  | -0.65            |
|            | constant chord   | 0.443 | 0.451  | -1.77            |
| 40 degree  | variable chord   | 0.459 | 0.439  | -4.54            |
|            | constant chord   | 0.434 | 0.437  | -0.69            |

5. Conclusion

In this study, we investigated the effect of the blade’s cone angle as an effective parameter in the performance and optimum design of a HAWT. The most important results are:

1. With an increase in the cone angle, the maximum power reduces and the optimum TSR decreases, which could improve the control conditions of the turbine.
2. With an increase in the cone angle, the value of moment coefficient within $TSR < TSR_{optimal}$ has been increased but for $TSR > TSR_{optimal}$, the moment coefficient has been reduced. This issue leads to amplification of the initial state of the turbine, but low rated power instead. With an increase in the cone angle up to 40, the variations become intense.
3. With increasing the cone angle, the TSR increases and leads to gradual increase in the thrust coefficient. With more cone angle incensement, the thrust coefficient goes even higher. The reason might be due to a reduction in the swept surface by the blades within the cone angle incensement and according to the thrust coefficient definition ($C_T = T/(0.5pA^2V^2)$) it reveals that the value of thrust coefficient gets higher.
4. It can be observed that the behavior of the blade’s power curve with the chord’s variable length is similar to the same blade with a constant length. The difference is that the intensity of the variations in the variable chord length is less than the other. This shows that the effect of cone angle impacts the constant chord length blade’s performance to a greater extent.
5. The power coefficient values have a low degree of difference when compared with each other and the maximum existing error is 4.56 percent.
6. The existence of the cone angle could be considered as an effective approach for controlling the wind turbine.
### Nomenclature

| Symbol | Definition                                      |
|--------|-------------------------------------------------|
| $a$    | Axial induction factor                          |
| $a'$   | Tangential induction factor                     |
| AOA    | Angle of attack                                 |
| Cd     | Drag coefficient                                |
| Cl     | Lift coefficient                                |
| Cm     | Torque coefficient                              |
| CN     | Normal force coefficient                        |
| Cp     | Power coefficient                               |
| Ct     | Thrust coefficient                              |
| $\rho$ | Air density                                     |
| $\sigma'$ | Local Blade solidity                           |
| $\phi$ | Flow angle                                      |
| $\Omega$ | Angular velocity                               |
| $\omega$ | Wake rotational speed                          |
| $\lambda$ | Tip speed ratio from the hub                    |
| $\lambda_r$ | Local Tip speed ratio                           |
| V1     | Wind velocity                                   |
| $\lambda$ | Tip speed ratio                                 |
| $\lambda_r$ | Local Tip speed ratio                           |
| BEM    | Blade element momentum theory                   |
| TSR    | Tip speed ratio                                 |
| HAWT   | Horizontal axis wind turbine                    |
| RANS   | Reynolds-averaged Navier-Stokes                 |

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