Effect of yaw angle on the global performances of Horizontal Axis Wind Turbine - QBlade simulation

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Abstract. The yaw angle has a great importance in the wind turbine working. Even though most of the large turbines have yaw mechanisms, they do not have an instant response. The aerodynamic forces and torque on the blades fluctuate, depending on the yaw angle. The design and the numerical simulation of the wind turbine were performed with the Blade Element Momentum method in open source QBlade software. The power coefficient, torque, thrust and power output generated by wind turbine in non-yawed flow were analysed. The simulations have been performed for non-yawed flow, in rotational speed range between 2100 and 3300 rpm and wind velocity of 15 m/s. Simulations for yaw angle range have been performed between ±60\(^\circ\), with 5\(^\circ\) step at rated rotational speed of 2700 rpm. The results are presented through charts for global parameters in both non-yawed flow, and yawed flow. The effect of yaw angle on global performances of the wind turbines is more important after the value of 25\(^\circ\) when the power output decrease with about 15\% from power output in non-yawed flow. The average value of the exponent from conventional relation of power coefficient in yawed flow is 1.77 in good concordance with experimental tests.

1. Introduction
Nowadays, the wind energy knows a continuous increase most of all because it is a renewable and non-polluting energy. The kinetic energy of the wind is converted into mechanical energy by wind turbines. The two main types of wind turbines are classified according rotational axis in HAWT (Horizontal Axis Wind Turbine) and VAWT (Vertical Axis Wind Turbine) [1]. The HAWT are used in the most of windy areas around the world due to higher efficiency, but in recent years in the most favourable areas already are installed wind turbines, so new research directions have been identified in order to increase the percentage of energy provided by wind turbines: installation of small wind turbines, expansion of offshore areas and increase of rotor dimensions [2].

Several methods to design and predict aerodynamic performances of wind turbines such as vortex methods, 3D viscous-inviscid interaction technique, computational fluid dynamics algorithms and Blade Element Momentum (BEM) method are used. The most used method by the designers of wind turbines is the BEM method. This method provides a good aerodynamic performance analysis with a relatively simple procedure in different flow regime such as different wind speeds, yaw angles, setting angles of blades [3,4]. The classical BEM method was first developed by Glauert [5] by combining momentum
theory and blade element theory. The BEM method involves discretization in $N$ annular elements with height $dr$ of the stream tube introduced in the 1-D momentum theory and no flow across the elements. The annular elements are considered independent one to another (no radial dependency) and the force on the blades are considered constant in each annular element due to hypothesis of a rotor with infinite number of blades [6].

The classical BEM method is a two-dimensional method extrapolated into the third dimension through applied semi-empirical corrections, tip and root losses induced by finite number of the blades and 3D corrections, derived from experimental tests or CFD computations. The BEM method have a main advantage in comparison to CFD computation due to less computational time, very low cost and possibility to develop and test rapidly different rotor design, reaching at a rotor model that will be studied with CFD technique in details [7].

Most of the working time, HAWT operate in yawed flow because the direction of wind varies continuously over time. Wind turbines working in yawed flow leads to difficult problems of aerodynamics, control and aeroelasticity. Some of these for the moment are unresolved, [8]. Yaw angle, figure 1, represent the angle between wind turbine rotor plane and wind direction. Several researchers have conducted numerical and to experimental test in order to predict the operation and to determinate the global performances of the HAWT in yawed flow [9, 10].

![Figure 1. Yaw angle of HAWT.](image)

Some researchers, based on the assumption that induction is constant with yaw angle, with $x=3$ (aerodynamics of the helicopter rotor in a forward flight) do not consider that aerodynamics of wind turbines has additional difficulties and differences from the aerodynamics of the helicopter rotor.

It is proposed that the power coefficient, and implicitly, power output in yawed flow have a cosinusoidal behaviour expressed in the conventional form in equation (1), [11].

$$C_P(\psi_0) = C_P(0°) \cdot \cos^x(\psi_0) \tag{1}$$

Experimental tests in wind tunnel and on field [12], shows that $x$ varies from 1.88 and 5.15 while in measurement on the rotor with diameter of 4.5 m in German Dutch Wind Tunnel [13], $x$ is about 1.8.

QBlade is an open source software dedicated to design and predict the aerodynamic performances of Horizontal Axis Wind Turbines and Vertical Axis Wind Turbines blades using BEM method and the integration in XFOIL enables to design custom airfoils and compute their polars and also allow to import experimental polars.

In this paper, power coefficient and power curve generated for a HAWT with three blades, with NACA 4415 airfoils and 0.58 m rotor diameter obtained with QBlade software in the range $\pm 60°$ for yaw angle have been analysed.
The relatively small geometrical dimensions of the wind turbine rotor are due to the fact that this research is part of a more complex analysis in which, in a further step, some experimental tests will be carried out. For experimental tests the MF-TA4 wind tunnel from the Department of Fluid Mechanics, Fluid Machinery and Fluid Power Systems will be used, for which the cross-section area of the test section is 2.853 m$^2$. In order to obtain a blockage ratio under 10% it was chosen that the swept area of the rotor to be equal to 0.2642 m$^2$, which correspond to the rotor diameter of 0.58 m.

2. Wind turbine rotor model

2.1. Airfoil characteristics

One of the important points in the design of wind turbine rotors is the selection of the blade airfoil. A wind turbine blade can contain one or more airfoils. There are a multitude of bidimensional airfoils that can be used in the design of HAWT blades. At low Reynolds numbers ($<10^5$), which is the case of this research, there is difficult to find experimental polars. In [14], Eastman N. J. and Sherman A., have conducted experimental tests for different airfoils at low Reynolds numbers, including NACA 4-digit series of airfoils. These series of airfoils have been used since the first half of the 20th century in different applications, including wind turbines [15]. In this paper a NACA 4415 airfoil was used for the entire blade length, being one of the airfoils that have been experimentally characterized for different Reynolds numbers. In figure 2 are presented the dimensionless coordinates of the NACA 4415 airfoil, having a maximum camber of 4% located at 40% from the leading edge and having a maximum thickness of 15% with respect to the airfoil chord length.

![NACA 4415 airfoil dimensionless coordinates](image)

Figure 2. NACA 4415 airfoil dimensionless coordinates.

2.2. Polars of NACA 4415 airfoil

In this paper, the variation of the lift coefficient ($C_L$) and drag coefficient ($C_D$) in the range of the incidence angle ($\alpha$) between -7° and 21.2° corresponding to a Reynolds number equal with 83000 for NACA 4415 airfoil were taken from charts resulting from experimental tests. Due to the small number of points on the charts of incidence angle range, an interpolation of 100 point with 5th degree polynomial was made. The polars of the airfoil was created in XFOIL and then was imported in QBlade software. In figure 3, (a) lift coefficient and 3, (b) drag coefficient for incident angle in the range -7 and 21.2 degrees are presented. In figure 3, (c) are presented the polar curves for NACA 4415 airfoil in QBlade. The optimum incidence angle is 6.387 degrees conditioned by maximum ratio between lift coefficient and drag coefficient equal with 40.055. At this value of the incidence angle, optimum lift coefficient and drag coefficient are equals with 1.0386 and respectively 0.0259.
The design of the blade was accomplished by using BEM method considering the rated parameters of the wind turbine rotor presented in table 1.

Table 1. Wind turbine rated parameters.

| Wind velocity V [m·s⁻¹] | Rotational speed n [rpm] | Tip speed ratio TSR [-] | Rotor diameter D [m] | Reynolds Number Re [-] |
|-------------------------|--------------------------|------------------------|----------------------|-----------------------|
| 15                      | 2700                     | 5.46                   | 0.58                 | 83000                 |

The total length of the blade is 0.27 m. The blade was divided in 23 sections with 2 circular airfoils with 0.016 m diameter, at radial positions 0.02 m and 0.03 m. Between section 2 (circular foil) and section 3 (NACA 4415 airfoil) automatic linear interpolation was performed by QBlade.

The NACA 4415 airfoil chord varies from 0.044874 m in section 3 and 0.016946 m in the final section. The chord along the blade is presented in figure 4, (a). The total twist of the blade is 13.43 degree between 13.957 degrees at first section of the active zone of the blade and 0.5234 degrees at tip of the blade. The variation of the twist angle along the blade is presented in figure 4, (b). Global solidity
of the blade is 6.1189 %. Geometry of the blade and airfoils used at each radial position are presented in figure 4, (c).

![Figure 4. Geometrical dimensions of the blade.](image)

3. *QBlade simulations and results*

The functional performance analysis of wind turbine rotor was performed in *BEM Simulation* menu for tip speed ratio range between 2 and 8 with 0.1 step. The air density and air viscosity are considered 1.225 kg/m³ and respectively 1.647e-05 Pa·s. Prandl correction, 3D correction and Reynolds number correction have been used. Figure 5, (a) shows the variation of Reynolds number along the blade and figure 5, (b) shows the absolute error between the Reynold number of imported polar and Reynolds number calculated by QBlade.

The largest absolute error is recorded at the hub area and at the inactive part of the blade (16504 at radius 0.03 m), while at active part of the blade the maximum absolute error for the Reynolds number is -3275 (at radius 0.0902 m), which corresponds to a relative error of less than 4%.
The multi-parametric analysis of functional performances was performed in Multi-Parameter BEM Simulation menu. The simulations were performed for rotational speed range between 2100 and 3300 rpm with 50 rpm step, and for wind velocity range between 5 and 25 m/s with 1 m/s step.

Global performances of the wind turbine rotor are showed in figure 6, (a) for power coefficient, (b) for power output, (c) for torque and (d) for thrust according to rotational speed. For rated rotational speed of 2700 rpm and rated wind velocity of 15 m/s, the values of the calculated parameters are presented in table 2 (red point from figure 6).

### Table 2. Wind turbine global performances parameters.

| Parameter  | Value     |
|------------|-----------|
| Power coeff | 0.40408   |
| Power      | 220.69    |
| Torque     | 0.7805    |
| Thrust     | 30.08     |

The influence of yaw angle on global performances of wind turbine rotor was studied using LLT (Lifting Line Theory) HAWT Simulation menu, [16] for the yaw angle range between ±60° with 5° step size under an windfield defined by the mean wind velocity of 15 m/s, by the hub height of 0.88 m, and by the turbulence intensity of 5 %. The LLT simulations were accomplish with 360 time steps, for 10
complete rotor revolution. In figure 7, (a) and 7, (b) are presented the positions of the wind turbine rotor and the near wake for positive and respectively negative values of yaw angle.

![Figure 7. Position of the wind turbine rotor.](image)

The results of the LLT simulations are in particular influenced by two free parameters used to adjust the initial core size and its growth rate in time, vortex time offset ($S_c$) and turbulent vortex viscosity ($\delta_\nu$). These parameters affect significant the performances of the wind turbine rotor analyzed. Too large values for them reduces the induction in the near wake and leads to over predictions of rotor power output, leading to significant discrepancies between the BEM results and LLT results, [16]. In this paper, two cases with different values of these two parameters, presented in table 3, were analyzed.

| Case  | $S_c$ [-] | $\delta_\nu$ [-] |
|-------|-----------|------------------|
| Case 1| 2         | 1                |
| Case 2| 0.2       | 0.2              |

Power coefficient and power output according to yaw angle range are presented in figure 8, (a) and respectively in figure 8, (b). The yaw angle increase causes a significant decrease of global parameters. Maximum values are obtaining at 0°, 0.504 for power coefficient and 275 W for power output in case 1 and 0.453 for power coefficient and 248 W for power output in case 2.

The effect of yaw angle on global performances of the wind turbines is more important after the value of 25° when the power output decrease with about 15% with respect to the power output in non-yawed flow in both cases. At yaw angles greater than 45° the power output generated by wind turbine decrease to half. Power coefficient and power output at equal positive and negative value of the yaw angle have small differences, with greater values obtained at positive yaw angles more important after 50 degrees. For example, power output is 115.75 W at -50° and 117.29 W at 50° in case 1 and respectively 98.7 W at -50° and 101.5 W at 50° in case 2.

At zero yaw angle, significant discrepancy between BEM results and LLT results has been noticed. This discrepancy is mainly due to the chosen values of the two free parameters (vortex time offset and turbulent vortex viscosity), the simulations time steps number and some limitation of the LLT method. The relative error between BEM results and the two cases of LLT simulations for power coefficient is 24.7 % in case 1 and 12.28 % in case 2.
Further, using the results obtained in case 2, the $x$ exponent of conventional expression for power coefficient from equation (1) in yawed flow was determined. In figure 9, the $x$ exponent values (green dots) according to yaw angle range from $-5^\circ$ to $5^\circ$ are presented. The LLT computed data was approximated with a 4th degree polynomial (brown line), described by equation (2):

$$x = 1.5581 \cdot 10^{-8} \cdot \psi^4 + 2.4558 \cdot 10^{-8} \cdot \psi^3 + 0.00024239 \cdot \psi^2 - 0.00074046 \cdot \psi + 1.3874$$  \hspace{1cm} (2)

The maximum and minimum values of the $x$ exponent, in case 2, equal to 2.56, and 1.18 have been obtained at $-60^\circ$, and respectively at $5^\circ$.

The mean of the exponent (red line), equal with 1.77 has been computed with data presented in figure 9, being in a good concordance with the value obtained from experimental tests conducted in German Dutch Wind Tunnel, which is 1.8, [13], and also with the lower value, equal to 1.88, of the $x$ exponent range presented in [12].

Relative deviation ($\epsilon$) of the $x$ exponent with respect to its mean value is showed in figure 10, for case 2. Maximum deviation of 45% has been observed for yaw angle of $-60^\circ$. The relative deviation decrease in the range $0^\circ \div \pm 40^\circ$, reaches a minimum point at $\pm 40^\circ$, and then increase till $\pm 60^\circ$. 

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**Figure 8.** Influence of yaw angle on power coefficient and power output.

**Figure 9.** Exponent of conventional equation for power coefficient.

**Figure 10.** Relative deviation for power coefficient.
4. Conclusion

In this study, the global performances of HAWT in non-yawed and yawed flow were analyzed using QBlade open source software. The design of the blades was accomplished in QBlade using BEM method. The most important design steps are the selection of optimum incidence and the calculation of airfoil polars for a good approximation of the Reynolds number.

The yaw angle affects the global performances of the wind turbines no matter how small it is. In this study has been observed that the effect of yaw angle is more important after the value of $25^\circ$, when the power output decrease with about 15% from the power output in non-yawed flow. Moreover, at yaw angles greater than $45^\circ$ the power output generated by wind turbine decrease to half.

Researchers opinions on the value of the $x$ exponent from conventional equation for power coefficient at different yaw angles are divergent. In this paper, mean value of the $x$ exponent of conventional equation for power coefficient in the range $\pm 60^\circ$ is 1.77, being in good concordance with the mean value obtained in several experimental tests.

The LLT results for those two cases analyzed in this paper have significant differences compared to BEM results at zero yaw angle. In case 1, values of the global parameters for wind turbine model are over predicted with 24.7 % compared to BEM results. In case 2, the relative error between LLT results and BEM results decrease at 12.28 %. This discrepancy between the two methods results is influenced by chosen values of the two free parameters used in LLT simulations and the simulations time steps number.

In order to obtain good prediction of the global parameters of wind turbines in LLT HAWT Simulation menu it is necessary to adapt the values of the vortex time offset ($S_\nu$) and turbulent vortex viscosity ($\delta_v$) to the dimension of computed wind turbine rotor. Large values for these parameters reduces induction in the near wake and leads to over predictions of global parameters of wind turbine.

In the future, some experimental tests (using MF-TA4 wind tunnel) and new numerical simulations (using ANSYS Fluent) are necessary to improve the knowledge about the effect of the yaw angle on the aerodynamic performances of HAWT and the value of the exponent from conventional expression for yaw angle.

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