Aerodynamic and structural analysis of a small-scale horizontal axis wind turbine using QBlade

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Abstract. In this paper the aerodynamic and structural analysis of a small-scale horizontal axis wind turbine using QBlade software will be presented. QBlade software will be used to validate the wind turbine design, according with the Blade Element Momentum theory. The influence of the tip and root losses on the power curve will be analysed. The pitch angle control curve will be obtained. The annual energy production will be analysed on the basis of Weibull parameters. The structural analysis in terms of modal and static structural will be presented for three different internal structures: solid blade, hollow blade without spar, and hollow blade with spar. It has been found that the natural frequencies obtained for lateral translations (flapwise and edgewise), chord rotation around the blade longitudinal axis and longitudinal translation are in a safety range from the harmonics of wind turbine rotational speed at the operating condition, thus avoiding the resonance.

1. Introduction

One of the most important open source software for design and simulation of wind turbines with horizontal and vertical axis is QBlade, [1]. QBlade software can be used for airfoils design and analysis [2], due to integrated XFOIL code [3]. QBlade software is based on the Blade Element Momentum (BEM) theory, thus is widely used for simulation [4], optimization [5], and validation of horizontal axis wind turbine design [6]. CFD analysis is used with good results for validation of QBlade computations for wind turbine design in [7]. Some other results that are used for validation of QBlade analysis against other similar software, and against experimental data are presented in [8]. QBlade is also used with good results for vertical axis wind turbine simulation [9].

In this paper, QBlade software will be used for aerodynamic and structural analysis of a 10-kW horizontal axis wind turbine. The wind turbine has been designed using BEM method with NREL’s S823 airfoil; QBlade software being used in this paper for design validation considering as design parameters the power coefficient and the power of the wind turbine. The influence of root and tip losses on the power and power coefficient will be also analysed. Using QBlade software, the distribution of the pitch angle of the rotor blade for which the wind turbine power will be limited to the rated power for high winds will be computed. The influence of the site wind potential on the wind turbine annual energy production will be also analysed.

From the point of view of blade structure, three constructive types will be considered: the solid blade, the hollow blade without spar, and the hollow blade with longitudinal spar. QBlade will be used for computing the blade mass, the modal frequencies for flapwise, edgewise, torsional and longitudinal directions, as well as for evaluating the von Misses stress.
2. Wind turbine characteristics

The wind turbine that will be analysed in this paper has been designed and presented as Bachelor’s thesis at “Gheorghe Asachi” Technical University of Iasi in 2017, [10]. It is about a wind turbine with horizontal axis and $z=3$ blades, with rated power $P_r=10$ kW, rated wind velocity $U_r=10$ m/s, and rated rotational speed $n_r=175$ rpm. The wind turbine has been designed for a site where the wind potential can be described by the following Weibull parameters: the shape parameter $k=1.85$ and the scale parameter $A=7.35$ m/s. The rated tip speed ratio of the wind turbine is $TSR=6.5$ while the rated power coefficient is $C_p^r=0.4$. The wind turbine has been designed using BEM theory.

3. Airfoil characteristics

The starting point of the designing process has been the selection of an airfoil and the analysis of the airfoil characteristic parameters (pressure coefficient, boundary layer shape, polars). For this wind turbine, the NREL’s S823 airfoil has been selected, for which the maximum thickness is 21.2% at 24.3% of the chord, and the maximum camber is 2.4% at 70.5% of the chord [11]. This airfoil is not included in the QBlade default airfoil database, therefore, has to be imported from an external file. The external file with airfoil geometric characteristics is obtained from online airfoil database, [11]. Once the airfoil is imported in the QBlade project, the distribution of the pressure coefficient and the boundary layer shape on the lower and the upper surfaces of the airfoil can be analysed. For example, in Figure 1 the pressure coefficient $C_p$ is presented for the optimum angle of attack $\alpha_{opt}=7^\circ$.

![Figure 1. The pressure coefficient.](image)

The angle of attack has a strong influence on the pressure coefficient, but also on the boundary layer shape. The boundary layer shape is comparatively presented in Figure 2, a) for the optimum value of angle of attack $\alpha_{opt}=7^\circ$, while figure 2, b) corresponds for the angle of attack of $11^\circ$. This kind of analysis shows that for the optimum angle of attack the boundary layer separation point on the upper side of the airfoil is very close to the trailing edge of the airfoil, Figure 2, a). Increasing the angle of attack value, the separation point is moving away from the trailing edge towards the leading edge, while the thickness of the boundary layer is increasing with respect to the optimum angle of attack case.

![Figure 2. Boundary layer and the separation point.](image)

Finally, the airfoil polars can be analysed, no matter the source of these polars: imported from external files with experimental data, or generated inside QBlade. These polars are obtained for a usual range of angle of attack, for example $-5^\circ$-$15^\circ$. Most likely is that during different working stages of the wind turbine, the airfoil will work under angles of attack outside the initial range, therefore the polars must be extrapolated on the full range $-180^\circ$-$180^\circ$. QBlade can perform this extrapolation using Montgomerie and Viterna methods [12, 13]. For this analysis, the Montgomerie method has been used and the lift,
drag and the lift to drag coefficients can be obtained. For example, the lift coefficient for full angles of attack range is presented in Figure 3.

![Figure 3](image-url)  
**Figure 3.** Lift coefficient for $-180^\circ \div 180^\circ$ with Montgomerie extrapolation method.

Analysing the airfoil polars, has been observed that the angle of attack for which the lift to drag ratio has the maximum value is $\alpha_{\text{opt}}=7^\circ$, and this will be the angle of attack for all blade sections starting from hub until the tip. For this specific angle of attack, the lift coefficient is 1.082, the drag coefficient is 0.01256, while the lift/drag ratio has its maximum value of 86.1265, [11].

The characteristic curves of the airfoil are strongly dependent of the Reynolds number, therefore the Reynolds number must be chosen before starting the aerodynamic design. This Reynolds number, known as polar Reynolds number, has been chosen to be $Re_p=5\times10^5$. During the aerodynamic design, based on the velocity resulted in the computation process, another Reynolds number will be computed, the blade Reynolds number. For this case, the blade Reynolds number resulted in the range $Re_b=(5.07\div5.32)\times10^5$ with smaller value close to the hub. Thus, there is a relative error between these two Reynolds numbers in range of $\varepsilon_{Re}=1.4\div6.4\%$, with smaller value close to the hub, figure 4. The graph presented in Figure 4 has been obtained using a fourth-degree polynomial fit. This error, noticed at the Reynolds number for the airfoil characteristic curves, indicates that the real wind turbine will have different global characteristics. However, in this particular case, the maximum relative error (6.4%) is small enough in order to consider that the computed global characteristics will be close to the real wind turbine characteristics.

![Figure 4](image-url)  
**Figure 4.** Relative error between the polar and the blade Reynolds numbers.

4. Blade characteristics

The main geometric parameters of the wind turbine blade are: the tip radius $R_t=3.6$ m, the hub radius $R_h=0.15$ m, the intermediate radius which will define the active part of the blade until the tip, as well as the inactive part of the blade until the hub $R_a=0.972$ m. For this study, the intermediate radius is defined by the radius ratio $k = R_a / R_t=0.27$. Thus, the blade length will be $L=2.628$ m. The chord length $c_{\text{opt}}[\text{m}]$ (computed with the Schmitz relationship, [12]) and the blade twist angle $\beta_{\text{opt}}[^\circ]$ along the blade are presented in figure 5 and figure 6.
The wind turbine blade is presented in Figure 7. There are indicated the position and the airfoil name for all sections along the blade. The active part of the blade is between the tip radius and the intermediate radius; for this part, a single airfoil is used in all sections. The inactive part of the blade is between the intermediate radius and the hub radius and is composed by two parts: the cylindrical part for connection with the hub, and the interpolated part between airfoil section and the circular section.

5. Aerodynamic analysis

After the blade and rotor definition several aerodynamic analyses can be performed. First of all, the power coefficient and the power of the wind turbine can be comparatively analysed for three cases: without tip and root losses, only with tip losses, and only with root losses. The tip and root losses are defined by the Prandtl’s loss factor, [14]. The Prandtl’s loss factors for the tip and for the root are presented in Figure 8. Figures 9, a) and 9, b) shows that there is a small influence of the root losses on both the power coefficient, and the power of wind turbine. On the other hand, the influence of the tip losses is very important and should never be neglected on the designing process of wind turbines. For example, from figure 9, b), the wind turbine power without any losses is 11.3 kW; if only the tip losses will be considered, then the power will be 10.3 kW with a decrease in power of around 8.85%, and finally, if only the root losses will be considered, the power, basically, does not change.

The point marked with a black circle represents the wind turbine rated point in terms of power coefficient (figure 9, a) and wind turbine power (figure 9, b). There is a good agreement between the wind turbine rated data ($TSR=6.5\Rightarrow CP_r=0.4$ and $P_r=10$ kW) and the values computed in QBlade ($TSR=6.5\Rightarrow CP=0.4123$ and $P=10.3$ kW).
Another aspect regarding the aerodynamic analysis is related with the power control of the wind turbine by pitch regulation, which is one of the most important method for limiting the rotor power and speed, \[15\]. Pitch regulation represents the process of mechanically adjusting of the blade pitch angle in order to maintain the rated power of the wind turbine for high wind speeds, above the wind speed rated value, which in this case is \(U_r=10\) m/s. QBlade is able to obtain the required distribution of the pitch angle for which the wind turbine power will be limited to the rated value \((P_r=10\) kW\) in case of high winds. This pitch angle curve will be further use for controlling the actuator which will rotate the blade around its longitudinal axis. The pitch angle curve control and the wind turbine power curve are presented in figure 10. Analysing these curves, can be observed the cut-in wind speed (the minimum wind speed at which the wind turbine will generate power) which is 4 m/s, and the cut-off wind speed (the maximum wind speed at which the wind turbine will generate power) which is 25 m/s. Between the cut-in wind speed and the rated wind speed there is the domain of partial-loads, where the wind turbine power depends with the wind speed based on a non-linear relationship. For this domain, the pitch angle is set to zero. Between the rated wind speed and the cut-off wind speed there is the domain of full loads, where the wind turbine power should have the constant value of the rated power. In order to maintain this constant value, despite the increase in wind speed, the aerodynamic angle of attack should change according with the pitch angle curve, starting from -6.5° at 11 m/s until -28.2° at 25 m/s, figure 10.
The annual energy production (AEP, [MWh/year]) of the wind turbine is the total amount of energy produced during a year and can be obtained by multiplying the power from the power curve with the wind speed frequency distribution. This wind turbine has been designed for a wind speed frequency defined by the shape parameter $k=1.85$ and the scale parameter $A=7.35$ m/s. However, the wind turbine can operate in different sites, for different wind potentials. For example, the influence of the Weibull parameters on the annual energy production is presented in Figure 11, a) for the scale parameter, and figure 11, b) for the shape parameter.

![Graph showing annual energy production](image)

**Figure 11. Annual energy production.**

The scale parameter is related with the mean wind speed, thus, increasing the scale parameter, the annual energy production will increase as well, Figure 11, a). The point parked with a black circle represents the annual energy production for the wind turbine, if it will operate on the designed site. For this case, the annual energy production is 31.149 MWh/year. On the other hand, the dimensionless shape parameter which is related with the breadth of the wind speed distribution, has a more complex influence on the annual energy production. The maximum annual energy production, which is 31.242 MWh/year can be obtained on a site characterized by the shape parameter 1.597, Figure 11, b). The red square on the Figure 11, b) represents the maximum annual energy production in terms of shape parameter.

### 6. Modal analysis

Three types of blades have been analysed: solid blade, hollow blade without spar, and hollow blade with a longitudinal spar. The blade is made by a generic double bias material with density of 1750 kg/m$^3$ and Young’s modulus 1.2e+10 Pa, while the spar is made by a generic triaxial material with density of 1850 kg/m$^3$ and Young’s modulus 2e+10 Pa. For the hollow blades, the shell thickness is variable along the blade with 2% of the chord thickness. The spar thickness is also variable along the blade with 8% of the chord thickness. The spar position is defined by 25% of the chord, and the spar angle is 0°. Considering all these characteristics, the blades mass computed with QBlade are: 92.4527 kg for the solid blade, 18.5303 kg for the hollow blade without spar, and 27.9298 kg for the hollow blade with spar.

Modal analysis consists in determining the modal frequencies (natural vibration frequencies) and the mode shapes for different rotor speed. In order to compare the modal frequencies with the excitation frequencies generated by the rotation of the rotor blades, the data computed with QBlade are presented in Campbell plot format, figure 12. Two types of excitation frequencies have been considered: the blade passing frequency associated with once-per-revolution (1P), and the rotor passing frequency associated with three-per-revolution (3P), as the wind turbine analysed in this paper has three blades. QBlade can compute modal frequencies for different bending direction: flapwise, edgewise, torsional and longitudinal. The results presented in figure 12 shows that the most dangerous bending direction is the flapwise for which the modal frequencies are closer to the excitation frequencies 1P and 3P than the modal frequencies in edgewise bending direction. However, even the flapwise modal frequencies are in a safety range from the excitation frequencies 1P and 3P for all the wind turbine operating conditions. For example, at rated speed of 175 rpm the excitation frequencies are 2.9167 Hz (1P) and 8.75 Hz (3P), while the modal frequencies in flapwise direction are 21.1694 Hz (solid blade), 19.1978 Hz (hollow blade without spar), and 20.0929 Hz (hollow blade with spar).
Because of the order of magnitude, only flapwise and edgewise modal frequencies has been presented in Figure 12. This decision is justified, because, for example, for the solid blade, the 1st mode of the torsional modal frequencies are around 273 Hz, while for the longitudinal direction the 1st mode of modal frequencies are around 326 Hz; these values are far from the excitation frequencies 1P (2.9167 Hz) and 3P (8.75 Hz), thus, will not be presented. Moreover, only the 1st mode of modal frequencies will be presented, as for the 2nd, the 3rd, and so on, the modal frequencies are higher than for the 1st mode. For example, for the solid blade and the flapwise direction, the modal frequencies for the 2nd, the 3rd, and the 4th modes are: 62.5463 Hz, 102.095 Hz and 144.288 Hz (at rated speed of 175 rpm).

7. Structural analysis
The von Misses stress has been computed for all three blades (solid blade, hollow blade without spar and hollow blade with spar) for aerodynamic loading defined by the rated wind speed of 10 m/s, figure 13. From the point of view of structural behaviour, the best option is the solid blade; however due to the high mass which is 92.4527 kg, other options should be considered. The smallest value of the mass is for the hollow blade without spar; however, for this case the highest von Misses stress values occur. On the other hand, the solid blade with spar is in-between the other two constructive solutions in terms of mass and von Misses stress. Another interesting thing that can be observed from figure 13 is about the position of maximum von Misses stress, which is at the hub radius $R_h=0.15$ m for the hollow blades, and around the intermediate radius $R_a=0.972$ m for the solid blade.

8. Conclusions
QBlade is a very useful tool for performing different design and validation tasks in the field of wind turbines: airfoil and polar design, blade and wind turbine design, static structural and modal analysis. Several aerodynamic analyses can be made at detailed level, for example the influence of tip and root losses on the wind turbine power parameters. Good agreement has been observed between the rated and computed data: 3% for the power and 3.075% for the power coefficient.

The pitch angle control curve is another extremely important result which establishes the required range for the pitch angle $0\pm 28.2^\circ$ for maintaining the rated power of 10 kW for wind speeds is the domain 10–25 m/s.
The annual energy production obtained for the designed site \((k=1.85, ~A=7.35 ~m/s)\) is 31.149 MWh/year. However, better annual energy production can be obtained for sites with smaller shape parameter, in range \(k=1.43\pm1.85\), with a maximum value of 31.242 MWh/year for \(k=1.597\).

The modal analysis shows that the most dangerous situation is defined by the hollow blade without spar and the flapwise bending direction; however, even for this case there is a safety margin of around 120%. A better behaviour has been noticed for the hollow blade with spar; the safety margin in this case is around 130%. The hollow blade with spar is the better option from the point of view of the relationship between the mass blade and the von Misses stress. However, because of the QBlade material limitation, the results obtained for the modal and static structural analyses can be considered only as a first approximation.

Due to the specific approximations of the BEM theory, which represents also default limitations of the QBlade software, these results, even if they are encouraging and obtained with very low computational effort, should be used only as preliminary design. As consequence, further investigations using more accurate methods, like CFD analysis, should be performed for obtaining results more closely to the wind turbine real behaviour, which of course, can be exactly determined only by experiment.

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