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QBLADE: AN OPEN SOURCE TOOL FOR DESIGN AND SIMULATION OF HORIZONTAL AND VERTICAL AXIS WIND TURBINES

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ABSTRACT

The software QBlade is developed as an open source framework for the simulation and design of wind turbines. QBlade utilizes the Blade Element Momentum (BEM) method for the simulation of horizontal axis- and a Double Multiple Streamtube (DMS) algorithm for the simulation of vertical axis wind turbine performance. For the design of custom airfoils and the computation of airfoil lift- and drag coefficient polars the viscous-inviscid coupled panel method code XFOIL is integrated within the graphical user interface of QBlade. Additionally, a module for the extrapolation of airfoil polars, beyond the stall point, for a 360° range of angles of attack is integrated. The resulting functionality allows the use of QBlade as a comprehensive tool for wind turbine design. QBlade is constantly being maintained, validated and advanced with new functionality. This paper describes the software and its modules, at the current state, in theory and application.

Keywords: QBlade, Wind Energy, Horizontal & Vertical Axis Wind Turbine Simulation, BEM, DMS

1. INTRODUCTION

The software project QBlade [1] was started in 2010 at the chair of fluid mechanics of the TU Berlin. The motivation was to create a single tool that comprises all the functionality needed for aerodynamic wind turbine design and simulation without the need to import, convert or process data from other sources (Fig.1.). Another focus was on embedding the code in a convenient graphical user interface to improve accessibility over comparable simulation codes. In order to facilitate research on wind turbines worldwide the software is distributed freely under a GPL license and also utilizes functions and modules from other proven and tested open-source projects. QBlade has been downloaded more than 20.000 times during the last two years and is applied by universities, companies and individuals around the world. The benefits of such a large user base are the constant questioning of results, frequent validation and fast debugging of the simulation routines from user feedback. The functionality of QBlade includes the following modules:

- Airfoil design and analysis
- Lift and drag polar extrapolation
- Blade design and optimization
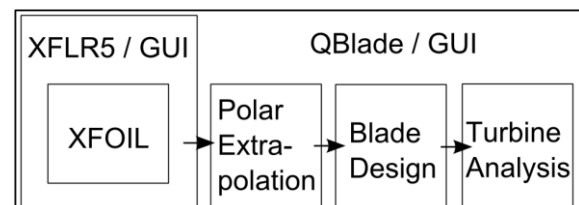- Turbine definition and simulation

2. THE SOFTWARE MODULES

Fig.1. Software modules inside QBlade

2.1 Airfoil Design and Analysis

The BEM and DMS algorithms, that are applied to simulate a wind turbine, require tabulated data of lift and drag coefficients over different angles of attack (AoA). This data is either obtained via experiments or through two dimensional flow simulations. The software XFOIL [2], developed by Drela and Giles at MIT, is a program to analyze and compute the flow around subsonic isolated airfoils. XFOIL combines a high-order panel method with a fully coupled viscous/inviscid interaction method (Fig.2.). XFOIL has been validated numerous times [3] and is considered as one of the standard low order airfoil analysis tools.

In 2003 Depperois created XFLR5 [4], by combining a graphical user interface with XFOIL and porting the software from FORTRAN to C++. XFOIL also has the capability to design and analyze custom airfoils, using splines or dynamic coordinate mixing. The software XFLR5, with all its functionality, is integrated seamlessly into QBlade to generate two dimensional airfoil coordinates for blade design and airfoil lift and drag coefficients for turbine simulations.
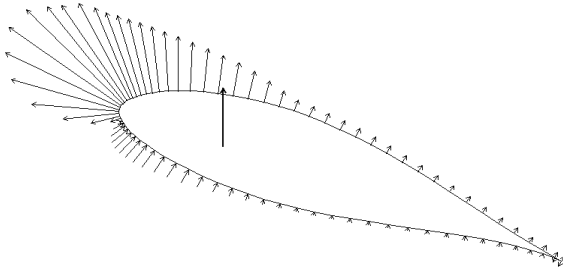

Fig.2. Pressure distribution at 15° AoA around a NACA 63(4)-421 airfoil, computed with XFLR5

2.2 Extrapolating Lift and Drag Coefficients to 360° Angle of Attack

The XFOIL algorithm is based on potential flow theory and therefore is limited to predict lift and drag coefficients at angles that lie before and just beyond stall. For very high or low angles of attack the algorithm is not converging. This is not a constraint in the aircraft design context that XFOIL was written for. However, during the operation of a HAWT, angles of attack as high as 70° can occur in the inner regions of the rotor blades. Moreover, stall controlled HAWT and VAWT in general can experience very high or low AoA during operation. To ensure the smooth operation of the BEM and DMS algorithms the XFOIL generated or imported airfoil polars need to be extrapolated to the full range of 360° AoA (Fig.3.). The general procedure for this extrapolation is to apply curve fits to the completely stalled polar curves of a thin plate, under the assumption that at high AoA an airfoil behaves very much like a thin plate with a sharp leading edge. Two different approaches, of how to generate this extrapolation, are implemented in QBlade. Polars can be extrapolated after the Viterna-Corrigan post stall model [5] that is often used by the industry or after the more recently developed model of Montgomerie [6]. It is very important to note that the simulated turbine performance, especially of stall controlled HAWT or VAWT, is very sensitive to this extrapolation.
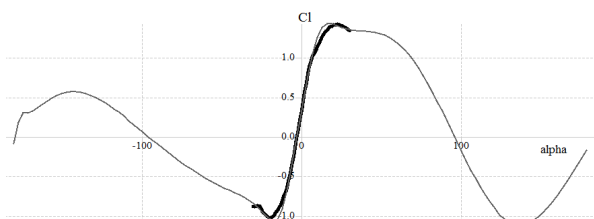

Fig.3. NACA-63(4)-421 polar extrapolation to 360°

2.3 Blade Design and Optimization

The blade design module (Fig.4.) allows for the efficient and intuitive design of rotors and blade shapes. OpenGL visualization (Fig.5.) of the blade and rotor design as well as a geometry export function to the .stl CAD format is implemented. A rotor blade is defined by distributing airfoils, created inside the airfoil module, over different radial (HAWT) or height (VAWT) sections of the blade. The geometry is further defined by specifying chord length, twist angle, edgewise or flapwise blade curvature, azimuthal angle and the twist axis of each individual airfoil.
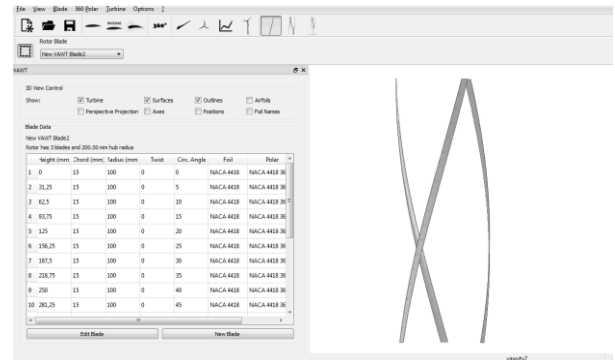

Fig.4. VAWT blade design module in QBlade

Furthermore, optimization algorithms for an optimal distribution of blade twist angles and chord lengths for a chosen tip speed ratio (TSR) can be applied. For HAWTs the blade twist distribution is optimized such that each section faces the relative wind vector at an angle that offers the highest glide ratio at the chosen design TSR. The chord lengths for HAWT can either be optimized after Schmitz [7]:

$$c(r) = \frac{16\pi R}{BC_L(\alpha)} \sin^2 \left(\frac{1}{3} \tan^{-1} \left(\frac{R}{\lambda_0 r} \right) \right) \qquad (1)$$

or after Betz [7]:

$$c(r) = \frac{16}{9} \frac{\pi R}{BC_L(\alpha)\lambda_0} \frac{1}{\sqrt{\left(\lambda_0 \frac{r}{R}\right)^2 + \frac{4}{9}}} \qquad (2)$$

For a VAWT blade the distribution of the radial positions of the blade sections can be optimized by means of numerically solving elliptic integrals to approximate a Troposkien shape (Fig.5.) [8]. A Troposkien shape is a blade shape where the blade stresses resulting from centrifugal forces only act normal to the blades cross sections.
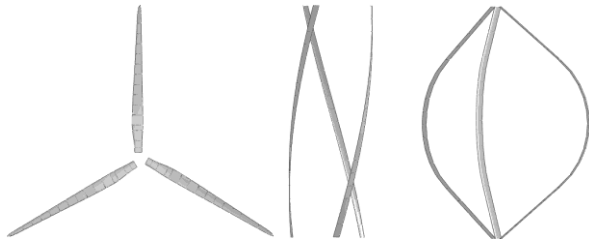
Fig.5. Wind turbine rotors designed and visualized in QBlade: HAWT rotor, swept VAWT rotor, Troposkien shaped VAWT rotor

2.4 Turbine Definition and Simulation

In addition to the rotor geometry the wind turbine type has to be further specified. The form of power regulation (stall, pitch, prescribed pitch) and rotational speed (single, two step, variable) and additional parameters such as cut in and cut out velocity or generator efficiency need to be defined. When the setup is completed the turbine can be simulated in three different ways. A 'dimensionless simulation' is carried out over a number of tip speed ratios and yields only dimensionless results, which is particularly useful for comparing different rotor geometries.
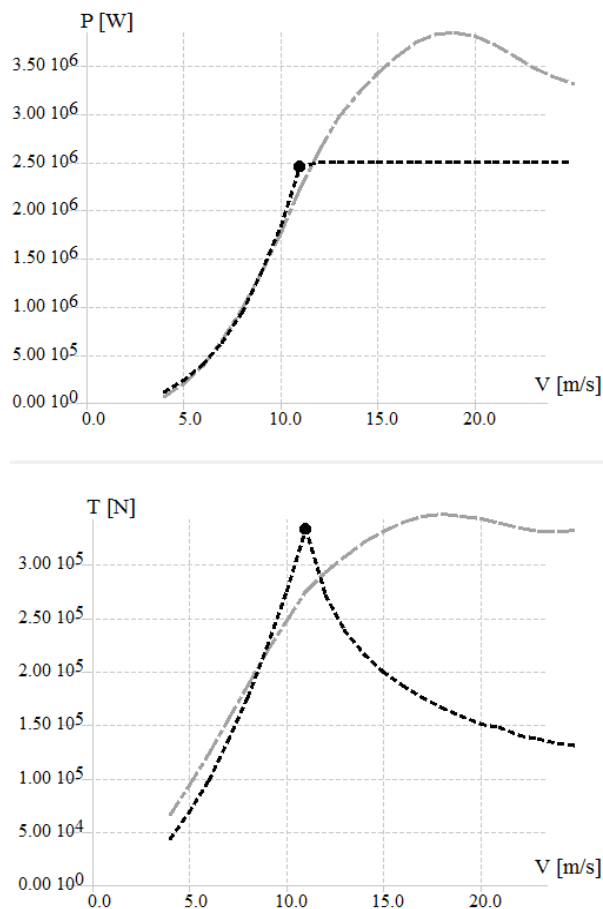

Fig.6. Screenshot of simulation results of a pitch and stall regulated HAWT, comparing power and thrust

The 'turbine simulation' (Fig.6.) results in the specified turbines performance over a range of wind speeds and also yields the annual energy production for a given Weibull wind speed distribution.

A 'multi-parameter simulation' can be carried out over a set of rotational speeds, blade pitch angles and wind speeds and results in the turbines full operational envelope. This is helpful to develop custom turbine controller strategies or to investigate the turbine characteristics in several operation states.

All simulation results are visualized in a post processor module and can be analyzed with more than 30 variables.
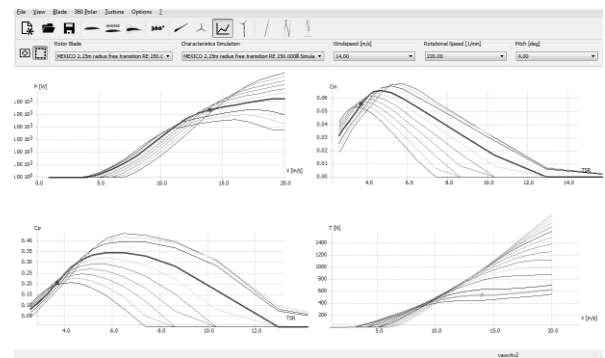

Fig.7. QBlades multi parameter simulation module

3. SIMULATION ALGORITHM

Methods that are based on the blade element theory coupled with a momentum balance over single or multiple streamtubes are widely applied in the wind turbine industry. With these methods the rapid development and comparison of different rotor designs against one another is possible. Also, the use of lower order accuracy analysis techniques greatly facilitates a preliminary wind turbine design that can later be studied in greater detail with more sophisticated CFD techniques. The verification of these computationally efficient "engineering methods" with wind tunnel data and field measurements justifies their application to analyze the rotor blades from a simplified, two dimensional airfoil, point of view.

3.1 Blade Element Momentum Method

The analysis of a HAWT is based on the classical blade element momentum method, as described by Hansen [9]. The BEM combines the blade element theory, to account for the local blade forces, with a momentum balance over the rotor disc that models the flow field. Blade forces and flow momentum are related over discrete angular rotor sections. This relation leads to a set of equations that can be solved iteratively. The BEM assumes uniform, steady state inflow and radial independence of the two dimensional airfoil sections. From these assumptions three dimensional effects, that play an important role in wind turbine aerodynamics, are not considered in the equations.

However the impact of these effects on the turbines loads and performance is considered by additional semi-empirical correctional equations. The optional corrections to the BEM that are included in QBlade are:

- Prandtl blade tip and root vortex correction [9]
- Shen blade tip and root vortex correction [10]
- Snel's correction for the Himmelskamp effect (three dimensional blade crossflow) [11]
- Buhl's modification of Glauert's correction for the turbulent wake state [12]
- Reynolds number drag correction after Hernandez and Crespo [13]

Despite the rather simplified approach to model a wind turbine the BEM is the most widely used simulation method in the industry. Almost all modern HAWT rotors, that exist today, were designed using a BEM based method. The reasons are the BEM algorithms robustness, its computational efficiency and the long-term experience that exists with this method and its results.

3.2 Double Multiple Streamtube Method

The aerodynamic simulation module for a VAWT in QBlade [14] is based on the DMS algorithm as developed by Paraschivoiu [15]. The same as the BEM method the DMS algorithm also combines the blade forces with a momentum balance. Because the airflow passes the rotor one time in the upwind half and one time in the downwind half of rotation, a VAWT can be idealized as two HAWTs in a row. Furthermore the AoA, between rotor blade and relative velocity, now also depends on the circumferential angle, or the blades current position, during a rotation. Therefore the DMS can be seen as a slightly extended version of the BEM algorithm. Numerous empirical corrections for dynamic stall effects or the influence of struts and the tower exists. Also, more sophisticated model formulations that take into account streamtube expansion are available in the literature. In the present version of the software only an optional correction for tip loss and finite aspect ratio effects and optional variable interference factors are implemented in QBlade.

4. VALIDATION

The BEM algorithm of QBlade has been validated against experimental data (Fig.8.) [1]. The community of users compared it with different established and commercial BEM tools, such as Flex5 [16] by DTU and the GL certified WT_Perf [17] from NWTC. The comparisons show good agreement between the different codes and evaluation with experimental data is also promising. To validate the recently integrated DMS algorithm, the predicted performance of the Sandia 17m turbine [18] was compared to measured and simulated performance data from the CARDAA [14] code. The comparison shows good agreement between the two similar codes and the measured data. All other resulting simulation variables were compared to published [14] CARDAA results and show similar distributions.
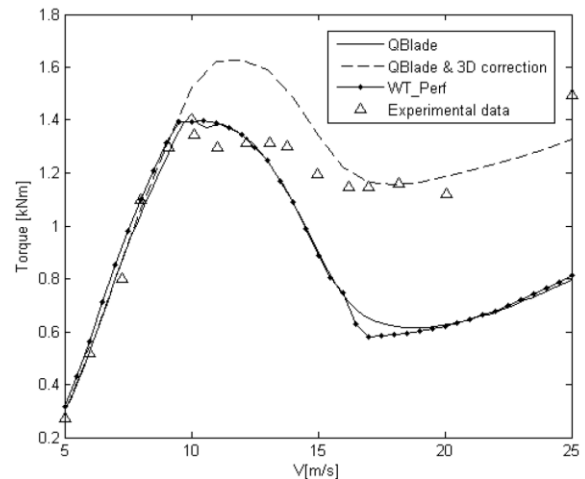

Fig.8. QBlade BEM Module: torque comparison with WT_Perf and experimental data, from [1]
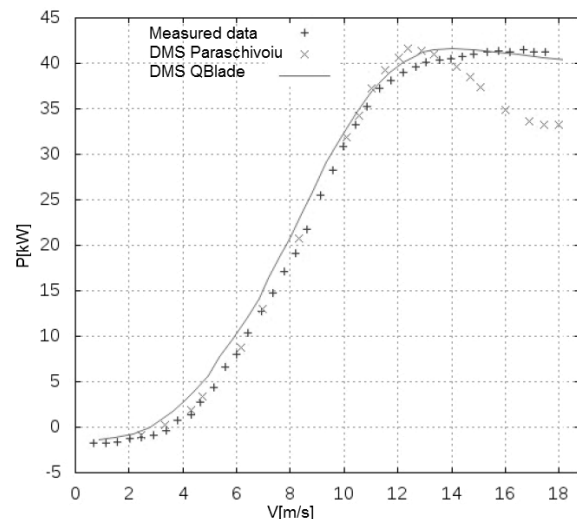

Fig.9. QBlade DMS Module: power comparison with measured and simulated data, from [14]

5. APPLICATION

The software QBlade has been applied by many researchers for different projects. Pechlivanoglou [19] used QBlade to project the lift increase of a leading edge slat measured in a wind tunnel to the increase in annual energy production of a 1.5MW turbine. Soland [16] performed an analysis of outer blade sections, under the influence of surface roughness, for a virtual 7.0MW wind turbine. Weinzierl [20] extended QBlades functionality to enable parametric investigations of an active controlled trailing edge flap for load alleviation on wind turbines. Mueller-Vahl [21] applied the QBlade software to predict the potential for a performance increase through vortex generators installed on the blade of a HAWT using experimental polar data measured at the TU Berlin wind tunnel. Furthermore many universities and educational institutes have included QBlade in their wind turbine lectures as an intuitive tool to investigate the fundamentals of wind turbine aerodynamics.

6. CONCLUSION / OUTLOOK

The integration of robust and accurate wind turbine simulation algorithms with rotor blade design tools and the functionality of XFOIL in a graphical user interface was successful and results in a very capable and accessible tool for wind turbine design. The free distribution of QBlade leads to a broad application and thorough validation of the software by the research community. The modular, object-oriented programming approach renders the tool an ideal platform for future implementations and extensions of its functionality. In the near future it is planned to extend the range of functions to unsteady wind turbine simulations and the generation of non uniform wind fields as input data. Subsequently, the open source structural wind turbine simulation code FAST [22] from NWTC will be coupled with the aerodynamic simulation to yield an aero-elastic simulation tool. Furthermore, a genetic algorithm will be included to exploit the combination of parametric airfoil design and wind turbine simulation to generate blade shapes that maximize annual energy production for specific wind sites. In its current state the software is available for various operating systems. Software and source code can be downloaded on: sourceforge.net/projects/qblade/.

Fig.10. QBlades webpage is found at:
qblade.fd.tu-berlin.de
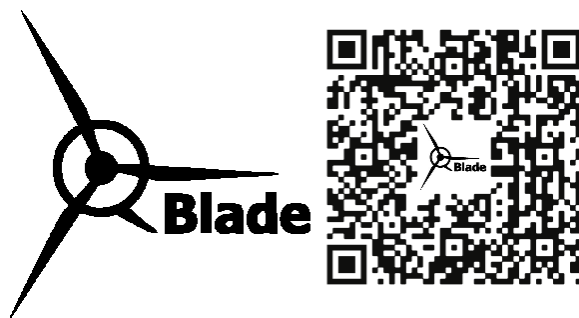
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NOMENCLATURE

Symbol

c	chord	(m)
r	radius	(m)
R	rotor blade length	(m)
B	blade number	
C_L	lift coefficient	
λ_0	Design tip speed ratio	
α	Angle of attack	

Abbreviations

HAWT	horizontal axis wind turbine
VAVT	vertical axis wind turbine
TSR	tip speed ratio
DMS	double multiple streamtube
BEM	blade element momentum method
CFD	computational fluid mechanics
AoA	angle of attack

AUTHOR BIOGRAPHY

David Marten works as a PhD student in the wind energy group of the chair of fluid mechanics at TU Berlin. He started the QBlade software project in 2010 as a part of his diploma thesis. He has research interest in steady and unsteady aerodynamics, numerical simulation, structural mechanics of wind turbines, assessment of wind power potential, aerodynamics of buildings and software development.

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