# Integration of an unsteady nonlinear lifting line free wake algorithm in a wind turbine design framework

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## Introduction

One very important aspect of wind energy, compared to other technologies, is the importance of computational efficiency of wind turbine simulation tools. The design load spectrum, which is calculated during a wind turbine certification, covers the full statistics of 20 years of turbine lifetime, broken down into 10 minute time series. For a single wind turbine model, this results in approximately 1 to 7 million time steps [1], requiring the same number of converged aerodynamic calculations.

As computational efficiency is the main driver in the selection of wind turbine simulation methods steady state Blade Element Momentum (BEM) based tools are the most widely spread and are used in every wind turbine certification. However, because BEM codes are based on very simplified physics, a large number of empirical correction models had to be added over the years to achieve tolerable accuracy for cases where any of the limiting BEM assumptions are violated. As these added corrections are often based on empirical data, they are often not universally applicable for any boundary condition or turbine states resulting in incorrect load and performance predictions in certain cases. Generally it can be said that the higher the unsteadiness, non-uniformity of induction over the rotor or deflection of rotor blades, the larger the deviation of BEM simulation from experimental results or data from more sophisticated aerodynamic simulations (compare with [2]).

On the other side of the spectrum, in terms of modeling of the physics, are the advanced computational fluid dynamics (CFD) solvers. They are based on discretization of the Navier-Stokes equation and model both the large and small scale flow phenomena with high detail. But neither the Reynolds-Averaged (RANS) or Large-Eddy (LES) formulation based solvers have a sufficient computational efficiency to be used in a certification or design context. Consequently they are only used in the research environment to help answer fundamental questions or to investigate isolated flow phenomena or specific test cases.

Between BEM and CFD are the codes of intermediate complexity, the so called "vortex methods". Many different formulations for the vortex methods, such as Panel-, Vortex Lattice-, or the Lifting Line Theory (LLT), exists, with either a free- (Fig 1) or prescribed wake formulation. They all have in common that the flow field is modeled as inviscid where the vorticity is introduced through regularized singular Lagrangian elements (such as vortex panels, lines or points, see [3]). Their appeal is their inherent physical character paired with simplicity and a computational cost that is orders of magnitude lower than that of CFD. Due to the sound modeling of the macroscopic flow physics, only very few empirical models related to microscopic boundary layer fluid dynamics such as dynamic stall or stall delay need to be added. In many studies, vortex methods are identified [1; 4] as suitable to replace BEM codes in the near future to achieve a higher accuracy in turbine design and certification applications. An advantage of the LLT formulation is that the rotor blades are represented in a similar way to the BEM method using tabulated 2D airfoil data making comparisons between BEM and LLT codes a straightforward matter. Hauptmann [5] found in a comparison between the LLT and BEM methods that the BEM is not conservative for all certification load cases and that the differences between both methods can be as large as 25%.

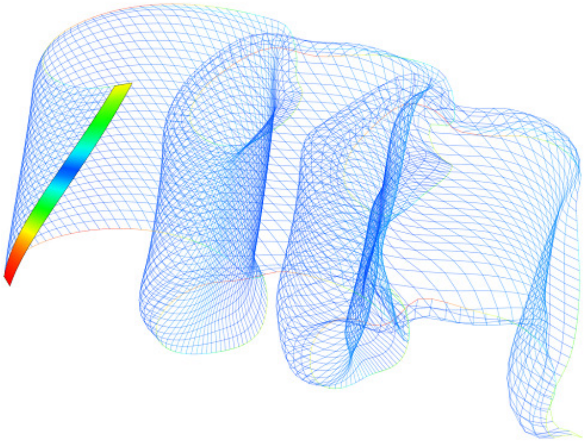

**Fig 1. Free wake evolution of a VAWT; from QBlade**

## Integration of an unsteady nonlinear lifting line free vortex wake code in QBlade

As means to improve the aerodynamic modeling an efficient nonlinear unsteady lifting line free vortex wake algorithm was implemented in the open-source wind turbine design and simulation tool *QBlade* [6]. Due to the physical origin of the LLT formulation, it is very general and can be applied to model any device based on lifting bodies such as airplanes, helicopters, flapping wings or kites. Consequently it is well suited to model both horizontal (HAWT) and vertical axis (VAWT) wind turbines. The software *QBlade* already encompasses methods and modules for 2D airfoil analysis and simulation and rotor blade design for both HAWT and VAWT rotors. The large benefit of this new integration is that already existing blade and airfoil designs can be seamlessly incorporated in unsteady LLT simulations, with minimal pre- and post processing effort. This usability, paired with a high accuracy and computational efficiency enables rapid investigations, parametric studies and blade design iterations. The new release of *QBlade* maintains its open-source licensing to facilitate wind energy research of the scientific community by applying, modifying or coupling the new unsteady aerodynamics module to custom codes.

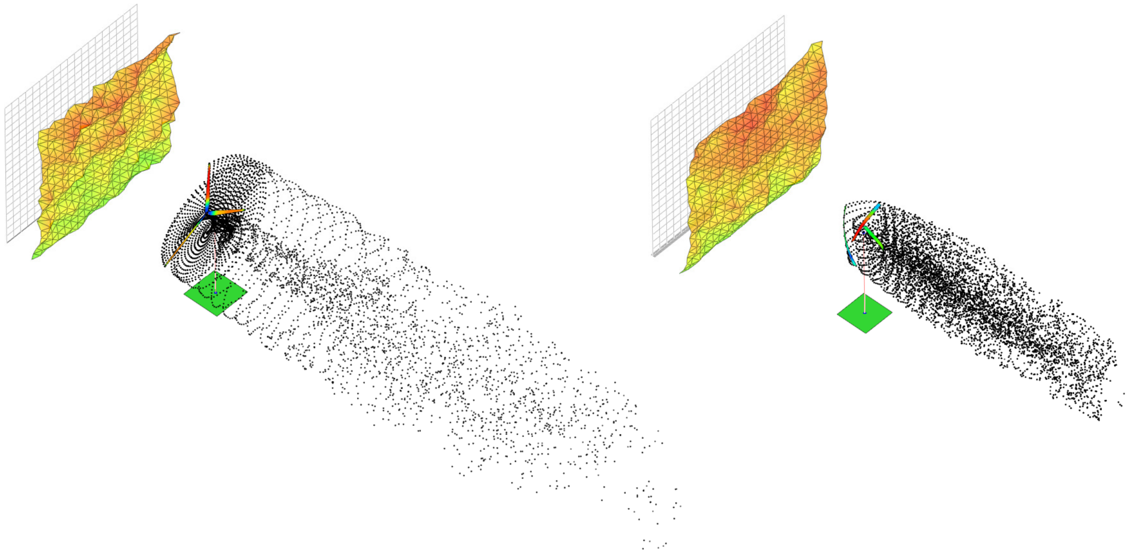

**Fig 2. QBlade visualization of HAWT and VAWT simulation in turbulent windfield, wake visualized with vortex nodes**

In the full paper, specific details of the implemented algorithm and models, their applicability and validation will be discussed. The implementation is loosely based on the work of van Garrel [7] but includes a range of extra functionality and improvements such as the vortex core modeling, time stepping, iteration loop and provisions for computational efficiency; multi-threading and wake connectivity tracking. The implementation encompasses a large range of user defined parameters to control the simulation algorithm and various models, to be switched on or off, which control the boundary conditions of the simulation. A simulation is defined through a simple setup dialog before execution.

Some of the simulation parameters are:

- Operating point: rotational speed, tip speed ratio, inflow velocity
- Time stepping : simulation length, azimuthal or temporal discretization step
- Wake parameters: total length, conversion length, thin factor, free evolution
- Vortex core modeling: turbulent vortex viscosity, vortex time offset
- Algorithm / Environmental: relax. factor, convergence crit., density, kin. viscosity
- Velocity integration: simple Euler forward-, predictor corrector scheme
- Blade discretization: custom, linear, sinusoidal

Examples for additional models, boundary conditions:

- Modeling of ground effects through vortex mirroring
- Tower model: tower radius, tower drag coefficient
- Inflow: inflow angle, turbulent, power law, uniform, custom time series
- Rotor angles: yaw, cone, teether, up- / downwind

Additionally, dynamic simulations can be defined to simulate transient events. This is realized through AeroDyn [8] hub height type- and similar input files where the desired boundary conditions can be defined for any point in time. Using input files a large range of different scenarios can be simulated such as ramp-up tests or transient yaw cases. Through the graphical user interface it is simple to set up a large number of test cases using different rotor geometries which makes the tool a multipurpose companion during wind tunnel or field measurement campaigns, allowing to quickly predict outcomes or to design test cases.

During the simulation a live visualization of the simulated case is presented along with all currently computed performance data and sectional parameters, such as Power, Cp, induction, angle of attack or root bending moment. All wake positions are stored for every time step, which later allows to reconstruct the exact wake geometry and velocity field at any time step. In the post processor the evolution of more than 40 output parameters can be investigated in dynamic graphs; simulations can be played back, and velocity distributions can be computed and exported at any timestep and location (Fig 3). Furthermore projects are stored in a runtime database and can be easily saved and shared.

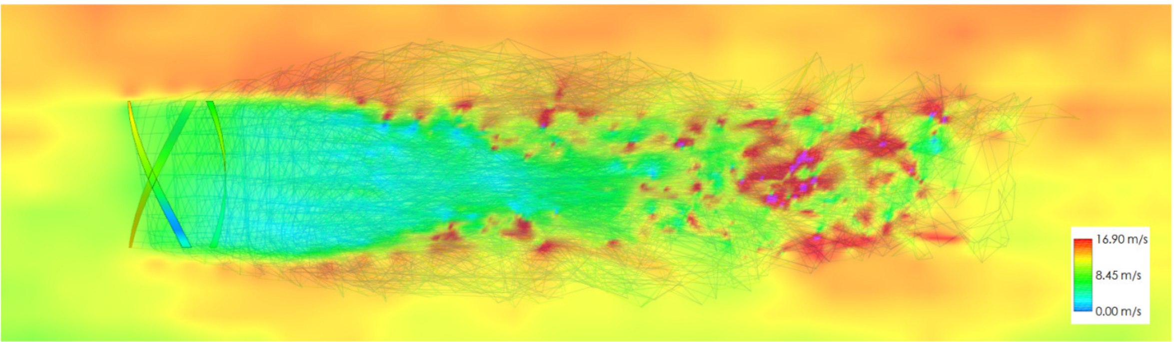

**Fig 3. QBlade visualization of velocity field around helix VAWT rotor in turbulent wind field (TU = 15%), showing velocity magnitude and wake structure in the background**

The implemented algorithms, both for HAWT and VAWT turbines were extensively validated against published experimental and numerical data (for instance against the Mexnext [9] project: Fig 4; Fig 5) and consistently shows good agreement.

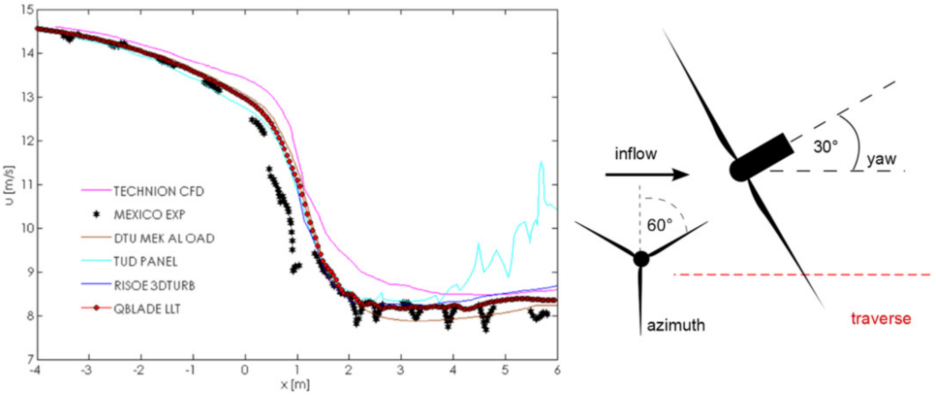

**Fig 4 QBlade LLT compared to codes and experiment from IEA Task 29 Mexnext; axial velocity decay at y = -1.4m, 15m/s inflow, azimuthal angle 60° and yaw = 30°**

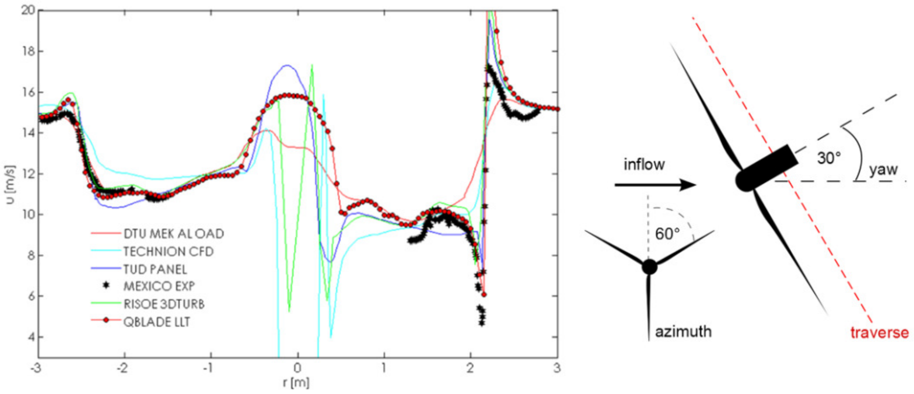

**Fig 5 QBlade LLT compared to codes and experiment from IEA Task 29 Mexnext; axial velocity over traverse parallel to rotorplane, 0.15m behind rotor, 15m/s inflow, azimuthal angle 60° and yaw = 30°**

## Conclusion

An unsteady nonlinear free vortex wake lifting line algorithm, recently implemented in the wind turbine design and simulation tool *QBlade,* was presented. The new module is fully implemented within a graphical user interface offering a large range of pre- and post processing capabilities. The algorithm is optimized for computational efficiency through the modeling and selection of vortex elements and core model, the wake discretization pattern and parallelization of the Biot-Savart kernel. Performance and results were extensively validated for a number of both HAWT and VAWT test cases. The resulting software is freely distributed under an open-source license to facilitate worldwide wind energy research and can be found under *sourceforge.net/projects/qblade*.

## Learning Objectives

The reasoning for the selection of the LLT simulation method in a wind turbine design code is presented along with the basic theory and methodology of the aforementioned algorithm. Furthermore modeling details and the functionality of the new implementation are described. Through a comparison to other simulation methods and experimental data a sense for the achievable accuracy and the feasibility of this method for unsteady aerodynamic wind turbine simulations is conveyed.

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