Nonlinear Lifting Line Theory Applied To Vertical Axis Wind Turbines: Development of a Practical Design Tool

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Long Abstract

Introduction

Recently a new interest in vertical axis wind turbine (VAWT) technology is fuelled by research on floating support structures for large scale offshore wind energy application. In deep water floating structures are essential to reach a competitive cost of energy (CoE). For the application on floating structures at multi megawatt size, the VAWT concept may offer distinct advantages over the conventional horizontal axis wind turbine (HAWT) design. As an example VAWT turbines are better suited for upscaling and, at multi megawatt size, the problem of periodic fatigue cycles reduces significantly due to a very low rotational speed. Additionally, the possibility to store the transmission and electricity generation system at the bottom, compared to the tower top as in a HAWT, can lead to a considerable reduction of material and therefore CoE. However, as most VAWT research stalled in the mid 90's [1], no established and sophisticated tools to investigate this concept further exist today. Due to the complex interaction between unsteady aerodynamics and movement of the floating structure fully coupled simulation tools, modelling both aero- and structural dynamics are needed. Besides having a high accuracy, their main requirement is to have a high computational efficiency, as in the early stages of design many concept and parameter studies are necessary. As a comparison: certification computations for an onshore HAWT, considering all relevant load cases, encompass up to 7 million [2] converged time steps.

1. Simulation methods for vertical axis wind turbine aerodynamics

The aerodynamics and the flow field around a VAWT are very complex. During one revolution of the rotor the angle of attack, and thus the blade loads, are constantly changing. Additionally, at low tip speed ratios (TSR), the blades experience dynamic stall at certain azimuthal positions. This inherent unsteadiness during operation is the main reason why no practical, efficient and robust design tool exists for VAWT, which is comparable to the blade element momentum (BEM) method that is widely used for HAWT design and certification. Paraschivoiu [3] developed the double multiple stream tube algorithm (DMST), as an extension of the BEM method, for VAWT. In contrast to the BEM the DMST algorithm employs two actuator discs, one for the upstream and one for the downstream half circle of rotation. This method is used to compute the performance of VAWT for low soliditys or low tip speed ratios but fails to accurately predict performance for high solidity, high TSR cases [4], and thus is not well suited as a universal design method. The main problem is that momentum balance based codes assume a steady state flowfield which is strongly violated in the case of a VAWT. On the other hand Reynolds-averaged Navier-Stokes (RANS) CFD simulations are still too computationally expensive to be used in coupled dynamics simulations. Lifting line theory (LLT) based simulations, combined with a free vortex wake modeling are a promising candidate to be used in VAWT design tools, as the LLT theory can capture the unsteady blade loading, whereas the complex wake structure (see Figure 1) is modeled through free convecting vortex elements. LLT based codes have been successfully applied to VAWT simulation (as by Ferreira [5]), but up to date no such code is, either commercially or publicly, available.

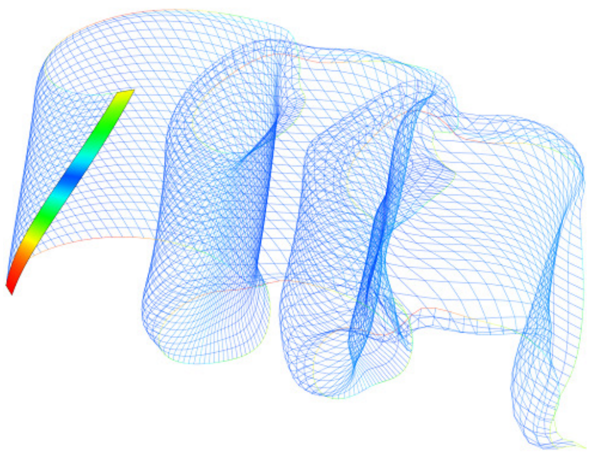

Figure 1. Detail of free evolving wake of single blade VAWT, QBlade screenshot

2. Development and application of an unsteady nonlinear LLT algorithm to VAWT

This paper describes a newly developed, efficient and accurate LLT based design and simulation tool for VAWT. The unsteady LLT simulation module for VAWT is integrated with the open source wind turbine simulation tool QBlade [6]. As a result of this integration, advanced simulations can be setup using QBlades airfoil, polar and blade database. Simulations can be performed under turbulent inflow conditions (see Figure 2). Aerodynamic models for the tower or ground effects can be included and 6 degree of freedom platform movement prescribed. The focus of this paper is on the specific differences and treatments that distinguish the implementation of a LLT code for VAWT from an implementation for HAWT rotors and how these affect robustness, efficiency and accuracy. Furthermore the performance of the code will be demonstrated in a validation study, comparing the obtained results to published data from CFD simulations and experiments. The resulting software is freely distributed under an open source license and can be found under: sourceforge/projects/qblade.

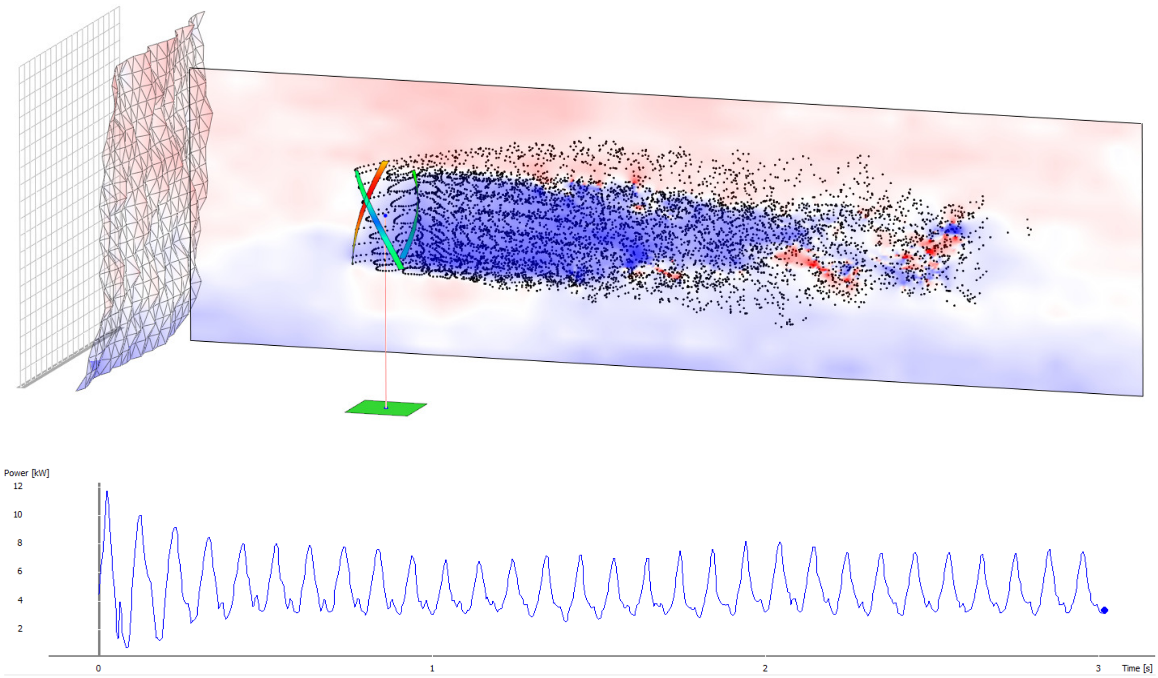

Figure 2. A Visualization of unsteady LLT simulation in turbulent windfield, resulting torque over time

References

[1] H. J. Sutherland and D. E. Berg. A retrospective of VAWT Technology. *SANDIA Laboratories Report*, SAND2012-0304, 2012.

[2] J. G. Schepers. Engineering models in wind energy aerodynamics. *Doctoral Thesis,* TU Delft, 2012.

[3] I. Paraschivoiu. Wind Turbine Design – With Emphasis on Darrieus Concept, Presses Internationales Polytechnique, 2012

[4] M. Borg, A. Shires and M. Collu. Offshore floating vertical axis wind turbines, dynamics modelling state of the art. part I: Aerodynamics, Ren. and Sust. Energy Reviews 39, 2014, 1214-1225

[5] C. S. Ferreira. The near wake of the VAWT. 2D and 3D views of VAWT aerodynamics, Doctoral Thesis, TU Delft, 2009

[5] D. Marten, J. Wendler et al. Development and application of a simulation tool for vertical and horizontal axis wind turbines, GT-2013-94979, Proceedings of ASME Turbo Expo, 2013.