Modelling of stall-delay due to rotation

1. The importance and relevance of the scientific content

A wind turbine should not always extract the highest possible power from the wind. Very high wind speed are rare and do not add much to the energy production during the year. To with stand such speeds in normal operation the turbine would have to be heavy and expensive. Therefore, wind turbines are designed with a maximum power level that will be reached dozens of times per year. A control mechanism is required in order to not exceed this so-called rated power level, which is just reached at the rated wind speed (figure 1).

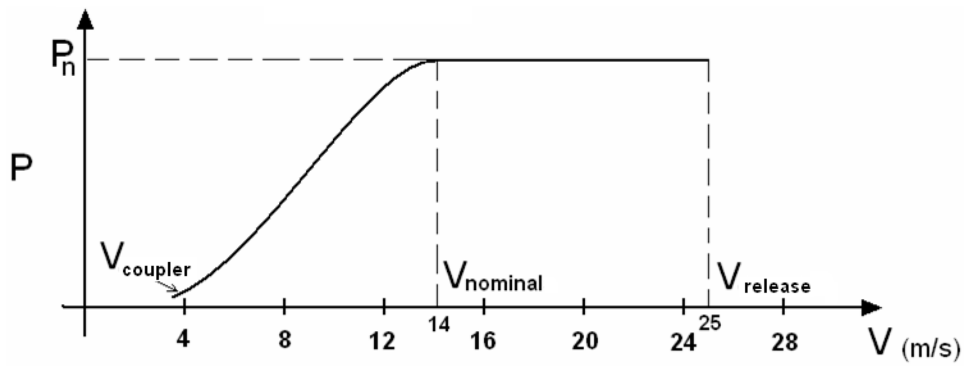

Figure 1. A power curve of a wind turbine with indicative numerical values

Modern utility-sized wind turbines rely mainly on two mechanisms for power control at high wind speeds, namely pitch and stall control [1-3]. Pitch control relies on an active full-span variation of the global blade angle, thereby guaranteeing that all sections of the blade remain in a regime which can be characterized by mostly laminar and unseparated flow around the blade. A theoretical description in this regime can be performed by essentially inviscid flow models, yielding reliable results for the local lifting forces and the overall torque developed by the blade [4]. Drag forces are negligible in this regime. Passive stall control where the power control is an intrinsic property of the rotor, on the other hand, operates in an aerodynamic regime characterized by (local) flow separation and strong drag forces. An adequate theoretical description requires a solution of the full equations of viscid motion, which is impractical in most cases; therefore a number of semi-empirical models [2,5] have been developed which have to be adjusted manually to the exact blade parameters and conditions. Pitch-controlled wind turbines can operate at both fixed and variable speed (rotor frequency), whereas stall control heavily relies on a fixed rotor frequency. Recently, however, an advanced concept has been introduced by industry, known as ***active stall***, which allows for variable speed operation using a full-span rotation of the rotor blades such as in pitch control, but in the opposite direction [1].

Small wind turbines with rated power values in the 0.5-20 kW range, mainly utilize furling (or yawing) as their mechanism for power regulation, although passive pitch control is also used in some models such as the traditional Jacobs machines [6]. Although furling is a robust and well-suited mechanism for its typical applications (water pumping, rural electrification) at medium wind speeds, the performance of typical commercial systems at higher wind speeds is poor, resulting in a low overall efficiency at high-wind speed sites (the prediction of the power production at high yaw angles is not straightforward, which complicates an efficient and safe design) [7]. The reasons why stall control has not been used in small wind turbines is probably due to the fact that it requires both sophisticated modelling tools and advanced manufacturing techniques, both of which are not generally available to small developers [9].

In high winds, when much of a wind turbine blade can be stalled, existing performance methods can predict power outputs that are considerable lower than those actually measured. While part of the problem is the imprecise treatment of delayed stall as a result of unsteady aerodynamic effects, there are also subtle three-dimensional effects that contribute to the problem [10]. While a full understanding and modelling of these problems is the subject of ongoing research, they can, in most cases, be traced to three-dimensional boundary layer developments on the rotating blades.

One aspect of the three-dimensional aerodynamic problem is the centrifugal and Coriolis effects acting on the boundary layer in a rotating environment. Several experimental and computational studies have provided insight into the problem [11-16]. From an order of magnitude analysis of the three-dimensional boundary layer equations applied to a rotating flow environment, Snell [12] has found that the Coriolis acceleration terms can act to alleviate adverse pressure gradients and so may delay the onset of flow separation and stall. When the flow separates, Dumitrescu and co-workers [13] using after separation an idealized zero skin-friction inviscid flow and laminar boundary-layer equations, have found that the Coriolis action produces an inboard standing vortex structure and so may augment the aerodynamic forces (figures 2 and 3).

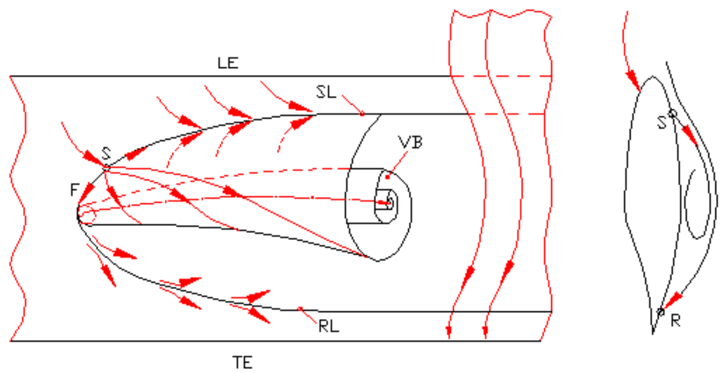

Figure 2. Formation of the standing vortex in the radial direction

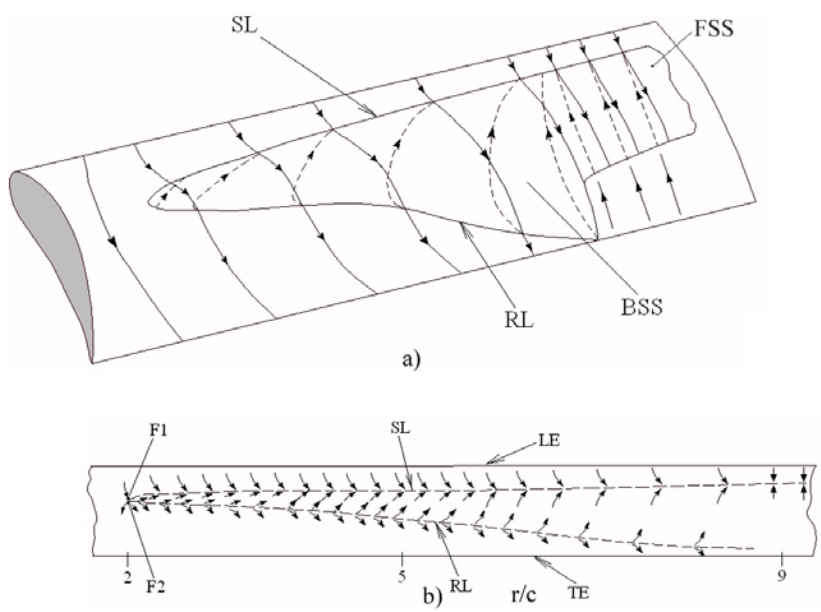

Figure 3. Topological structures of separation on rotating blade: a) types of separation surface; b) separation/reattachment.

The effects are pronounced at the inboard part of the blade, for which experimental results have shown significant increases in sectional maximum lift coeffficients beyound what would be expected based on two-dimensional static measurements (figure 4).

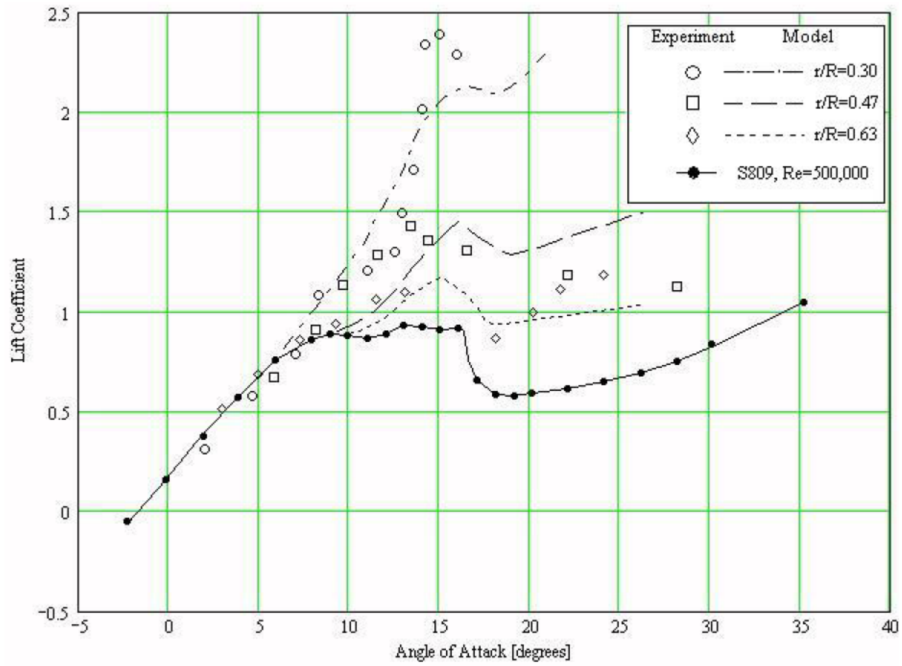

Fig.4. Effect of the radial position on the lift coefficient

Similar results have been suggested using CFD methods [14,15]. The experiments of Schreck and Robinson [16] also suggest favorable effects on the spanwise development of the boundary layer on a rotating blade, which tend to delay the onset of flow separation at a higher angle of attack. Various ad-hoc methods to model the observed effects have been developed [17,18], but a rigorous approach is lacking.

In the present project we will show that an adequate prediction of the performance of stall-regulated wind turbines of different sizes and with different blade designs can be obtained with a refined though simple blade element momentum (BEM) model, where the main adjustments come from the treatment of the stall regime.

We believe this to be an important result, since it has been suggested in literature [19] that BEM has inherent shortcomings for the prediction of the stall regime behaviour and that a computationally more demanding technique known as lifting surface wake theory more accurately models stall conditions.

We believe that the results of this work are particularly useful for small wind turbines used in remote applications such as rural electrification and water pumping [20] where still important aerodynamic design opportunities exist, as opposed to utility-scale turbines where the optimization of the structural properties is currently the main design driver [8].

2. Objectives of this work

The main objective of this work is to develop a relatively simple engineering model that should provide an approximate prediction of the steady state power curve of stall-regulated wind turbines, containing no free (fit) parameters. From the literature [1,4,21-26] it be concluded that, despite the great number of computational models with varying complexity (ranging from simple momentum theories to Reynolds-averaged Navier-Stokes (RANS) models), no universal model is currently available that provides a reliable prediction of the steady state power production of wind turbines in the stall regime. In addition to create a completely new model, we looked at existing models and their possible modifications.

BEM theory has proven very successful for blade design [1-3,21,24] and has also been used for the prediction of the flow field near wind turbines [27,28] in spite of its constraining assumptions. It is therefore our natural starting point. Special emphasis is laid on three points:

1. The stall regime is characterized by local flow separation at the blade; our model should therefore distinguish between the global flow through the rotor disc and the flow local to the blade. We found that the framework provided by reference 1 adequately accounts for this difference.
2. The three-dimensional nature of the blade strongly influences the aerodynamic coefficients of the blade under stall conditions, which should be accounted for.

3. Blade rotation induces a phenomenon known as *stall delay*, producing high lift coefficients for angles beyond the onset of flow separation in non-rotating wind tunnel (two-dimensional) experiments, followed by a sharper drop than in the case of non-rotating experiments.

The project has six stages:

1. Vortex structure topology for three-dimensional separation (sept.2007-dec.2007).
2. Quasi-three- dimensional Navier-Stokes model for rotating airfoil (jan.2008-june.2008)
3. Three-dimensional boundary layer formulation on rotating blade (july.2008-dec.2008)
4. Viscous-inviscid interaction method for rotating blades (jan.2009-june.2009)
5. Rotational effect on boundary layer behaviour and flow field structure (july.2009-dec.2009)
6. Implementation of stall-delay model in a BEM model (blade element-momentum) for design (jan.2010-aug.2010)

3. Methodology of this work

The steps taken in order to develop a useful working model for the power curve prediction of stall-regulated wind turbines are the following:

1. A home-build computer code is developed for the solution of BEM model equations considering different combinations of models for the stall regime.
2. The model is tuned to the power curve obtained by the NREL/NASA Ames wind tunnel experiment [29,30], the results of which have been analysed thoroughly in the literature [19,22,23,25]. The dependence of this new model on different parameters such as Reynolds number and data source for C_L and C_D data (wind tunnel) is then studied in a detailed manner and some consistency checks are performed.
3. Once a model is found that provided an adequate description of the NREL/NASA Ames power curve, we proceed to validate this model against field data from the Annex XIV/XVIII project [31], an international effort funded by the International Energy Agency (IEA) that provided an ample database available on the Internet for the interested public.
4. Finally, a quantitative measure of the agreement of the prediction of our theoretical model with the measured power curves (a figure of merit) is calculated in terms of the energy production predicted for both the theoretical and experimental power curves.

NREL-National Renewable Energy Laboratory, Golden, Colorado

References

1. T Burton, D Sharpe, N Jenkins, E Bossanyi: Wind Energy Handbook. Wiley, Chichester 2001

2. H Dumitrescu, V Cardos, F Frunzulica, Al Dumitrache: Aerodinamica nestationara, aeroelasticitate si aeroacustica pentru turbine de vant. Ed Academiei Romane, Bucuresti, 2007

3. MOL Hansen:Aerodynamics of wind turbines: rotors, loads and structure. James & James, London 2000

4. LA Viterna, RD Corrigan: Fixed pitch rotor performance of large horizontal axis wind turbines. DOE/NASA Workshop on Large Horizontal Axis Wind Turbines, Cleveland,OH, 1981, pp 69-85

5. JL Tangler, C Ostowari: Horizontal axis wind turbine post stall airfoil characteristics synthesization. SERI/TP-257-4400, Solar Energy Research Institute, 1991

6. DM Dodge: An illustrated history of wind power development (online). Available: http://telosnet.com/wind/index.html

7. AJ Bowen, N Zakay, RL Ives: The field performance of a remote 10 kW wind turbine. Renewable Energy 2003, 28, pp 13-33

8. PS Veers, TD Ashwill, HJ Sutherland et al: Trends in the design, manufacture and evaluation of wind turbine blades. Wind Energy 2003, 6, pp 245-259

9. PD Clausen, DH Wood: Research and development issues for small wind turbines. Renewable Energy 1999, 16, pp 922-927

10. S Schreck, MC Robinson, MM Haird, DA Simms: Contrasting blade flow field archetypes on the horizontal axis wind wind turbine operating regime. Journal of Solar Energy Engineering, vol 123, Nov 2001

11. H Madsen, H Christensen: On the relative importance of rotational, unsteady and three-dimensional effects on the HAWT rotor aerodynamics. Wind Engineering 1990, vol 14 (6), pp 405-415
12. H Snel: Scaling laws for the boundary layer flow on rotating wind turbine blades. The 4th IEA Symposium on Aerodynamics for Wind Turbines, Rome, 1991
13. H Dumitrescu, M Alexandrescu, N Alexandrescu: Boundary layer state and flow field structure on wind turbine blades. Proceedings of the Romanian Academy 2005, Series A, 6(3), pp 219-228
14. JC Narramore, R Vermeland: Navier-Stokes calculations of inboard stall delay due to rotation. Journal of Aircraft 1992, 29 (1), pp 73-78
15. G Xu, LN Sankar: Development of engineering aerodynamics models using a viscous flow methodology on the NREL Phase VI rotor, Wind Energy 2002, 5(2/3), pp 171-183
16. S Schreck, M Robinson: Rotational augmentation of horizontal axis wind turbine blade aerodynmic response. Wind Energy 2002, 5(2/3), pp 133-150
17. J Corrigan: Empirical model for stall delay due to rotation. American Helicopter Society Aeromechanics Specialist Meeting , San Francisco, CA, Jan 19-21, 1994
18. ZH Du, MS Seling: A 3D stall delay model for HAWT performance prediction. AIAA Paper 89-0021,1998
19. JL Tangler: The nebulous art of using wind tunnel aerofoil data for predicting rotor performance. Wind Energy 2002, 5, pp 245-257
20. M Velasco, O Probst, S Acevedo: Theory of wind-electric water pumping. Renewable Energy 2004, 29, pp 873-893
21. H Snel: Review of aerodynamics for wind turbines. Wind Energy 2003, 6, pp 203-211
22. FN Coton, T Wang, RAMcD Galbraith: An examination of key aerodynamic modelling issues raised by the NREL comparison. Wind Energy 2002, 5, pp 199-212
23. NN Sorensen, JA Michelsen, S Shreck: Navier –Stokes predictions of the NREL Phase VI rotor in the NASA Ames 80 ft x 120 ft wind tunnel. Wind Energy 2002, 5, pp 151-169
24. DC Quarton: The evolution of wind turbine design analysis – a 20 year progress review. Wind Energy 1998, 1, pp 5-24
25. G Xu, LN Sankar: Development of engineering aerodynamics models using a viscous flow methodology on the NREL Phase VI rotor. Wind Energy 2002, 5, pp 171-183
26. GP Corten: Flow separation on wind turbine blades. PhD Thesis, Energy Research Centre of the Netherlands (online). Available: http://www.ecn.nl/library/thesis/corten.html
27. M Magnusson: Near-wake behaviour of wind turbines. Journal of Wind Engineering and Industrial Aerodynamics 1999, 80, pp 147-167
28. M Magnusson, AS Sedman: Air flow behind wind turbines. Journal of Wind Engineering and Industrial Aerodynamics 1999, 80, pp 169-189
29. S Schreck: The NREL full-scale wind tunnel experiment. Wind Energy 2002, vol 5, pp 77-84
30. NREL 10 m wind turbine testing in NASA Ames 80’x80’ wind tunnel (online). Available: http://wind.nrel.gov/amestest/intro.htm. (15 June 2004)
31. IEA Annex XIV/XVIII: Field rotor aerodynamics/EFRAD (online). Available: http://www.ecn.nl/wind/other/IEA/index.en.html (15 June 2004)