Ongoing research in Wind Turbine Aerodynamics in Denmark.

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ABSTRACT

This paper gives a review of ongoing research in wind turbine aerodynamics in Denmark 1998. The review is based on participation in Danish and EC sponsored research programmes. Engineering methods, i.e. aeroelastic codes, are applied routinely in the wind turbine industry to predict the power output and fatigue loads on new machines. The output of these methods depends strongly on the available airfoil data, i.e. lift and drag as a function of mainly the angle of attack, and it is therefore of great importance to predict these data accurately. Much of the aerodynamic research today is therefore devoted to develop and refine tools, which can provide these lift and drag data.

INTRODUCTION

To predict the aerodynamic loads on a horizontal axis wind turbine it is common practise to apply the Blade Element Momentum method as described by Glauert [1]. The BEM method needs as input lift and drag coefficients as a function of the angle of attack and Reynolds number along the blades. Normally tabulated 2-D airfoil data from wind tunnel measurements are applied like the ones in [2]. Most of the data available in the literature, however, are for relatively thin airfoils and for angles of attack not much larger than the onset of stall. A wind turbine often operates in deep stall and for structural reasons very thick airfoils are applied, especially near the root of the blades, where high bending moments exist. To complicate things further, the boundary layers on the rotating blades are influenced by 3-D rotational effects from the Coriolis and centrifugal forces, which are known to alter the airfoil data at high angles of attack, see e.g. [3] and [4]. To find good airfoil data is therefore difficult and it is often necessary to calibrate the data afterwards, in order to reproduce a measured power curve numerically. If a measured power curve is not available, significant engineering skills and experience are needed in order to extrapolate and alter available 2-D airfoil data to predict the performance of a new design. A big effort is therefore put into refining numerical tools and wind tunnel measurement techniques to provide reliable airfoil data for the BEM method. In the 'Blade Design Project' 1995-1997 funded by the Danish Ministry of Energy Research Programme (DMERP) a method was developed to measure 2-D airfoil data from a test rig inserted into an open jet flow wind tunnel, see [5] and [6]. In the 'Aeroelasticity' project funded by DMERP and in 'VISCWIND' funded by the European Union a big effort is put on numerical predictions of the aerodynamic forces on wind turbine blades.

NUMERICAL MODELS

In the VISCWIND project a variety of codes and turbulence models were applied by different European partners to compute the viscous flow past wind turbine blades. The main results are shown in [7] and one of the important conclusions learned from the project is that of the tested turbulence models only a few, i.e. the $k-\omega, SST$ model [8], The Spalart-Allmaras model and the Baldwin-Barth model, seem to give reasonable results in post stall condition. In the VISCEL project, which is a continuation and extension of the VISCWIND project, some newer models might turn out to be even better. The best results in the VISCWIND project for a 3-D rotating blade were obtained using the EllipSys3D code applying the $k-\omega, SST$ turbulence model on a 500 kW stall regulated Nordtank wind turbine. The result from the computed mechanical power is shown in figure 1, where it is seen that the computation agree very well below stall but that it tends to overpredict the power at high wind speeds. It turned out in VISCWIND that the computed stall behaviour is very dependent on the

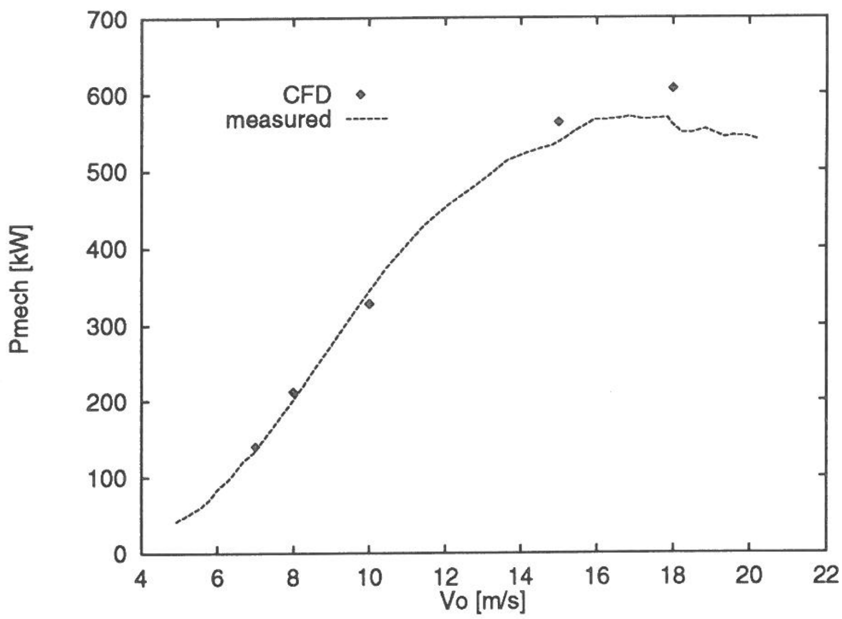

Figure 1: *Comparison of the computed and measured power curve of an Nordtank 500 kW stall regulated wind turbine.*

choice of turbulence model, e.g. the partners using the Baldwin-Lomax model grossly overpredicted the power at high wind speeds indicating that the computed boundary layer with this model tends to stay attached long after it should have separated. EllipSys3D is a finite-volume based Navier-Stokes solver developed partly by Risø [9] and by DTU [10]. In [11] a detailed description of the code can be found. The direct result from a 3-D Navier-Stokes solution is the force distribution along the blades, i.e. the normal and tangential force per length at the different radial positions. To transform this distribution into usable lift and drag data, it is necessary to evaluate the angle of attack in a manner consistent with the Blade Element Momentum method. Such methods are presently being investigated in the Danish 'Aeroelasticity' project. One of the alternatives is to use a so called actuator disc model, where the rotor is simulated by distributing the forces in annular elements and solving for the flow using a Navier-Stokes solver. This is completely similar to the BEM method and is therefore expected to give compatible values of the angle of attack in the rotor plane. In the VISCWIND project [7] also 2-D dynamic stall computations were performed and especially for the high mean angles of attack a good agreement between measurements and computations were observed. Further, the 3-D rotational effects on the NACA63415 profile was investigated numerically with the EllipSys3D code by constructing a grid around a non-tapered and non-twisted blade. To avoid end effects the grid is enclosed between two cylinders, where the blade starts at the inner cylinder and ends at the outer cylinder. A slip condition is enforced on the cylindrical walls, whereas a no-slip condition is applied on the blade. The results are compared to a 2-D computation. The detailed description of the grid and computation is given in [4]. The general results are that for angles of attack below stall the 2-D and 3-D solutions agree well as indicated in figure 2, where the 2-D pressure distribution is compared to the 3-D pressure distribution at $k = 4.22$ at an an angle of attack of approximately 10^o. $k = \frac{r}{c}$ is an additional parameter indicating the radial distance measured in chords to the rotational axis. In figure 3 the pressure distributions at $k = 4.22$ and $k = 11.9$ are compared to the 2-D pressure distribution at an angle of attack of approximately 25^o. It is seen that the 3-D effects decreases with increasing

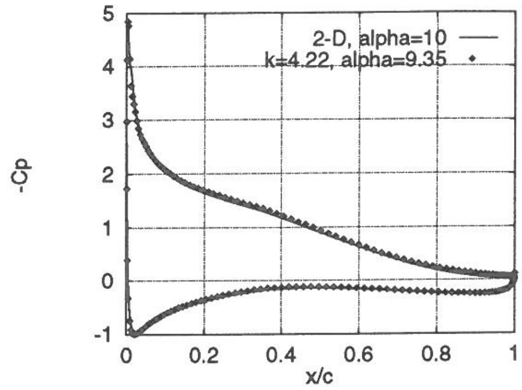

Figure 2: *2-D and 3-D (k = $\frac{r}{c}$ = 4.22) pressure coefficient distribution for an angle of attack of approximately 10^0.*

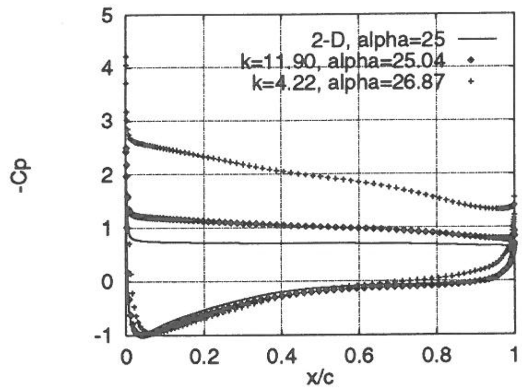

Figure 3: *2-D and 3-D ($\frac{r}{c}$ = 4.22 and $\frac{r}{c}$ = 11.90) pressure coefficient distribution for an angle of attack of approximately 25^0.*

distance from the rotational axis, which is consistent with Snel et al. [3]. It must, however, be emphasized that these numerical results need to be validated against experiments before full confidence can be placed upon them. In the following some other ongoing activties are listed. A quasi-3D model [13] is being developed, where the 3-D effects after some assumptions of the spanwise derivatives can be treated as source terms in a 2-D computation. This model can be used to quantify the 3-D rotational effects. An extended BEM method is under development to take flexible blades and coned rotors into account. The actuator disc model is used to investigate different wake states [14]. Finally, in a recent paper the status and perspectives on CFD in wind energy is given [15].

EXPERIMENTS

Nowadays special airfoils are developed for wind turbines often using CFD and general optimization tools. To validate these designs it was considered important in the Danish 'Blade Design Project' to develop a wind tunnel measurement technique [5-6]. The technique has been successfully validated against similar measurements in a Swedish wind tunnel [12].

CONCLUSION

To provide the engineering models with good airfoil data, several techniques are being investigated in various Danish and European research programmes. Using a proper turbulence model good results can be obtained for the power curve of a stall regulated wind turbine. With the present turbulence models the power production is, however, slightly overpredicted for high wind speeds. To extract the angles of attack from the computations some methods are presently being investigated. It is possible to compute 3-D rotational effects directly, but more experimental validation is required before full confidence can be placed in the results. Further, an experimental facility to test airfoils has been developed in Denmark and is now validated against similar facilities.

REFERENCES

[1] Glauert, H., 'Airplane Propellers', from Aerodynamic Theory, vol. 4, Division L, edited by Durand W.F., Berlin: Julius Springer, 1935, pp 169-360.

[2] Abbot, H. and von Doenhoff, A.E., 'Theory of Wing Sections', Dover Publications (1959).

[3] Snel, H., Houwink, R., Bosschers, J., Piers, W.J., van Bussel, G.J.W and Bruining, A., 'Sectional Prediction of 3-D Effects for Stalled Flow on Rotating Blades and Comparison with Measurements', in proc. of European Community Wind Energy Conference, Lübeck 1993, pp 395-399.

[4] M.O.L.Hansen, N.N.Sørensen, J.N.Sørensen and J.A.Michelsen. *Extraction of Lift, Drag and Angle of Attack from Computed 3-D Viscous Flow around a Rotating Blade.*, to appear in the proceedings of the EWEC97 Conf., Dublin, 1997.

[5] I.Antoniou, P.Fuglsang and H.A.Madsen, 'Wind Tunnel Verification of a new 14% thick Wind Turbine Airfoil', To appear in the proceedings of the EWEC97 Conf., Dublin, 1997.

[6] P.Fuglsang, I.Antoniou, N.N.Sørensen and H.A.Madsen, 'Validation of a Wind Tunnel Testing Facility for Blade Surface Pressure Measurements, Risø-R-981(EN), To be published 1998.

[7] J.N.Sørensen and M.O.L.Hansen. *VISCWIND: A European Collaborate Effort on Viscous Effects on Wind Turbine Blades.* To be published in the proceedings of the EWEC97 Conf., Dublin, 1997.

[8] Menter, F.R., 'Zonal Two Equation $k-\omega$ Turbulence Models for Aerodynamic Flows', AIAA paper 93-2906, 1993.

[9] Sørensen, N.N., 'General purpose flow solver applied to flow over hills', Ph.D. dissertation Risø National Laboratory, Risø-R-827(EN), Denmark, 1995.

[10] Michelsen, J.A., 'Basis3D - a Platform for Development of Multiblock PDE Solvers', Technical Note AFM92-05, Dept. of Fluid Mech. DTU, Denmark, 1992.

[11] Sørensen, N.N. and Hansen, M.O.L., 'Rotor Performance Predictions Using a Navier-Stokes Method', to be published as an AIAA paper at the 36th Aerospace Sciences Meeting and Exhibit, Reno 1998.

[12] A.Bjorck, 'A guide to data files from wind tunnel test of a NACA63-215 airfoil at FFA', FFAP-V-018, FFA, Sweden, March 1996.

[13] Shen, W.Z. and Sørensen, J.N., 'Quasi-3D Navier-Stokes Model for Rotating Airfoil', accepted for publication in J. Computational Physics.

[14] Sørensen, J.N., Shen, W.Z. and Munduate, X., 'Analysis of Wake States by Full-field Actuator Disc Model', to appear in Wind Energy, vol. 1, 1998.

[15] Sørensen, J.N., 'Status and Perspectives on CFD in Wind Energy', proc. fourth European Computational Fluid Dynamics Conference, Athens, September 1998, pp. 442-449.