Unsteady Aerodynamic Simulation of Horizontal Axis Wind Turbine Blade

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Abstract

In this paper, steady and unsteady aerodynamic simulations were performed based on the Blade Element Momentum theory (BEM) by using an open source code (AeroDyn) developed by the National Renewable Energy Laboratory (NREL). The reference wind turbine used in the simulations is the Controls Advanced Research Turbine (CART) which is a machine rated at 600 kW for a specific airfoil family set. The aerodynamic steady wind simulations obtained using AeroDyn are verified using finite element analysis. To be able to capture the un-steady effect of wind on the blade, a Kaimal turbulence power spectral density model has been used. The normal and tangential force components are determined due to the unsteady wind. The dynamic coefficient of lift has also been obtained in the stall region.

Keywords: BEM, Unsteady Aerodynamic, Wind Energy.

1. Introduction

The unsteady aerodynamics of wind turbines is one of the most incentive issues in wind energy research and development [1], [2]. The aerodynamic analysis of the Horizontal Axis Wind Turbine (HAWT) may be performed either by the solution of the full Navier-Stokes equations or the BEM. Incompressible Navier-Stokes analyses have been used by Sorensen and Michelsen [3]. Sorensen et al. [4] have reported excellent Navier-Stokes simulations for the National Renewable Energy Laboratory [NREL] Phase VI rotor tested at the NASA Ames Research Center. The effect of transition and turbulence models on the Navier-Stokes predictions has been studied by Xu and Sankar [5] and by Benjanirat et al. [6]. The unsteady BEM has also been widely used for aerodynamic simulations of wind turbines [7], [8].

In this paper, steady and unsteady aerodynamic simulations were performed based on the BEM. The reference wind turbine used in the simulations is the CART[9]. The blade profiles were selected from the NREL airfoil families.

2. Steady Simulation of CART0 Wind Turbine

To obtain aerodynamic response of the CART wind turbine, the NREL wind turbine airfoil family set: S816 blade profile for the tip, S817 blade profile for the primary and S818 blade profile for the root has been selected. This family set is recommended for a wind turbine rotor diameter of 30-50 meters [10] and the rotor diameter for the CART wind turbine is 42.7 m. To avoid the sudden change in the cross section area of the different blade elements, blended airfoils were used between root and primary, primary and tip in all simulations.

For a given local pitch angle distribution (Figure 1) which represents the initial pitch = 0° + given twist angle, the resulting angle of attack distribution for a constant applied wind field of 12 m/s is shown in Figure 2. This decaying distribution is due to the variation in the velocity distribution along the blade length as well as the change in the calculated axial induction factor shown in Figure 3. The axial induction factor indicates the degree with which the wind velocity at the upstream of the rotor is slowed down by the turbine. From the simple momentum theory, an induction factor of a = 1/3 would produce maximum power output; Also, an a > 0.5 would render the theory invalid because the wind then would have slowed down to zero velocity behind the rotor which is not really practical. Hence, the results obtained from the BEM are rendered invalid after 94% of the blade length. To obtain valid BEM results for the remaining blade region, pitch angle can be modified. Figure 4 shows the tangential (angular) induction factor. The values in the plots are less than 0.1 which is desirable to maintain small wakes behind the rotor. These angle of attack distributions together with the axial and tangential induced velocity factors resulted in the tangential and normal force distributions shown in Figure 5 and Figure 6 respectively. In fact, the larger the tangential forces acting on the blades, the more the power output from the wind turbine while the less the normal forces acting on the blade the less the flapwise deformations.

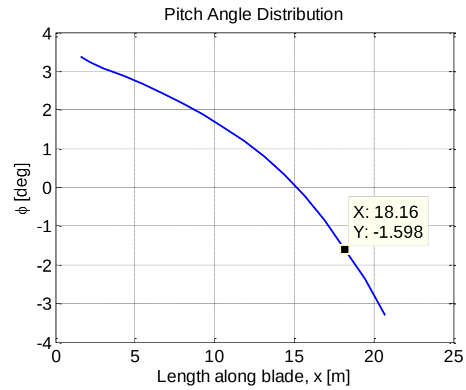

Figure 1 Pitch Angle Distribution

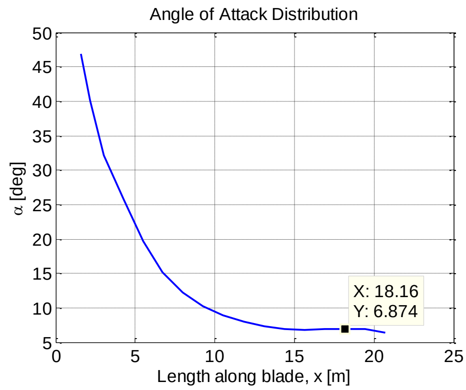

Figure 2 Angle of attack Distribution

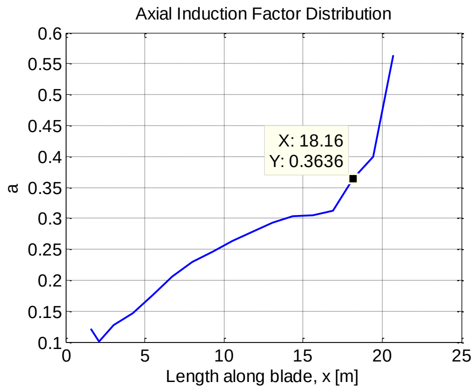

Figure 3 Axial Induction Factor Distribution

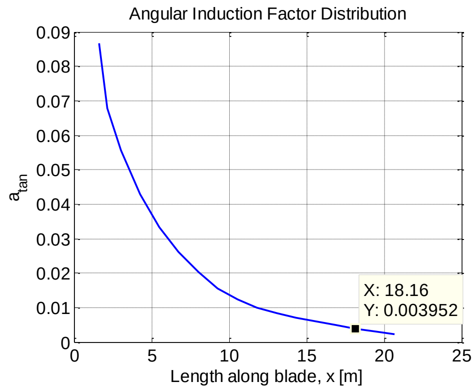

Figure 4 Angular Induction Factor Distribution

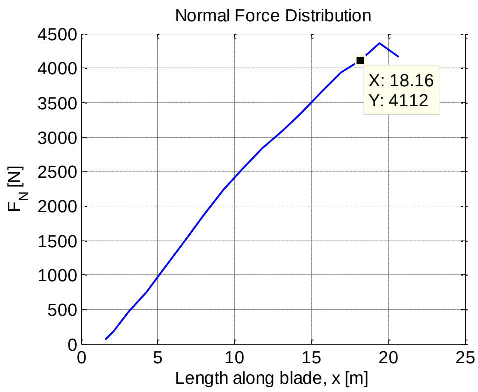

Figure 5 Normal Force Distribution

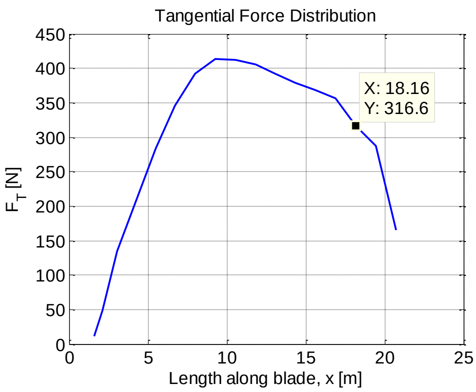

Figure 6 Tangential Force Distribution

3. Verification with ANSYS commercial software

To verify the results obtained from AeroDyn with Ansys CFX, an element at a spanwise position of 18.17 m is selected. At this element position, the airfoil cross section used is S817. It is important to note that AeroDyn solves the aerodynamic forces on a given wind turbine using the blade element momentum (BEM) theorem [11], where each blade element is modeled as a two-dimensional airfoil. On the other hand, Ansys CFX computes pressure and velocity distribution using the finite volume method [12] around a given cross sectional area.

To compare Ansys CFX results with AeroDyn, it is important to calculate the correct inflow angle and the magnitude of the relative velocity that should be used as an input to CFX. At a radius r = 18.17 m, the calculated AeroDyn results for pitch angle (= pretwist angle in this case) from Figure 1 is -1.598° and an angle of attack from Figure 2 = 6.87°, the axial induction factor from Figure 3 = 0.36, and the tangential induction factor from Figure 4 = 0.004. Plugging all these values in the velocity triangle shown in Figure 7 for our blade element and using the rated angular velocity of 4.5 rad/s, the calculated relative velocity would be almost 80 m/s with an inflow angle of 5.3°. These are the values that were used in Ansys CFX to calculate the aerodynamic forces.

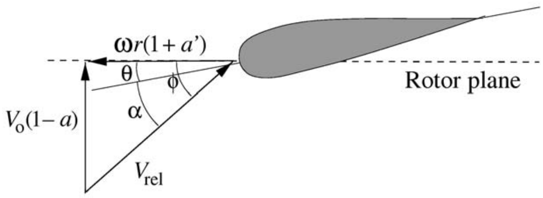

Figure 7 Velocities at the rotor plane [13]

Figure 8 shows the grid generation for the CFX study around an S817 airfoil cross-section. Figure 9 shows the pressure distribution over the airfoil respectively. Integrating the pressure coefficient values determined using CFX and shown in Figure 10 results in a normal and tangential forces of 4212 N and 365 N respectively. These values are similar and compared to those obtained from AeroDyn 4112 N and 316 N as shown in Figure 5 and Figure 6. The slightly less values from AeroDyn can be traced to the neglecting the in-plane and out-of plane velocity components due to blade deformations in Ansys solution. Also due to the variation in the solution technique from the Finite volume method with all its approximations compared with that used in AeroDyn which is the blade element momentum method again with all the approximations inherent in the technique.

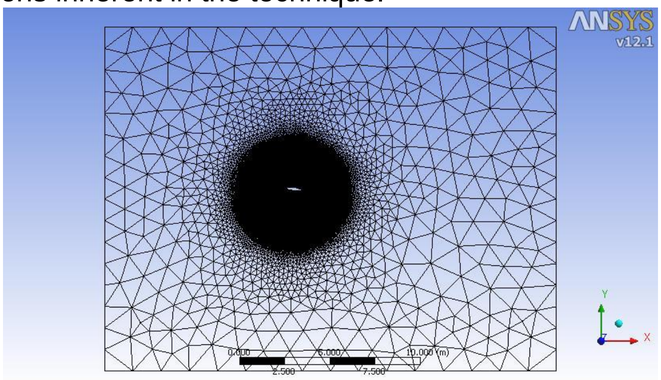

Figure 8 The grid generation of the flow domain

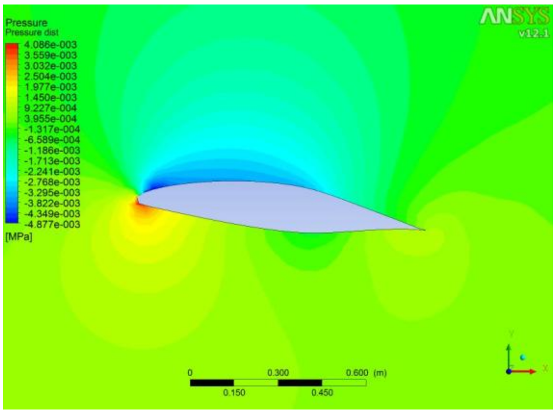

Figure 9 Contour of the pressure distribution around the S817 airfoil

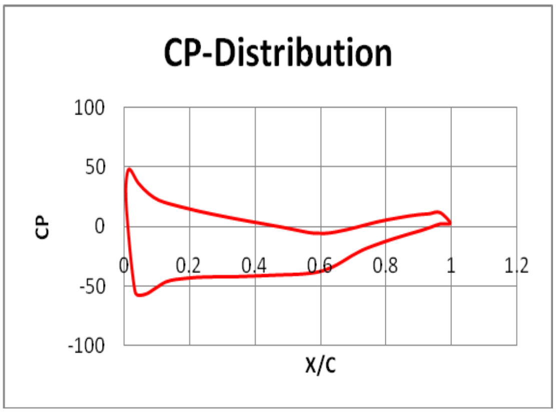

Figure 10 Pressure coefficient (Cp) distribution over the S817 airfoil

4. Unsteady Simulation of the CART0 Wind Turbine

The wind varies every second due to turbulence caused by land features, thermals and weather. It also blows more strongly higher above the ground than closer to it, due to surface friction. All these effects lead to turbulence which varies the loads on the blades of the turbine as they rotate, and mean that the aerodynamic and structural design needs to cope with conditions that are rarely optimal [6]. There are different turbulence models available that simulate the wind turbulence, one of them is Kaimal spectral density function model which is the model used in the simulation, and defined by [12],

$$S(f) = \left(\frac{0.2}{\ln\left(\frac{z}{z_o}\right)} \right)^2 \frac{105 z V_o}{\left(1 + \frac{33 fz}{V_o}\right)^{\frac{5}{3}}} \tag{1}$$

Where S is the single-sided longitudinal velocity component spectrum, f is the frequency, z is the height above ground, z_o is the surface roughness coefficient, and V_o is the average wind velocity at hub height.

To fully analyze unsteady aerodynamic simulations, it is important to include the dynamic stall behavior for the given wind turbine blade. This requires the whole range of lift and drag coefficients be determined. Viterna equations [12] were used to extrapolate the limited data of lift and drag coefficients to the entire ± 180° angle of attack range. Dynamic stall calculations based on the works of Beddoes and Leishman [14] are used. Figure 11 and Figure 12 illustrates dynamic stall event measured at the 5% span location of the CART wind turbine rotor. These dynamic coefficients affect the tangential and normal forces to be determined later.

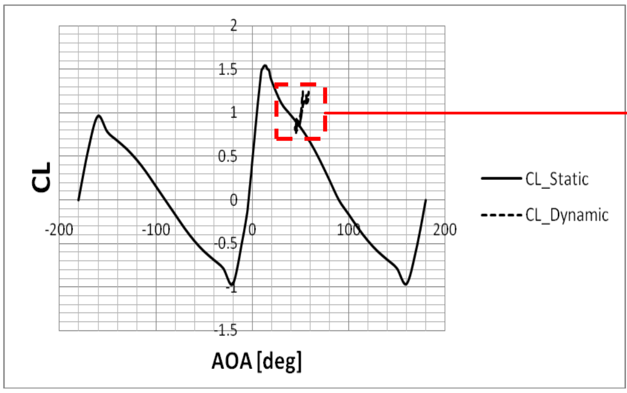

Figure 11 The dynamic versus the static lift coefficient of the S818 blade element

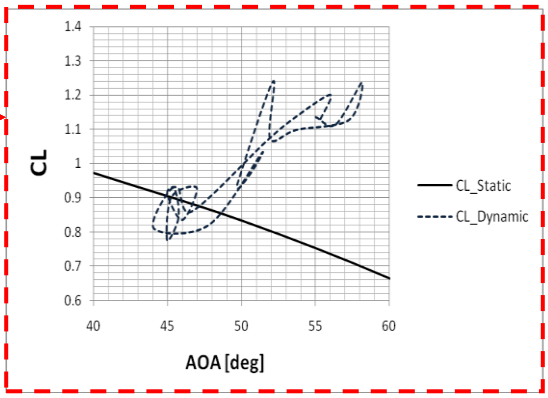

Figure 12 Zoom on the operating range

The unsteady simulation of CART wind turbine will be studied at a mean wind speed of 12 m/sec with the Kaimal turbulence model for 60 seconds as shown in Figure 13. As a critical case, the distributions of the tangential and normal forces on the blade elements at the point of the maximum absolute velocity are shown in Figure 14 and Figure 15 for three different pitch angles. From an aerodynamic point of view, the larger the tangential forces acting on the blades, the more the power output from the wind turbine. It is clear from Figure 14 that the largest power output would be obtained from the zero initial pitch angle. Figure 15 shows the normal forces acting on the blade and from a structural point of view, the less the normal force the less the flapwise deformations. Also the forces increases to reach its maximum value at the blade quarter as the chord increases and then decreases as going to the blade tip as the blade chord decreases.

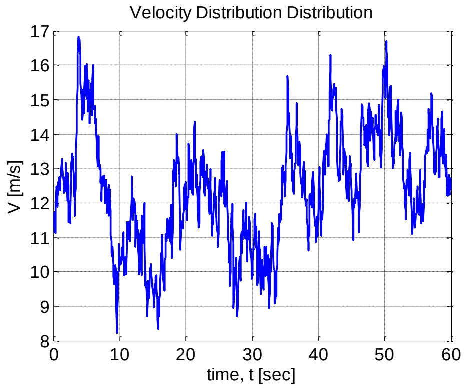

Figure 13 the velocity distribution generated according to Kaimal distribution

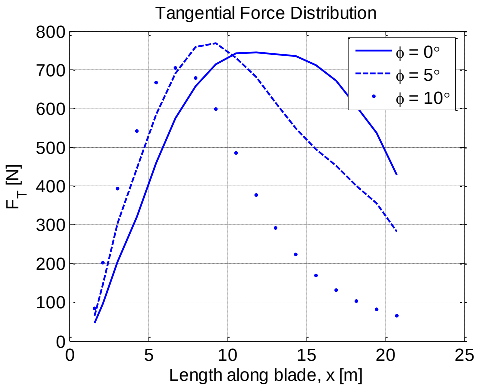

Figure 14 the tangential force distribution at 3.767 seconds

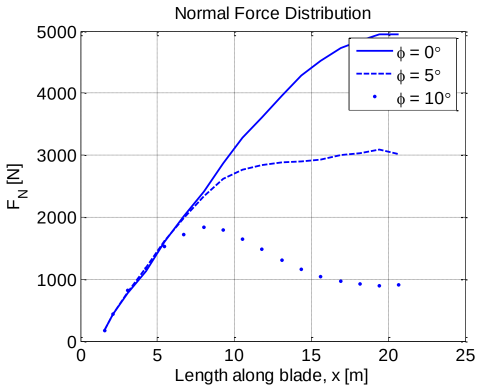

Figure 15 the normal force distribution at 3.767 seconds

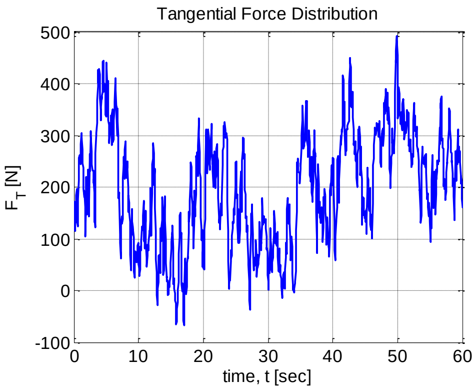

Figure 16 the tangential force distribution at the blade tip

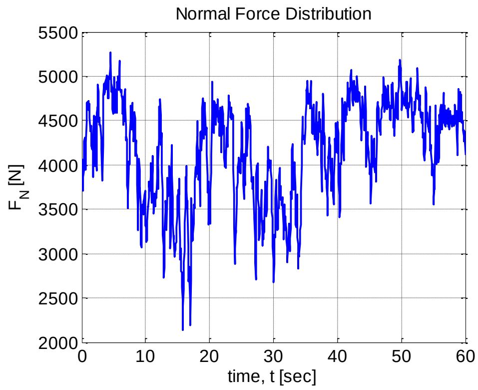

Figure 17 the normal force distribution at the blade tip

The forces distribution over the whole simulation time plotted at the blade tip are shown in

Figure 16 and Figure 17.

5. Conclusions

In this paper, steady and unsteady aerodynamic simulations were performed based on BEM using NREL AeroDyn code. Normal and tangential force distributions were obtained under steady wind conditions and verified using ANSYS CFX software. Unsteady simulations were performed while taking into account turbulent wind following Kaimal power spectral density function and Beddoes and Leishman dynamic stall model. Results obtained show that for the given wind turbine and selected airfoil blade family set, a zero pitch angle would produce maximum power at the expense of more flapwise deformations.

6. Acknowledgement

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7. References

[1] Manwell, J. F., McGowan, J. G., and Rogers, A. L., Wind Energy Explained Theory, Design and Application, John Wiley and Sons Ltd, 2nd edition, 2009.

[2] Martin O. L. Hansen, Aerodynamics of Wind Turbines, Earthscan, 2nd Edition, 2008.

[3] Sorensen, N. N., and Michelsen, J. A., “Aerodynamic Predictions for the Unsteady Aerodynamics Experiment Phase-II Rotor at the National Renewable Energy Laboratory,” AIAA Paper 2000-0037.

[4] Sorensen, N. N., Michelsen, J. A., and Schreck, S., “Prediction of the NREL/NASA Ames Wind Tunnel Test,” AIAA Paper 2002-0031.

[5] Xu, G., and Sankar, L. N., “Effects of Transition, Turbulence and Yaw on the Performance of Horizontal Axis Wind Turbines,” AIAA Paper 2000-0048.

[6] Benjanirat, S., Sankar, L. N., and Xu, G., “Evaluation of Turbulence Models for the Prediction of Wind Turbine Aerodynamics,” AIAA Paper 2003-0517

[7] Hansen, M., Sørensen, J., Voutsinas, S., Sørensen, N., Madsen, H., "State of the art in wind turbine aerodynamics and aeroelasticity", Progress in Aerospace Sciences 42, pp. 285–330, 2006.

[8] David J. Laino, A. Craig Hansen, "CONTINUED VALIDATION OF THE AERODYN SUBROUTINES USING NREL UNSTEADY AERODYNAMICS EXPERIMENT DATA", AIAA-2003-0518

[9] Stol, K. A., Geometry and structural properties for the controls advanced research turbine (CART) from model tuning. NREL/SR 500–32087, National Renewable Energy Laboratory, 2003.

[10] http://wind.nrel.gov

[11] Moriarty, Patrick and Hansen, Craig, “AeroDyn Theory Manual” Prepared under Task No. WER43101, WER53101, Software date and version. AeroDyn 12.50, 6-Dec-2005.

[12] ANSYS Inc, "ANSYS CFX 12.1 (Theory Guide)," 2010

[13] David, J., Laino, A., Hansen, C., “YawDyn USER'S GUIDE,” Prepared for the National Renewable Energy Laboratory under Subcontract No. TCX-9-29209-01. Program date and version YawDyn 12.14, 13-January-2003

[14] Leishman, J. G., Beddoes, T. S., “A Semi-Empirical Model for Dynamic Stall,” Journal of the American Helicopter Society. 34(3): 3-17, 1989.