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Validation of AWTSim as Aerodynamic Analysis for Design Wind Turbine Blade

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Abstract. This paper presents the results of validation AWTSim code and this code has been used to analyze aerodynamic performance in the optimization design blade wind turbine. The validation was performed to know the accuracy of AWTSim code compared to WT_Perf by using the test wind turbine blade AWT-27. Blade AWT-27 was taken as the case for all through of this study and the design pitch angle for blade AWT-27 was 1.2° to stall (-1.2). However, in order to compare the results with available results, pitch angles 0, 1 and 2 degrees to stall were considered for simulation. The results of validation show that the predicted power curve, power coefficient and thrust by two codes are almost similar or less than 1%.

Introduction

Several softwares for design and analysis aerodynamic blade wind turbine have been available for blade designer. The softwares such as Garrad Hassan's BLADED, WT_Perf and The University of Utah's YawDyn are common used to analyze aerodynamic performance of design blade wind turbine. WT_Perf, for example is a wind-turbine performance prediction code developed and in use in the National Renewable Energy Laboratory (NREL). This code was created by M. Buhl of NWTC and a brief-description can be found in [1]. This code was derived from Aerovironment's PROP code, the original theory is covered in many papers [2,3,4]. The PROP code is based upon work done by Robert Wilson and Stel Walker of Oregon State University [5] that is based on blade element momentum theory (BEMT) with capabilities to account for yawed and tilted operation as well as operation in the turbulent windmill and propeller brake states.

The similar concept to WT_Perf, Aero Wind Turbine Simulation (AWTSim) has been developed as analysis tool to analyze aerodynamic performance of horizontal axis wind turbines in the optimisation design blade. This software is a series of routine written to perform the aerodynamic calculation and is used in conjuction with aeroelastic simulation code to predict the aerodynamic of horizontal axis wind turbine.

In order to AWTSim code deserve as a tool to analyze aerodynamic performance as well as other softwares this code has been validated against the latest version of WTPerf by using the test wind turbine AWT-27. AWT-27 is a 2-bladed wind turbine, one of the very few wind turbines with known specifications to public and this blade is taken as the case for study all through this study.

This paper compares the results of simulation from AWTSim against newest release of version WT_Perf for the results simulation of rotor mechanical power, power coefficient and thrust coefficient in the different pitch angle.

BEMT Calculation in AWTSim

In the predicting of the performance wind turbines, BEMT is typically used to analyze and simulate design wind turbine blade. This theory is an extension of actuator disk, proposed by Rankine and Froude in the late 19th century and it was continually to Betz and Glauert (1935).

The BEMT comes originally from two different theories: Blade Element or Strip Theory and Momentum or Actuator Disk Theory [6,7]. Blade Element Theory assumes that blade is divided up into a number of span-wise elements or strips at radial stations along the blade span that act independently of surrounding elements and operate aerodynamically as two-dimensional aerofoil whose aerodynamic forces can be calculated based on the local flow conditions. These elemental forces are summed along the blade span to calculate the total forces and moments exerted on the blade. The other half of BEMT the momentum theory assumes that the loss of pressure or momentum in the rotor plane is caused by the work done by airflow passing through the rotor plane on the blade elements. Using the momentum theory, one can be calculated the induced velocity from the momentum lost in the flow in axial and tangential directions. These induced velocities affect the inflow in the rotor plane therefore also affect the force calculated by blade element theory. This coupling of two theories ties together blade element momentum theory and sets up an iterative process to determine the aerodynamic forces and also the induced velocities near the rotor.

Algorithm below shows the steps of calculating the extracted mechanical power by a stall-regulated wind turbine based on the BEMT method. These algorithms require a discretised-blade, rotor characteristics and lift and drag tables corresponding to the aerofoil used in the blade.

Algorithm BEMT calculator :

Given:

- $\{\varepsilon_a, \varepsilon_{a'}\}, \{D, b, \rho, h_{hub}, z_0, \delta, \gamma\}, \{V_{hub}, \Omega, pitch\}$
- $\{n_{seg}, n_{\sec}\}, \{r_i^*, c_i^*, \beta_{0,i}, AF_i, t_{\max,i}^*; i = 1 : n_{seg}\}and\{\psi_j; j = 1 : n_{\sec}\}$ (discretised blade)
- $C_L - \alpha$ and $C_D - \alpha$ tabulated data for all aerofoils used in the blade

Step 1-Initialise $C_{L,i}, C_{D,i}, \varphi_i, \alpha_i, V_{rel,i} \leftarrow 0$; $i = 1 : n_{seg}$.

Step 2-Dimensionalise $\Delta r = R\Delta r^*$ and $r_i = Rr_i^*$, $c_i = Rc_i^*$, $t_{\max,i} = c_i t_{\max,i}^*$; $i = 1 : n_{seg}$ ($R = 0.5D$).

Step 3-For each azimuth angle ψ_j ; $j = 1 : n_{\sec}$,do:

3.1. Find wind shear field:

3.1.1. $z_i = h_{hub} - r_i \sin\psi_j$; $i = 1 : n_{seg}$

3.1.2. $S_{i,j} = \ln(z_i / z_0) / \ln(h_{hub} / z_0)$; $i = 1 : n_{seg}$

3.2. Find wind speed at the centre of each blade segment: $V_{i,j} = V_{hub} S_{i,j}$

Step 4- For $j = 1 : n_{\sec}$, do:

4.1. For $i = 1 : n_{seg}$, do:

4.1.1. Calculate local speed ratio $\lambda_{r_i} = r_i\Omega / V_{i,j}$ and local solidity ratio $\sigma_{r_i} = Bc_i / 2\pi r_i$

4.1.2. Initialise $a \leftarrow 1/3$; $a' \leftarrow 0$; $converged \leftarrow false$

4.1.3. While ($converged = false$) do:

4.1.3.1. Calculate inflow angle $\varphi_i = \tan^{-1}\left(\dfrac{V_{i,j} \cos\delta \cos\gamma(1-a)}{r_i\Omega(1+a') - V_{i,j} \sin\gamma \sin\psi_j \cos\delta}\right)$

4.1.3.2. Calculate tip and hub losses $F = F_{tip} F_{hub}$.

If $f_{tip} = \left|B(R-r)/2r\sin\varphi\right| \le 7 : F_{tip} = \dfrac{2}{\pi}\cos^{-1}\{\exp(-f_{tip})\}$; otherwise: $F_{tip} = 1$.

If $f_{hub} = \left|B(r-R_{hub})/2R_{hub}\sin\varphi\right| \le 7 : F_{hub} = \dfrac{2}{\pi}\cos^{-1}\{\exp(-f_{hub})\}$;otherwise: $F_{hub} = 1$.

4.1.3.3. Calculate inflow angle at zero drag: $\varphi_0 = \tan^{-1}\left(\dfrac{\cos\delta F(1-a)}{\lambda_{r,i}}\right)$

4.1.3.4. Calculate angle of attack $\alpha_i = \varphi_i - \beta_{0,i} - pitch + \Delta\alpha_c$;

$$\Delta\alpha_c = \frac{B\cos\varphi_0 A_a}{2\pi r_i c_i} + \frac{1}{4}\left\{\tan^{-1}\frac{(1-a)r_i}{(1+2a')R} - \tan^{-1}\frac{(1-a)r_i}{R}\right\};\ A_a = 0.68 c_i t_{\max,i}$$

4.1.3.5. Use α_i read off life and drag coefficients from tables: $C_{L,i}$ and $C_{D,i}$

4.1.3.6. Calculate thrust coefficient at zero lift: $C_{T_0} = \dfrac{\sigma_{r,i}\cos^2\delta(1-a)^2 C_{L,i}\cos\varphi_i}{\sin^2\varphi_i}$

4.1.3.7. Calculate a_{new}. If $C_{T_0} > 0.96F$: $a_{new} = \left(-B_1 + \sqrt{B_1^2 - 4B_0(B_2 - C_{T_0})}\right)\Big/ 2B_0$,

otherwise $a_{new} = \left(1 - \sqrt{1 - C_{T_0}/F}\right)\Big/2$;

($B_0 = 2/(1-a_c)^2 - 4F$; $B_1 = -4a_c/(1-a_c)^2 + 4F$; $B_2 = 2 + (4a_c - 2)/(1-a_c)^2$; $a_c = 0.4$).

4.1.3.8. Calculate $a'_{new} = a_{new}\tan\varphi_i / \lambda_{r,i}\cos\delta$

4.1.3.9. If $\left(|a - a_{new}| \le \varepsilon_a \wedge |a' - a'_{new}| \le \varepsilon_{a'}\right)$: $converged \leftarrow true$; Else: $a \leftarrow a_{new}$, $a' \leftarrow a'_{new}$.

4.1.4. Calculate $V_{rel,i} = \sqrt{\left(V_{i,j}\cos\gamma\cos\delta(1-a)\right)^2 + \left(V_{i,j}\sin\gamma\cos\delta\sin\psi_j - r_i\Omega(1+a')\right)^2}$

4.1.5. Calculate $\Delta M_i = \frac{1}{2}\rho V_{rel,i}^2 B c_i \left(C_{L,i}\sin\varphi_i - C_{D,i}\cos\varphi_i\right) r_i \Delta r \cos\delta$

4.2. Calculate $P_j = \Omega\sum_{i=1}^{n_{seg}} \Delta M_i$

Step 5 Calculate $P = \dfrac{1}{n_{\sec}}\sum_{j=1}^{n_{\sec}} P_j$

AWTSim Code

AWTSim is an interactive aerodynamic code for predicting and calculating aerodynamic performance and the blade loading of a horizontal axis wind turbine (load and rotor mechanical power) between cut-in and cut-out velocities by using a Rayleigh Probability Distribution Function (PDF) . This software includes two primary modules for blade discretisation and BEMT calculations, and some secondary modules for calculating the annual average power and blade external/internal loading. It also includes modules required for analyzeis of wind turbines utilising unconventional blades.

Theory behind AWTSim is blade element momentum theory, BEMT. This module calculates the aerodynamic lift and drag of aerofoil section and breaking each blade into a number of segments along the span as specified by an aero module input file. The AWTSim gathers information about the blade topology, operating condition, blade element velocity and condition, and wind inflow from input files and the aeroelastic simulation program and then uses this information to calculate the various forces for each segment on the turbine blades.

As a analysis-tool AWTSim can predict the mechanical power of horizontal axis wind turbine and blade aerodynamic loading using two different brake state models of Classical and Wilson Walker. Hub losses, cascade correction and some modification to the Prandtl tip losses are also included. Post-stall aerodynamic characteristics of the aerofoil can be estimated by both Viterna-Corrigan and flat-plate model internally to make the aerofoil aerodynamic characteristic file. In the calculating of aerodynamic performance the AWTSim also divides the blade into segments automatically therefore this makes the input files shorter and easier to generate. Two embedded iteration loops are used to find the axial and rotational induction factors and applying a relaxation factor and using an accelerator algorithm prevent divergence and fluctuating behaviour of the solution and improve the convergence rate in the axial induction factor iteration.

In order to analyze the aerodynamic performance of constant speed stall regulated wind turbine, AWTSim requires five sets of inputs:

1. Blade geometry and topology data. These data include span-wise distribution of chord $c(r)$, pretwist $\beta_0(r)$, aerofoil $AF(r)$ and aerofoil maximum thickness $t_{\max}(r)$ as well as rotor radius R (or diameter D), hub radius R_{hub} and blade pitch angle $pitch$.
2. Blade aerodynamic data. For each aerofoil used in the blade tabulated $\alpha - C_L$ and $\alpha - C_D$ data are required.
3. Rotor characteristics: rotor speed Ω, cone angle δ, number of blades B and hub height h_{hub}.
4. Wind turbine operating data: Wind speed at hub height V_W and yaw angle γ.

   Site data: Site average wind speed V_{av} and probability distribution function, and ground surface roughness length z_0.

Result and Discussion

AWTSim has been validated against the latest version of WT_Perf using the test wind turbine AWT-27. In order to compare the results obtained by AWTSim with those of WT_Perf, the input data files of a typical test run of WT_Perf has been downloaded and used to generate the input data files as required by AWTSim. The design pitch angle for AWT-27 is 1.2° to stall (-1.2). However, in order to compare the results with available results, pitch angles 0, 1 and 2 degrees to stall are considered for simulation.

Fig. 1 to Fig. 3 show the power curves, power coefficient and thrust curves for this wind turbine obtained by WT_Perf and AWTSim.

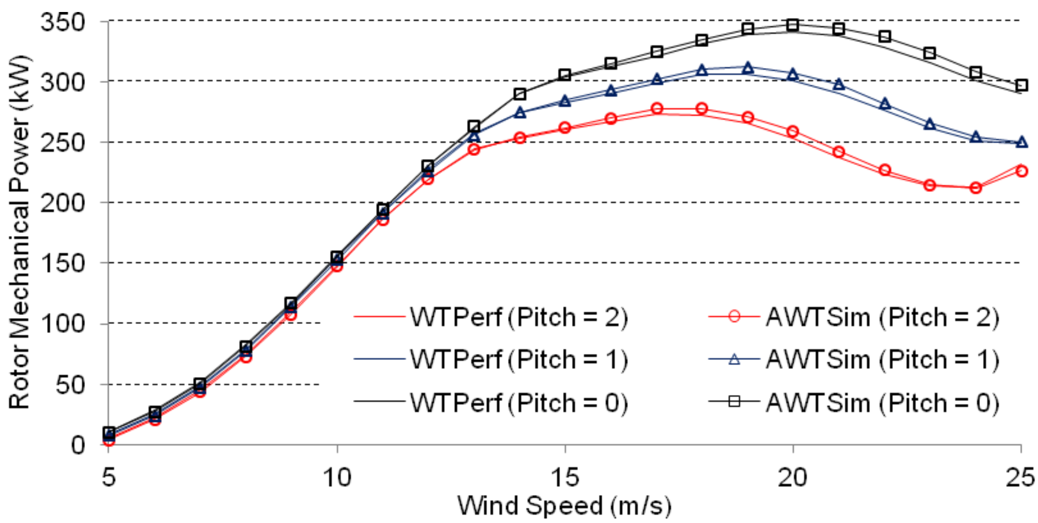

Figure 1 AWTSim versus WT_Perf – Power curves at different pitch angles

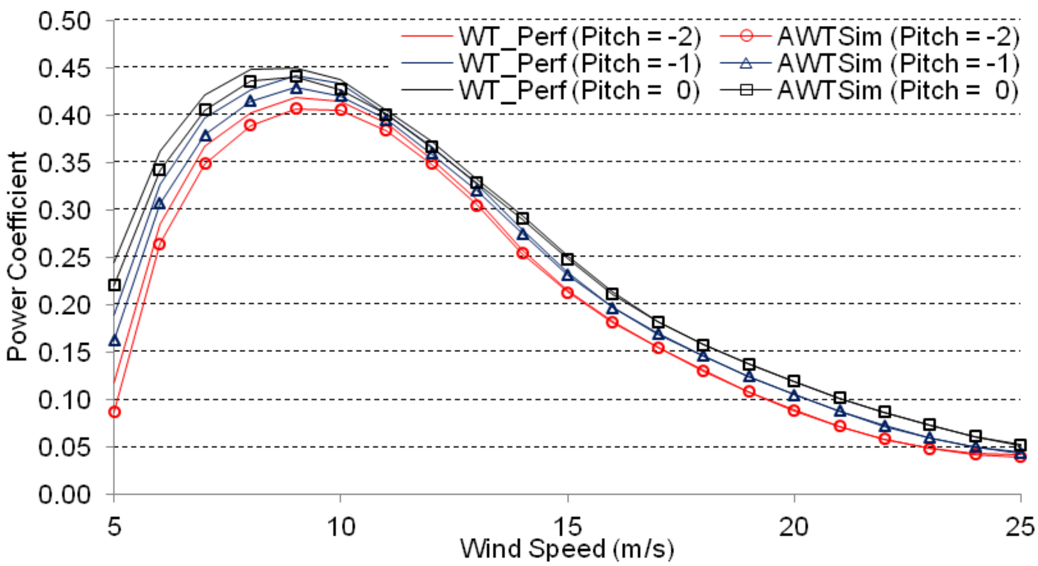

Figure 2 AWTSim versus WT_Perf – Power coefficient at different pitch angles

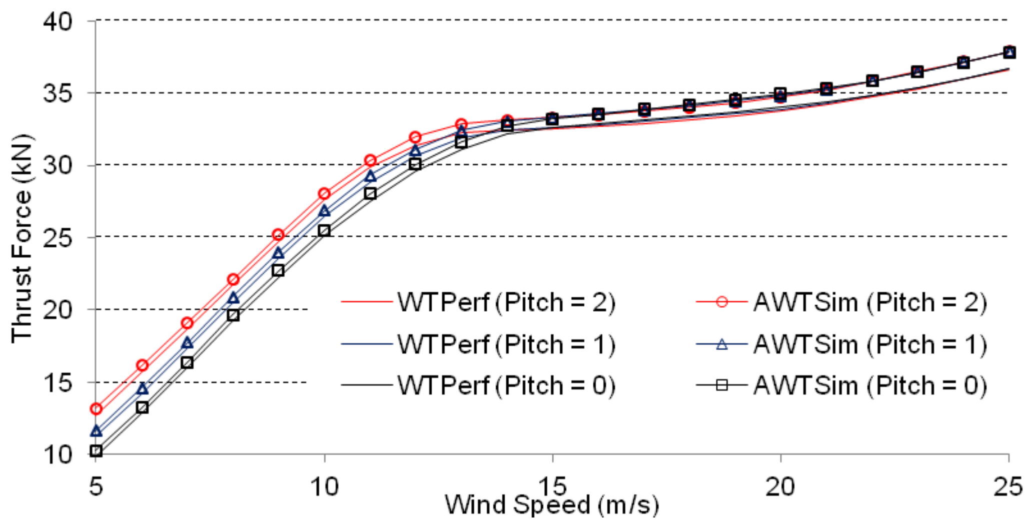

Figure 3 AWTSim versus WT_Perf – Thrust force at different pitch angles

As can be seen from Fig. 1 to Fig. 3, it can be observed that the difference between the predicted power curve, power coefficient and thrust by two codes are very small or less than 1%. The reasons for this difference can be explained as follows. The blade aerodynamic loading and therefore the rotor mechanical power are very sensitive to the accuracy of the predicted angle of attack. The more the number of segments, more accurately the angle of attack is calculated. WT_Perf is using 17 unequal segments in this run while AWTSim has divided the blade into 20 equal segments.

Summary

According to the above figures the following conclusion can be drawn :

1. The result simulation of rotor mechanical power, power coefficient, and thrust by two codes are almost the same or less than 1%.
2. Validation of AWTSim in this study shows that this software has a good-accuracy to analyze aerodynamic performance of design blade therefore AWTSim code is deserve used to optimisation design blade wind turbine.

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