Wind turbine power curve prediction with consideration of rotational augmentation effects

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Abstract. Wind turbine power curve expresses the relationship between the rotor power and the hub wind speed. Wind turbine power curve prediction is of vital importance for power control and wind energy management. To predict power curve, the Blade Element Moment (BEM) method is used in both academic and industrial communities. Due to the limited range of angles of attack measured in wind tunnel testing and the three-dimensional (3D) rotational augmentation effects in rotating turbines, wind turbine power curve prediction remains a challenge especially at high wind speeds. This paper presents an investigation of considering the rotational augmentation effects using characterized lift and drag coefficients from 3D computational fluid dynamics (CFD) simulations coupled in the BEM method. A Matlab code was developed to implement the numerical calculation. The predicted power outputs were compared with the NREL Phase VI wind turbine measurements. The results demonstrate that the coupled method improves the wind turbine power curve prediction.

1. Introduction
Wind energy has been increasingly focused as a widespread green energy source all over the world. For the last decades, wind turbine technology has been undergoing great development. Aerodynamic design is the fundamental process in wind turbine development, as the forces and power produced by the rotor are firstly predicted. The power curve is the rotor power versus the wind speed at the hub height. It is of highly importance for wind turbine development and power production estimation with a candidate site. In both industrial and academic communities, the most popular method for wind turbine design and power prediction is the Blade Element Moment (BEM) based method [1] (also known as Strip theory or Glauert/Wilson method). By dividing the wind turbine blades into sectional blade elements and applying linear momentum conservation to the annular elements, the forces and power are calculated by integration based on the sectional airfoil lift and drag coefficients. The lift and drag coefficients are one of the most important criticalities for the accuracy of power curve prediction in the BEM. These coefficients are often characterized and originally obtained from two-dimensional (2D) airfoil wind tunnel testing. The aerodynamic coefficients of an airfoil are measured over a limited range of angles of attack and are rarely available over the entire range of ±180°. Moreover, the flow pattern in a rotating wind turbine is distinctively different from that in airfoil wind tunnel test. It was pointed out that methods relying on purely 2D flow characterization are not capable of simulating the complex three-dimensional (3D) flows [2]. And the under-prediction of power output using 2D coefficients at high wind speeds for rotating wind turbines is due to the three-dimensional rotational augmentation effects named as “stall-delay” [3].
To build stall-delay models and to represent the lift and drag coefficients, several empirical models have been developed and applied with the BEM method as well as the lifting surface wake theory, such as the Viterna-Corrigan (V-C) model [3] and Du-Selig (D-S) [4]. Snel [5] presented an empirical correction model for lift coefficient but no drag correction was mentioned. Bak [6] developed a correction model based on the pressure distribution, which is a function of span-wise and chord-wise positions. The normal and tangential coefficients are then obtained from integration of the pressure differential model. Hansen [7] proposed a correction model for 3D rotational effects from a quasi-3D Navier-Stokes method. Some researchers tried to find a correct mathematical representation of lift and drag airfoil, i.e. Lanzafame [8] implemented a fifth-order logarithmic polynomial to fit the wind tunnel experimental data in a design code based on the data of the NREL Phase II and VI wind turbine. Some researchers tried using coefficients from 2D CFD and stall-delay model in the BEM method [9]. Other researchers used a disc model with volumetric forces added through source terms in the momentum equations for the simulation of a marine current turbine [10]. These efforts have greatly improved the power performance prediction.

The purpose of this study is to investigate the lift and drag characterization for wind turbine power curve modelling. A Matlab code was developed to implemented the BEM method employing different aerodynamic models for representing the lift and drag coefficients. A 3D computational fluid dynamics (CFD) approach was exploited for characterizing the lift and drag coefficients used in the BEM method for power performance prediction. The discussion was based on the NREL Phase VI wind turbine [11] which is used for validation. A coupled model for representing the lift and drag coefficients covering the pre-stall, stall-develop, post-stall and deep-stall regions was proposed in the BEM method and the results were compared with measurements. The method can be applied to any wind turbines.

2. BEM modelling

2.1. BEM procedure

The analytical aerodynamic approach used for power performance prediction is based on the BEM theory [1]. In the BEM theory, the blade is divided into several sections and each section sweeps an annular area when the rotor rotates. These annuli are separated and no interaction between each other. In other words, the stream tube is decomposed along different radius positions and each annulus has its own momentum balance. By dividing the wind turbine blades into annular blade elements and applying one-dimensional linear momentum conservation to the annular elements, the forces and power are calculated and integrated based on the sectional airfoil lift and drag coefficients, the chords and twist angles of the blade. Based on the standard BEM method, both the Glauert wake model and Prandtl tip-hub loss model were employed. The total power produced by a rotor was then integrated from the root sections to the tip sections in the form of local speed ratio, the effect of the drag was also included.

The aerodynamic coefficients of an airfoil are measured over a limited range of angles of attack and are rarely available over the entire range of ±180°. Viterna and Corrigan [3] developed a method to do this extrapolation. The Viterna and Corrigan (V-C) model is still widely used for wind turbine power performance prediction nowadays.

Considering the three-dimensional rotational augmentation effects in the wind turbine, Du and Selig [4] tried to build stall delay model. The Du-Selig (D-S) model was used to correct the lift and drag coefficients at high angles of attack where stall-delay exists. The rotor radial locations and the wind speeds are considered in the model.

For a rotating wind turbine blade, the stall is postponed and the lift is augmented. The lift coefficient curve keeps on ascending after the 2D stall angle (observed in 2D wind tunnel testing). From detailed 3D flow analysis, it is obvious that the sectional airfoils in the 3D blade generally experience four stages including pre-stall, stall-develop (up to stall), post-stall and deep-stall. To cover these stages, a coupled model is proposed for the power curve prediction:
In the linear pre-stall stage, represents the lift and drag coefficient from 2D wind tunnel testing. In the stall-develop stage, represents the derived coefficients from 3D CFD and pressure measurements or the stall-delay models can be employed. In the post-stall region, the turbine can be regarded as a quasi-flat plate, and afterwards the turbine is in deep-stall thus it is considered as a disk and the standard flat plate equations are employed.

A Matlab code was developed to calculate the power coefficients versus different tip speed ratios and the wind turbine power output at different wind speeds. The Glauert wake, Prandtl tip-hub loss and drag effects were considered in the performance calculation. The lift and drag coefficients were interpolated and extrapolated based on the 2D wind tunnel testing, D-S model and V-C model. The 3D coefficients from CFD simulations were also employed and discussed later. The flow chart of the power performance calculation is explained in Figure 1.

![Flow chart of power performance calculation](image)

Figure 1. Flow chart of power performance calculation
2.2. BEM validation
To validate the developed BEM code in Matlab, a comparison was conducted with the GH-Blade \[^{[12]}\] code and the AeroDyn \[^{[13]}\] code. Figure 2 compares the power coefficient of the NREL Phase VI wind turbine predicted by the develop Matlab code with GH-Blade and AeroDyn. Good agreements were obtained thus the BEM method was correctly implemented.

3. CFD modelling

3.1. CFD approach
The 3D CFD simulations based on the Reynolds-averaged Navier–Stokes (RANS) equations were conducted to analyze the detailed flow pattern along the blade. The turbine and the flow domain are illustrated in Figure 3. Figure 3 depicts the whole flow domain which combines two sub-domains, i.e. the outer domain and the inner domain. The whole domain is 5 times rotor radius in length upstream before the rotor and 15 times rotor radius downstream behind the rotor to allow fully wake development. The outer domain radius is 5 times rotor radius at the inlet and 8 times rotor radius at the outlet. The radius of the inner domain is slightly larger than the rotor radius. The multiple reference frames (MFR) method and sliding mesh method are used to model the rotating wind turbine rotor, i.e. the outer domain is defined as stationary while the inner domain is defined to be rotating with the rotor blades. These boundary conditions are applied: velocity inlet, pressure outlet, far wall, periodic and interface. The blade surface is regarded as non-slip ping wall. The two domains interact through mesh interfaces. Periodic boundary was defined to solve a half domain only. These settings are considered to be similar to the real wind tunnel test.

Due to very large size scale difference between the tiny blade surface boundary and the large far field, and also the free-form surface of the turbine blade, the mesh is the most challenging part of wind turbine simulation. Considering the balance between the calculation time and accuracy, a mesh dependency study was performed until there is no obvious change in results. Different mesh scheme and mesh size were tested and evaluated. Finally, a hybrid mesh scheme was applied: a fine tetrahedral mesh was used near blade in the inner domain; a coarser hexahedral mesh was applied to the outer domain. A number of 3.6 million cells in total were generated in ICEM and the minimum Y plus of the first layer near the blade surface is around 1.0 to solve the boundary flow.

A turbulence model dependency study was executed involving the standard k-\(\varepsilon\) model, the k-\(\varepsilon\)-

![Figure 2. Power coefficient comparison](image-url)
model with enhanced wall treatment, the SST k-ω turbulence model and the SST transition model. Among these models, the SST transition model is capable of simulating turbines accurately but it is very time consuming compared to other models. For this case, the SST k-ω turbulence model provided with reasonably good results within general time limits, thus it was used for all the calculations afterwards. All the calculation was performed in transient mode in FLUENT and a series of time step sizes were examined to secure transient behavior. Again, this is a balance between accuracy and computing time. Providing the monitored results showed no big difference, the setting of 0.001s/step and 1660 steps therefore was then selected considering the balance between accuracy and computing time. All the calculations converged with the residuals under $10^{-5}$.

![Figure 3. Domain topology and boundary conditions](image)

3.2. CFD validation
Figure 4 plots the calculated pressure distributions compared with measurements for different locations along the blade at wind speed of 7m/s. More pressure distributions were obtained but not presented here due to limited pages. As shown in Figure 4, the results of the CFD simulations well agree with the measurements. Though small quantitative difference exists due to boundary laminar bubble and flow separation, the overall distributions are generally well predicted for all the span locations.
4. Results and discussion

Figure 5 gives a plot of different series of lift and drag coefficients: (1) 2D coefficients from wind tunnel tests; For the NREL Phase VI wind turbine, the aerodynamic coefficients of S809 from the Delft University of Technology wind tunnel tests at Reynolds number of $1 \times 10^6$\cite{11} were used, which are named as 2D $C_l$ and $C_d$; (2) corrected coefficients based on D-S model, named as D-S $C_l$ and $C_d$; (3) 2D coefficients plus 3D coefficients and corrected coefficients based on V-C model, named as 2D+3D+V-C $C_l$ and $C_d$; (4) 2D coefficients plus 3D coefficients and coefficients based on modified Flat Plate theory, named as 2D+3D+mFP $C_l$ and $C_d$.

According to the D-S model from (11) to (16), the D-S $C_l$ and $C_d$ coefficients were calculated based on the 2D wind tunnel coefficients, as presented in Figure 5. Based on the CFD simulations, the inner span locations were regarded as typical stall delay locations other than outer locations. For simplicity, only one radius location $r/R=0.3$ was implemented, and the coefficients were corrected at the wind speed of 10m/s.

By applying the V-C method, the input aspect ratio was selected as 14 according to the tip chord of 0.358m and radius of 5.029m for the Phase VI turbine blade. Three initial stall angles of 9.21°, 15.23° and 20° were tried, however, none of these initial stall angles produced satisfactory results. With an input of initial stall angle of attack and corresponding lift and drag coefficients, the V-C method showed limited improvement in power prediction. It is noticed that the lift to drag ratios at these two angles of attack do not follow the flat plate theory, and serious “drop” of the lift coefficient curve occurred at these initial stall angles, where the V-C correction starts to work. At the same time, the lift coefficient is claimed to be arising after stall as due to stall-delay in 3D wind turbine flows. Thus it is
necessary to solve the problem of the “drop” between the 2D tested aerodynamic coefficients and the V-C corrected coefficients at the angle of attack where the V-C correction model starts to work and keep the corresponding lift to drag ratio been guided by the flat plate theory.

To cope with this “drop”, the extracted 3D coefficients derived from the surface pressure of the rotating blades at five span locations based on the CFD calculation were used to “bridge up” this gap, as shown in Figure 5. These 3D coefficients calculated from the blade surface pressure were applied for the angles of attack from 9° to 20°, and there is no big “gap” existed in the 2D+3D+V-C Cl and Cd coefficients.

For the series of 2D+3D+mFP Cl and Cd coefficients, the TUDelft wind tunnel tested lift and drag coefficients are used for angles of attack from 0° to 6.16° for pre-stall region, while for the angles of attack from 6.16° to 20° for stall-develop region, the bridged coefficients from 3D simulations are applied. When the angle of attack is above 20° for post-stall and deep-stall, the coefficients are calculated according to the equations from (2) to (5):

\[
C_l = 2 \cdot C_{l,\text{max}} \cdot \sin \alpha \cdot \cos \alpha, \quad 20^\circ < \alpha \leq 30^\circ \\
C_d = C_{d,\text{max}} \cdot \sin^2 \alpha, \quad 20^\circ < \alpha \leq 30^\circ \\
C_l = 2 \cdot \sin \alpha \cdot \cos \alpha, \quad 30^\circ < \alpha < 90^\circ \\
C_d = 2 \cdot \sin^2 \alpha, \quad 30^\circ < \alpha < 90^\circ 
\]

Here, \( C_{l,\text{max}} = C_{l,\alpha=45^\circ} \) and \( C_{d,\text{max}} = C_{d,\alpha=90^\circ} = 2 \).

Figure 5. Lift and Drag Coefficients

Providing the lift and drag coefficients, the power curve can be well predicted based on the BEM approach. Figure 6 demonstrates the corresponding power curves for the different series of coefficients in Figure 5. Among these, the “2D+3D+V-C” and the “2D+3D+mFP” curves show excellent agreement in power curve prediction compared with the measurements. It is also demonstrated that the power prediction produced by the “2D+3D+mFP” method for at high wind speeds is improved comparing with the “2D+3D+V-C” method. The “2D+FP” method under-predicts the power comparing to the measurements, which is due to stall-delay in real 3D flows. The “2D+V-C with gap” curve shows a big drop due to the serious “drop” in 2D wind tunnel coefficients and the V-C coefficients as discussed in Figure 5. The “2D+D-S” method has good agreements for low and moderate wind speeds. The predicted power coincides well with the measured power when the wind speed is up to 10m/s. While at higher wind speeds, the prediction is higher than the measurement. Similar results were also reported by Breton [14]. The over-predicted power at high wind speed is mainly caused by the over-corrected lift coefficients at high angles of attack. This is affected by the simplification in the execution of the D-S model. As stated in the D-S model, different radial locations and wind speeds are considered, thus the more the rotor radius locations and wind speeds are
calculated, the better prediction is to be obtained. Moreover, the drag coefficients produced by the D-S model are almost the same with those from 2D wind tunnel tests while in fact a higher drag is pronounced in stall-delay. This may also attribute to the over-prediction of the power curve.

![Figure 6. Power curve prediction with different models.](image)

5. Conclusion
The wind turbine power curve prediction was conducted based on the BEM method and the RANS CFD methods. A Matlab code was developed to implement the BEM method employing different aerodynamic models for representing the lift and drag coefficients. A 3D CFD approach was exploited for characterizing the lift and drag coefficients. A coupled model for representing the lift and drag coefficients covering the pre-stall, stall-develop, post-stall and deep-stall regions was proposed in the BEM method. The lift and drag coefficients derived from the 3D CFD simulations were coupled into the BEM method considering the 3D augmentation effects in the stall-develop stage. The results were compared with the measurements of the NREL Phase VI wind turbine. The proposed coupled model contributes to an improved power prediction especially at moderate and high wind speeds. With advanced turbulence models the results can be further improved. The approach can be applied to any wind turbines for power performance prediction, turbine operation and estimation of wind turbine power production.

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