Enhancing BEM simulations of a stalled wind turbine using a 3D correction model

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Abstract. Nowadays wind turbine rotors are usually employed with pitch control mechanisms to avoid deep stall conditions. Despite that, wind turbines often operate under pitch fault situation causing massive flow separation to occur. Pure Blade Element Momentum (BEM) approaches are not designed for this situation and inaccurate load predictions are already expected. In the present studies, BEM predictions are improved through the inclusion of a stall delay model for a wind turbine rotor operating under pitch fault situation of -2.3\textdegree towards stall. The accuracy of the stall delay model is assessed by comparing the results with available Computational Fluid Dynamics (CFD) simulations data.
1. Introduction

The increased fossil fuel depletion in past decades has led to a shortage in electricity production. It causes an increasing need in finding alternatives to fossil energy sources. Wind energy has been identified as one of the most promising sources for renewable energy industry [1, 2]. Currently, there are two categories of modern wind turbines, namely Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs), which are used mainly for electricity generation. HAWTs are more commercially dominant since they have received significant research and development works over the decades [3].

Several control mechanisms have been investigated and applied in wind turbine rotors, mainly to maintain a stable power production and to alleviate occurring unsteady aerodynamic loads on the rotor. For example, the development of an active pitch control system can reduce the tendency of massive flow separation on wind turbine blade at high wind speed cases [4]. It is agreed that blade pitch control system is critical for turbine operation, as pitching is an important action for enhancing energy capture, mitigating operational load, stalling and aerodynamic braking [5]. In pitch fault condition, a wind turbine rotor may be imposed to strong aerodynamic loads that can be dangerous to the structural stability of this rotating machine. Bangga et al. [6–9] documented that massive separation occurs in this situation and can cause three dimensional (3D) effects or rotational augmentation (RA).

Blade Element Momentum (BEM) approaches are not designed for the aforementioned conditions since the methods are based only on the 2D airfoil polar data and no three-dimensionality can be captured [10]. Even so, the methods are, ironically, widely used in the early design phase and load prediction of wind turbines because of its robustness and low computational cost. Thus, inaccurate prediction of wind rotor loads under pitch-faulted conditions is already expected. BEM often underpredicts the rotor loads in the blade root area due to the absence of RA in these simple approaches [6].

The main purpose of the present studies is to improve BEM predictions for a wind turbine rotor operating under pitch-fault condition of -2.3° towards stall. This is done through the inclusion of a stall delay model to correct the 2D airfoil polar data. The investigations are carried out on the generic MEXICO (Model Experiments in Controlled Conditions) rotor [11] studied in the MEXNEXT project. CFD simulation data obtained from Bangga et al. [8, 12] is used to verify the BEM computations. The following sections are divided into: description of BEM and the employed stall delay model in Sections 2 and 3, respectively; results of the simulations and discussion in Section 4; and all conclusions are summarized in Section 5.

2. Blade element momentum theory

BEM theory (BEMT) has its origins in momentum theory and the development from this to BEMT is well explained in many texts [13–15]. The mathematical descriptions of this approach are given in the following discussions, divided into two sections. The first one is to use momentum balance on a rotating annular stream tube passing on a turbine (momentum theory). The second is to examine the forces generated by the airfoil sections at various sections along the blade (blade element theory). These two methods then give a series of equations that can be solved iteratively (BEMT).

2.1. One dimensional momentum theory and the momentum transfer

In this section, one dimensional momentum theory as the foundation of the BEM theory is described. The approach assumes the flow to be steady, inviscid, incompressible and axisymmetric. The rotor in this case is modelled as a frictionless permeable actuator disc which is assumed to impart no rotational velocity to the flow [13]. The momentum theory basically consists of a control volume for conservation of mass, axial and angular momentum balances, and energy conservation [16]. This surrounds the actuator disc and is bounded by a
stream-tube, with two cross sections far upstream and far downstream of the disc [13]. The used general assumption is that the stream-tube has no interaction with the fluid flow outside of the boundary. The actuator disc removes energy from the stream-tube by providing a drag (axial) force that produces a pressure drop in the fluid just downstream of the disc. Both upstream and downstream surfaces of the stream-tube are assumed at ambient static pressure and so the flow speed must drop downstream to satisfy Bernoulli’s equation.

Using Equations (1) and (2), the axial force can be defined in terms of the pressure differential, upstream-and-downstream-vicinity of the actuator disc. By assuming the cross sectional areas of the stream tubes just upstream and downstream of the disc are effectively the area of the disc, $A_{\text{disc}}$, the axial force can be rewritten as in Equation (3)

$$p_{\text{amb}} + \frac{1}{2} \rho U^2 = p_{\text{ud}} + \frac{1}{2} \rho U_{\text{disc}}^2,$$

$$p_{dd} + \frac{1}{2} \rho U_{\text{disc}}^2 = p_{\text{amb}} + \frac{1}{2} \rho U_1^2,$$

$$F_A = \frac{1}{2} \rho A_{\text{disc}} (U^2 - U_1^2).$$

The axial force can also be calculated using the conservation of momentum as follows:

$$F_A = \dot{m} (U - U_1).$$

Equating Equations (3) and (4) yields

$$U_{\text{disc}} = \frac{U + U_1}{2}.$$

Introducing the axial induction or interference factor, $a$, as the fractional reduction in flow speed between free-stream and the actuator disc.

$$a = \frac{U - U_{\text{disc}}}{U}$$

Figure 1: Rotating annular stream tube at various streamwise positions.
The axial force in Equation (3) then can be rewritten as in Equation (9)

\[ F_A = 2\rho A_{disc}U^2a(1-a) \]  

Using the axial induction factor with Equation (3), one may obtain the following equation for power extraction:

\[ P = 2\rho A_{disc}U^3 a (1 - a)^2. \]  

According to one dimensional momentum theory, there is a pressure drop (energy lost) when the wind flows through the rotor. Some of the energy loss from this axial flow is converted into rotational momentum of the stream-tube, as a reaction to the rotational torque imparted to the turbine rotor thus rotating annular stream tube is then introduced.

Rotating annular stream tube is shown in Figure 1. Four stations are shown in the diagram, some way upstream of the turbine (1), just before the blades (2), just after the blades (3) and some way downstream of the blades (4). As the wind passes between stations 2 and 3, the motion of the turbine causes the wind to rotate in the wake downstream of the turbine. The blade wake rotates with an angular velocity \( \omega \) and the blades rotate with an angular velocity of \( \Omega \). Recalling the conservation of angular momentum, the torque calculation of a rotating annular element of fluid at a radius \( r \) can be written as

\[ dT = dm \left( \frac{\omega r}{2\Omega} \right) r \]

by introducing the angular (tangential) induction factor \( b = \frac{\omega}{2\Omega} \), the elemental torque can then be rewritten as

\[ dT = 4b(1-a)\rho U\Omega r^2 \pi rdr \]  

2.2. Blade element theory

As described earlier in Section 2, the blade element theory divides the blades into discrete span-wise elements (airfoils). This theory relies on two key assumptions: (1) There are no aerodynamic interactions between the 2D airfoil elements in different sections, and (2) the forces acting on the elements are solely determined by the lift and drag characteristics of the airfoils shape.

In Figure 2, the definitions of the velocity vector and the lift (\( L \)) and drag (\( D \)) acting on the blade section are illustrated. The total angle between the circumferential direction to the relative inflow (\( V \)) is denoted by \( \phi \). This angle is composed by the local angle of attack (\( \alpha \)) and the sum of the pitch and twist angle (\( \theta \)). It shall be noted that \( U_{\infty} \) defines the inflow wind speed and \( \Omega \) is the rotational speed of the turbine. The variable \( U_{\infty} \) is the same as \( U \) used in Section 2.

The axial force and torque acting on the blade element can be obtained using the relations for lift and drag, that are represented by the lift (\( C_L \)) and drag (\( C_D \)) coefficients assuming the chord length (\( c \)) of the blade element is known from the geometrical model. These are formulated as follows

\[ dF_A = N \frac{1}{2} \rho V^2 c (C_L \cos \phi + C_D \sin \phi) dr \]
Figure 2: Velocity vector and forces acting on the blade element.

\[ dT = N \frac{1}{2} \rho V^2 c r (C_L \sin \phi - C_D \cos \phi) dr. \] (14)

Furthermore, by introducing a new parameter defining the ratio between the tangential relative to the inflow velocity, \( \lambda = \frac{\Omega r}{U_\infty} \), the total flow angle can be redefined as [13]

\[ \phi = \tan^{-1} \left( \frac{U(1-a)}{r \Omega (1+b)} \right) = \tan^{-1} \left( \frac{(1-a)}{\lambda(1+b)} \right) \] (15)

3. Stall delay model

In this section, the mathematical formulation of the employed stall delay model is described. As mentioned briefly in Introduction, the BEM method is not designed to account for flow three-dimensionality as no interaction between each blade section to the neighbouring sections is assumed in the model. Thus, the approach depends strongly on the supplied aerodynamic polars. Due to this limitation, the 3D effects shall be stimulated in the given polars. In the present works, the 3D correction model based on Chaviaropoulos and Hansen [17] is used.

The model was developed by adopting the idea from Snel [18] to express the 3-D correction of the lift coefficient \((C_L)\) as a fraction of the difference \((\Delta C_L)\) between the inviscid \((C_{L,INV})\) and the corresponding 2-D value \((C_{L,2D})\). In this model, the influence of twist angle is introduced in the \(\Delta C_L\) multiplier. The model can be formulated as follows

\[ C_{L,3D} = C_{L,2D} + a(c/r)^h \cos^n (\text{twist})(C_{L,INV} - C_{L,2D}) \] (16)

where \(a = 2.2\), \(h = 1.3\) and \(n = 4\). Chaviaropoulos and Hansen [17] also introduced a correction for drag coefficient \((C_D)\) increase. However, Bangga et al. [7] pointed out that the 3D behaviour for drag is not general, and even decreases for the AVATAR rotor. The drag reduction was also observed for the MEXICO rotor in [8]. Thus, no drag correction is applied in the present studies. The same correction model has been applied in [19].

4. Results and discussion

The present section describes the results of the BEM simulation with and without the inclusion of the stall delay model. The computations were carried out using the QBlade code [20] which has been developed at the Technical University of Berlin.

4.1. Polar correction

Figure 3 presents the lift coefficient polar after being corrected by the stall delay model described in Section 3 compared to the corresponding 2D inviscid and 2D viscous lift coefficient values.
Four different blade sections are presented, namely $0.2R$, $0.3R$, $0.4R$ and $0.6R$. It shall be noted that the value of the chord to radius ratio ($c/r$) decreases as the radial distance from the center of rotation increases.

It can be clearly seen that the 3D effects the lift coefficient magnitude in the blade inboard area compared to the 2D viscous $C_L$. The corrected 3D lift coefficient is even close to the corresponding 2D inviscid polar at $0.2R$ in Figure 3a. This is reasonable since a strong radial flow occurs within the blade area where separation occurs. Despite that, the lift augmentation is mainly observed only in the inboard blade area where $c/r$ is large. This becomes evident from Figure 3 as the lift augmentation becomes weaker at larger radial distances. According to Bangga et al [7], the augmentation becomes less pronounced at $c/r < 0.1$, and this corresponds to $r/R > 0.6$ for the MEXICO rotor. This behaviour is clearly observed in the Polar plots in Figure 3. A similar characteristic was also observed in the CFD studies in [8].

![Figure 3a](image1.png)
![Figure 3b](image2.png)
![Figure 3c](image3.png)
![Figure 3d](image4.png)

Figure 3: 3D corrected polar in comparison to the 2D inviscid and viscous polars.
4.2. Sectional blade forces

In this section, the results of the BEM simulation in terms of sectional loads are presented. The sectional lift and drag coefficients along the blade span are given in Figures 4a and 4b, respectively. The effects for lift is clear as demonstrated in Section 4.1. The lift coefficient increases in the inboard area compared to the 2D situation. Thus, the 3D CFD results from Ref. [8] are substantially higher than the pure BEM simulation without any 3D correction model. By the inclusion of the 3D model from haviaropoulos and Hansen [17], the BEM prediction is improved, becoming closer to the CFD data. It shall be noted, however, that there might be uncertainty provided by the angle of attack estimation, where the azimuthal averaging technique [21] was employed for the CFD results.

Figure 4: Lift and drag coefficients along the blade span.

Figure 5: Sectional loads acting on the blade.
In Figure 4b, the drag coefficient distribution along the blade span is presented. The drag predicted by BEM with and without the stall delay model agrees reasonably well with the CFD data even though an overestimation is observed within $0.2 < r/R < 0.4$. Two reasons may cause this phenomenon: (1) the uncertainty in the angle of attack estimation and/or (2) the local downwash or upwash effect may alleviate the drag force as explained in [7]. It is worth mentioning that no drag correction was applied in the BEM simulation but the prediction for drag is different. This is mainly caused by the deviation in the prediction of the local induction factor of the blade section which affects the local angle of attack. As a result, drag is influenced since the direction of the vector is different.

Figure 5 presents the sectional blade loads in terms of the axial force (Fig. 5a) and tangential force (Fig. 5b) relative to the rotor plane. It is observed that the BEM simulation employing the stall delay model is able to mimic the CFD results fairly well for both forces. On the other hand, the pure BEM computation fails to predict the aerodynamic loads not only on the magnitude, but also on the trends and slope as well especially for the tangential force. This indicates that the power prediction using pure BEM simulation is inaccurate as the rotor driving moment is represented by the tangential force.

5. Conclusion and outlook
Numerical studies employing the Blade Element Momentum (BEM) approach have been performed and the results were compared to available CFD data from the literature. It was shown that the employed stall delay model augments the 3D lift coefficient polars at the inboard blade sections. The observed 3D effects becomes weaker as the ratio of the chord to radius ($c/r$) reduces. The observation confirmed that the limit of observable lift augmentation is for $c/r > 0.1$. The inclusion of this stall delay model is able to improve the prediction of the aerodynamic loads acting on the blade. The lift and drag distributions from the CFD data were reasonably mimicked by the BEM approach employing the stall delay model. In terms of the tangential load, a strong deviation was shown between the pure BEM computation compared to the CFD data, not only on the magnitude but also on the trends and slope. In contrast, the BEM simulation employing the stall delay model was able to mimic the behaviour of the tangential load accurately in comparison to the CFD data. This indicates that the inclusion of a 3D correction model is important for accurate load prediction using BEM. For future works, a new correction model will be developed and studied further.

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