

Article

Development of Stall Delay Built-In Actuator Line Model (SD-ALM) for Wind Turbine Rotor CFD

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Abstract

In the analysis and design of wind turbines, aeroelastic analysis is required that considers elastic structure and control in addition to aerodynamic characteristics. In recent years, with the increase in size and reduction in the cost of wind turbines, problems have emerged that cannot be addressed with the standard analysis methods. The accuracy of the Blade Element and Momentum (BEM) theory, which is the most common aerodynamic analysis and design theory, is reduced in conditions where three-dimensional effects such as radial flow are not negligible. Furthermore, full-model Computational Fluid Dynamics (CFD), which is commonly used for complex aerodynamic problems, is not applicable for the design calculation of wind turbines considering its computational demands. To address these challenges, the Actuator Line Model (ALM) can be utilized as practical load analysis methods that account for structural elasticity, control, and fluctuating winds—offering a level of fidelity between both approaches. However, the conventional ALM does not account for the stall delay (SD) observed in the inboard section of rotor. In this study, an ALM based on CFD is developed by incorporating Snel's stall delay model, which was developed for BEM. Additionally, the use of the NREL 5 MW reference wind turbine rotor results in the load distribution of the inboard section of this developed model to be comparable to that of the full-model CFD; however, a similar observation is not made for the conventional BEM.

Keywords: CFD; actuator line model; rotor; blade; stall delay



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1. Introduction

Wind turbines are generally designed according to international design standards and guidelines such as references [1,2]. The design loads are calculated through time domain response analyses, considering the aerodynamic, structural, and control characteristics of the wind turbine, as well as fluctuating wind conditions, based on various environmental and operational conditions. This process requires an extensive amount of analysis. For the aerodynamic analysis, the Blade Element and Momentum (BEM) theory has been commonly used. Originally, the BEM is a two-dimensional theory based on the assumption that load acts on a rotor in uniform steady flow parallel to the axis within the same plane. However,

to apply it to the analysis and design of actual wind turbines, various improvements have been developed and incorporated into turbine design [3].

Despite these advancements, recent technological developments have revealed that conventional BEM cannot achieve sufficient accuracy for some advanced technologies. The detailed characteristics of the wake, which are necessary for the wind farm design and operation, are not calculated using it. Additionally, since the conventional BEM assumes that the load (momentum change) occurs within the same plane, its accuracy diminishes when the load is generated outside this plane. Winglet is not modeled in the BEM as the large out-of-plane blade deformation. And in large yaw misalignment such case in yaw steering [4], a technology aimed at mitigating the impact on wind turbines downstream of wind farms by operating turbines with significant yaw misalignments to deflect wake flow, the accuracy of BEM decreases. Furthermore, when floating offshore wind turbines yaw or tilt, BEM accuracy decreases because the load no longer acts within the plane. Aerodynamic interference is another phenomenon that BEM struggles to accurately model.

Full-model CFD is a commonly used method for addressing complex problems where the accuracy of conventional BEM is insufficient. It allows for the analysis of all aerodynamic phenomena relevant to wind turbines. Halawa et al. [5] report FSI results in steady-state and uniform winds, while Guma et al. [6] report FSI results in turbulent flows. However, full-model CFD requires an extremely fine computational grid. Additionally, incorporating elastic deformation, control systems, and fluctuating winds—factors essential for wind turbine design—demands enormous time and an extensive number of simulations. Consequently, using FSI for wind turbine design calculations is not considered a practical option.

The Actuator Line Model (ALM) [7] is an intermediate-fidelity analysis method positioned between BEM and CFD. It calculates lift and drag forces at discrete nodes arranged along a line at 25% of the chord length of the wing cross-section, based on blade element theory within a CFD framework (Section 2.2). Compared to full-model CFD, ALM significantly reduces the time required for computational grid generation and analysis, thus potentially addressing a large number of challenges associated with Fluid–Structure Interaction (FSI) and BEM-based aeroelastic analysis methods. ALM has primarily been developed for wake analysis [8]. However, its application to wind turbine analysis remains limited, as seen in studies like Elfarra et al. [9], which used ALM to analyze winglets. Although ALM, like BEM, is grounded in blade element theory, it can directly analyze certain three-dimensional properties of BEM, such as tip and root losses, as well as dynamic effects like dynamic inflow. The effects of the dynamic stall have also been studied, as reported by Mendoza et al. [10]. In addition to these studies, in recent years, sampling methods have been improved [11] and applied to floating offshore wind power generation [12]. Furthermore, integration with machine learning has also been attempted to achieve even higher fidelity [13]. Attempts have also been made to combine ALM with other methods, including the use of the Immersed Boundary Method [14].

It is well known that in the inboard section of wind turbine blades, a phenomenon called “stall delay (SD)” occurs, where the lift force under near-stall conditions during rotation is significantly higher than that of a two-dimensional blade. Within the boundary layer on the blade surface, there exists a region where flow velocity decreases near the base of the layer. In this region, the influence of centrifugal force on the inertial force of the fluid increases, and the Coriolis force pushes the fluid downstream in the external flow, thereby delaying the stall. Ronsten [15] reported that the maximum lift coefficient of the blade cross-section at 30% of the radius of a rotor with a diameter of 2.375 m is approximately 1.0 in non-rotational mode but increases to around 2.0 during rotation. Given these circumstances, ALM is considered promising for solving aeroelastic problems

that cannot be addressed by BEM. However, conventional ALM does not account for the stall delay. Ignoring this effect during the analysis and design of wind turbines may result in unfeasible two-dimensional blades and an underestimation of load and performance. In conventional BEM, the stall delay is either ignored or accounted for through the use of aerodynamic data that has been pre-adjusted to incorporate the effect. Among the methods for analyzing stall delay in two-dimensional airfoil characteristics, Snel's model [16] is well recognized and widely used.

To validate such models, the NREL 5 MW reference wind turbine [17] is an ideal choice, as numbers of previous studies are available. Dose et al. performed aeroelastic analysis of the 5 MW wind turbine using in-house software [18]. Zhang and Wang numerically investigated the aerodynamic performance of the 5 MW wind turbine using the RANS Realizable $k - \varepsilon$ model. After discussing the pressure distribution and wake, they compared the aerodynamic performance with the NREL documents [17,19]. Lin et al. [20] also performed a similar analysis. Yu et al. [21] analyzed the 5 MW wind turbine using ALM. In these studies, Raynolds-Averaged Navier–Stokes (RANS) or Unsteady RANS (URANS) were used, and in [21] the tip loss correction was reproduced by applying the Prandtl model. In this study, LES (Large Eddy Simulation) was used for the analysis, and the aerodynamic force reduction at the blade tips was reproduced without applying the Prandtl model.

In this study, the Stall Delay Built-in Actuator Line Model (SD-ALM) was developed by integrating Snel's stall delay model into ALM, aiming to reproduce the characteristics of the full-model CFD with a smaller computational load. Its effectiveness and validity were verified using the 5 MW reference wind turbine rotor. Section 2 provides an overview of the analysis method, Section 3 details the analysis conditions, Sections 4 and 5 present the verification results and discussion, and Section 6 concludes this study.

2. Outline of the Method

The outline of each analysis method developed in this study is shown here. These are implemented as User-Defined Function (UDF) in Ansys Fluent 2023R1.

2.1. BEM

The analysis using BEM is performed for the purpose of comparison with the SD-ALM developed in this study. Aerodyn [22] was used for the analysis. The outline of BEM is detailed in the literature [3]. Since ALM, like BEM, is based on blade element theory, we will focus on BEM formulation that is relevant to the subsequent ALM formulation.

Within the BEM framework, a blade element is modeled as shown in Figure 1, where the lift and drag forces per unit span are defined by Equations (1) and (2). Here, ρ , W , ϕ and α represent the air density, relative inflow velocity, inflow angle, and angle of attack, respectively. The terms C_l and C_d denote the two-dimensional static lift and drag coefficients, which—for incompressible flows—are functions of α and the Reynolds number. The inflow parameters W and ϕ are determined by Equations (3) and (4) in terms of the axial (a) and tangential (a') induction factors. In these expressions, U_∞ is the free-stream velocity, μ is the non-dimensional radial position, λ is the tip-speed ratio, and f is the tip/root loss factor. The angle of attack α is derived from Equation (5) using the twist angle β and blade pitch θ . Finally, the axial and tangential forces are calculated as follows, with σ_r representing the local solidity at radius r . The set of aerodynamic parameters is determined such that Equations (1)–(7) are simultaneously satisfied.

$$\frac{dL}{dr} = \frac{1}{2} \rho W^2 c C_l \quad (1)$$

$$\frac{dD}{dr} = \frac{1}{2} \rho W^2 c C_d \quad (2)$$

$$W = U_{\infty} \sqrt{\left(1 - \frac{a}{f}\right)^2 + \left[\lambda \mu \left(1 + \frac{a'}{f}\right)\right]^2} \quad (3)$$

$$\phi = \tan^{-1} \left[\frac{1 - \frac{a}{f}}{\left(1 + \frac{a'}{f}\right) \lambda \mu} \right] \quad (4)$$

$$\alpha = \phi - \beta - \theta \quad (5)$$

$$\frac{W^2}{U_{\infty}^2} \sigma_r (C_l \cos \phi + C_d \sin \phi) = 4a(1-a) \quad (6)$$

$$\frac{W^2}{U_{\infty}^2} \sigma_r (C_l \sin \phi - C_d \cos \phi) = 4\lambda \mu a' (1-a) \quad (7)$$

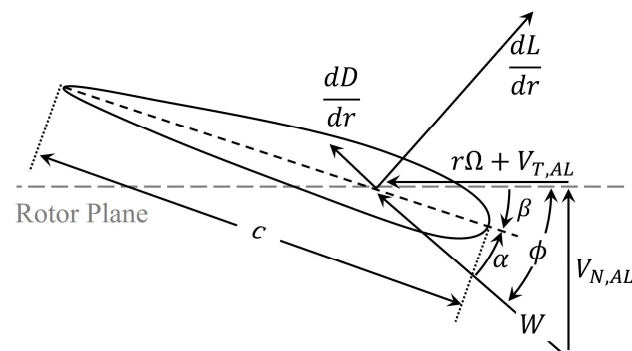


Figure 1. Intuitive depiction of aerodynamic parameters and forces on a blade element.

2.2. Actuator Line Model (ALM)

In the Actuator Line Model (ALM) framework, the lift and drag forces acting on a blade element are also calculated using Equations (1) and (2). While the BEM framework determines aerodynamic parameters using axial and tangential induction factors, the ALM derives these parameters from the local velocity distribution around the blades (actuator lines: AL).

The ALM calculates the lift and drag forces and smoothly distributes them using a Gaussian kernel η , which is formulated as Equation (8).

$$\eta = \frac{1}{\varepsilon^3 \pi^{1.5}} \exp \left[-\left(\frac{d}{\varepsilon} \right)^2 \right] \quad (8)$$

Here, d is the distance from the node of the actuator line (Figure 2) to the center of each cell, and ε is the Gaussian kernel width; a smaller value results in a sharper peak, whereas a larger value leads to a smoother profile. Integrating η over the entire domain yields 1, regardless of the value of ε .

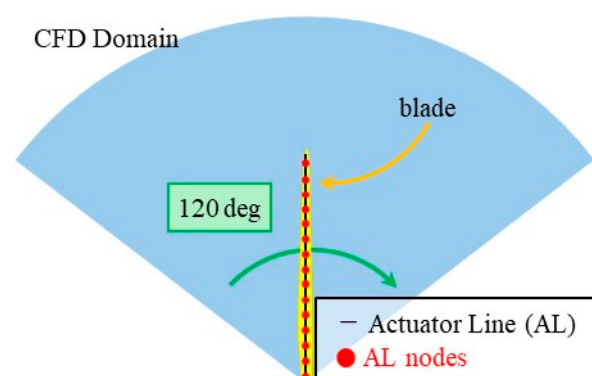


Figure 2. Nodes of ALM for a 3-bladed rotor.

Using this function, the velocity sampling is performed as expressed in Equations (9) and (10) [23]. $V_{T,AL}$ and $V_{N,AL}$ are the tangential and normal velocity components at the AL nodes, respectively. V_T and V_N represent the tangential and normal velocity components for each cell, calculated from the respective cell velocities. Together with the rotational speed of the blade Ω , the relative inflow velocity and inflow angle in the ALM are calculated as shown in Equations (11) and (12). The angle of attack α is determined by Equation (5) by substituting ϕ_{AL} into ϕ , consistent with the BEM approach. Here, ALM does not consider the radial force (centrifugal force), as well as the boundary layer that is reproduced in full-model CFD.

$$V_{T,AL} = \int V_T \eta dV \quad (9)$$

$$V_{N,AL} = \int V_N \eta dV \quad (10)$$

$$W_{AL} = \sqrt{(V_{N,AL}^2 + (r\Omega + V_{T,AL})^2)} \quad (11)$$

$$\phi_{AL} = \tan^{-1}\left(\frac{V_{N,AL}}{r\Omega + V_{T,AL}}\right) \quad (12)$$

$$\frac{dL_{AL}}{dr} = \frac{1}{2}\rho W_{AL}^2 c C_l \quad (13)$$

$$\frac{dD_{AL}}{dr} = \frac{1}{2}\rho W_{AL}^2 c C_d \quad (14)$$

2.3. Stall Delay Model

As previously described, both BEM and ALM rely on two-dimensional (2D) static lift and drag coefficients, which do not inherently account for three-dimensional (3D) effects. While several approaches utilize lift and drag coefficients modified for stall delay, there appears to be a paucity of research incorporating stall delay models specifically into the ALM framework. In this study, the authors integrate the Snel stall delay model, selected for its computational simplicity and its proven performance within BEM implementations. This model is formulated as shown in Equations (15) and (16).

$$\Delta C_l = \frac{\partial C_l}{\partial \alpha} (\alpha - \alpha_0) - C_l \quad (15)$$

Equation (15) defines ΔC_l as the discrepancy between the lift coefficient linearly extrapolated below the stall angle and the 2D static lift coefficient. Here, α and α_0 represent the angle of attack and the zero-lift angle of attack, respectively. The linear extrapolation is obtained by multiplying the lift slope by the difference $\alpha - \alpha_0$, from which the static lift coefficient is subtracted to yield ΔC_l .

$$C_L = C_l + 3\left(\frac{c}{r}\right)^2 \Delta C_l \quad (16)$$

Using this ΔC_l , the 3D lift coefficient accounting for stall delay is expressed as Equation (16) as a function of the chord length c and the radial position r . The stall-delay-corrected lift force is then calculated by replacing the 2D lift coefficient in Equation (13) with this 3D lift coefficient. In the present study, the Snel model is applied exclusively to the lift coefficient, which significantly contributes to the aerodynamic loading, while the 2D static values are retained for the drag coefficient as a preliminary study. More complex models will be studied in the next step.

3. Analysis Model and Conditions

3.1. Rotor Model

The aerodynamic characteristics were verified using the 5 MW reference wind turbine, which is documented by NREL [17]. Overview and the basic specifications of the wind turbine are shown in Figure 3 and Table 1. The distributions of chord length and maximum blade thickness ratio of the blades, as well as the twist angle, are shown in Figure 4 and Figure 5, respectively.

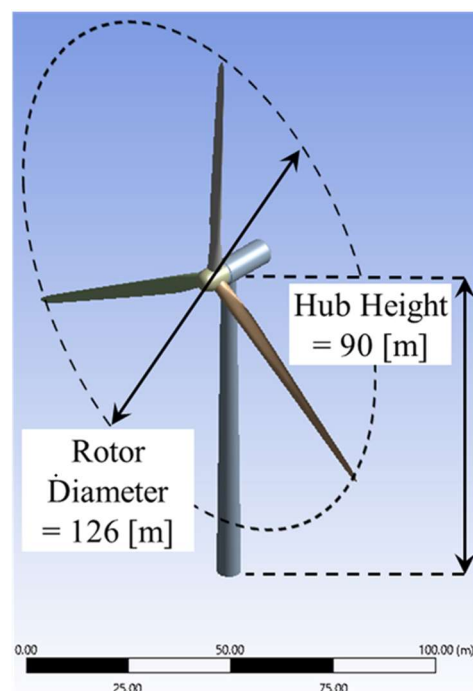


Figure 3. Overview of NREL 5 MW Reference wind turbine.

Table 1. General specifications of 5 MW wind turbine.

Rotor Diameter	126 m
Number of blades	3
Pre-coning angle	−2.5 deg
Rated power	5000 kW

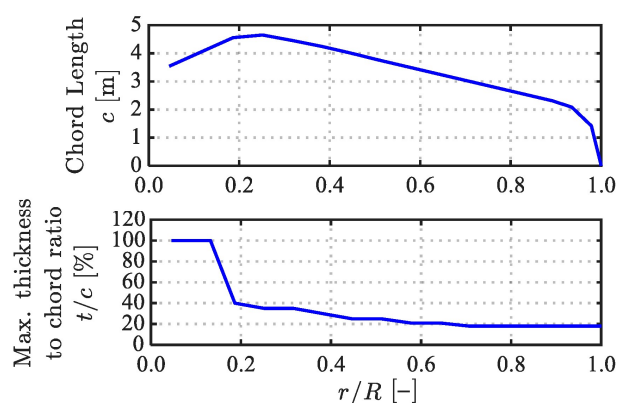


Figure 4. Blade chord length and maximum thickness-to-chord ratio [17].

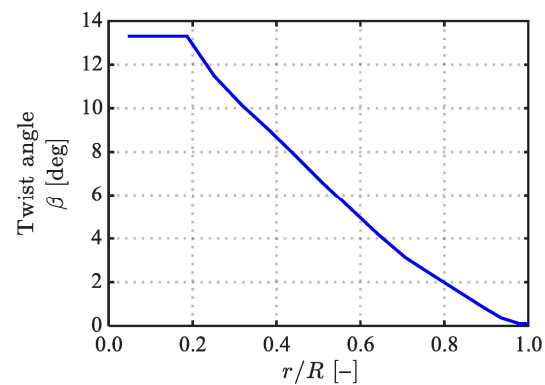


Figure 5. Blade twist angle [17].

3.2. Airfoil Data

The lift coefficient and drag coefficient for the angle of attack of representative airfoils of this blade are shown in Figures 6 and 7. The data of these airfoils were linearly interpolated according to the maximum blade thickness ratio shown in Figure 4, and the obtained values were used in the BEM and ALM.

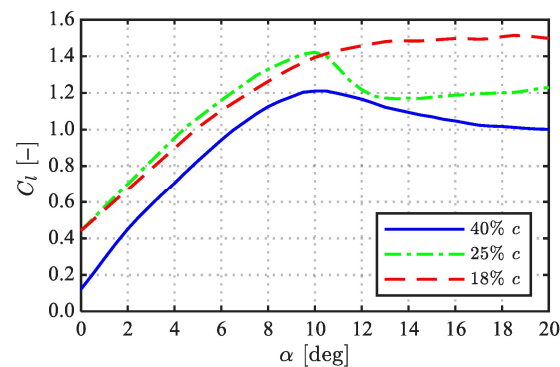


Figure 6. Lift coefficient to AOA [24].

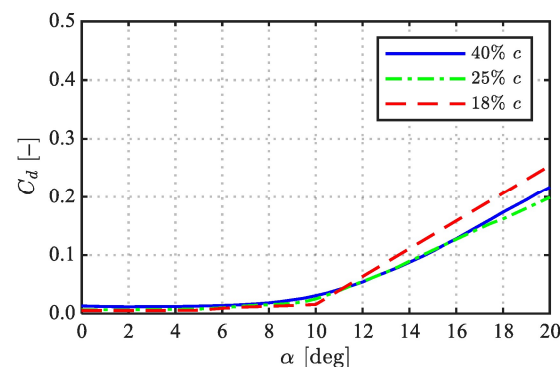


Figure 7. Drag coefficient to AOA [24].

3.3. Analysis Conditions of ALM

The aerodynamic characteristics, shown in the previous section, were implemented using a User-Defined Function (UDF) that allows for the customization of ANSYS Fluent ver. 2023R1 [25] settings. To enhance computational efficiency, the application of the UDF was restricted to a specific region, hereafter referred to as the Actuator Line Model (ALM) zone. A Multiple Reference Frame (MRF) zone was defined to encompass this ALM zone. Within the ALM zone, the actuator lines were fixed, and within both zones, the aerodynamic loads acting on the blades were calculated by virtually rotating the flow. Furthermore, a one-third cylindrical domain, designated as the external zone, was defined

to enclose these zones (Figure 8). Polyhedral cells, recognized for their superior numerical stability, were used for the mesh geometry. Compared to tetrahedral elements, polyhedral cells allow for a reduction in the total number of elements, which is expected to decrease the overall CPU time of the ALM. The element sizes for the ALM zone, MRF zone, and external zone were set to 0.25 m, 2.0 m, and 6.0 m, respectively.

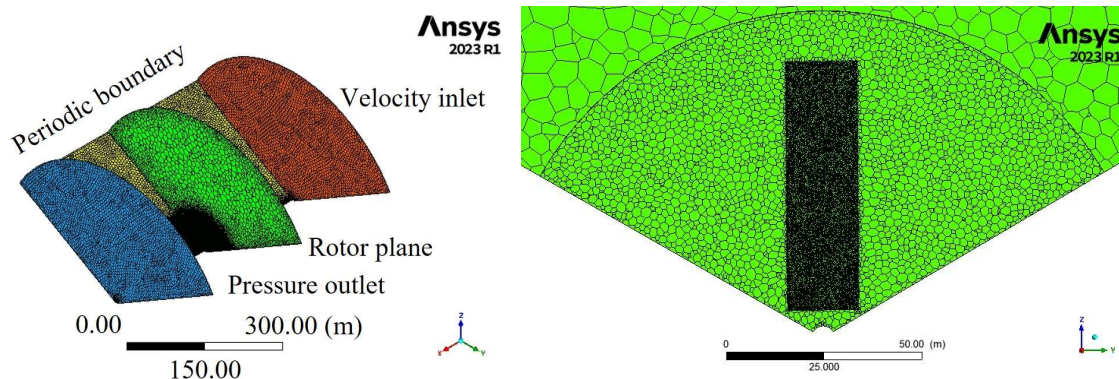


Figure 8. Domain (left) and mesh at rotor plane (right) of ALM.

The mesh sensitivity analysis was conducted. Figure 9 shows the thrust coefficient (left) and power coefficient (right) with respect to number of elements, at the rated condition. From Figure 8, it appears that both coefficients converge around 1.7 million elements. X-velocity distribution at 3.0 million elements is shown in Figure 10. It shows the mesh is too fine for the resolution of the AL nodes, as the local velocities between AL nodes are remarkably higher than other regions, which is not seen in 1.7 million elements. So, the mesh with 1.7 million elements was selected in this study.

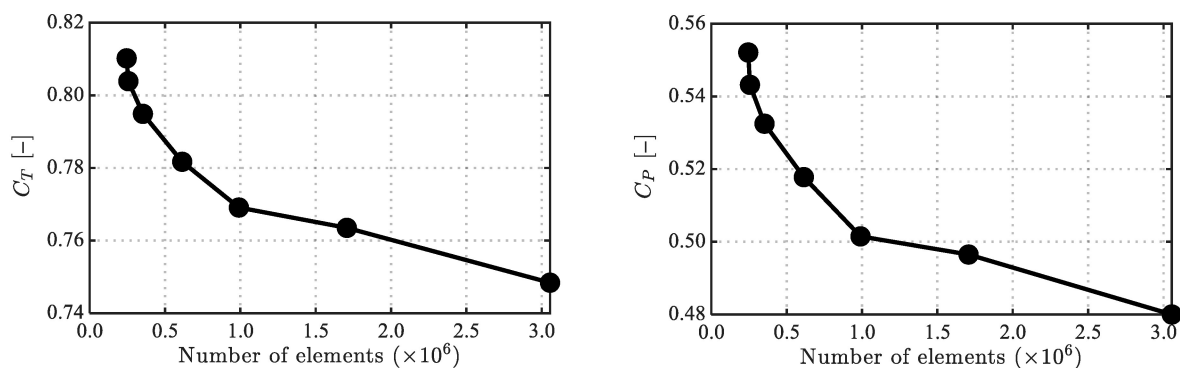


Figure 9. Mesh sensitivity survey for cell size of ALM zone. Thrust coefficient (left) and power coefficient (right).

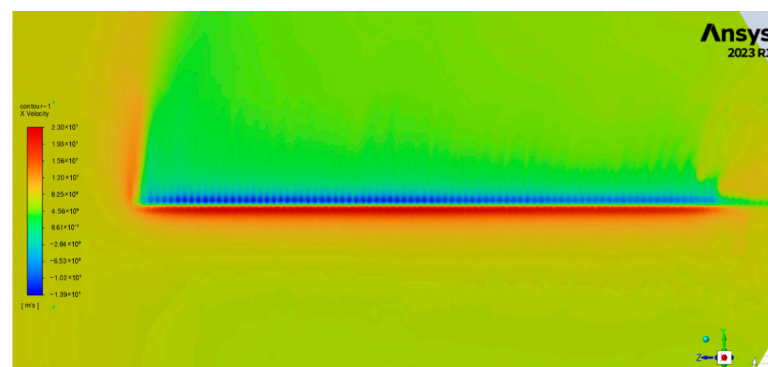


Figure 10. X-velocity distribution around the Actuator Line (cell number: 3.06 million).

Regarding the boundary conditions, the red, blue, and yellow surfaces in Figure 8 represent the velocity inlet, pressure outlet, and periodic boundary conditions, respectively. The green surface in the figure corresponds to the rotor plane.

The Large-Eddy Simulation (LES) $S-\Omega$ model was applied as the viscosity model and sub-grid scale model. This model was selected for the full-model CFD described later to appropriately capture blade separation with a relatively small number of mesh elements even with a high Reynolds number. Generally, the use of LES in conjunction with the MRF method is uncommon. It was compared with URANS, which is proven in MRF, in Figure 11. No significant differences are shown for the inflow velocity and angle of attack between the two methods.

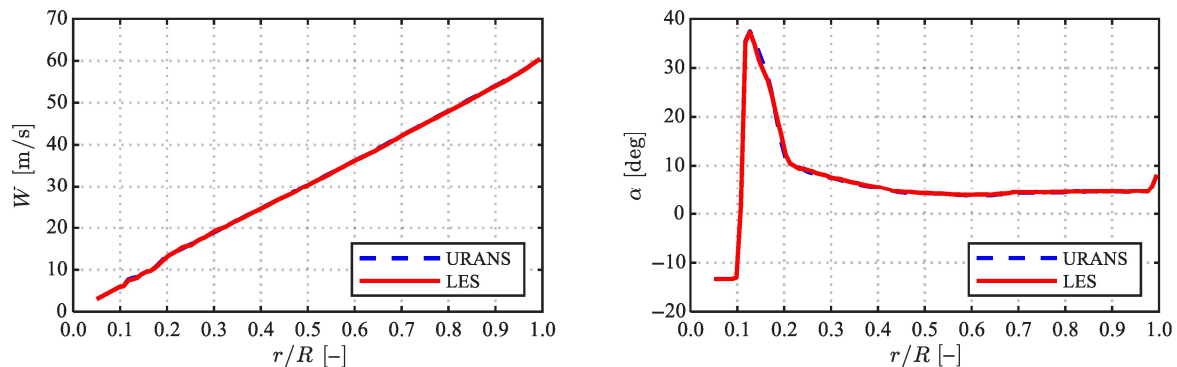


Figure 11. Comparison of URANS and LES analysis in optimal condition. Inflow velocity (left) and angle of attack (right).

The number of ALM nodes was set to 100. While previous research [26] has primarily investigated cases with up to approximately 60 nodes, it was determined that 100 nodes were necessary to capture tip losses without relying on Prandtl's tip-loss correction model.

The Gaussian regularization width for the ALM was set to 2.0 times the distance between nodes. Trolborg [27] suggested that a width of twice the node distance or element size was most accurate. We also followed this rule.

The ALM analysis was performed under these conditions. The wind speed at the velocity inlet and the rotational speed of the rotor are summarized in Table 2.

Table 2. Analysis conditions.

	Optimal Condition	Rated Condition
Density [kg/m ³]	1.225	1.225
Wind speed [m/s]	8.0	11.4
Rotor speed [rpm]	9.1	12.1
Blade pitch angle [deg]	0	0
Coning Angle [deg]	0	0
Time step [s]	0.01	0.01
Simulation Time [s]	20.0	20.0

(1) Domain conditions:

- Domain shape: 1/3-cylinder, periodic boundary condition
- Radius: 240 m (6.3 R)
- Central Angle: 120 deg
- Length of domain: 480 m (7.6 R)

(2) AL conditions:

- Number of nodes: 100
- $\varepsilon = 2.0\Delta x$

3.4. Analysis Conditions of Full-Model CFD

The computational domain for the full-model CFD was configured similarly to that of the ALM. The sole difference lies in the ALM zone, where the geometry data of a 5 MW blade was defined. To accommodate potential analyses involving blade pitch angle adjustments in the future, the mesh within this zone was designed to be rotatable.

To calculate the aerodynamic loads on the blade surface, 16 strips with a width of 0.63 m (0.1 R) were defined, consistent with the 5 MW Baseline data for OpenFAST [28]. For the subsequent aerodynamic load evaluation, the forces acting on these strips at the end of the simulation were exported and post-processed.

To accurately capture flow separation, inflation layers were applied to the mesh around the blade. Specifically, 30 layers were defined with an initial layer thickness of 1 mm and an expansion rate of 1.1. This configuration ensures that the Wall y^+ remains approximately 200 or less, providing sufficient resolution for the WMLES (Wall Modeled Large-Eddy Simulation) $S-\Omega$ model [19]. For the precise calculation of aerodynamic loads, the element size on the blade surface was set to 0.01 m. The resulting mesh around the blade, incorporating these settings, is illustrated in Figure 12.

All other computational conditions remain identical to those employed in the ALM analysis.

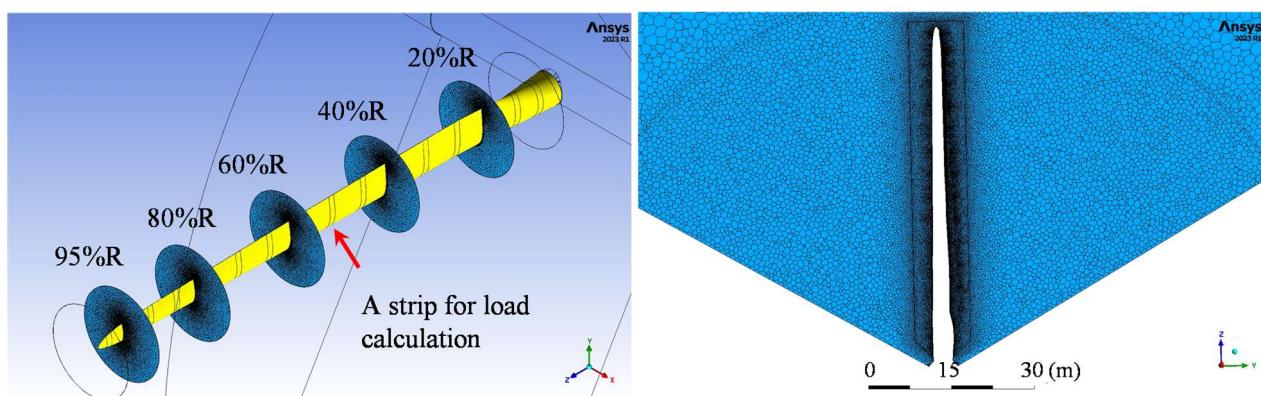


Figure 12. (Left): Geometry of 5 MW wind turbine (yellow) and mesh at cross sections (blue). (Right): close view of full model's mesh scene.

3.5. Analysis Conditions

The analysis was performed under two conditions in Table 2. 9.1 rpm is the rotor speed at the optimal point (8 m/s), and 12.1 rpm is the rotor speed at the rated wind speed (11.4 m/s).

At both rotor speeds, the blade rotates one degree in approximately 0.01 s, and the time step is based on this. The whole time was 20 s from the convergence of the results. The shape of the computational grid is polyhedral for the stability of the analysis, and an inflation grid is defined in the near the surface of the blade. WMLES is defined as the viscous model, and $S-\Omega$ is defined as the sub-grid scale model. Reynolds number of the blade is approximately 10^6 . Since even high Reynolds numbers can be analyzed with a relatively small number of computational grids [20], the viscosity model and sub-grid scale model, described above, are defined.

3.6. Computational Resources

A workstation with a 52-core/104 logical core CPU and 512 GB of RAM was used for the analysis under the above conditions. ANSYS 2023 R1 was used, with 64 logical cores, to

perform ALM analysis and full-model CFD on this machine. In terms of analysis time, the former required approximately 10 h, and the latter around 100 h. This result also supports the superiority of ALM in terms of computer resources.

4. Results

4.1. Inflow Velocity/Angle of Attack Distribution

The inflow velocity distribution of each blade element is shown on the left side of Figure 13, and the angle of attack distribution is shown on the right side of the figure. The inflow velocity distributions are in good agreement with all the results, regardless of the stall delay. On the other hand, the distributions of angle of attack are lower on the inboard region than the 30% radius when the stall delay is considered. This is because the lift coefficient increases by considering the stall delay, and as a result, the $V_{N,AL}$ in Equation (11) decrease, and the inflow angle increases.

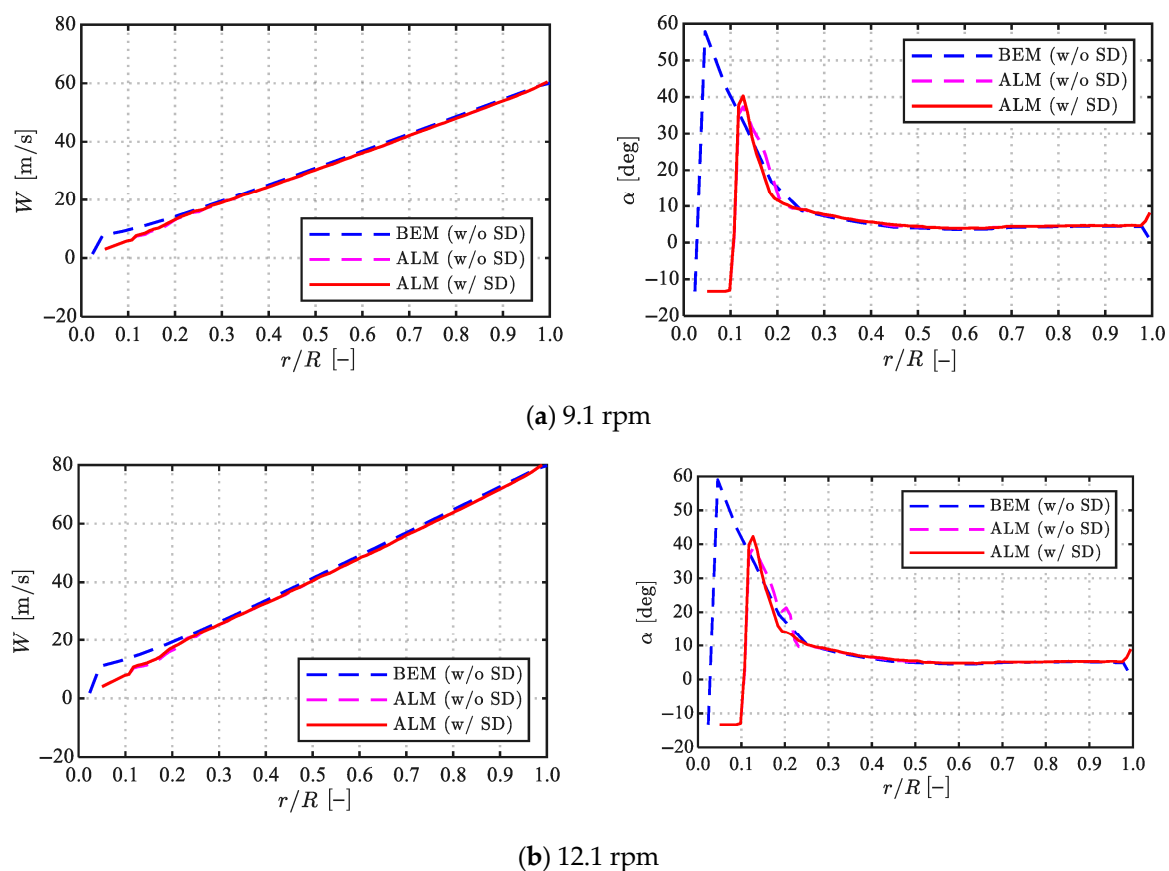


Figure 13. Inflow velocity (left) and angle of attack (right).

4.2. Lift/Drag Coefficient Distribution

The lift coefficient distribution (left side of Figure 14) is in good agreement with both methods on the outboard section. However, on the inboard section less than the 30% of radius, the lift coefficient increases when the stall delay is considered. Interestingly, the range of the stall delay varies depending on the speed of the rotor, and this range decreases as the rotor speed increases. This is consistent with different ranges of the angle of attack distribution. At the same time, the lift coefficient increases even though the angle of attack decreases under both conditions, indicating that the Snel model works, which is represented by Equations (15) and (16).

Furthermore, the drag coefficient distribution (the right side of Figure 14) is shown, but since it is not corrected by the Snel model, its influence is small.

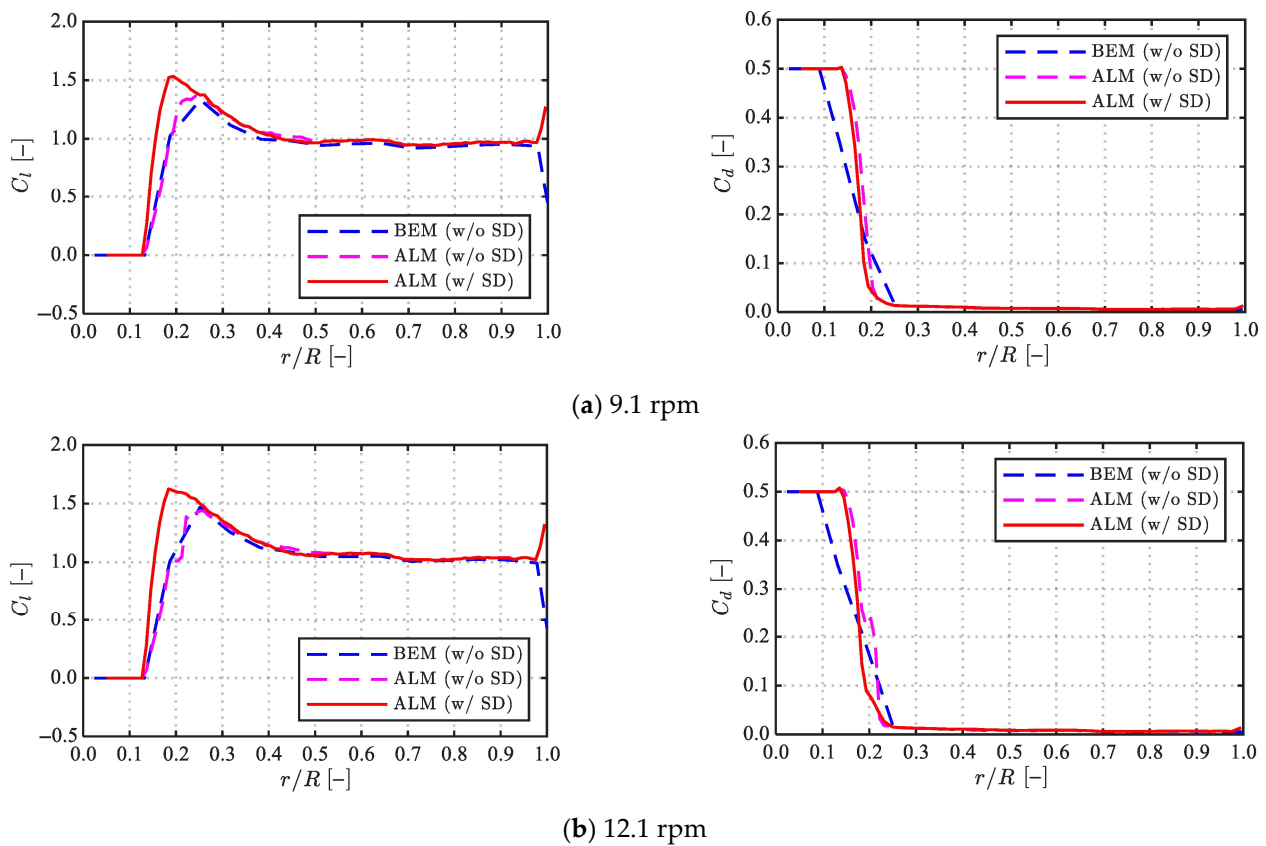


Figure 14. Comparison of lift coefficient (left) and drag coefficient (right).

4.3. Out-of-Plane/In-Plane Aerodynamic Load Distribution of Blades

The out-of-plane load distribution of the blades is shown on the left side of Figure 15. The lift force dominates the out-of-plane load near the design point, but there is a difference on the inner region from the 30% radius as well as the lift coefficient distribution. The results of the ALM and BEM which neglected stall delay were consistent, and the results of the SD-ALM and the full-model CFD were consistent, which considers the stall delay. It can be said that the SD-ALM reproduces the load on the inboard section more accurately.

The in-plane load distribution of the blade is shown on the right side of Figure 15. As with the out-of-plane loads, the results of the SD-ALM and the full-model CFD are generally consistent with the inner region of the 30% radius.

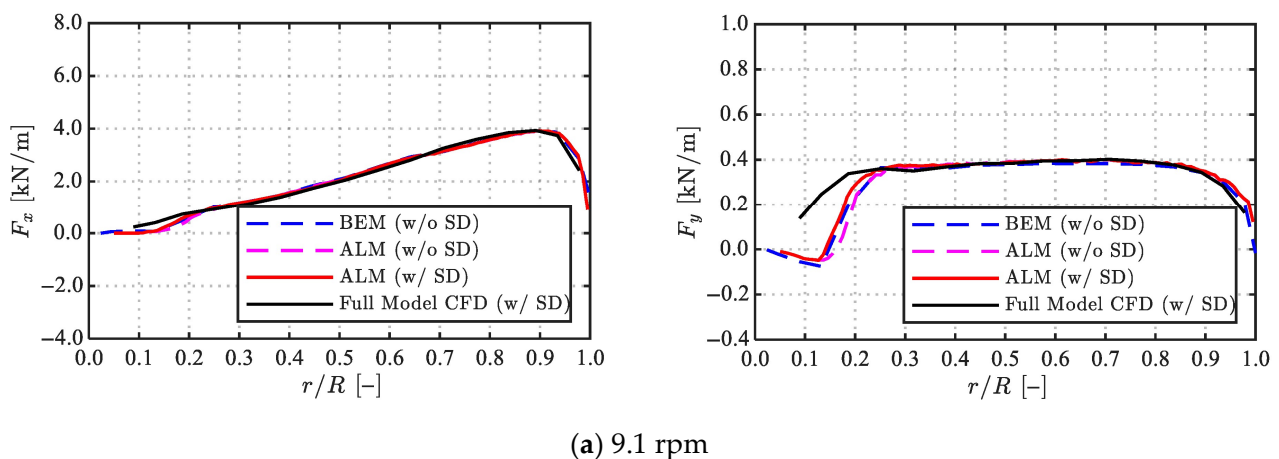
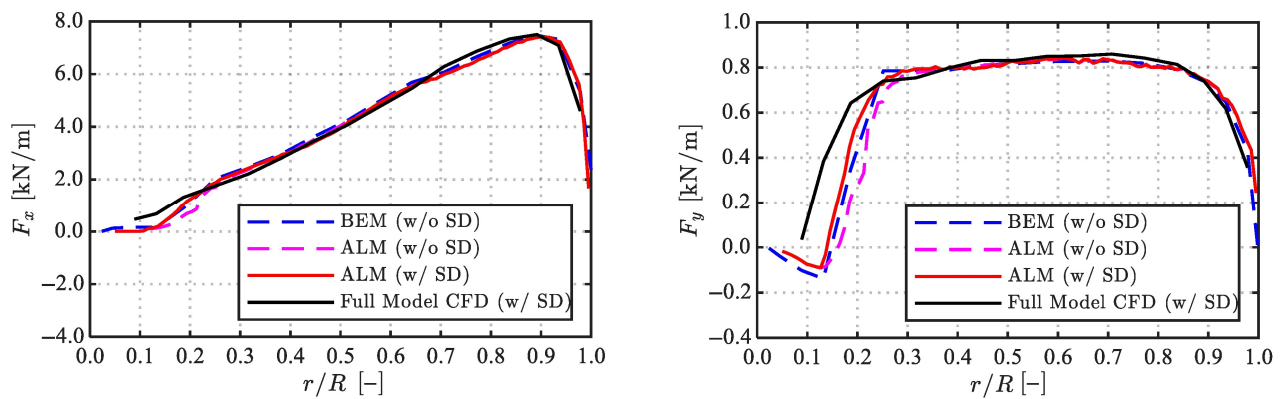


Figure 15. Cont.

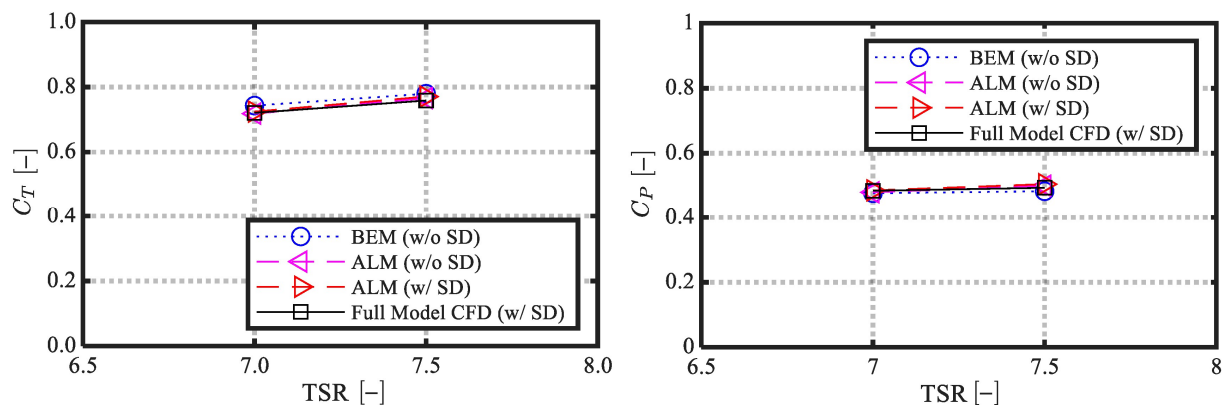


(b) 12.1 rpm

Figure 15. Comparison of out-of-plane (left) and in-plane (right) aerodynamic loads.

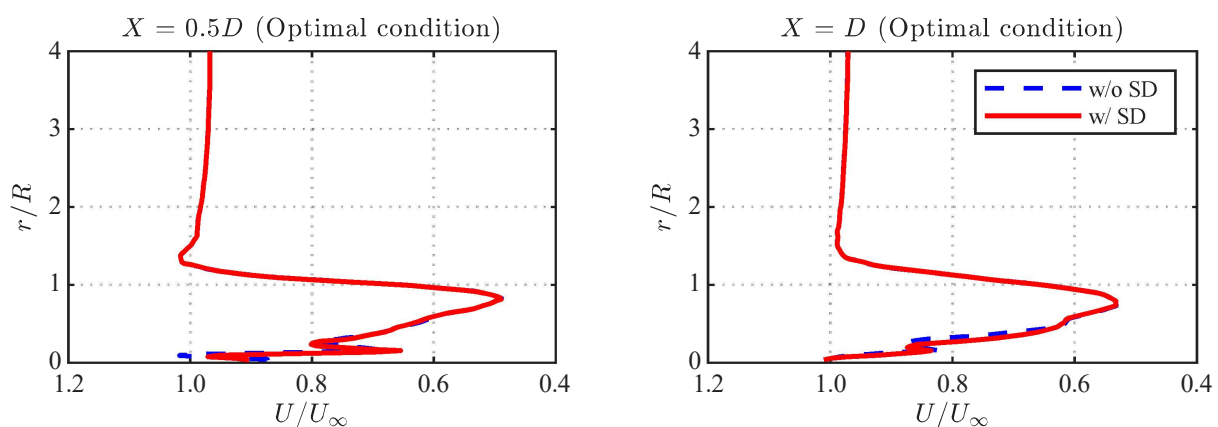
4.4. Thrust Coefficients and Power Coefficients

The thrust and power coefficients are shown in Figure 16. SD-ALM reproduces the full-model CFD better than ALM, although the differences are not so remarkable.

**Figure 16.** TSR vs. thrust coefficient (left) and TSR vs. power coefficient (right).

4.5. Wake Profile

Figure 17 shows the X-direction velocity profile of the wake. Since the thrust increases in the blade inboard section, the velocity in that area decreases. However, since the inflow velocity in the inboard section is small, even if the lift coefficient increases, the lift is small, so the difference is not so large.

**Figure 17.** Cont.

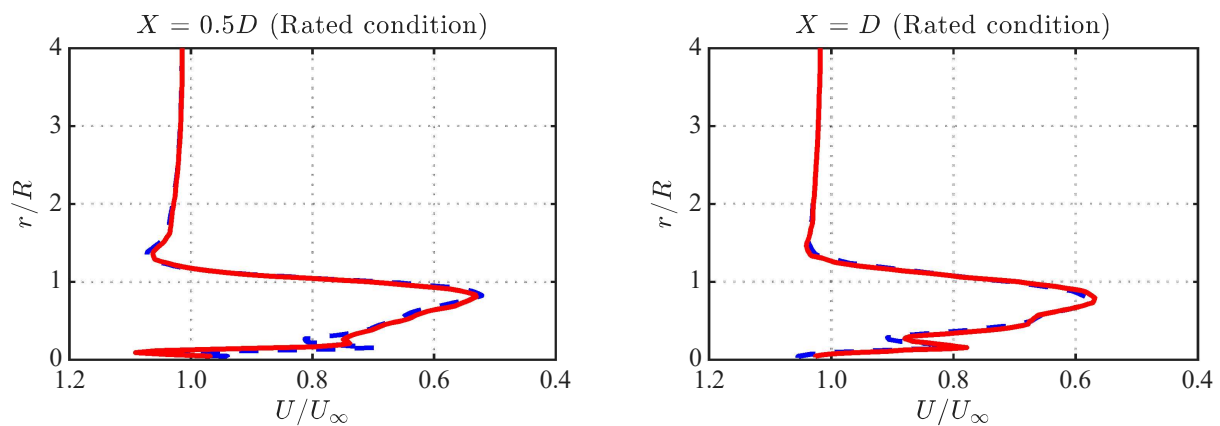


Figure 17. Wake profile (X-velocity profile) at $X = 0.5D$ and $X = 1D$.

5. Discussion

In this study, the SD-ALM method which incorporates the Snel stall delay model into ALM was developed. As shown in Figure 15, the aerodynamic load distribution is closer to the full-model CFD model than BEM or conventional ALM. We expected to reproduce the full-model CFD results more accurately, but the 5 MW reference wind turbine is cylindrical up to approximately 20% radius. This means that stall delay is only reproduced in the very narrow region from 20% radius to 30% radius.

Now, as is clear from Figure 13, the angle of attack of SD-ALM decreases inboard of 30% radius. The angles of attack for BEM and ALM are between 10° and 60° , the angle at which stall normally occurs. The Snel model increases the lift coefficient, decreasing the normal velocity V_N shown in Equation (10), which reduces the inflow angle and, furthermore, the angle of attack. This creates a state in which stalls do not occur, even though above the static stall angle of attack.

The present model can calculate the angle of attack at 25% chord for the blade inboard section, which is not calculated by the full-model CFD. It enables us to determine the lift coefficient there. While this is not particularly advantageous for ALM analyses in uniform flow, it can be a significant advantage, especially when considering aerodynamic interference with the nacelle and spinner.

6. Conclusions

Among wind turbine technologies, the Blade Element and Momentum (BEM) theory has been commonly used in wind turbine design. However, it has become clear that there are problems that cannot be solved. We implemented Snel's stall delay model, which has a proven track record in the BEM, for CFD, which is considered promising for such problems, and for the stall delay problem that has not been considered in the ALM based on blade element theory. As a result of the analysis using 5 MW reference wind turbine blades, the load is significantly underestimated compared to the full-model CFD in the BEM and ALM, which do not consider the stall delay, and is inside the 30% radius. On the other hand, it was confirmed that the Stall Delay Built-in ALM (SD-ALM) implemented in this study yielded the same results as the full-model CFD. Finally, it was found that the calculation accuracy of the aerodynamic load of the blade was improved, and that it contributed to the improvement of the calculation accuracy of the rotor thrust and power.

The stall delay of the wind turbine rotor is a complex phenomenon, which is related to the influences of rotor blockage, rotor coning, yaw misalignment, boundary layers, centrifugal force, and so on. The Snel model is known to reproduce the stall delay phenomena in BEM analysis with a simple model for the blockage effect, even though it does not

consider other factors in the phenomena. The development of the detailed model should be proceeded step by step. This study was also conducted to integrate the Snel model for the first step. For example, the 5 MW reference wind turbine which is focused on the present research has -2.5 degrees of coning angle. This angle causes the radial flow, which may change the boundary layer and affect stall delay. The present research was conducted for the symmetric flow around the 0° coning rotor, to avoid the influences of the radial flow caused by the coning or wind-rotor misalignment. So, applicability of the present SD-ALM for other conditions should be confirmed in future studies.

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Abbreviations

The following abbreviations are used in this manuscript:

Symbols

A	Axial induction factor in BEM
a'	Tangential induction factor in BEM
B	Number of blades
c	Chord length
C_d	2D drag coefficient
C_l	2D lift coefficient
C_L	3D lift coefficient
C_P	Power coefficient
C_T	Thrust coefficient
D	Rotor diameter
d	Distance between a node of actuator line and any cell
F	Tip/root loss function in BEM
R	Rotor radius
r	Blade station radius
V	Velocity
U_∞	Wind speed
W	In flow velocity
Greek	
α	Angle of attack
ΔC_l	Deviation between linear C_L and stall considered for C_L
ε	Gaussian kernel width in ALM
η	Gaussian kernel function
λ	Tip speed ratio
μ	Blade station radius normalized by the rotor radius
ξ	x position normalized by c
σ_r	Local solidity at r

Subscripts

N	Normal to the rotor plane
T	Tangential to the rotor plane
X, Y, Z	Coordinate of inertia
AL	Data on AL (Actuator Line) node

Abbreviations

AL	Actuator Line
ALM	Actuator Line Model
AOA	Angle of attack
BEM	Blade Element and Momentum (Method)
CFD	Computational Fluid Dynamics
IP	In-Plane of the rotor
LES	Large-Eddy Simulation
WMLES	Wall-Modeled Large-Eddy Simulation
MRF	Multiple Reference Frame
OP	Out-of-Plane of the rotor
RANS	Reynolds-Averaged Navier–Stokes
SST	Shear Stress Transport
TSR	Tip speed ratio
UDF	User-Defined Function (for Ansys Fluent)
URANS	Unsteady Reynolds-Averaged Navier–Stokes

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