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Effect of leading-edge erosion on the performance of offshore horizontal axis wind turbine using BEM method

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Abstract. This research focuses on the effect of leading-edge erosion on the performance of wind turbines, specifically the GE1.5XLE horizontal axis wind turbine. The blade element momentum (BEM) method is used to predict the performance of the eroded blade configurations, and the open-source code QBLADE is used for simulation. The importance of including the effects of blade erosion in the design phase is highlighted, as it can optimize turbine performance and ensure operational efficiency. The high blade tip velocity in large rotors, which can reach 90-110 m/s, makes them susceptible to sand and rain erosion, which can significantly affect the turbine's performance. The research compares the performance of clean and eroded blade configurations, with different levels of leading-edge erosion as percentages of the chord (0.5%, 1.0%, 1.5%, and 2.0%). The results show that the worst-case scenario of 2.0% leading-edge erosion reduced the lift-to-drag ratio of an airfoil by 65% and reduced the power output by 20%. The low-fidelity analysis methodology presented in this research is fast and can be easily implemented in the early design phase of wind turbines to predict the effect of leading-edge blade erosion. This allows for cost-effective and efficient design solutions that take into account the effects of erosion on wind turbine performance. The research provides valuable insights for the wind energy industry to improve the reliability and performance of wind turbines.

1. Introduction

Wind turbines that operate at the lower levels of the atmospheric boundary layer are vulnerable to harsh environmental conditions, such as rain, hail, and sandstorms. These conditions cause significant structural degradation, one of which is a severe erosion of the turbine blades. Modern wind turbines are getting larger to extract the most energy out of the wind [1, 2, 3]. However, increased rotational tip speeds intensify blade leading-edge erosion, resulting in detrimental aerodynamic effects that reduce lift-to-drag ratios and power output. Most wind turbines are exposed to various inclement and tribological effects due to their challenging operating environments [4]. The combination of these effects and advanced designs increases engineering challenges, especially for blades with high rotational speeds that result in significant leading-edge erosion. Dalili *et al.*[5] conducted a study on the impact of icing on wind turbine blade performance. They found that surface contamination, caused by insects or icing, affects the blade surface, leading to increased drag and a reduction in power output by almost 50%. Corten *et al.*[6] carried out flow visualization experiments to demonstrate that the surface roughness of a turbine blade increases with insect contamination, resulting in a power loss of over 25%. They further observed that contamination rates are high during low wind conditions. They anticipated that severe erosion and surface delamination would further increase power loss. Janiszewska *et al.*[7] experimentally tested the S814 airfoil model in a subsonic wind tunnel to investigate the performance loss caused by surface roughness. They measured a 25% decrease in the lift coefficient and a 60% increase in drag due to roughness. Sareen *et al.*[8] examined the erosion effect on DU 96-W-180 wind turbine airfoils by varying erosion levels. They found that the maximum lift of an eroded airfoil was reduced by 17% and drag increased by 6∼50% depending on erosion levels. Using experimentally measured aerodynamic polar curves, they employed the BEM theory to conclude that increased erosion results in almost 25% loss in annual energy production. However, their assumption of the same level of erosion across the blade span is not valid for real turbines. To increase the power output of wind turbines, Fernandez-Gamiz *et al.*[9] utilized micro tabs as add-ons and demonstrated that the wind turbine power can be increased. They evaluated the airfoil's polar curves using CFD simulations and incorporated this data into the BEM to estimate the power output. Corsini *et al.*[10] numerically simulated the effect of rain erosion on a 6MW wind turbine by optimizing the wind turbine blade aerodynamically and comparing the optimized design with a baseline configuration. They used a steady-state Euler-Lagrangian method to simulate rain erosion but did not report any reduction in the power output. Although wind turbine airfoils such as S809 are designed to be resistant to roughness [11], this assertion may not hold true for unstable conditions or adverse environmental effects. Ramsay *et al.*[12] applied leading-edge grit roughness to investigate contamination effects. Sheng *et al.*[13] used sand strips pasted on the upper and lower surface of the blade to estimate the roughness of the S809 airfoil. Gharali *et al.* [14] numerically studied the leading-edge erosion for the S809 airfoil, considering three models for the predefined leading-edge erosion and specifying the shape by varying the length and thickness of the pits. They concluded that the reduction in the lift coefficient depends on the erosion thickness rather than the length and that erosion changes the aerodynamic behavior of the airfoil and affects stall prediction. They conducted 2D CFD simulations and estimated a 34% decrease in the lift coefficient, which escalated to 76% for the maximum eroded case. However, they did not calculate the impact of erosion on the wind turbine's power output.

The present study focuses on the impact of predefined leading-edge erosion on the General Electric GE1.5XLE [15, 16] wind turbine. The turbine data is obtained from a publicly accessible report [17] and is used for the verification and validation study. Various levels of leading-edge erosion are considered in this study, and the aerodynamic polar curves for each level are generated using the XFOIL code [18]. These polar curves are then extrapolated to cover a complete 360^o angle of attack range using the Montgomery extrapolation method [19]. The resulting 360^o polar curves are incorporated into the BEM method to estimate wind turbine performance. The article is structured to provide an overview of the BEM method and its implementation in QBLADE [20] first, followed by a validation case. After describing the geometry and modeling of the wind turbine blade, the results of the clean blade are compared with the available measured data to validate the turbine model. Finally, different erosion levels are modeled and simulated to evaluate the impact of blade erosion on wind turbine performance.

2. Background and theory

2.1. Blade Element Momentum model

Although CFD methods provide more accurate predictions of aerodynamics, recently low-fidelity variants of CFD in the form of reduced order models (ROM) have been used in numerous studies, as referenced in [21, 22, 23, 24]. However, these methods are computationally expensive and time-consuming, as reported in [25, 26]. Vortex methods are another alternative to CFD computations, but they have limitations in modeling viscous behavior. Because of these constraints, BEM models are mainly used to predict the performance of horizontal axis wind turbines (HAWT) in early design iterations. The main benefit of using BEM over CFD is that this method is computationally fast. Although it underestimates the turbine's performance and overestimates peak power, as mentioned in [27], it is still widely utilized in the wind turbine industry as it simplifies the design procedure. BEM enables different rotor designs to be developed and tested in the preliminary stage, which can be later refined by high-fidelity CFD simulations. The validation and verification of the BEM method with wind tunnel and actual measurements further justify its use, as reported in [28]. Its robustness and low computational expense compensate for its inaccuracy and deficiencies.

The BEM method combines blade element theory and momentum theory to obtain the turbine's performance based on the blade's geometry and parameters, such as free stream velocity, rotational speed, pitch angle, etc. The first algorithm outlining the BEM method was given by Glauert [29], which described rotor performance in a steady uniform flow. The blade is discretized into a finite number of elements, and each blade section is defined by its radial position, airfoil section, chord length, and twist angle. Momentum theory is used to compute the relative speed for each section, which permits the calculation of the angle of attack and derivation of lift and drag coefficients. By using the area of the element and aerodynamic coefficients, the normal and tangential forces are evaluated, enabling the computation of thrust and torque. The total thrust and rotor torque are obtained by summing up each element. Branlard [30] provided a detailed mathematical derivation and explanation of BEM. The axial and radial factors are the iterative variables of the BEM method, as shown in Figure 1.

$$a = \left(\frac{4sin^2\phi}{\sigma C_n} + 1 \right)^{-1} \tag{1}$$

$$a^* = \left(\frac{4sin\phi cos\phi}{\sigma C_t} - 1 \right)^{-1} \tag{2}$$

Where ϕ represents the inflow angle, C_t and C_n represent the tangential and normal force coefficients respectively, and σ is the rotor solidity, which is defined by equation (3).

$$\sigma = \frac{cB}{2\pi r} \tag{3}$$

The angle $\theta = \theta_p + \beta$ is used to combine the pitch and twist angles. The lift and drag coefficients are then calculated, resulting in new induction factors. This iterative process continues until a convergence criterion is reached. Once that happens, the next element is computed, and the process continues for each element of the blade.

2.2. Modeling tool - QBLADE

All of the simulations in this study were conducted using the BEM-based tool, QBLADE [20], which employs functions and modules from other established open-source codes, such as XFOIL [18] and FAST [31]. The code structure of QBLADE is depicted in Figure 2. The BEM method is used to compute the turbine's performance, which requires aerodynamic data, such as lift and drag coefficients, for various angles of attack. Experimentation and CFD analysis can be time-consuming for obtaining aerodynamic data for a wide range of angles of attack and Reynolds number [32, 33, 34], and this needs to be repeated for each airfoil section. Therefore, XFOIL is used to quickly and efficiently perform this task. This code has been previously validated and verified [35] and is considered a standard low-fidelity airfoil analyzer. The graphical user interface

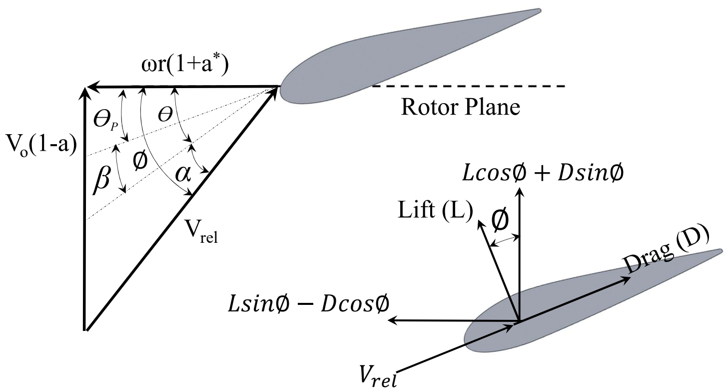


Figure 1. Velocity triangle and the resulting aerodynamic forces applied to an airfoil section of a wind turbine blade. ϕ is the inflow angle, β is the twist angle and θ is the combined blade pitch θ_p and twist angle.

(GUI) is a post-processor that conducts rotor simulations and provides in-depth insights into all relevant results.

The XFOIL code uses the potential flow theory, which restricts its ability to calculate lift and drag coefficients beyond the stall angle of attack. While this may not be an issue in aircraft design, wind turbines often require blade angles of attack beyond this limit. To overcome this limitation, the airfoil polar curves generated by XFOIL are extrapolated to cover the entire 360^o angle of attack range (-180^o to +180^o). This is typically achieved through curve fitting techniques, under the assumption that the airfoil behaves like a thin flat plate at high angles of attack. In this work, the Montgomery extrapolation method [19] was used to obtain the complete 360^o curve, as shown in Figure 3.

After obtaining the extrapolated curve, the turbine blade geometry is defined by the chord length, twist angle, azimuth angle, and profile at various intermediate sections. Other input data, such as rotational speed, cut-in and cut-out velocities, pitch, and loss factor, must be specified after the geometric specifications. Once all of the features have been defined, the simulation can be performed for a range of rotational speeds, blade pitches, and oncoming wind speeds. This provides a comprehensive operational envelope and enables the assessment of the wind turbine's performance.

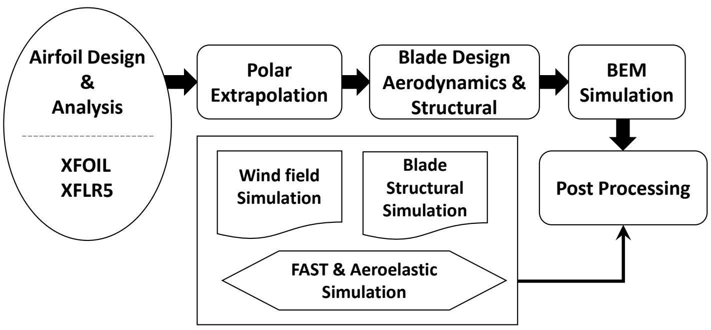


Figure 2. The code structure of QBLADE is presented and shows the data objects and their flow. The airfoil section details and geometric blade details are specified in separate modules. Additionally, a graphical user interface (GUI) is utilized as a post-processor, providing a detailed insight into all relevant information [20].

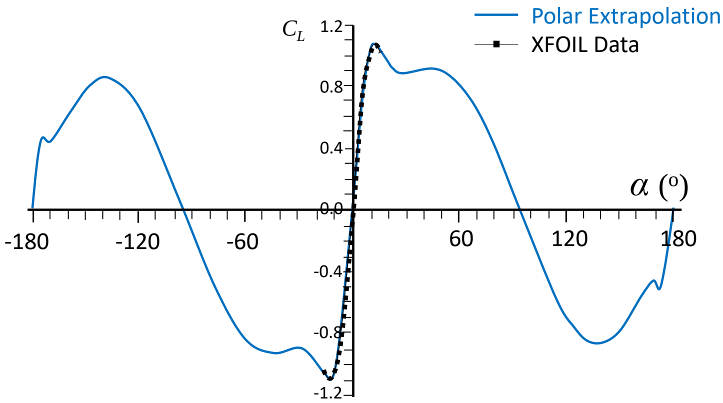


Figure 3. Extrapolated polar using Montgomery method to obtain the 360^o polar curve for the lift coefficient. All the aerodynamic coefficients are stored as data for the complete 360^o range of the angles of attack.

2.3. Verification and validation study

The QBLADE results were validated by simulating the UAE Phase VI turbine and comparing the obtained results with experimental data from NASA-Ames wind tunnel [36] and with another turbine performance estimation code, "WT_Perf" developed by NWTC [37]. The comparison of results is shown in Figure 4, which indicates good agreement up to a velocity of 14m/s. However, beyond this velocity, the simulation results (without 3D correction) deviate from the experimental data. This deviation occurs because the turbine experiences a deep stall at this velocity, and extrapolated results have been used. Nevertheless, when 3D corrections are applied, the simulation matches the experimental data at the stall regions.

2.4. Blade Erosion Mechanism

This section aims to provide a basic explanation of the blade erosion mechanism. As the blade encounters the oncoming wind, its leading edge becomes more susceptible to erosion. The progressive blade erosion process involves several stages, as follows:

(i) Stage 1: Minor pitting occurs in the topcoat.

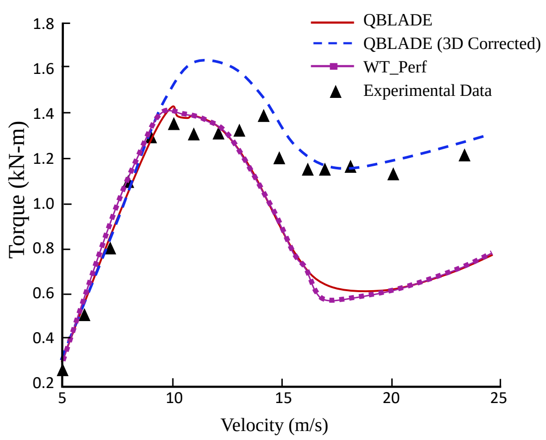


Figure 4. Torque vs. the free stream velocity for a 10m rotor-diameter wind turbine. The Comparison shows the simulation results of QBLADE and WT_Perf (the BEM code of NREL).

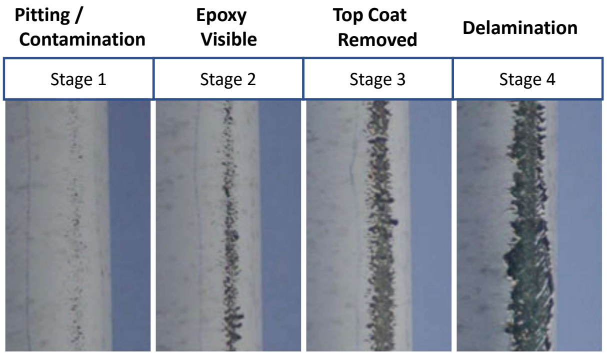


Figure 5. Leading-edge erosion damage seen on one blade at various positions [38]. The four different erosion stages are shown as a sample on a single turbine blade.

(ii) Stage 2: The topcoat is completely removed, and the underlying epoxy becomes intermittently visible.

(iii) Stage 3 and Stage 4: The epoxy is fully exposed with damage widths of approximately 15mm. After this, delamination occurs.

According to literature sources [38], contamination in Stage 1 occurs within the first year of turbine operation, which increases the surface roughness and affects turbine performance. Stages 3 and 4 are likely to occur after about ten years of service. Without proper maintenance procedures, delamination failure could happen, leading to a severe decrease in the turbine's power output. Figure 5 displays different stages of leading-edge erosion.

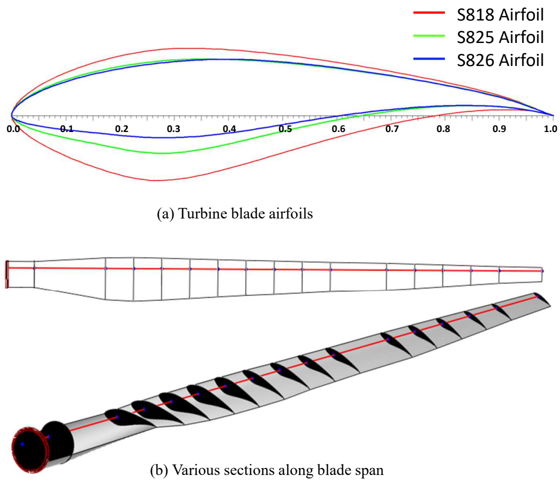
3. Geometry and specifications

3.1. Geometric details – GE1.5XLE

The turbine blade is designed to generate the required power output at the operational wind speed. The blade geometry plays a critical role, and even minor changes can significantly impact the rotor power. In Figure 6(a), one can see the three airfoils used to generate the blade geometry for the GE1.5XLE wind turbine. The chord length, twist angle, and airfoil shape of each section are the critical geometric parameters. The blending of different sections forms the entire blade geometry, as shown in Figure 6(b). Aerodynamic performance is the most fundamental part of an efficient rotor design. The power generated by the turbine is dependent on the lift force, so maximizing the lift force is crucial. The drag force competes against the blade motion, so it must be minimized. Therefore, it is evident that the airfoil section with a high lift-to-drag ratio must be selected for an efficient blade design. The lift coefficient depends on the angle of attack, and the lift and drag values of an inclined airfoil change. This airfoil inclination is translated as the twist in the blade. Thus, the shape of the airfoil and the twist angle both play a role in controlling the lift and drag forces. Table 1 shows the complete geometric details, including the position, chord, and twist angle. This geometry information is then added to the QBLADE (geometry module) to generate the complete rotor blade for the GE1.5XLE wind turbine.

3.2. Turbine specification

The turbine selected for this work is a GE1.5XLE horizontal axis wind turbine manufactured by General Electric (GE) [15, 38, 39]. The rated power for this turbine is 1.5 MW with a rotor diameter of 82.5 m. There are three blades with pitch control and swept area of 5346 m^2. Commissioned in 2005, the operational interval (rotations) vary from 10 $\sim$ 22 RPM, with a cut-in speed of 3 m/s and a cut-off speed of 20 m/s.



(a) Turbine blade airfoils

(b) Various sections along blade span

Figure 6. The GE1.5XLE wind turbine's geometric construction is composed of three different airfoils that define the blade profile, as shown in (a). These airfoils are blended to create the complete turbine blade geometry, as illustrated in (b).

Position(m)	Chord(m)	Twist (deg)	Section
0.000	2.000	0.00	Circular
2.000	2.000	0.00	Circular
7.219	3.074	26.91	S818
9.281	3.210	20.77	S818
11.344	3.111	16.12	S818
13.406	2.965	12.51	S818
16.000	2.818	9.02	S818
18.500	2.673	6.42	S818
21.000	2.527	4.35	S818
23.000	2.381	2.98	S818
25.500	2.234	4.54	S825
27.844	2.050	3.41	S825
29.906	1.900	2.54	S825
30.969	1.750	1.78	S825
34.031	1.600	1.60	S826
37.000	1.450	0.76	S826
40.125	1.200	-0.04	S826

Table 1. The GE1.5XLE wind turbine's blade geometry is characterized by the radial distance of each section, which determines its position, and the blade twist (β), which is the angle change of the blade from the root to the tip. The section's profile defines the blade's shape at each position.

4. Results and discussion

4.1. Erosion simulation using BEM

The erosion process in a turbine blade is complex and involves several stages. To analyze erosion, the geometry of the airfoil's leading edge was modeled using a sharp cut to simulate erosion formation. This allowed for the integration of erosion into the analysis. This method of representing airfoil erosion has been used previously by many researchers [40, 41]. In this study, different eroded levels were considered, with each level representing a specific erosion stage. These eroded levels were specified as a percentage of the airfoil chord, as illustrated in Figure 7. For the S818 airfoil, four different eroded profiles were created, and the same process was repeated for the other two airfoil sections, S825 and S826. These sections could then be combined in various ways to create blades with eroded leading edges. This method also helped to overcome the limitation of assuming uniform erosion across all blades. Since there is typically more erosion near the tip section in actual scenarios, a maximum erosion percentage could be set for that area.

In the context of leading-edge erosion, the BEM method can be used to analyze changes in a blade's aerodynamics resulting from surface roughness or irregularities caused by erosion. This includes assessing changes in lift and drag forces acting on the blade, as well as changes in the blade's stability and balance. By estimating the degradation of performance due to leading-edge erosion, the BEM method provides insight into the power output and efficiency of wind turbines. It is important to note, however, that the BEM method is a simplified approach to simulating wind turbine performance and is subject to certain assumptions and limitations. Despite these limitations, the BEM method remains a valuable tool for assessing the effects of leading-edge erosion on wind turbine performance.

Case#	Eroded Percentage of Chord
1	0.5%
2	1.0%
3	1.5%
4	2.0%

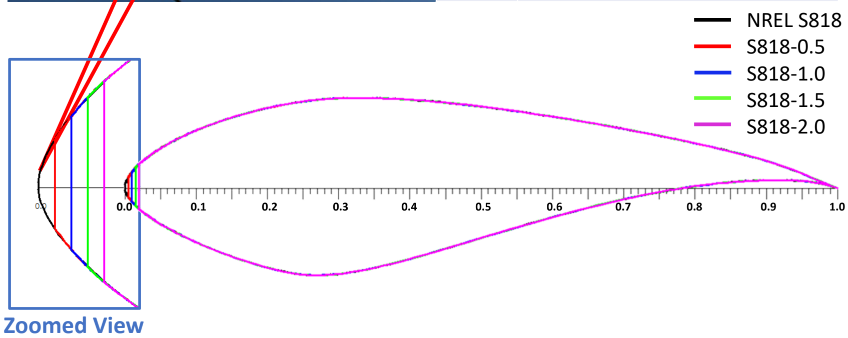


Figure 7. The top right image shows the actual eroded wind turbine blade, while the bottom schematic displays four different erosion stages (0.5%, 1.0%, 1.5%, and 2.0%) for a single airfoil section (S818). The zoomed view reveals the clipped leading edge for each erosion level.

4.2. Clean Blade Comparison

Initially, clean airfoil sections are employed to assess power output and performance coefficient (CP) and to compare the results with the available measured data of the GE1.5XLE wind turbine. As shown in Figure 8, BEM and CFD results are compared with available data for the GE1.5XLE wind turbine [16].

The CFD analysis was conducted for the clean turbine configuration. Although the specifics of the analysis are not provided here, it is important to note that all necessary preparations for the CFD analysis were completed. This includes ensuring mesh and domain size independence and selecting an appropriate turbulence model. By meeting these prerequisites, the CFD analysis provides reliable and meaningful results that can help understand the performance of the clean turbine configuration. The overall estimated values are in good agreement with the measured

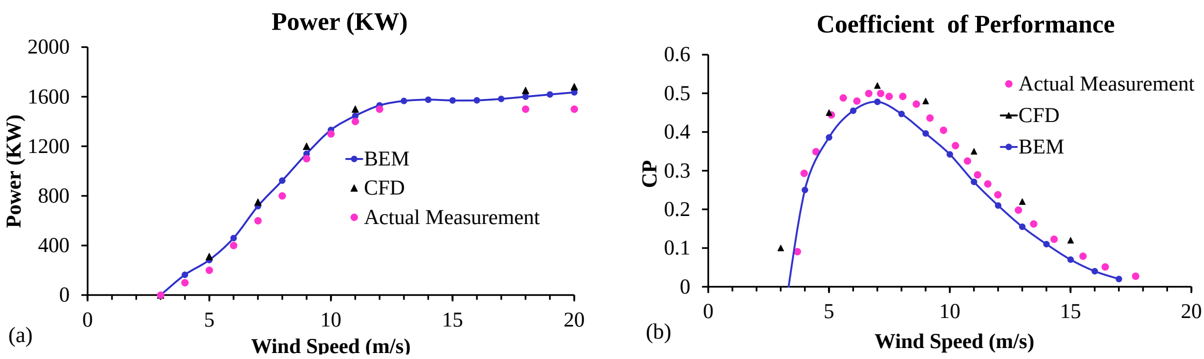


Figure 8. The performance parameters for a clean blade are compared in the figures below. Figure (a) shows the power output and Figure (b) shows the coefficient of performance (CP). The simulations were conducted for a velocity range of 3m/s to 20m/s and rotor rotations of 10 RPM.

data. This indicates that the BEM method (using the XFOIL polars and extrapolated data) provides a reasonable estimate for turbine performance. However, the results deviate at some points, especially for the velocity range of 9-13 m/s, although they are still satisfactory for predicting the eroded leading-edge case. The power output results from both the BEM approach and CFD study are in close agreement. However, both methods overestimate the power output compared to the measured data. In terms of the coefficient of performance, the CFD data matches well with the experimental data, while the BEM method slightly underestimates turbine performance. The underlying assumptions of the BEM approach account for these variations in results. Despite these inaccuracies, the BEM approach is still useful due to its robustness and low processing cost.

4.3. Eroded Blade Comparison

Following the successful comparison of the clean blade, the BEM analysis was extended to compute the performance of the eroded leading-edge blade for the GE1.5XLE wind turbine. Four different erosion scenarios with varying levels of erosion were considered, although only the power output and performance coefficient are included for comparison and explanation. Although additional performance data could be collected, the current results provide valuable insight into the impact of leading-edge erosion on turbine performance.

Airfoil polars were obtained for each erosion case, and the BEM method was used to estimate the eroded blade configurations' performance. As shown in Figure 9, blade erosion can result in a significant reduction in a wind turbine's power output, with the maximum reduction being 20% for a scenario where all airfoil sections are eroded by 2% of the chord length. In this case, the lift-to-drag ratio is also reduced by approximately 65%. Even a less severe case of 0.5% leading-edge erosion (5mm for a 1000mm chord length) can result in a 7% reduction in power output and a 20% reduction in lift-to-drag ratio. These reductions in power output and coefficient of performance are a significant concern for wind energy production, and wind energy producers must take steps to minimize the impact of blade erosion. A reduction in the lift-to-drag ratio also increases the turbine's workload, leading to increased wear and tear and a shorter lifespan. This information can be useful in developing techniques for minimizing blade erosion's impact on turbine performance and selecting appropriate materials for wind turbine blades.

5. Conclusion

The purpose of this study is to analyze the impact of leading-edge erosion on the performance of the GE1.5XLE wind turbine, using the blade element momentum (BEM) method. To

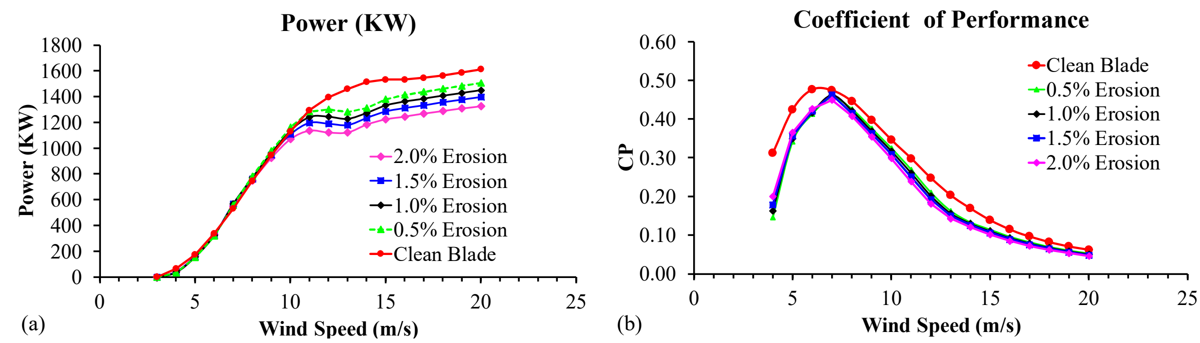


Figure 9. Comparison of the performance parameters of eroded blades, specifically the power output and coefficient of performance (CP). The simulations were conducted at a velocity range of 3-20 m/s and 10 RPM for each erosion level.

incorporate the effect of erosion, different levels of erosion were introduced in the airfoils (S818, S826, and S825), and their aerodynamic polar data was obtained and extrapolated to create a complete 360-degree polar curve. The BEM method was then used with the clean and eroded blade aerodynamic data to estimate the effect of erosion on performance parameters, such as power output and coefficient of performance.

Based on the results, the following conclusions can be drawn:

(i) The BEM approach is a quick and cost-effective way to evaluate the performance of eroded wind turbine blades, making it a useful tool in the early design stages where frequent modifications are made.

(ii) The simulation of different combinations of blade erosion levels, including changes in leading-edge erosion across the blade, is possible with the BEM method.

(iii) The degradation in aerodynamic performance, as indicated by the decrease in the lift-to-drag ratio of the airfoil, can lead to a reduction in power output. However, the degree of power reduction may vary based on the percentage decrease.

(iv) Despite the low-order nature of the BEM method, it is still effective in predicting the trend of power degradation for wind turbines, albeit with some errors. This will require validation and comparison with experiment or CFD simulation.

(v) In the case of the GE1.5XLE wind turbine, a 2% erosion level across all airfoil sections results in a 20% decrease in power output.

These findings underscore the importance of comprehending the impact of blade erosion, particularly on offshore wind turbine performance, and the significance of using the BEM method to assess this effect. As per the study's results, even minor erosion can have a significant impact on wind turbine operation. This highlights the need for effective measures to mitigate the effects of blade erosion and the use of resistant materials. The BEM method offers a fast and low-cost evaluation that can be used in the early stages of wind turbine design, leading to the development of more efficient and effective wind energy systems. It is crucial to consider the effects of blade erosion during the early design phase to enhance the efficiency and effectiveness of wind energy systems.

In future studies, the identical eroded blade profiles analyzed in this study using the BEM approach will be modeled using CFD techniques. This will aid in identifying the source of inaccuracies in the BEM calculations and enhance the reliability of the results. Comparing BEM and CFD data will provide critical insights into the usefulness of assessing the impact of leading-edge erosion on wind turbine performance.

References

[1] Mandar Tabib, M Salman Siddiqui, Adil Rasheed, and Trond Kvamsdal. Industrial scale turbine and associated wake development-comparison of rans based actuator line vs sliding mesh interface vs multiple reference frame method. *Energy Procedia*, 137:487–496, 2017.

[2] M Salman Siddiqui, Naveed Durrani, and Imran Akhtar. Quantification of the effects of geometric approximations on the performance of a vertical axis wind turbine. *Renewable Energy*, 74:661–670, 2015.

[3] M Salman Siddiqui, Adil Rasheed, Trond Kvamsdal, and Mandar Tabib. Effect of turbulence intensity on the performance of an offshore vertical axis wind turbine. *Energy Procedia*, 80:312–320, 2015.

[4] M Salman Siddiqui, Adil Rasheed, Mandar Tabib, and Trond Kvamsdal. Numerical modeling framework for wind turbine analysis & atmospheric boundary layer interaction. In *35th Wind Energy Symposium*, page 1162, 2017.

[5] N Dalili, Afsaneh Edrisy, and Rupp Carriveau. A review of surface engineering issues critical to wind turbine performance. *Renewable and Sustainable energy reviews*, 13(2):428–438, 2009.

[6] Gustave P Corten and Herman F Veldkamp. Insects can halve wind-turbine power. *Nature*, 412(6842):41–42, 2001.

[7] JM Janiszewska, R Reuss Ramsay, MJ Hoffmann, and GM Gregorek. Effects of grit roughness and pitch oscillations on the s814 airfoil. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 1996.

[8] Agrim Sareen, Chinmay A Sapre, and Michael S Selig. Effects of leading edge erosion on wind turbine blade performance. *Wind energy*, 17(10):1531–1542, 2014.

[9] Unai Fernandez-Gamiz, Ekaitz Zulueta, Ana Boyano, Josean A Ramos-Hernanz, and Jose Manuel Lopez-Guede. Microtab design and implementation on a 5 mw wind turbine. *Applied Sciences*, 7(6):536, 2017.

[10] Alessandro Corsini, Alessio Castorrini, Enrico Morei, Franco Rispoli, Fabrizio Sciulli, and Paolo Venturini. Modeling of rain drop erosion in a multi-mw wind turbine. In *Turbo Expo: Power for Land, Sea, and Air*, volume 56802, page V009T46A001. American Society of Mechanical Engineers, 2015.

[11] Dan M Somers. Design and experimental results for the s809 airfoil. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 1997.

[12] RF Ramsay, MJ Hoffman, and GM Gregorek. Effects of grit roughness and pitch oscillations on the s809 airfoil. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 1995.

[13] Wanan Sheng, Roderick A McD Galbraith, and Frank N Coton. On the s809 airfoil's unsteady aerodynamic characteristics. *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology*, 12(8):752–767, 2009.

[14] Kobra Gharali and David A Johnson. Numerical modeling of an s809 airfoil under dynamic stall, erosion and high reduced frequencies. *Applied Energy*, 93:45–52, 2012.

[15] Gagan SahuP and RK RathoreP. Determination of torque produced by horizontal axis wind turbine blade using fsi analysis for low wind speed regime. *IJISET-International Journal of Innovative Science, Engineering & Technology*, 2(5), 2015.

[16] NEPRA. Modification in generation license wpgl/04/2006 tgl. *Annual Report,National Electric Power Regulatory Authority Pakistan*, (https://nepra.org.pk/licensing/Licences/Licence%20Modification/LModification-I-of-Tenaga-Feb-23-2012.PDF):33, 2012.

[17] Nawapon Sompong and Pongtorn Prombut. Effects of bend-twist coupling deformation on the aerodynamic performance of a wind turbine blade. *GEOMATE Journal*, 12(34):15–20, 2017.

[18] Mark Drela. Xfoil: An analysis and design system for low reynolds number airfoils. In *Low Reynolds Number Aerodynamics: Proceedings of the Conference Notre Dame, Indiana, USA, 5–7 June 1989*, pages 1–12. Springer, 1989.

[19] Björn Montgomerie. Methods for root effects, tip effects and extending the angle of attack range to {+-} 180 deg., with application to aerodynamics for blades on wind turbines and propellers. 2004.

[20] David Marten, Jan Wendler, Georgios Pechlivanoglou, Christian Navid Nayeri, and Christian Oliver Paschereit. Qblade: an open source tool for design and simulation of horizontal and vertical axis wind turbines. *International Journal of Emerging Technology and Advanced Engineering*, 3(3):264–269, 2013.

[21] Tariq Rabbani, M Khalid, M. Salman Siddiqui, and Imran Akhtar. Reduced order modeling of loads on a vertical-axis wind turbine. In *Applied Sciences and Technology (IBCAST), 2014 11th International Bhurban Conference on*, pages 298–303. IEEE, 2014.

[22] Muhammad Saif Ullah Khalid, Tariq Rabbani, Imran Akhtar, Naveed Durrani, and M Salman Siddiqui. Reduced-order modeling of torque on a vertical-axis wind turbine at varying tip speed ratios. *Journal of Computational and Nonlinear Dynamics*, 10(4):041012, 2015.

[23] Eivind Fonn, Mandar Tabib, M Salman Siddiqui, Adil Rasheed, and Trond Kvamsdal. A step towards reduced order modelling of flow characterized by wakes using proper orthogonal decomposition. *Energy Procedia*, 137:452–459, 2017.

[24] M Salman Siddiqui, Eivind Fonn, Trond Kvamsdal, and Adil Rasheed. Finite-volume high-fidelity simulation combined with finite-element-based reduced-order modeling of incompressible flow problems. *Energies*, 12(7):1271, 2019.

[25] M Salman Siddiqui, Adil Rasheed, and Trond Kvamsdal. Numerical assessment of rans turbulence models for the development of data driven reduced order models. *Ocean Engineering*, 196:106799, 2020.

[26] M Salman Siddiqui, Sidra Tul Muntaha Latif, Muhammad Saeed, Muhammad Rahman, Abdul Waheed Badar, and Syed Maaz Hasan. Reduced order model of offshore wind turbine wake by proper orthogonal decomposition. *International Journal of Heat and Fluid Flow*, 82:108554, 2020.

[27] James L Tangler. The nebulous art of using wind-tunnel airfoil data for predicting rotor performance. In *Wind Energy Symposium*, volume 7476, pages 190–196, 2002.

[28] Hamid Rahimi, B Dose, B Stoevesandt, and J Peinke. Investigation of the validity of bem for simulation of wind turbines in complex load cases and comparison with experiment and cfd. In *Journal of Physics: Conference Series*, volume 749, page 012015. IOP Publishing, 2016.

[29] Hermann Glauert. Airplane propellers. *Aerodynamic theory*, 1935.

[30] Emmanuel Branlard. Wind turbine aerodynamics and vorticity-based methods: Fundamentals and recent

applications. 2017.

[31] Jason Jonkman. Nwtc computer-aided engineering tools (fast). *Last modified*, 27, 2013.

[32] M Salman Siddiqui, Muhammad Hamza Khalid, Rizwan Zahoor, Fahad Sarfraz Butt, Muhammed Saeed, and Abdul Waheed Badar. A numerical investigation to analyze effect of turbulence and ground clearance on the performance of a roof top vertical–axis wind turbine. *Renewable Energy*, 164:978–989, 2021.

[33] M Salman Siddiqui, Adil Rasheed, Mandar Tabib, and Trond Kvamsdal. Numerical investigation of modeling frameworks and geometric approximations on nrel 5 mw wind turbine. *Renewable Energy*, 132:1058–1075, 2019.

[34] M Salman Siddiqui, Adil Rasheed, Trond Kvamsdal, and Mandar Tabib. Quasi-static & dynamic numerical modeling of full scale nrel 5mw wind turbine. *Energy Procedia*, 137:460–467, 2017.

[35] Peter Fuglsang, Ioannis Antoniou, Niels N Sørensen, and Helge Aa Madsen. Validation of a wind tunnel testing facility for blade surface pressure measurements. 1998.

[36] C Lindenburg. Investigation into rotor blade aerodynamics. *ECN, Peten*, 2003.

[37] M Buhl. Nwtc design codes wt_perf a wind-turbine performance predictor, 2009.

[38] Mohamed Elhadi Ibrahim and Mamoun Medraj. Water droplet erosion of wind turbine blades: Mechanics, testing, modeling and future perspectives. *Materials*, 13(1):157, 2019.

[39] Naji Abdullah Mezaal, KV Osintsev, and SV Alyukov. The computational fluid dynamics performance analysis of horizontal axis wind turbine. *International Journal of Power Electronics and Drive Systems*, 10(2):1072, 2019.

[40] Xiaohang Wang, Zhenbo Tang, Na Yan, and Guojun Zhu. Effect of different types of erosion on the aerodynamic performance of wind turbine airfoils. *Sustainability*, 14(19):12344, 2022.

[41] Matthias Schramm, Hamid Rahimi, Bernhard Stoevesandt, and Kim Tangager. The influence of eroded blades on wind turbine performance using numerical simulations. *Energies*, 10(9):1420, 2017.