Original Research Article

Impact of leading-Edge pitting erosion on the aerodynamic performance of S809 airfoil

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Abstract: Based on the morphological characteristics of wind turbine blade leading-edge erosion at different stages observed in actual wind farms, this study investigates the effects of leading-edge erosion morphology on the aerodynamic performance of wind turbine airfoils. The S809 airfoil was geometrically modified to simulate erosion features, and the Reynolds-Averaged Navier-Stokes (RANS) equations were solved using the SST k-ω turbulence model. The lift/drag coefficients and flow field characteristics were systematically analyzed. Results indicate that erosion morphologies characterized by pitting and minor cavities exhibit negligible impacts on the lift and drag coefficients of the airfoil.

Keywords: Numerical simulation; Wind turbine; Aerodynamic performance; Erosion

1. Introduction

Wind turbines often operate in harsh natural environments where blade surfaces are inevitably eroded by particle impacts from sand, rain, hail, and insects, leading to surface erosion, particularly severe at the leading edge[1-2]. As operational time increases, leading-edge erosion intensifies, and surface roughness progressively grows. Studies on blade surface roughness and leading-edge erosion demonstrate that leading-edge roughness significantly degrades aerodynamic performance[3-4]. Specifically, increased leading-edge roughness reduces lift coefficients, substantially elevates drag coefficients[5,6], and causes a notable decline in wind turbine power output—up to 25%[7]—disrupting normal power generation.

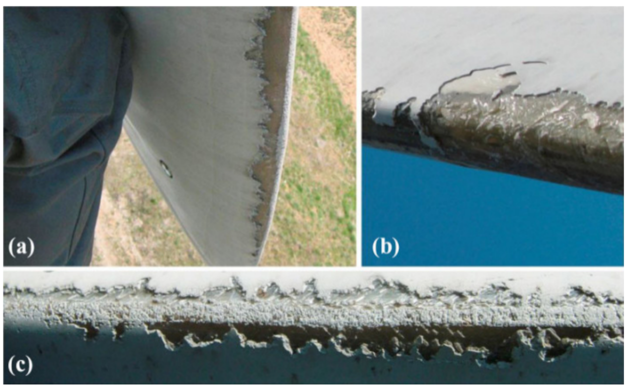

Figure 1. Leading-edge erosion pattern of an operational wind turbine blade.

Combining the morphological characteristics of leading-edge erosion observed in operational wind turbine blades, this study established modified geometric models of the S809 wind turbine airfoil by reconstructing its leading-edge profile to simulate erosion patterns at different erosion stages. Through CFD-based numerical simulations of the airfoil's aerodynamic performance, we systematically investigated the impact of leading-edge erosion morphology by comparing the aerodynamic characteristics (including lift/drag coefficients and flow separation behavior) of eroded configurations with those of the pristine airfoil. This approach provides quantitative insights into the degradation mechanisms of wind turbine blade performance under realistic erosion conditions.

2. Mathematical modeling

To visually present the enhancement of the lift-to-drag ratio of the airfoil due to the installation of small cylinders at the leading edge of the erosion airfoil on a line chart, a function c is defined as $C_l/C_{d\ Difference\ value}$

$$C_l/C_{d\ Difference\ value} = C_l/C_{dxx} - C_l/C_{d\ erosion}$$

C_l/C_{dxx}——the lift-to-drag ratio of the airfoil after the installation of small cylinders at the XX position

$C_l/C_{d\ erosion}$——the lift-to-drag ratio of the erosion airfoil

3. Numerical simulation methods

3.1. Geometric models of leading-Edge erosion

This chapter quantifies the early-stage pitting erosion processes associated with three erosion morphologies. Based on the symmetrical leading-edge C-shaped erosion pit as a baseline, triangular, quadrilateral, arc-shaped, and stochastic erosion pit models were constructed according to the temporal evolution patterns of erosion morphologies. The geometric configurations of the C-shaped, triangular, quadrilateral, and arc-shaped erosion pits.

3.2. Computational domain and geometric models

The specific grid details are presented in Figure 2, ensuring compliance with the requirement $y^+<1$ as per the turbulence model. The Reynolds number for this study is set to $Re=1\times10^6$.

Table 1. Correspondence between erosion shapes and severity levels in the line graph.

	triangular erosion pits	quadrilateral erosion pits	arc-shaped erosion pits
slight erosion(1)	triangular(1)	quadrilateral(1)	arc-shaped(1)
moderate erosion(2)	triangular(2)	quadrilateral(2)	arc-shaped(2)
severe erosion(3)	triangular(3)	quadrilateral(3)	arc-shaped(3)

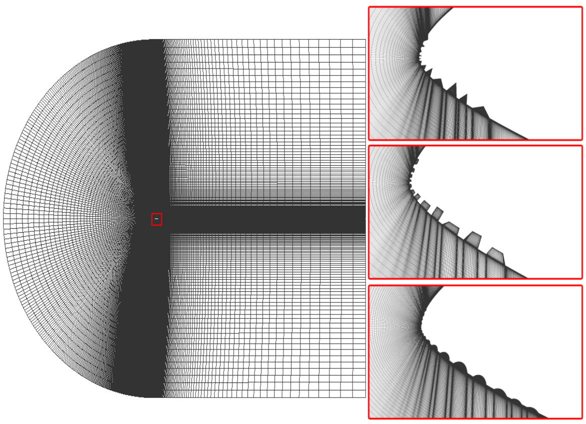

Figure 2. Leading edge grid local magnification.

4. Results and analysis

4.1. Analysis of aerodynamic performance impacts from three leading-Edge erosion pit shapes

Given the minimal differences in lift-to-drag ratios among the three leading-edge erosion pit shapes (triangular, quadrilateral, and arc-shaped) observed in the computational results, a differential analysis was conducted to clarify their aerodynamic distinctions. The lift-to-drag ratio of the triangular pit—which exhibited the most pronounced deviation—was subtracted from those of the quadrilateral and arc-shaped pits, generating comparative lift-to-drag difference curves.

As illustrated in Figure 3, under mild erosion conditions, the arc-shaped pit demonstrated the lowest lift-to-drag ratio, trailing both triangular and quadrilateral pits, while the latter two showed nearly identical performance. At moderate erosion levels, the quadrilateral pit achieved the highest lift-to-drag ratio, followed by the arc-shaped and triangular pits. However, under severe erosion, the arc-shaped pit outperformed both polygonal configurations. Overall, the geometric shape and dimensions of leading-edge erosion pits exhibit limited influence on airfoil aerodynamic perform.

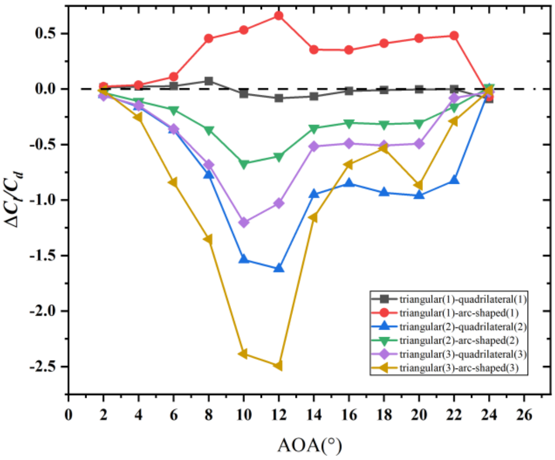

Figure 3. Comparison of lift-to-drag ratio differences for airfoils with triangular, quadrilateral, and arc-shaped erosion-induced pits at the leading edge.

4.2. Flow field analysis inside leading-Edge erosion pits with three different shapes

To investigate the influence mechanisms of geometric shapes and dimensions of erosion pits on the airfoil flow field, a detailed analysis of the flow fields inside the pits is essential. Figure 4 presents the flow field contours and streamlines near the leading-edge regions and inside triangular, quadrilateral, and arc-shaped erosion pits. The streamline patterns reveal distinct flow characteristics among different pit geometries:

Triangular pits predominantly contain two vortices — a larger primary vortex near the pit opening and a smaller secondary vortex trapped at the bottom. The confined secondary vortex gradually dissipates within the pit, corresponding to the most significant lift-to-drag ratio variations among the three configurations. Quadrilateral pits exhibit the most complex flow patterns, demonstrating transitional vortex configurations ranging from single to triple vortices. However, the bottom vortices maintain smaller scales and lower energy dissipation compared to triangular pits. Arc-shaped pits consistently maintain a single dominant vortex structure. The stagnant vortex in arc-shaped pits demonstrates easier overflow characteristics and minimal fluid energy dissipation, resulting in the most stable lift-to-drag ratio curves across three scaling configurations.

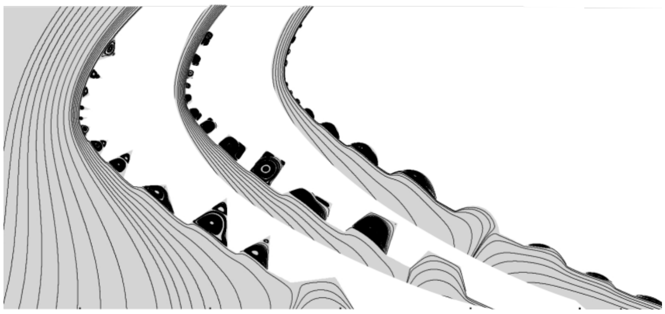

Figure 4. Leading-edge flow field visualization of airfoils with triangular, quadrilateral, and arc-shaped erosion pits.

5. Conclusion

This study investigates the leading-edge erosion phenomenon of wind turbine blades, focusing specifically on the pitting erosion stage. Taking the S809 airfoil as the research object, three types of erosion pit models with varying geometric configurations (triangular, quadrilateral, and arc-shaped) under different erosion severities were constructed. Numerical simulations were conducted to analyze the effects of stochastic pitting on aerodynamic performance. Key findings include:

(1) When non-continuous regular erosion pits concentrated on the pressure side of the leading edge develop, the aerodynamic performance shows negligible deterioration with increasing pit dimensions. Among these configurations, triangular pits exhibit the maximum discrepancy (up to 7.2%) in aerodynamic curves across different pit sizes.

(2) As the geometric edge number of leading-edge pits increases, the flow characteristics of internal stagnant vortices become more complex. Notably, arc-shaped pits demonstrate significant vortex overflow within the cavity, functioning similarly to vortex generators. This flow control mechanism effectively stabilizes the aerodynamic performance curves, resulting in the minimal discrepancy (<2.1%) among the three arc-shaped pit configurations with varying dimensions.

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