

Effect of Leading-Edge Roughness on the Aerodynamic Characteristics of the Wind Turbine Blade

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Abstract

Leading-Edge Roughness (LER) strongly dictates boundary layer transition and performance degradation on an airfoil operating at transitional Reynolds numbers, an aerodynamic regime where shear-layer stability mechanisms remain highly complex. The wind tunnel experiments were conducted to investigate the aerodynamic impacts of surface roughness applied over 25% of the chord of a NACA 0018 airfoil using two discrete roughness gradations. Surface roughness induces an early boundary layer trip, causing elevated section drag and reduced maximum lift in the linear regime. However, the rough configurations demonstrate superior lift retention past the conventional stall margin compared to the baseline clean airfoil. Low roughness heights prove particularly advantageous, boosting lift at moderate incidence angles and establishing remarkably smooth, predictable post-stall dynamics. In contrast, higher roughness severely disrupts the laminar boundary layer, capping peak lift performance due to premature shear-layer thickening. Surface pressure and force data confirm that controlled leading-edge roughness functions as a robust passive flow control technique by delaying large-scale flow separation and sustaining partial flow attachment beyond stall. By utilizing shear-layer momentum and forcing early laminar-to-turbulent transition, LER provides the critical turbulent kinetic energy required to resist severe flow detachment. These insights demonstrate that engineered leading-edge surface modifications offer a reliable passive flow control solution to enhance energy capture and structural stability in wind energy applications.

Keywords: Leading-edge roughness, passive flow control, aerodynamic performance, wind turbine, stall delay

INTRODUCTION

In recent years, leading-edge roughness (LER) induced by surface erosion has emerged as a critical technical challenge within the wind energy sector. The urgency of addressing this phenomenon stems directly from the ongoing physical scaling of modern wind turbine rotors, alongside the aggressive expansion of offshore installations operating in severe environmental conditions [1]. As rotor diameters expand and tip speeds increase, blade surface materials face unprecedented environmental exposure. Based on the underlying drivers and surface phenomena involved, leading-edge degradation is broadly classified into two categories: contamination and erosion [2]. Contamination involves the surface

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accretion of foreign matter, such as insect debris, atmospheric icing, and airborne particulates like dust. Conversely, erosion represents the mechanical degradation of the primary surface caused by continuous high-velocity impacts from abrasive airborne media, including raindrops and hailstones. This impact-driven erosion systematically degrades the outer protective coating, escalating surface roughness and initiating complex downstream flow disturbances across the airfoil [3]. There is a drop in Annual Energy Production (AEP) by 3.7% due to the contamination at the blade tips on a 5MW NREL turbine blade [4]. This leading-edge defect in the

wind turbine shows that the lift coefficient has decreased by 53% and the drag coefficient has increased by 314% [4]. To assess the negative impacts of roughness, it is essential to examine the flow dynamics surrounding the turbine blades. Also, the density of erosion is notably higher at the leading edge of blades and decreases along the chordwise direction. This phenomenon occurs because the accumulation of contaminants and subsequent erosion generally initiates at the leading edge [5]. Consequently, this accumulation and erosion have a substantial impact on the power performance and load variation of wind turbines [5].

In the presence of roughness, laminar flow tends to transition to turbulent flow earlier than expected and further decreases the lift-to-drag ratio of wind turbine airfoils [6]. Roughness with a height of 0.02% of the chord length degrades the aerodynamic performance in airplanes [5]. The increasing Tip Speed Ratios (TSR) of the turbine blades make them more susceptible to roughness caused by erosion due to raindrops or hailstones [7]. The roughness of the blade surface increased the transition from laminar to turbulent flow and induced flow separation, hence diminishing the aerodynamic performance [8]. LER can induce minor perturbations in near-wall turbulent flow and possibly enhance flow instability [9], and it also induces unsteady flow separation, which increases aerodynamic hysteresis in the dynamic stall of wind turbine airfoils [10, 11]. Vestas tested 1.5-MW active-stall wind turbines with various degrees of contamination at the leading edge of the blades and found that extreme contamination lowers annual energy production (AEP) by 10% to 13% [4]. Insects primarily contribute to contamination in areas with low wind speeds, temperatures of 10 °C or above, and low humidity [12]. Furthermore, it is found that in these situations, output power diminishes by as much as 25% when the wind speed exceeds the rated wind speed [12].

Overall, the roughness has both positive and negative influences on the aerodynamic performance of wind turbines. Beyond direct aerodynamic degradation, LER accelerates structural fatigue and increases operational expenditure (OpEx) through elevated cyclic loading and premature blade repair cycles. Furthermore, modern visual and acoustic monitoring, coupled with advanced Computational Fluid Dynamics (CFD) modelling, such as Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulations (LES), are becoming standard tools to predict roughness-induced boundary-layer transition. To mitigate these penalties, recent engineering efforts focus on developing advanced passive flow control devices (e.g., vortex generators), optimized LER-resistant airfoil profiles, and durable multi-layer hydrophobic Polyurethane (PU) protective coatings tailored specifically for high-impact offshore environments.

EXPERIMENTAL APPROACH

In this study, a NACA 0018 airfoil was used with a chord length of 0.1m and a span length of 0.3m. The roughness was created on the leading edge (up to 25% of the chord length from the leading edge) of the airfoil by using a silicon carbide emery sheet, and the configuration of roughness is illustrated in Table 1. It is subjected to a series of wind tunnel tests at a fixed chord Reynolds number of 2.6×10^5 for the angles of attack ranging from 0° to 25° with increments of 2.5°. The low subsonic wind tunnel facility at SASTRA Deemed University was used for performing the experimental investigation. It has a test section of 0.3×0.3 m with a length of 1.5m, with a free-stream turbulence intensity of 0.7% [13]. A diagrammatic representation of the wind tunnel setup with the test model mounted in the test section is shown in Figure 1. To investigate the aerodynamic characteristics, the airfoil has been provided with 21 distributed pressure ports situated on the airfoil surface, with 10 pressure ports on both the upper and lower surfaces, with a stagnation port facing the flow, as shown in Figure 1.

A 64-channel Ethernet-based MPS 4264 pressure scanner was used to measure the simultaneous pressure data from 21 ports with a sampling frequency of 700 HZ, and 10000 data samples were collected at each port. The raw pressure data collected from the surface of the airfoil with and without roughness are presented in Figure 2. All errors resulting from uncertainty will be resolved by the huge data sets. The surface pressure data obtained were integrated to calculate the aerodynamic coefficients based on the approach followed in [14, 15]. To investigate the effect of roughness, two distinct emery sheets with large coarse and superfine abrasive sizes were chosen from a large array of sheets.

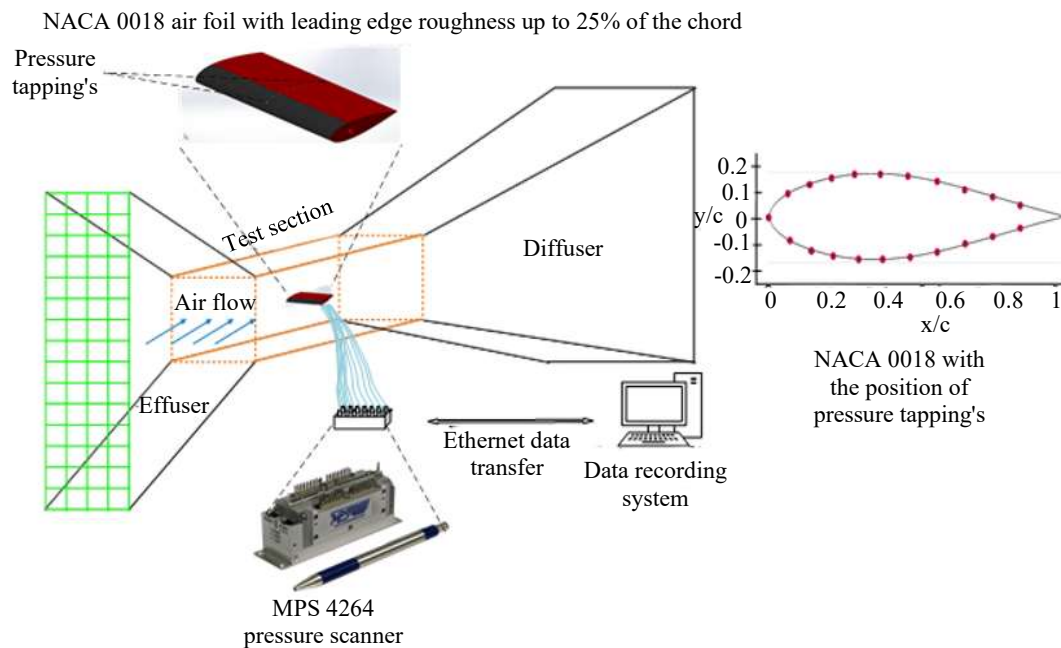


Figure 1. Experimental setup in wind tunnel.

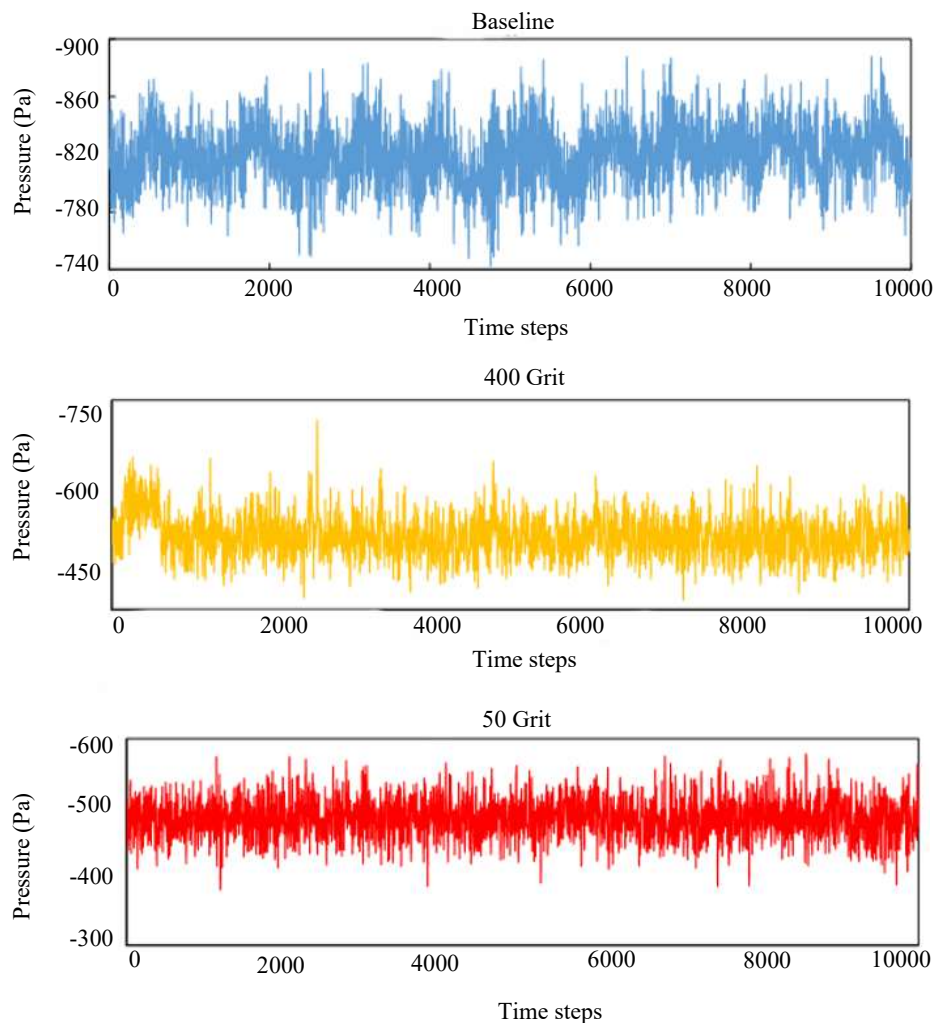


Figure 2. Raw pressure data obtained from the suction surface pressure port at $x/c = 0.25$, $\alpha = 10^\circ$.

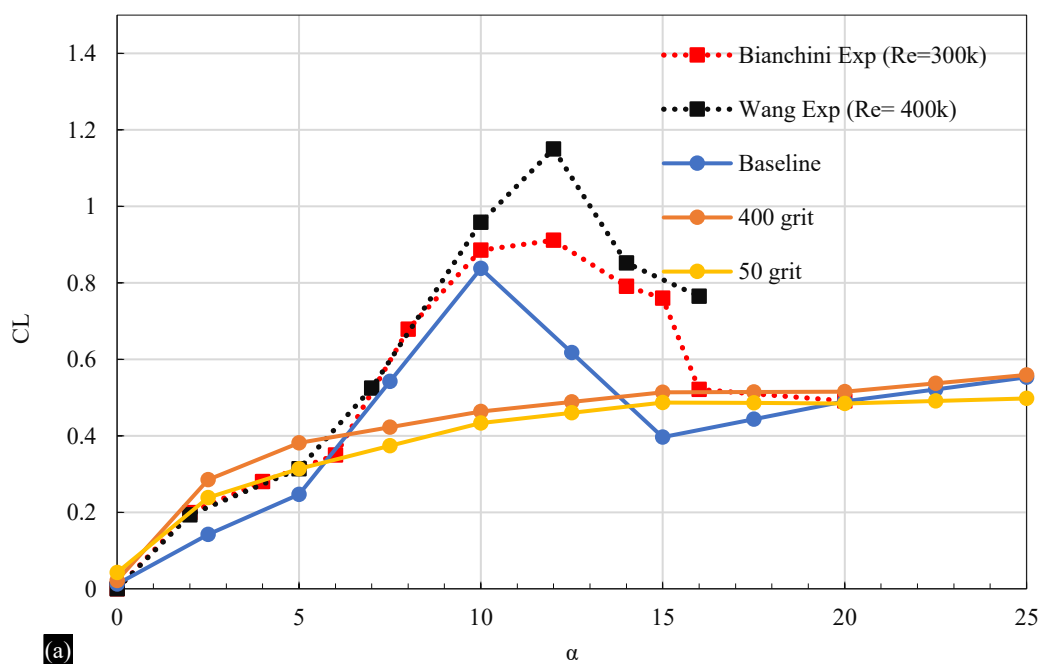
Table 1. Standard grit size used for the manufacturing of emery sheet [16].

Grit type	Roughness average (Ra)	
	ISO (μm)	FEPA mean (μm)
P50 (Coarse)	330-345	336
P400 (Fine)	33.5-36.5	35

Table 1 shows the standard roughness average (Ra) for different abrasive materials specified by the International Organization for Standardization (ISO) and the Federation of European Producers of Abrasives (FEPA) [16]. Whereas in India, we follow the FEPA standards.

RESULTS AND DISCUSSIONS

The roughness added to the leading edge of the airfoil was experimentally tested to obtain the aerodynamic coefficients for varying angles of attack. Figure 3 (a) and (b) shows the aerodynamic characteristics of the NACA 0018 airfoil with and without leading-edge roughness, and the baseline lift curve almost matches the results obtained in [17, 18]. Compared to the baseline, the fine roughness of 400 grit exhibits higher lift at lower angles of attack up to 5° , followed by 50 grit. The baseline exhibits the maximum lift coefficient of 0.89 at $\alpha=10^\circ$. It shows that up to 5° , lift increases linearly, and after the angle of attack increases from 5° to 10° , the laminar separation bubble forms near the leading edge. This creates the peak lift at $\alpha=10^\circ$, and the thick symmetric airfoils at transitional Reynolds number often give a very strong lift spike [19]. The laminar separation bubble bursts after $\alpha=10^\circ$, and there is a sudden loss of the suction peak, resulting in a large drop in lift, indicating a deep stall. At $\alpha \sim 15^\circ$ to 17° , flow begins to reattach due to the stabilization of the leading-edge vortex. There is a gradual recovery in lift after the angle of attack $\alpha \sim 17.5^\circ$, due to the vortex at the leading edge starting to produce suction. For the rough surface, at the angle of attack of $\alpha=6^\circ$ to 10° , the roughness prevents the laminar bubble formation, leading to the earlier transition of the boundary layer and suppressing the peak lift coefficient. At $\alpha=10^\circ$ to 15° , the turbulent boundary layer stays attached for the rough surfaces of 400 grit and 50 grit, which makes the stall happen gradually, not abruptly, as in the case of the baseline. In the post-stall region ($\alpha=15^\circ$ to 25°), the lift coefficient increases gradually for the rough surfaces. These results demonstrate that the coarse roughness (50 grit) has the highest lift at the low angle of attack, and creates an earlier transition, while the fine roughness has a smoother lift curve and a small linear and gradual increase in lift after the post-stall regime.



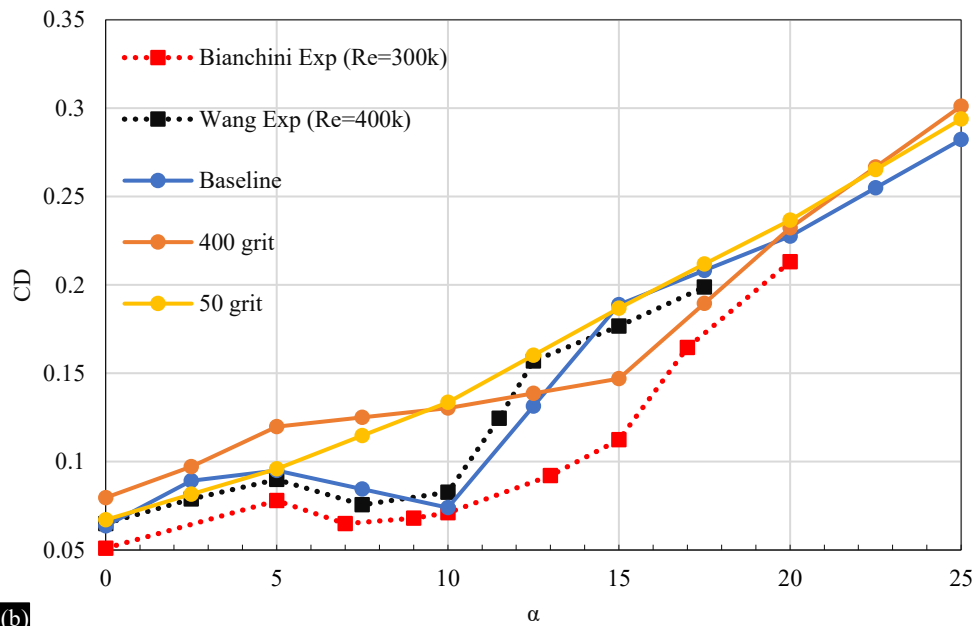
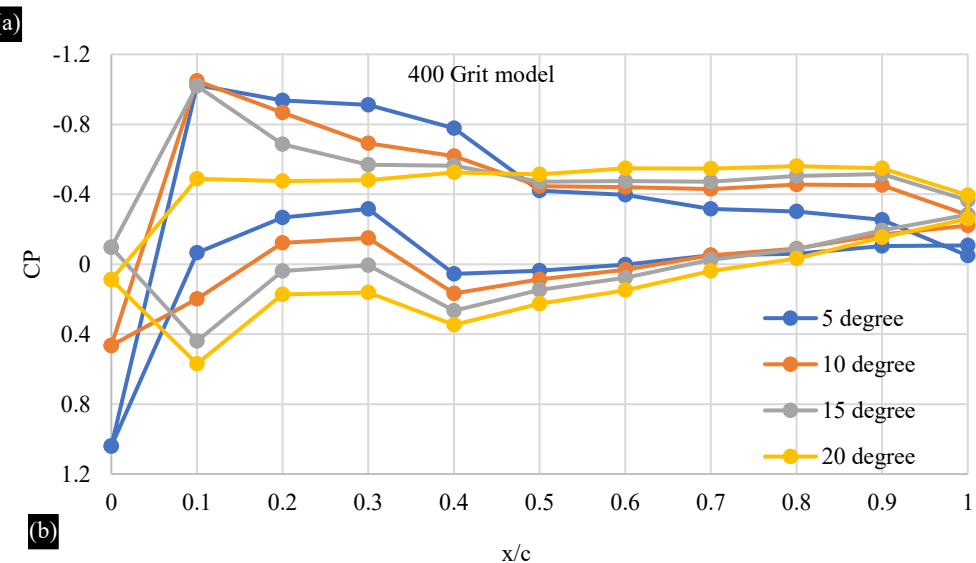
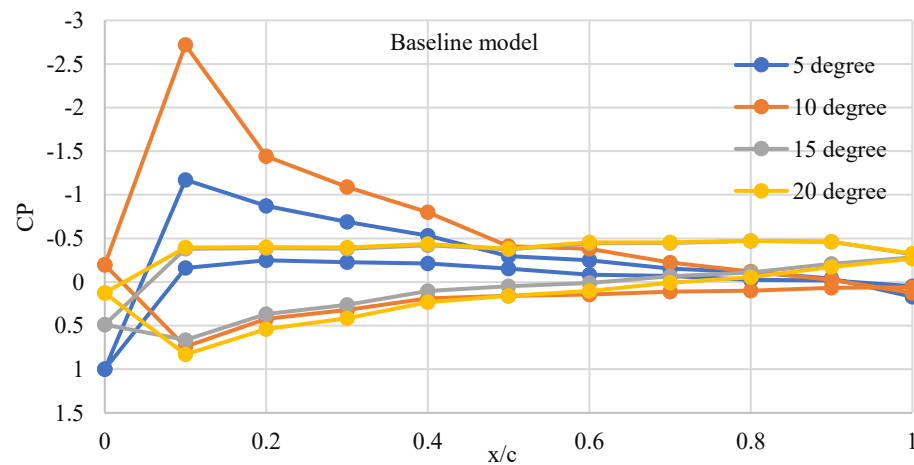


Figure 3. Comparison of aerodynamic characteristics between the conventional model and the modified model with roughness. (a) Lift Characteristic (b) Drag Characteristic.



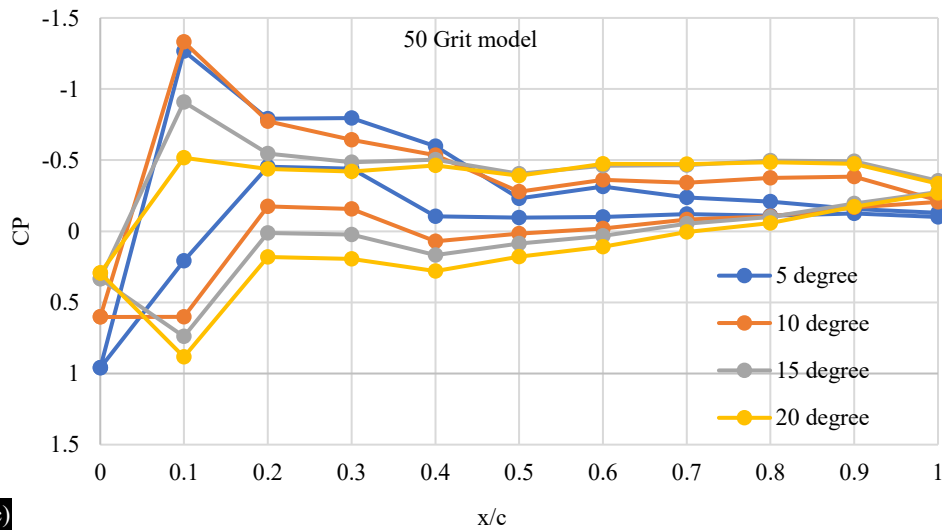


Figure 4. Comparative pressure distribution (C_p vs x/c) plot for baseline airfoil and roughness-added airfoil at pre-stall and post-stall regions.

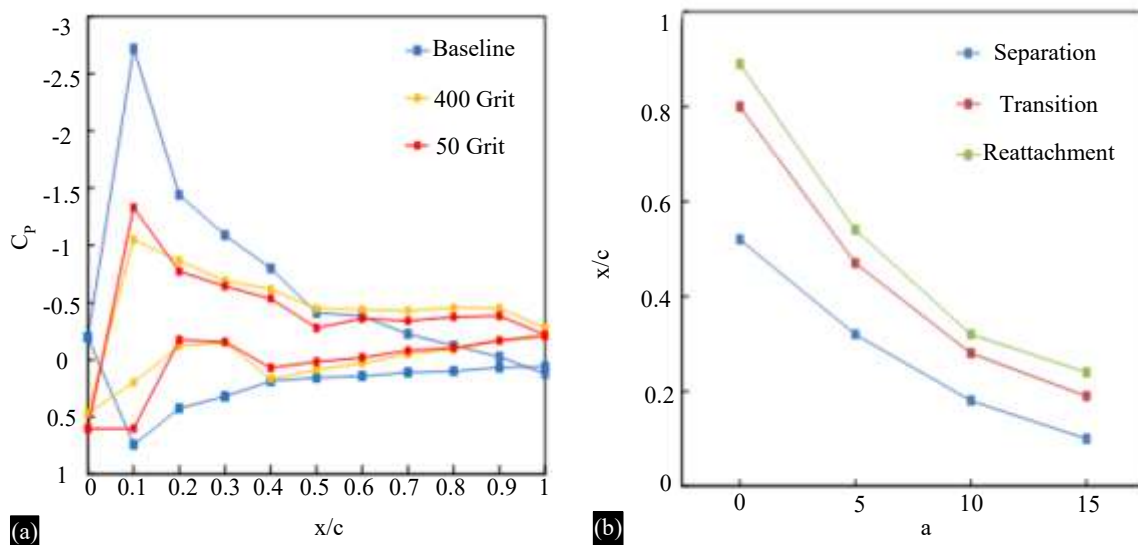


Figure 5. (a). Comparative pressure distribution (C_p vs x/c) plot for baseline airfoil and roughness-added airfoil at $\alpha=10^\circ$. (b). Variation of positions of mean Separation, Transition and Reattachment with different angles of attack.

The influence of leading-edge roughness can be further understood from the pressure distributions, as shown in Figure 4. The pressure distribution shows that as the angle of attack increases from 5° to 10° , the suction peak on the upper surface becomes stronger, indicating higher lift. While at 15° and 20° , the suction peak weakens and the pressure profile flattens, showing partial to full flow separation, as shown in Figure 4(a). The laminar separation bubble moves towards the leading edge for increasing angles of attack [20], which is illustrated in Figure 5(b), and the corresponding pressure distributions are illustrated in Figure 5(a). The fine roughness (400 grit) shows reduced suction peaks and smoother pressure recovery compared to the baseline model, as shown in Figure 4(b). The roughness promotes earlier boundary layer transition, delaying separation and maintaining more uniform pressure at higher angles of attack. As a result, lift reduction after stall is less severe, indicating improved post-stall stability and delayed flow separation despite the roughened surface. The coarse roughness shows a noticeable decrease in suction peak magnitude and a flatter pressure gradient across all angles of attack, as shown in Figure 4(c). The coarse roughness induces early boundary layer transition, leading to

increased skin friction drag and reduced lift, especially at lower angles. However, it also delays large-scale flow separation at higher angles of attack, resulting in a more stable post-stall pressure distribution compared to the baseline and fine-roughness cases.

CONCLUSION

From the series of experiments conducted on an airfoil with various gradations of roughness at the leading edge, the following findings were observed:

1. At a higher angle of attack, there is an increase in lift coefficient of 29.49% for the airfoil with leading edge fine roughness (400 Grit), and 28.68% for coarse roughness (50 Grit) compared to the baseline model, simultaneous decrease in drag coefficient of 22.15% for fine roughness.
2. The stall characteristics of the roughness-added airfoil show a noticeable stall delay after a static stall angle of 10° . This demonstrates that roughness influences the aerodynamic characteristics at the post-stall regime.
3. The leading-edge roughness induced flow transition by increasing turbulent kinetic energy at higher angles of attack, as a result of which the stall also tends to be smoother.

From these findings, it is clear that at low angles of attack up to 10° , the roughness does not influence aerodynamic characteristics. The lift coefficient has also decreased by 44.68% and 48.29% for fine roughness (400 Grit) and coarse roughness (50 Grit), respectively, at a stall angle of $\alpha=10^\circ$. However, at higher angles of attack, roughness effectively enhances flow transition and reattachment, compared to the baseline. Further analysis can be conducted by introducing different gradations of roughness at various locations to effectively demonstrate how roughness can be utilized for improved passive flow control in wind turbine applications.

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