Experimental Investigations on the Performance Degradation of a Low-Reynolds-Number Airfoil with Distributed Leading Edge Roughness

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Modern wind turbines usually suffer unexpected power losses after long operating periods due to the contaminations accumulated at the leading edge of blades. In order to investigate the underlying physics, experiments were conducted to study the performance degradation of low-Reynolds-number airfoils induced by distributed leading edge roughness. Roughness was simulated by precisely manufactured plastic strips with different roughness height and distribution patterns. Both force and PIV measurements were performed under selected experimental conditions. Considerable reductions of lift coefficients were found for all roughness cases. While small roughness tends to delay the stalling angle, large roughness significantly advanced the aerodynamic stall. Hysteresis effects were also eliminated by applying roughness to the leading edge. Detailed PIV results revealed that small roughness tends to stabilize the boundary layer flow and delay the airfoil stall, whereas large roughness could cause earlier airfoil stall at a smaller angle of attack. In addition, comparing to distribution patterns, the roughness height was found to be a more essential factor for roughness induced performance degradation.

Nomenclature

\[ C_L = \text{Lift coefficient} \]
\[ C_D = \text{Drag coefficient} \]
\[ C_p = \text{pressure coefficient} \]
\[ K = \text{Roughness height} \]
\[ Re_{kc} = \text{Critical roughness Reynolds number} \]
\[ T.K.E = \text{Turbulent kinetic energy} \]
\[ AOA = \text{Angle of attack} \]

I. Introduction

Modern wind turbines are usually exposed to a variety of complicated natural conditions. Inevitable leading edge contaminations due to insect debris, sand accumulation and ice accretion can cause large-scale degradation of performance in power output, particularly for stall-regulated turbine rotors. Corten and Veldkamp verified that the accumulated insect debris on the leading edge of wind turbine blades is responsible for nearly 25% power losses reported on wind farms in California. They indicated the major reason for the power loss can be attributed to the fact that the insect contamination formed in low wind speed, disturbed the suction peak in high wind speed and advanced aerodynamic stall. Khalfallah and Koliub investigated the leading edge dust accumulation effects of a real 300KW stall regulated HAWT in a dusty area of Egypt. They reported a 50% mean power loss nine months after cleaning the leading edge of the turbine blades. Significant performance degradation can be also introduced by larger scale icing problems. Comparing to insects and sand, ice accretion and its aerodynamic effects to both the aircraft flight and wind turbine operation have been extensively studied during last few decades. Previously published data have shown that leading edge icing give rise to a large and premature separation on the suction side of the airfoil. The performance degradation of a certain airfoil is dependent on the ice shape, accretion height and accretion location. It was found that the critical location that ice could significantly degrade the
Aerodynamic performance is around the point of maximum adverse pressure gradient, while extended icing area on the suction surface would actually increase the maximum lift coefficient. It is widely accepted that the characteristics of laminar separation bubbles have a significant impact on the aerodynamic performance of a low Reynolds airfoil. The laminar boundary layer flow separates from the surface due to a large adverse pressure gradient. Because of the well-known Kelvin-Helmholtz instability, the separated boundary layer flow would rapidly transit to turbulence, and then reattach to the airfoil surface as a turbulent boundary layer when the adverse pressure gradient over the airfoil surface is adequate. For an airfoil with a clean surface and moderate free-stream disturbance, such boundary layer transition usually happens due to the gradual development of Tollmein-Schlichting (T-S) waves led by the viscous nature of the flow. The linearized waves grow to non-linear three dimensional instabilities and eventually break down to fully turbulent randomness. With different kinds of roughness introduced to the leading edge, the transition behavior is known to be altered as a result of changes of underlying mechanism. Two-dimensional isolated spanwise roughness has been extensively investigated since 1970s. The vast existing evidences have verified that the premature transition is triggered by the amplification of T-S waves in the large separation region behind the roughness. Three-dimensional isolated roughness was found to produce relatively less amplification of T-S waves, and the interactions between roughness and the transition is largely dependent on critical roughness Reynolds number (defined as $Re_{k} = k u_{k} / \nu$, where $k$ is the roughness height). When local $Re_{k}$ is smaller than $Re_{k_c}$, horseshoe vortices were found directly behind the isolated roughness. As the $Re_{k}$ increases and exceeds $Re_{k_c}$, hairpin vortices will be shed periodically from the roughness element and eventually break down to smaller vortices to start turbulence. Additionally the value of $Re_{k}$ was found to be quite different from one research to another, depending on the specific surface geometry they used. For instance roughness on flat plates have a $Re_{k_c}$ around 550, while increasing to as high as 1500 using NACA 0012 airfoil.

While a certain agreement among researchers has been reached on isolated roughness effects, the transition mechanism induced by distributed leading roughness, to some extent, still remains unknown. Early studies on distributed roughness effect have shown both experimentally and numerically that the transition is not simply a result of the T-S mechanism. Kerho and Bragg argued that the transition mechanism is markedly different from the natural transition process which is governed by T-S waves. They found the fully turbulent boundary layer, instead of being switched on near the roughness, occurs at least 30% chord behind the roughness location. Further efforts are still needed to elucidate the underlying relationships between isolated and distributed roughness, and determine the real mechanism which controls the interactions between the boundary layer and the distributed roughness.

Associated with wind turbine efficiency, the studies on leading edge roughness effects are of great importance. Preceding studies in past decades have revealed a detailed picture about how surface roughness effects impact the fluid flow from different perspectives. However, to the authors’ knowledge, very few could be found to elucidate the distributed leading edge roughness influences on the flow characteristics around low-Reynolds number airfoil by conducting full-field visualization measurement. In this study, a high-resolution PIV measurement combined with surface pressure measurements on a typical low-Reynolds number airfoil GA(W)-1 have been conducted to investigate the different flow patterns induced by different distributed leading edge roughness on the suction surface. The roughness was simulated using four types of precisely fabricated plastic strips with distinct roughness height and distribution patterns. The purpose of this experimental study is to quantitatively verify the performance changes of a low-Reynolds-number airfoil due to different leading edge roughness and to improve the understanding of the fundamental physics of this complicated phenomenon.

II. Experimental Setup and Procedures

The experiments were performed in a closed-circuit low-speed wind tunnel located in the Department of Aerospace Engineering in Iowa State University. The tunnel has a test section with a 1.0 ft × 1.0 ft (30 cm × 30 cm) cross section and optically transparent walls. The tunnel has a contraction section upstream of the test section with honeycomb, screen structures, and cooling system installed ahead of the contraction section to provide uniform low turbulent incoming flow to enter the test section.

Figure 1 shows the geometry and the pressure tap locations of the airfoil used in the present study. Compared with standard NACA airfoils, the GA (W)-1 airfoil was specially designed for low-speed general aviation applications with a large leading-edge radius in order to flatten the peak in pressure coefficient near the airfoil nose to discourage flow separation. The testing airfoil model has a chord length of 0.101m, with a thickness of 17% chord.
length. The airfoil model was equipped with 43 pressure taps at its median span with the spanwise length of the airfoil being 1.0 ft.

During surface pressure measurements, 43 pressure taps were connected to three 16 channels pressure acquisition equipment (model DSA3217, Scanivalve Corp) by Tygon tubings. The DSA3217 digital sensor arrays incorporate temperature compensated piezo-resistive pressure sensors with a pneumatic calibration valve, RAM, 16 bit A/D converter, and a microprocessor in a compact self-contained module. The precision of the pressure acquisition system is ± 0.2% of the full scale (± 10 inch H2O). During the experiment, each pressure transducer input was scanned at 400 Hz for 20 seconds.

Leading edge roughness was simulated by thin plastic strips with roughness elements which were precisely fabricated using a rapid prototyping machine. The roughness elements were designed to be of hemispherical shape. In order to investigate different factors that could possibly affect the results, four different roughness patterns (two roughness heights and two distribution patterns) were designed to compare with the clean leading edge case, as shown in Figure 2:

- Aligned, roughness height 250 micron, k/c=0.0025 (a250)
- Aligned, roughness height 500 micron, k/c=0.005 (a500)
- Staggered, roughness height 250 micron, k/c=0.0025 (s250)
- Staggered, roughness height 500 micron, k/c=0.005 (s500)

As shown in Figure 1, 5% chord length from the leading edge was covered in order to get most evident effects according to the results of previous studies. Measurements were conducted under 3 different Re numbers: 78,000(11m/s), 169,000(24m/s), 260,000(37m/s); and 10 different angles of attack (AOA) from 0 deg. to 18 deg. at each Re number case. Moreover, in order to get an understanding of how hysteresis phenomenon changes with different Re numbers and leading edge roughness, pressure data were taken twice with different directions to adjust the AOA, i.e. gradually increasing and decreasing AOA.

From the pressure acquisition system, pressure coefficients can be easily obtained and mapped. Because the applied roughness strips were carefully trimmed along the spanwise direction, it is reasonable to assume a two-dimensional flow around the test airfoil. The lift and drag coefficients, C_L and C_D, were determined by numerically integrating the pressure distribution around the airfoil. It should be noted that using this calculation method can lead to an underestimation of C_D as the frictional drag could not be represented by the pressure distribution. However, higher AOAs (near stalling angle), where pressure drag is dominant, are the real investigating targets of the present study. Therefore, this “systematic error” is believed to be negligible of the present study.

In order to discover more detailed information, several cases with Re=169,000 (24m/s), at 12, 14, 15, 16, and 18 degrees AOA were selected to be further studied using a PIV technique. Figure 3 shows the schematic of the experimental setup used for the PIV measurements. The test airfoil was installed in the middle of the test section. A PIV system was used to make flow velocity field measurements along the chord at the middle span of the airfoil. The flow was seeded with 1-5 μm oil droplets. Illumination was provided by a double-pulsed Nd:YAG laser (NewWave Gemini 200) adjusted on the second harmonic and emitting two laser pulses of 200 mJ at a wavelength of 532 nm with a repetition rate of 10 Hz. The laser beam was shaped to a laser sheet (thickness ~1 mm) by using a set of mirrors, spherical and cylindrical lenses. A high resolution (2048×2048 pixels, Cooke Corp.) charge-coupled device (CCD) camera was used for PIV image acquisition with its axis perpendicular to the laser sheet. The CCD
camera and the double-pulsed Nd:YAG lasers were connected to a workstation via a digital delay generator, which controlled the timing of the laser illumination and the image acquisition.

The CCD camera was focused to a measurement window of 95×65 mm size in order to capture all transition information on the suction surface. Instantaneous PIV velocity vectors were obtained by a frame to frame cross-correlation technique involving successive frames of patterns of particle images in an interrogation window with 32×32 pixels. An effective overlap of 50% was employed to satisfy the Nyquist criterion. After the instantaneous velocity vectors were determined, spanwise vorticity could be derived. The time-averaged quantities such as mean velocity, turbulent velocity fluctuations and normalized turbulent kinetic energy, and Reynolds stress distributions were obtained from a cinema sequence of 500 frames of instantaneous velocity fields for each case. The measurement uncertainty level for the velocity vectors is estimated to be within 2.0%, and that of the turbulent velocity fluctuations and turbulent kinetic energy are about 5.0%. The uncertainty level of the spanwise vorticity data is expected to be within 10.0%.

III. Pressure and Force Measurement Results

A. Lift and Drag

Lift and drag coefficients versus different AOAs at different free-stream Re numbers are presented in Figure 4. For the sake of clarity, only increasing AOA branch results are shown here. It is clearly revealed that the leading edge roughness indeed have a great influence on the overall aerodynamic performance of the low-Reynolds-number airfoil. At a relatively low Reynolds number (Figure 4a), a considerable amount of drop of lift coefficients were found in all the cases that applied leading edge roughness. Particularly, the maximum lift coefficient drops from 1.1 to about 0.9 (about 18%) in all four leading edge roughness cases. Slightly increased drag was also found near the stall angle region. In spite of the apparently changed lift-to-drag ratio, the angles of attack at which aerodynamic stall happens were not influenced too much after applying the leading edge roughness. All of these cases stall at 13 degree under Re=78,000 according to Figure 4a. As the Reynolds number increased to 169,000, significantly distinct flow behaviors were generated due to different leading edge roughness. In the clean case, the maximum lift coefficient increases prominently to 1.3 and stall was delayed to 16 degree compared with those under Re=78,000. For the case of 250 micron leading edge roughness, although the lift coefficients were still reduced significantly from the clean case, it kept increasing within the range of investigated angles of attack without an abrupt drop, which indicates the 250 micron leading edge roughness help prevent the stall from happening before 18  degree. On the contrary, 500 micron leading edge roughness triggered a much earlier stall at 12 and 13 degrees (staggered and aligned patterns respectively). Meanwhile, an even larger reduction (38%) on lift coefficients was also induced by the rougher leading edge condition. When Reynolds number was at 260,000 (Figure 4c) changes of lift and drag coefficients became much milder for the clean case. Gently dropping lift coefficient at larger angles of attack indicates a trailing edge stall, instead of abrupt leading edge stall, was gradually formed. Same tendencies were found for roughness cases. While small roughness tends to improve the performance of the airfoil over large angles of attack, the larger roughness brings opposite effects will lead to severe lift degradation and advanced stall.
Generally, different roughness distribution patterns, i.e. aligned or staggered, have similar effects for both 250 and 500 micron cases. From Figure 4, it is difficult to identify which pattern could induce more performance degradation. However, it is safe to believe that the roughness height is a more dominant parameter to determine whether or not the leading edge roughness will negatively affects the aerodynamic performance of the airfoil. One would suspect that there exists a critical roughness height which lies in between the positive and negative effects. In the present study, the critical roughness height was speculated, associated with a critical roughness Reynolds number ($Re=550$) suggested by previous researchers\textsuperscript{13}, to be around 330 micron. This assumption corresponds well with the results of current experiment and could be used as a rough indicator of the roughness induced aerodynamic performance.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{$C_L$ and $C_D$ profiles vs. angles of attack}
\end{figure}

\begin{itemize}
\item[a.] $Re=78,000$
\item[b.] $Re=169,000$
\item[c.] $Re=260,000$
\end{itemize}

**B. Pressure Distribution**

Discussions on the lift and drag coefficients suggested that all the cases start to behave differently only at a larger Reynolds number. Therefore the second case with $Re=169,000$ was selected as the target for further examination of the distinct influence induced by different leading edge roughness. Figure 5 shows the pressure coefficient distributions at five different critical AOAs, namely 12, 14, 15, 16 and 18 degrees. For the clean leading edge case, plateau regions near the leading edge could clearly be seen from 5% chord to 10%-15% chord positions. These plateau regions represent separation bubbles are formed due to the curvature of the leading edge shape. The boundary layer flow separates from the surface and quickly goes into transition due to the Kelvin-Helmholtz instability of the free shear flow. The turbulent boundary layer then reattaches to the surface and then the adverse pressure gradient is recovered from the reattaching point. Because of the better sustainability of the bubble-induced turbulent boundary layer, the adverse pressure gradient could be well maintained over the whole chord length on the suction surface up to 15 degree. When the AOA was increased to 16 degree, a constant pressure distribution was observed after 60% chord representing the turbulent separation has moved forward from the trailing edge, which...
gives rise to a moderate increase of drag coefficient as shown Figure 4b. However, since the pressure gradient still retains from the leading edge to 60% chord position and the suction peak becomes even more prominent, the lift coefficient actually further increased to a maximum value. At 18 degree, pressure coefficients on the suction surface suddenly collapsed to a flat line which implies the burst of the separation bubble. Due to the large leading edge curvature at large angle of attack, natural transition of the free shear flow could not provide the turbulent boundary layer sufficient energy to reattach to the surface. Such phenomenon is a typical leading edge separation for a moderate thick airfoil at low Reynolds number.

Fig. 5: $C_p$ distributions at AOA=12, 14, 15, 16, 18 degrees, Re=169,000.
As can be seen in Figure 5b, 5c, 5d and 5e, the most pronounced characteristic of these curves is that the suction peaks were significantly reduced and flattened due to the existence of the leading edge roughness. The considerable
drop of peak pressure coefficients is directly responsible for the decrease of the lift for all of these four cases as shown in Figure 4. For the 250 micron roughness cases (Figure 5b and 5c), pressure coefficient profiles over the suction surface stayed fairly constant in shape with the changing angles of attack, which suggest that no abrupt leading edge separation occurs within the range of 18 degree. Note that for the a250 case at 18 degree, the aerodynamic stall still did not happen due to the well attached flow behind the leading edge, although the turbulent separation point has spread to almost 30% chord on the suction surface and leads to a moderate increase in drag. Interestingly, pressure plateaus could also be found in both 250 micron roughness cases, particularly for the s250 case, but it spanned slightly longer at a relatively rear position. It reveals that the separation bubble’s generation and boundary layer transition could possibly be postponed as a result of 250 micron roughness at the leading edge. For the 500 micron roughness cases (Figure 5d and 5e), relatively flat pressure distributions were formed over 5% chord region from the leading edge, followed by sharp pressure recovery after that point. No separation bubbles were found in both cases. This means the boundary layer transition was purely induced by the disturbances of the leading edge roughness, rather than the Kelvin-Helmholtz instability introduced by a separation bubble. Without the burst of laminar separation bubble, the stall actually develops gradually as the turbulent separation point moves from the trailing edge to the leading edge. Deep stall occurred when AOA= 18 for a500 case and AOA=16 for s500 case.

C. Hysteresis

The aerodynamic coefficients of a low-Reynolds-number airfoil at the same AOA will not necessarily remain the same if adjusting the angle of attack from different directions, i.e. increasing or decreasing. As can be seen in Figure 6a, for a clean airfoil, stall will not happen until the angle of attack exceeds 16 degree on the increasing branch of hysteresis loop. However, reversely changing AOA from 18 to 0 will not follow the same trace of the increasing branch. Illustrated by Figure 6b, 6c, 6d, and 6e, on the contrary, lift coefficients curves matched together tightly and the hysteresis effect was vanished after applying leading edge roughness to the same airfoil. Widely investigated by previous researchers, the hysteresis phenomenon is known to be closely related to the formation and burst of the leading edge laminar separation bubble.\(^{19}\) For the 500 micron roughness cases, large leading edge disturbances lead to the absence of the laminar separation bubble, which then consequently eliminates the hysteresis effects. As for the 250 micron roughness cases, although an even longer bubble could possibly form on the suction surface, the pressure coefficient distributions imply that the separation bubble did not burst within 18 degree angle of attack and no large leading edge stall happened in both a250 and s250 cases. As a result, the smaller leading edge roughness could also eliminate the hysteresis effects within the range of investigated angles of attack.

IV. PIV Measurement Results

A. Instantaneous and ensemble-averaged velocity distributions

PIV measurements were conducted to elucidate the flow details induced by different leading edge roughness. For each of the leading edge condition, five angles of attack (12, 14, 15, 16, 18 deg.) were selected corresponding to the previous pressure measurements results. Without losing necessary information, Figure 7, 9, 10 only show the instantaneous and ensemble-averaged velocity fields at 12, 15 and 18 degrees for the sake of brevity. As shown in Figure 7, thin negative vorticity layers, which was caused by viscous shear within the boundary layer, remained well attached to the upper surface for all five cases, implying aerodynamic performance is not worsened too much by leading edge roughness at relatively lower angle of attack. Specifically, it could be revealed from instantaneous velocity fields that the thin vortex layers start to break away from the surface at about 70% chord for the clean, a250 and s250 cases. Corresponding ensemble-averaged velocity fields depict some low horizontal velocity regions at the trailing edge representing small-scale turbulent separation have occurred. Comparing to the former three cases, a500 and s500 roughness advance the break-away points to around 60% chord as shown by Figure 7d and 7e. Even larger “recirculation” regions shown in ensemble-averaged pictures indicate a more severe turbulent separation could be triggered due to the rougher leading edge disturbance even at a small angle of attack. Moreover, examining the animation of the instantaneous flow fields in time sequence (which could not be demonstrated here,) it clearly shows that the vorticity layer of s500 case fluctuates more vibrantly over the mid chord surface than a500 case does. Meanwhile, the free shear layer of the s500 case seems to be lifted up more from the upper surface, which could also be identified from the ensemble-averaged flow field. These characteristics of the vorticity layer could lead to an increase of the sensitivity to the change of AOA. Hence it is reasonable to speculate that staggered pattern of 500 micron roughness might have more negative influence on the aerodynamic performance of this airfoil. The features illustrated by the PIV results above agree quite well with the pressure distributions discussed in the previous section.
Fig. 8a shows the streamline patterns over a clean airfoil at 12 degree. Flow took off at about 5% chord from the leading edge and then landed on the surface again at less than 20% chord position. This visually captured bubble shape corresponds well with the pressure plateau shown in Figure 5a. As discussed previously, separation bubbles were also found in the 250 micron roughness cases but at a rear location and spans longer chord length than the clean case. As can be seen from Figure 8b, a separation bubble covering nearly 15% chord length also shows good agreements with the pressure coefficient distributions in previous sections.

Figure 9 displays the velocity fields as the AOA was changed to 15 degree. In Figure 9a, it is quite clear that the turbulent separation point at the trailing edge of the clean airfoil has moved forward significantly as compared to the 12 degree case. Further inspections on the time sequence of the instantaneous velocity fields reveal that the vorticity layer over the upper surface became quite unstable at this angle of attack. In contrast to the clean case, the cases with 250 micron leading edge roughness, as suggested by instantaneous velocity fields, could sustain a rather stable vorticity layer over the leading edge region. The low horizontal velocity regions in ensemble-averaged fields of the 250 micron roughness cases were also apparently smaller than the clean case. This could be attributed to the fact that the stably attached vorticity layer at the leading edge constrains the vortices shedding of the turbulent separation within a relatively smaller region than the wandering vorticity layer of the clean case. While 250 micron roughness tends to improve the flow condition over the upper surface, 500 micron roughness could induce a completely negative influence. As displayed by Figure 9d and 9e, flow separated directly from the leading edge roughness position and large separation region behind the airfoil has been developed, indicating a premature stall has occurred.
The flow was also characterized as periodically shedding vortices from the leading edge, but again the S500 triggered more shear layer fluctuations in space as indicated by the animations of instantaneous velocity fields.

Fig. 8: Streamlines and separation bubbles at AOA=12 degree. (Left: Clean, AOA= 12 degree, Re=169,000; Right: S250, AOA=12 degree, Re=169,000)
Increasing the AOA to 18 degree, as shown in Figure 10, both the clean case and the 500 micron cases moved into deep stall status. Flow completely separated from the upper surface, corresponding to a flat pressure distribution shown in Figure 5. Nevertheless, for both a250 and s250 cases, flow still followed the curvature of the suction
surface quite well and the velocity fields did not change too much comparing with those at 12 degree and 15 degree. The animation of the instantaneous flow fields reveals that the flow over the leading edge is considerably stabilized due to the existence of the 250 micron roughness.

In summary, PIV investigations on the velocity fields suggest that significantly delayed stall and considerable boundary layer stabilization could be obtained by adding reasonably small roughness elements to the leading edge region. However, opposite effects, such as advanced stall, could be generated if using larger size roughness elements instead.

![Images of flow fields for different roughness conditions: (a) clean, (b) a250, (c) s250]
Fig. 10. Instantaneous (left) and ensemble-averaged velocity (right) fields at AOA= 18 degree, Re=169,000. Contours represent magnitude of vorticity in instantaneous fields and U velocity in ensemble-averaged fields respectively.

B. Normalized Turbulent Kinetic Energy

Figure 11 presents the normalized turbulent kinetic energy distribution for five different cases at 12 and 18 degree angle of attack. At a smaller AOA, for a clean airfoil, a locally high T.K.E. region could be found over the leading edge due to the sharp curvature of the geometry shape. The T.K.E. contour continuously grew after the leading edge indicating a turbulent boundary layer was formed after the leading edge bubble. Interestingly, if 250 micron roughness was applied to the leading edge, the T.K.E. introduced at the leading edge would decrease remarkably and its distribution becomes less continuous as well (Figure 11b, 11c, left). This might suggest that the 250 micron roughness at the leading edge, instead of injecting more fluctuating energy into flow around the airfoil, actually has a stabilizing effect. For the 500 micron roughness cases, Figure 11d and 11e reveal that much higher T.K.E flow above the leading edge were induced immediately after the roughness positions, followed by continuously distributed T.K.E. bands. It should be noted that 500 micron leading edge roughness not only added more kinetic energy into the flow, but also slightly lifted up high T.K.E. flow from the upper surface. The flow, although could transition into turbulence faster, is more sensitive to changing angle of attack and need to entrain more energy to reattach to the surface.

At 18 degree, flow completely separated from the clean airfoil and a large T.K.E band was found to break away directly from the leading edge. Same situations were found for the 500 micron roughness cases. The wider distributions of T.K.E in the wake could be explained that the vortices shedding from the leading edge have a wandering motion in the wake due to the roughness disturbances. Higher T.K.E induced by staggered patterns shown in Figure 11 could also sufficiently verify the conclusion made by observation in the instantaneous velocity fields that the staggered pattern could have more negative effects on aerodynamic performance than the aligned
pattern. However, for the 250 roughness cases, nicely attached T.K.E. contours were revealed in Figure 11b and 11c. Turbulent flow did not separate from the surface until reaching around 50% chord, where obvious turbulent separation occurred due to the unsustainable adverse pressure gradient.

Fig. 11: Normalized Turbulent Kinetic Energy Contours. (Left: 12 degree; right: 18 degree.)
Fig. 12: Normalized Reynolds Stress Contours. (Left: 12 degree; right: 18 degree.)
C. Normalised Reynolds Stress

Normalized Reynolds stress contours for five cases at 12 and 18 degrees are presented in Figure 12. At AOA=12 degree the starting point of the Reynolds stress contour, representing the transition starting point, of the clean case was at about 17% chord. This is corresponding to the free shear induced transition above a laminar separation bubble and could match to the ending point of the pressure plateau in Figure 5a. By applying 250 micron roughness, the transition starting points moved backward remarkably to 33% and 25% chord for the a250 and s250 cases respectively, which could be closely related to the location and strength change of the separation bubble corresponding to the pressure plateau in Figure 5b and 5c. The magnitude of Reynolds stress was also found to be reduced, meaning a weaker turbulent flow reattaches to the surface than in the clean case. For the 500 micron roughness cases, transition starting points remained almost the same. However, the magnitude of Reynolds stress is larger, particularly for the s500 case, and the contours were found to be lifted up away from the surface as compared to the other cases, similar to the discussions for T.K.E. contours. Reynolds stress contours at 18 degree follow the similar fashion of the T.K.E. contours in Figure 11. High Reynolds stress regions were found in both 250 micron cases at about 50% chord, indicating well attached flow from the leading edge to that point. For the clean and the 500 roughness cases, larger Reynolds stress lies in the wake region meaning great reverse flow happens in the wake. Relatively larger Reynolds stress in the wake of the s500 case again illustrate a more fluctuated vortex shedding could be induced by the staggered pattern.

V. Concluding Remarks

Pressure measurements combined with PIV measurements on a low-Reynolds-number airfoil with different leading edge roughness conditions were conducted to investigate the underlying mechanisms of roughness induced performance degradation. Pressure measurements were performed at 10 different angles of attack from 0 to 18 degrees and 3 different Re numbers. Then detailed flow field information was examined by PIV measurement. Conclusion from the experiments could be summarized as follows:

- Pressure measurement results have proved that considerable reduction of lift could be caused due to the existence of leading edge roughness. At Re=78,000, the reduction of maximum lift is about 18% for all four roughness cases. With increasing Reynolds number, this reduction will be even larger. Particularly for the 500 micron roughness cases, it will reach 38%.

- Compared with the case with clean airfoil, 250 micron roughness tends to delay stalling angle to larger than 18 degree, whereas 500 micron roughness could induce a significantly advanced stall to 12 or 13 degree.

- Hysteresis effect was found to be eliminated for both 250 and 500 micron roughness cases due to the change or elimination of laminar separation bubble.

- Instantaneous and ensemble-averaged velocity fields show agreement with the pressure measures results. Large separation was found at AOA=18 for the 500 micron roughness cases and at AOA=18 for the clean case, while flow remain well attached at AOA=18 for the 250 micron roughness cases.

- PIV results suggest that 250 micron roughness tends to stabilize the laminar boundary flow and induces a late transition to turbulence. On the contrary, 500 micron roughness tends to promote the transition and lifts up the turbulent flow from the surface, which might increase the sensitivity of the boundary layer to the changing of angle of attack.

- Finally, although staggered patterns were found to induce a bit more fluctuations of the shedding vorticity layer, the size of the roughness element was verified to be more of an essential factor for this problem. Further studies could be performed to determine the critical roughness Reynolds number based on the roughness heights of different low-Reynolds-number airfoils.

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