An Experimental Study of Stall Hysteresis of a Low-Reynolds-Number Airfoil

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An experimental study was conducted to investigate static stall hysteresis of a NASA GA(W)-1 airfoil at the chord Reynolds number of $Re = 162,000$. In addition to mapping the surface pressure distribution around the airfoil, a digital PIV system was used to make detailed flowfield measurements to quantify the occurrence and behavior of laminar boundary layer separation and transition on the airfoil when static stall hysteresis occurs. The measurement results revealed clearly that, for a same angle of attack in the hysteresis loop, incoming flow streams were found to be able to attach to the airfoil upper surface in general with a thin separation bubble formed near the airfoil leading edge when the angle is at the increasing branch of the hysteresis loop. The attached flow pattern resulted in higher lift and lower drag acting on the airfoil as well as a lower Reynolds stress level and smaller unsteadiness in the wake of the airfoil. When the angle of attack is at the decreasing branch of the hysteresis loop, the laminar boundary layer was found to separate from the airfoil upper surface for good at a location very near to the airfoil leading edge. The turbulence transition of the separated laminar boundary layer was found to take place rapidly accompanied by periodical shedding of strong Kelvin-Helmholtz vortex structures in the wake of the airfoil. Large-scale flow separation was found to take place on almost the entire upper surface of the airfoil. As a result, the lower lift and higher drag acting on the airfoil were found with Reynolds stress and turbulence kinetic energy levels in the wake of the airfoil increased significantly. The present study elucidates quantitatively that static stall hysteresis of a low-Reynolds number airfoil is closely related to the behavior of laminar boundary layer separation and transition on the airfoil. The ability of the flow to remember its past history is responsible for the stall hysteretic behavior.

1. Introduction

A number of military and civilian applications require efficient operation of airfoils in low chord Reynolds numbers. The applications include propellers, sailplanes, ultra-light man-carrying/man-powered aircraft, high-altitude vehicles, wind turbines, Unmanned Aerial Vehicles (UAVs) and Micro-Air-Vehicles (MAVs). It is well known that many significant aerodynamic problems occur for low-Reynolds number airfoils (Carmichael, 1981). Stall hysteresis, a phenomenon where stall inception
and stall recovery do not occur at the same angle of attack, has been found to be relatively common in low-Reynolds-number airfoils. When stall hysteresis occurs, aerodynamic characteristics of an airfoil become history dependent, i.e., dependent on the sense of change of the angle of attack. The coefficients of lift, drag, and moment of the airfoil are found to be multiple-valued rather than single-valued functions of the angle of attack. Stall hysteresis is of practical importance because it produces widely different values of lift coefficient and lift-to-drag ratio for a given airfoil at a given angle of attack. It could also affect the recovery from stall and/or spin flight conditions. Whereas stall hysteresis associated with the pitching motion of airfoils (also known as dynamic stall) has been investigated extensively as summarized in the review article of McCorskey (1982), the stall hysteresis phenomena observed for static stall of an airfoil have received much less attention.

A good physical understanding is essential in order to provide guidance to minimize the detrimental effects of stall hysteresis for improved aerodynamic performance of low-Reynolds-number airfoils. This requires a detailed knowledge about stall hysteresis and associated flow behavior around the airfoil. Pohlen & Mueller (1984) and Mueller (1985) investigated the aerodynamic characteristics of Miley M06-13-128 and Lissaman 7769 airfoils at low Reynolds numbers, and found both airfoils produced stall hysteresis loops in the profiles of measured lift and drag forces when they operated below chord Reynolds numbers of 300,000. Based on qualitative flow visualization with smoke, Mueller (1985) suggested that airfoil hysteresis is related to laminar boundary layer transition and separation on the airfoils. Marchman (1987) conducted a systematic study of the aerodynamic characteristics of a Wortmann FX63-137 airfoil at Reynolds numbers between 50,000 and 500,000, and found that stall hysteresis behavior is very dependent on wind tunnel flow quality and acoustic properties. Hoffmann (1991) studied the aerodynamic characteristics of a NACA 0015 airfoil at a chord Reynolds number of 250,000, whereby the stall hysteresis loop was observed in the measured coefficients of lift and drag. Hoffmann (1991) also revealed that stall hysteresis could be observed for low free stream turbulence cases (up to ~2% turbulence intensity) but disappeared for high free stream turbulence cases. Biber & Zumwal (1993) and Biber (2005) reported that stall hysteresis phenomena occur for not only single-element airfoils but also multi-element airfoil configurations such as a GA(W)-2 airfoil equipped with a 25% slotted flap. Landman & Britcher (2001) reported similar results in wind-tunnel tests of a three-element airfoil. Mittal & Saxena (2002) conducted a numerical study to predict the aerodynamic hysteresis near the static stall angle of a NACA 0012 airfoil in comparison with the experimental data of Thibert et al. (1979).

Although much useful information has already been uncovered by those studies, the majority of the previous experimental studies were conducted based mainly on measuring overall aerodynamic forces and/or moments acting on airfoils, detailed flow field measurements have never been carried out to quantify the occurrence
and behavior of laminar boundary layer separation and transition on the airfoil when stall hysteresis occurs. Very little can be found in literature to bring to light the relation between the static stall hysteresis phenomena observed in the measured aerodynamic (lift, drag and moment) coefficients with the flow pattern and behavior of vortex and turbulent flow structures around the airfoils. In the present study, we conducted a detailed experimental study to investigate stall hysteresis of a GA(W)-1 airfoil at the Reynolds number of \( Re = 162,000 \). In addition to mapping surface pressure distribution around the airfoil with pressure sensors, a digital particle image velocimetry (PIV) system was used to make detailed flow field measurements to quantify the occurrence and behavior of laminar boundary layer separation and transition on the airfoil when stall hysteresis occurs. The detailed flow field measurements were correlated with the airfoil surface pressure measurements to demonstrate underlying fundamental physics associated with the stall hysteresis observed in the measured aerodynamic (lift and drag) coefficient profiles. To the best knowledge of the authors, this is the first effort of its nature. The primary objective of the present study is to gain further insight into the fundamental physics of stall hysteresis of low-Reynolds-number airfoils through detailed flow field measurements. In addition, the quantitative measurement results will be used as the database for the validation of computational fluid dynamics (CFD) simulations of such complicated flow phenomena for the optimum design of low-Reynolds-number airfoils.

2. Studied Airfoils and Experimental Setup

The experiments were performed in a closed-circuit low-speed wind tunnel located in the Aerospace Engineering Department of 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.

![Fig. 1. GA(W)-1 airfoil geometry and pressure tap locations.](image-url)
Figure 1 shows the schematic of the airfoil used in the present study: a GA (W)-1 airfoil (also labeled as NASA LSF-1-8417). The GA (W)-1 has a maximum thickness of 17% of the chord length. 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 (McGee & Beasley, 1973). The chord length of the airfoil model is 101 mm, i.e., $C = 101$ mm, for the present study. The flow velocity at the inlet of the test section was $U_{\infty} = 24.3$ m/s, which corresponds to a chord Reynolds number of $Re = 162,000$. The turbulence intensity of the incoming stream was found to be within 1.0%, measured by using a hot-wire anemometer.

The airfoil model is equipped with 43 pressure taps at its median span with the spanwise length of the airfoil being 1.0 ft. The locations of the pressure taps are indicated in Fig. 2. The 43 pressure taps were connected by plastic tubing to 43 channels of a pressure acquisition system (model DSA3217, Scanivalve Corp). The DSA3217 digital sensor arrays incorporate temperature compensated piezoresistive 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 H$_2$O). During the experiment, each pressure transducer input was scanned at 400 Hz for 20 seconds. The pressure coefficient distributions, $C_p = (P - P_{\infty})/(\frac{1}{2}\rho U_{\infty}^2)$, around the airfoil at various angles of attack were measured by using the pressure acquisition system. The lift and drag coefficients, $C_l = l/(\frac{1}{2}\rho U_{\infty}^2 \cdot C_s)$ and $C_d = d/(\frac{1}{2}\rho U_{\infty}^2 \cdot C_s)$, of the 2-D airfoil were determined by numerically integrating the measured pressure distribution around the airfoil. It should be noted that the drag coefficient of an airfoil is composed of two parts, the pressure drag component (which comes from the fore and aft unbalance in the pressure distribution around the airfoil) and the skin friction component (which comes from the viscous surface stresses around the airfoil). At low angles of attack skin friction dominates the total drag while the pressure drag component is minor. At high angles of attack the reverse is true. Since skin friction drag component was ignored in the present study, as a result, the drag coefficient of the airfoil was underestimated. However, since stall hysteresis of an airfoil is usually found to occur at high angles of attack, the pressure drag component is significant and skin friction drag is negligible when stall hysteresis occurs.

Figure 2 shows the schematic of the experimental setup used for the PIV measurement. 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 µm oil droplets. Illumination was provided by a double-pulsed Nd:YAG laser (NewWave Gemini 200) adjusted to 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 into a sheet by a
set of mirrors, spherical and cylindrical lenses. The thickness of the laser sheet in the measurement region was about 0.5 mm. A 12-bit (1376 × 1040 pixel) CCD camera was used for PIV image acquisition with the axis of the camera perpendicular to the laser sheet. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a Digital Delay Generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition. In the present study, a careful pre-test, which included testing different seeding methods, applying different paints to the airfoil model, adjusting laser excitation energy levels, camera positions and optic lens arrangements, was conducted in order to minimize the reflection from the airfoil surface for the near wall PIV measurements.

In the present study, PIV measurements were conducted at two spatial resolution levels: a coarse level to visualize the global features of the flow pattern around the airfoil with the measurement window size being about 150 mm × 120 mm; and a refined level to reveal further details about the transient behavior of the laminar boundary layer separation and transition near the leading edge of the airfoil with a measurement window size of about 40 mm × 30 mm. The time interval between the double-pulsed laser illumination for the PIV measurements was set as ∆t = 20.0 µs and 4.0 µs. 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 of 32 × 32 pixels. An effective overlap of 50% was employed for PIV image processing. The effective resolutions of the PIV measurements (i.e., grid sizes) at two resolution levels were ∆/C = 0.018 and 0.0045 respectively. After the instantaneous velocity vectors \((u_i, v_i)\) were determined, the distributions of spanwise vorticity \(\dot{\omega}_z\) were derived as suggested by Abrahamson & Lonnes (1995). The time-averaged quantities such as mean velocity \((U, V)\), turbulent velocity fluctuations \((\overline{u'}, \overline{v'})\), normalized Reynolds stress \(\overline{\tau} = -\overline{u'v'}/U_\infty^2\) and
normalized turbulent kinetic energy \( T.K.E. = 0.5 \times (u'^2 + v'^2) / U_\infty^2 \) were obtained from a cinema sequence of 200 frames of instantaneous velocity fields.

3. Experimental Results and Discussions

3.1. Measured lift, drag and surface pressure coefficients

During the experiments, in order to eliminate the effect of the flow disturbances due to the change of airfoil angle of attack (AOA), measurement data were taken at about 5.0 minutes later after the airfoil was set to a pre-determined angle of attack. Figure 3 shows the profiles of the measured lift and drag coefficients versus angle of attack. Static stall hysteresis in the aerodynamic coefficients can be observed clearly for angles of attack lying between 12.0 and 16.0 degrees. With increasing angle of attack, airfoil stall was found to occur at AOA = 15.0 deg, while for the decreasing angle of attack it occurs at AOA = 12.0 deg. The hysteresis loop was found to be clockwise in the lift coefficient profiles, and counter-clockwise in the drag coefficient profiles. The stall hysteresis resulted in significant variations of lift coefficient, \( C_l \), and lift-to-drag ratio, \( l/d \), for the airfoil at a given angle of attack. For example, the lift coefficient and lift-to-drag ratio at AOA = 14.0 degrees were found to be \( C_l = 1.33 \) and \( l/d = 23.5 \) when the angle was at the increasing branch of the hysteresis loop. The values were found to become \( C_l = 0.8 \) and \( l/d = 3.66 \) for the same 14.0 degrees angle of attack when it was at the decreasing angle branch of the hysteresis loop.

Figure 4 shows the measured surface pressure coefficient distributions around the airfoil as the angle of attack of the airfoil changed from 12.0 to 17.0 degrees along both the increasing and decreasing branches of the hysteresis loop. When the angles of attack are out of the hysteresis loop (i.e., AOA \( \leq 12.0 \) degrees or AOA \( \geq 16.0 \) degrees), the measured surface pressure coefficient distributions around the airfoil for the same angles of attack were found to be single-valued and almost invariant in
spite of the angles that were reached along increasing or decreasing branches of the hysteresis loop. However, when the angles of attack are inside the hysteresis loop (i.e., $12.0^\circ < \text{AOA} < 16.0^\circ$ degrees), the surface pressure distributions on the airfoil lower surface do not change very much, but the surface pressure distributions on the airfoil upper surface were found to vary significantly for the same angles of attack with the angles being reached along the increasing branch of the hysteresis loop compared with those along the decreasing branch of the hysteresis loop. When the \text{AOA} = 13.0^\circ, 14.0^\circ and 15.0^\circ degrees are at the increasing branch of the hysteresis loop, the surface pressure coefficient profiles along the airfoil upper surface were
found to reach a negative peak rapidly at a location near the airfoil leading edge. The surface pressure then recovered over the airfoil upper surface, which is similar to the case with AOA = 12.0 degrees. A region of nearly constant pressure (i.e., “plateau” region) was found at the locations of $X/C \approx 0.05$ with a sudden increase in surface pressure following the “plateau” region. Further downstream when $X/C > 0.15$, surface pressure was found to recover gradually and smoothly. Such a feature of the surface pressure coefficient profiles is actually closely related to laminar boundary layer separation and transition, and formation of laminar separation bubbles on low-Reynolds-number airfoils.

Based on the original ideas proposed by Horton (1969), Russell (1979) developed a theoretical model to characterize laminar separation bubbles formed on low-Reynolds-number airfoils, which is illustrated schematically in Fig. 5. Russell (1979) suggested that the starting point of the pressure plateau indicates the location where the laminar boundary layer would separate from the airfoil upper surface (i.e., separation point). Since the transition of the separated laminar boundary layer to turbulence will result in a rapid pressure rise brought about by fluid entrainment, the termination of the pressure plateau could be used to locate the transition point (i.e., where the transition of the separated laminar boundary layer to turbulence would begin to occur). The pressure rise due to the turbulence transition often overshoots the inviscid pressure that exists at the reattachment location. Therefore, the location of the point of equality between the actual and inviscid surface pressure marks the location of reattachment (i.e., reattachment point).

![Fig. 5. Typical surface pressure distribution when a laminar separation bubble is formed.](image-url)
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Following the work of Russell (1979), the locations of critical points (separation, transition, and reattachment points) at different angles of attack can be estimated based on the measured airfoil surface pressure profiles. Based on the measured surface pressure distribution given in Fig. 4, the separation, transition, and reattachment points at $\text{AOA} = 14.0$ degrees along the increasing branch of the hysteresis loop were estimated to be located at $X/C \approx 0.05$, $X/C \approx 0.10$, and $X/C \approx 0.15$ respectively. The length of the laminar separation bubble (i.e., the distance between the separation and reattachment points) was found to be about 10% of the airfoil chord length.

When the airfoil angles of attack of $\text{AOA} = 13.0, 14.0$ and $15.0$ degrees are at the decreasing branch of the hysteresis loop, the negative pressure coefficient peak near the airfoil leading edge was found to decrease significantly, which is very similar to the cases with $\text{AOA} = 16.0$ and $17.0$ degrees. The surface pressure over the airfoil upper surface was found to be nearly constant. Such surface pressure distribution indicates that large-scale flow separation has occurred over almost the entire upper surface of the airfoil, i.e., the airfoil is in stall state (O’Meara & Muller, 1987, Lin, et al., 1996 and Yaruseych et al., 2006), which was visualized quantitatively by the PIV measurement results given in Fig. 7.

3.2. PIV measurement results

While the measurements of the surface pressure distributions and the lift and drag coefficients can be used to reveal global characteristics of static stall hysteresis of the low-Reynolds-number airfoil, quantitative flow field measurements taken by using the digital PIV system can reveal many more details about the significant differences in flow pattern and behavior of vortex and turbulent flow structures around the airfoil when stall hysteresis occurs. As aforementioned, PIV measurements were conducted at two spatial resolution levels for the present study: a coarse level to visualize the global features of the flow pattern around the airfoil; and a refined level to reveal further details about the transient behavior of the laminar boundary layer separation and transition near the leading edge of the airfoil.

Figure 6 shows the PIV measurement results of the flow field around the low-Reynolds-number airfoil at $\text{AOA} = 14.0$ degrees in terms of instantaneous velocity field, instantaneous vorticity distribution, ensemble-averaged velocity field, and streamlines of the mean flow field when the angle is at the increasing branch of the hysteresis loop. As visualized clearly from the PIV measurement results, incoming flow streams were found to be able to attach to the airfoil upper surface in general when the $14.0$ degrees angle of attack was at the increasing branch of the hysteresis loop. The measured surface pressure distributions shown in Fig. 4 revealed that a separation bubble would be generated on the airfoil upper surface in the region of $X/C = 0.05$–0.15. However, since the thickness of separation bubbles generated on low-Reynolds-number airfoils is usually very small, i.e., <1% of the chord length.
Fig. 6. PIV measurement results with AOA = 14.0 degrees at the increasing branch of the hysteresis loop.

(see Fig. 8), the separation bubble could not be revealed clearly from the PIV measurement results given in Fig. 6 due to the limited spatial resolution of the PIV measurements (i.e., Δ/C = 0.018). However, the existence of the separation bubble in the region of X/C ≈ 0.05−0.15 can still be seen vaguely from the distributions of the mean velocity vectors and corresponding streamlines. Since the incoming flow streams could attach to the airfoil upper surface in general, the wake region downstream of the airfoil is reasonably small. The small wake region indicates a relatively small aerodynamic drag force acting on the airfoil, which is consistent with the measured airfoil drag coefficient data given in Fig. 3.

Figure 7 shows the PIV measurement results when the 14.0 degrees angle of attack was at the decreasing branch of the hysteresis loop. The flow pattern around the airfoil was found to be completely different from that with the 14.0 degrees angle of attack at the increasing branch of the hysteresis loop. As visualized clearly from the instantaneous PIV measurement results given in Fig. 7(a) and Fig. 7(b), the laminar boundary layer (i.e., the thin vortex layer) affixing to the airfoil upper surface at the airfoil leading edge was found to separate from the airfoil upper surface for good at a location quite near the airfoil leading edge. Strong unsteady vortex and turbulent structures were found to shed periodically in the wake of the airfoil
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Fig. 7: PIV measurement results with AOA = 14.0 degrees at the decreasing branch of the hysteresis loop.

...after the separation of the laminar boundary layer. Both the mean velocity vectors and the corresponding streamlines reveal clearly that large-scale flow separation occurred on almost the entire upper surface of the airfoil, i.e., the airfoil is in a state of stall, when the 14.0 degrees angle of attack is at the decreasing branch of the hysteresis loop. Another interesting feature that can be identified from the distribution of the streamlines of the mean flow field is that the boundary layer, which separated from the airfoil upper surface near the airfoil leading edge, seems to try to reattach to the airfoil upper surface in the neighborhood of $X/C \approx 0.35$. However, the strong reversing flow from the airfoil trailing edge prevented the separated boundary layer from reattaching to the airfoil upper surface and kept the airfoil in stall state. Since the airfoil was in stall state before it was changed to AOA = 14.0 degrees along the decreasing branch of the aerodynamic hysteresis loop, the flowfield around the airfoil seems to be able to “remember” its past history (i.e., stall state) when the angle of attack was changed inside the hysteresis loop. The large-scale flow separation on the airfoil upper surface caused the generation of a very large circulation region in the wake of the airfoil, indicating a significant aerodynamic drag force acting on the airfoil. This was confirmed again from the measured drag coefficient data given in Fig. 3.

While the PIV measurement results given in Figs. 6 and 7 revealed clearly that the flow pattern and behavior of the vortex and turbulent flow structures around the airfoil with AOA = 14.0 degrees at the decreasing branch of the hysteresis loop...
were significantly different from those with the same angle of attack of 14.0 degrees at the increasing branch of the hysteresis loop, further details about the occurrence and transient behavior of the laminar boundary layer separation and transition near the leading edge of the airfoil could not be uncovered successfully due to the limited spatial resolution of the PIV measurements. Refined PIV measurements near the leading edge of the airfoil with much higher spatial resolution ($\Delta/C = 0.0046$)

Fig. 8. Refined PIV measurement results with $\theta = 14.0$ degrees at the increasing branch of the hysteresis loop.
were carried out in order to provide further insights into the underlying physics associated with stall hysteresis of the low-Reynolds-number airfoil. The refined PIV measurement results are shown in Fig. 8 and Fig. 9 with the same angle of attack of 14.0 degrees at the decreasing and increasing branches of the hysteresis loop, respectively.

When the 14.0 degrees angle of attack is at the increasing branch of the hysteresis loop, the laminar boundary layer was revealed clearly as a thin vortex layer
affixed to the airfoil upper surface from the instantaneous PIV measurement results shown in Fig. 8(a) and Fig. 8(b). The laminar boundary layer was found to attach to the airfoil upper surface near the airfoil leading edge, as it is expected. Because of the severe adverse pressure gradient on the airfoil upper surface at AOA = 14.0 degrees, as revealed from the surface pressure measurements given in Fig. 3, the laminar boundary layer (i.e., the thin vortex layer) was found to separate slightly from the airfoil upper surface, at first, then reattach to the airfoil upper surface at a downstream location, which results in the formation of a separation bubble between the separation point and the reattachment point. Time sequencing of instantaneous PIV measurements reveals clearly that, while the locations of the separation points and reattachment points varied dynamically from one frame to another, most of the separation points were found to be located at \( X/C \approx 0.05 \) and reattachment points at \( X/C \approx 0.15 \). The formation of the separation bubble can be seen more clearly from the ensemble-averaged velocity field and the streamlines of the mean flow field shown in Fig. 8(c) and Fig. 8(d). Based on the PIV measurement results, the ensemble-averaged location of the separation point (i.e., from where the streamlines of the mean flow separate from the airfoil upper surface) was found to be in the neighborhood of \( X/C \approx 0.05 \), which agrees reasonably well with the starting point of the pressure plateau in the measured airfoil surface pressure profile when the 14.0 degrees angle of attack is at the increasing branch of the hysteresis loop. The ensemble-averaged PIV measurement results also revealed that the reattachment point (i.e., where the separated streamline would reattach to the airfoil upper surface) was in the neighborhood of \( X/C \approx 0.15 \), which also agrees with the estimated location of the reattachment point based on the airfoil surface pressure measurements. While the total length of the separation bubble was found to be about 10% of the airfoil chord length, the separation bubble was found to be very thin, with its height only about \( \sim 1\% \) of the chord length.

Figure 8(e) shows the distribution of the measured normalized Reynolds stress \( (-u'v' / U_\infty^2) \). It should be noted that only the contour lines of the normalized Reynolds stress above a critical value of 0.001 are shown in the Fig. 8(e). This critical value has been chosen in the literature to locate the onset of the turbulent transition in separated shear layers (Ol et al., 2005, and Burgmann et al., 2006 and 2007). Following the work of Ol et al., (2005) and Burgmann et al., (2007), the transition onset position was estimated as the streamwise location where the normalized Reynolds stress first reaches a value of 0.001. Therefore, the transition onset position was found to be in the neighborhood of \( X/C \approx 0.10 \) based on the measured Reynolds stress distribution, which also agrees well with the estimated location of the transition point based on the surface pressure measurements described above.

Since the incoming flow streams could attach to the airfoil upper surface in general with a very thin separation bubble formed near the airfoil leading edge, no apparent large-scale flow separation can be found in the flowfield around the airfoil. As shown in Fig. 8(f), the turbulent kinetic energy \( (TKE = \frac{1}{2} (u'^2 + v'^2)) \) level of the
As it is expected, the regions with relatively high T.K.E. values were found to be concentrated in a thin layer close to the airfoil upper surface when the 14.0 degrees angle of attack is at the increasing branch of the hysteresis loop.

The flow structures around the airfoil leading edge were found to change significantly when the 14.0 degrees angle of attack was at the decreasing branch of the hysteresis loop. As visualized clearly from the PIV measurement results given in Fig. 9, the laminar boundary layer on the airfoil upper surface was found to separate from the airfoil upper surface for good at a location near to the airfoil leading edge. The instantaneous velocity vectors and corresponding vorticity distribution show clearly that the separated laminar boundary layer would transit to turbulence rapidly accompanied by generating strong unsteady vortex structures due to the Kelvin-Helmholtz instabilities. Compared to the case with the AOA = 14.0 degrees at the increasing branch of the hysteresis loop (Fig. 8), the separated boundary layer was found to be “lifted” up far away from the upper surface of the airfoil, which could not reattach to the airfoil upper surface anymore. Flow separation close to the airfoil leading edge can be seen very clearly from the ensemble-averaged velocity field and corresponding streamlines of the mean flow, which reveals again that large-scale flow separation occurs almost on the entire upper surface of the airfoil, i.e., the airfoil is in stall state, when the 14.0 degrees angle of attack is at the decreasing branch of the hysteresis loop. The streamline distribution of the mean flow field shown in Fig. 9(d) elucidate again that the separated boundary layer seems to try to reattach to the airfoil upper surface near X/C ≈ 0.35. However, the strong reversing flow from the airfoil trailing edge prevented the separated boundary layer from reattaching to the airfoil upper surface and kept the airfoil in stall state. The PIV measurement results suggest that the flowfield around the airfoil seemed to be able to “remember” its past history when the angle of attack was changed inside the hysteresis loop.

Compared to the case with the AOA = 14.0 degrees at the increasing branch of the hysteresis loop, the measured normalized Reynolds stress distribution shown in Fig. 9(e) revealed that turbulent transition of the separated shear layer would take place earlier when the 14.0 degrees angle of attack is at the decreasing branch of the hysteresis loop. For example, the streamwise location where the normalized Reynolds stress first reaches a value of 0.001 was found to move to upstream location of X/C ≈ 0.03. The size of the regions with high values of normalized Reynolds stress was found to increase tremendously. The measured turbulent kinetic energy (T.K.E.) distribution given in Fig. 9(f) revealed that the T.K.E. level of the flowfield around the airfoil became significantly higher when the AOA = 14.0 degrees was at the decreasing branch of the hysteresis loop. The regions with higher T.K.E. values were found to be along the shedding path of the strong unsteady Kelvin-Helmholtz vortex structures.
4. Concluding Remarks

An experimental study was conducted to investigate static stall hysteresis of a low-Reynolds-number airfoil. The experimental investigation was conducted in a closed-circuit, low-speed wind tunnel with the chord Reynolds number of $Re = 162,000$. In addition to mapping surface pressure distribution around the airfoil with pressure sensors, a digital particle image velocimetry (PIV) system was used to make detailed flow field measurements to quantify the occurrence and behavior of laminar boundary layer separation and transition on the airfoil when stall hysteresis occurs. The flow field measurements were correlated with the airfoil surface pressure measurements to elucidate underlying fundamental physics associated with the stall hysteresis phenomena of low-Reynolds-number airfoils.

The measurement results revealed clearly that, for the same angle of attack in the hysteresis loop, flow pattern and behavior of the vortex and turbulent flow structures around the airfoil would be completely different for the cases with the angle at the increasing branch of the hysteresis loop and those at the same angle of attack but at the decreasing branch of the hysteresis loop. Incoming flow streams were found to be able to attach to the airfoil upper surface in general when the angles are at the increasing branch of the hysteresis loop. A thin separation bubble was found to form on the upper surface of the airfoil with its length about 10% of the airfoil chord length and height only about 1% of the chord length. The critical points (i.e., separation, transition, and reattachment points) of the separation bubble identified from the PIV measurements were found to agree well with those estimated based on the surface pressure measurements. The attached flow pattern resulted in higher lift and lower drag acting on the airfoil as well as lower Reynolds stress level and less unsteadiness in the wake of the airfoil.

When the angles of attack are at the decreasing branch of the hysteresis loop, incoming flow streams were found to separate from the airfoil upper surface for good at a location quite near to the airfoil leading edge. The turbulence transition of the separated laminar boundary layer was found to take place much earlier at a further upstream location accompanied by periodical shedding of strong Kelvin-Helmholtz vortex structures in the wake of the airfoil. While the separated boundary layer was found to try to reattach to the airfoil upper surface, the strong reversing flow from the airfoil trailing edge prevented the separated boundary layer from reattaching to the airfoil upper surface, thus keeping the airfoil in stall state. As a result, the lower lift and higher drag acting on the airfoil were found with Reynolds stress and turbulence kinetic energy levels in the wake of the airfoil increased significantly.

The present study revealed quantitatively that stall hysteresis of low-Reynolds number airfoils is closely related to the behavior of the laminar boundary layer separation and transition on the airfoils. The ability of the flow to remember its past history is suggested to be responsible for the stall hysteretic behavior.
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References


