

Flow Physics Study of Sweeping Jet Actuation on an NACA 0015 Swept Wing Configuration

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Results from a recently completed active flow control (AFC) experiment on a low aspect ratio, $AR = 4.35$, 30° swept, semispan wing with a 30% chord trailing edge flap are presented. The constant chord NACA 0015 wing is configured with sweeping jet actuators at the flap shoulder to facilitate our study of three-dimensional, swept wing separated and AFC controlled flowfields on the flap. Two flap deflection angles ($\delta_f = 0^\circ$ and 20°) are examined. Oil and tuft flow visualization data, steady and unsteady pressure data, and particle image velocimetry (PIV) complement the balance lift and drag data. These results are used to examine smooth body separation, fixed separation, and the AFC-controlled flap flowfield downstream of a sweeping jet actuator. A momentum coefficient of 1.1% reattaches the flow to the flap surface when $\delta_f = 20^\circ$ increasing lift by ≈ 0.26 . This fundamental study is a first step in a research effort focused on improving the efficiency of AFC systems for swept wing applications.

Nomenclature

A_{jet}	sweeping jet nozzle area
C_L	lift coefficient
c_l	sectional lift coefficient
C_D	drag coefficient
c_{dp}	sectional pressure drag coefficient
C_μ	SWJ actuator momentum coefficient, $\dot{m}U_{jet}/(q_\infty S_{ref})$
C_p	pressure coefficient, $\equiv (P - P_s)/q / \cos^2 \Lambda'$
$C_{p,TE}$	model trailing edge C_p
f	frequency
h	height of actuator nozzle
M	Mach number
$\dot{m}$	mass flow rate, $\rho U_{jet} A_{jet} n_{jet}$
n_{jet}	total number of sweeping jet actuators
NPR	nozzle pressure ratio, P_s/P_∞
P	pressure
P_∞	freestream static pressure
P_s	actuator plenum static pressure
q_∞	freestream dynamic pressure, $1/2 \rho_\infty U_\infty^2$
Re_c	Reynolds number based on mean aerodynamic chord
S_{ref}	reference surface area
U_{jet}	actuator nozzle velocity
U_∞	freestream velocity
w	width of actuator nozzle
x, y, z	model coordinate system
x_o, y_o, z_o	flap coordinate system when $\delta_f = 0^\circ$
x_{20}, y_{20}, z_{20}	flap coordinate system when $\delta_f = 20^\circ$
α	angle of attack
δ_f	flap deflection angle, degrees

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Λ	sweep angle, deg
Λ'	$\arctan(\Lambda)\cos(\alpha)$
ρ	density
ρ_∞	freestream density

Abbreviations

3D	three dimensional
AFC	active flow control
BART	Basic Aerodynamics Research Tunnel
CRM-HL	High-Lift version of the Common Research Model
CRM-SHL-AFC	Simplified High-Lift version of the Common Research model
HELP	High Efficiency Low Power
LaRC	Langley Research Center
PIV	Particle Image Velocimetry
SHL	simplified high-lift
SLA	stereolithography
SWJ	sweeping jet

I. Introduction

Results from small-scale, flow physics experiments performed to examine flow separation and its control on a three dimensional swept wing configuration are presented. The experiments followed the successful wind tunnel test campaign that investigated active flow control (AFC) on the 10%-scale high-lift version of the Common Research Model (CRM-HL) equipped with a simple-hinged flap (CRM-SHL-AFC) [1]. AFC on the inboard flap of the CRM-SHL-AFC promoted flow attachment. CFD results [2], confirmed by experimental results, showed that controlling separation on the outboard flap of the CRM-SHL-AFC using two rows of sweeping jet actuators was challenging due to the spanwise flow that dominated the three-dimensional (3D), separated flowfield of the highly deflected (55°) outboard flap. A new actuation concept, the high-efficiency low power (HELP) actuator, developed for the CRM-SHL-AFC model was effective and efficient at controlling separation [1, 3]. However, as noted in Ref. [1], the HELP actuator was developed to obtain the desired lift increment and further development was planned to explore whether additional improvements in AFC system efficiency could be obtained.

A modified version of the swept wing model of Greenblatt and Washburn [4] was used for the experiment. Prior to their 2006 publication, research [5, 6] on the effectiveness of AFC using unsteady excitation for separation control on geometries with sweep was limited. Since the study of Greenblatt and Washburn [4], there have been a number of swept wing AFC studies. For example, the AFC research supporting the full-scale flight test of AFC on the vertical tail [7-11] contributed significantly to the body of AFC research on a swept wing configuration. In a study that varied both sweep angle and wing aspect ratio, Tewes et al. [12] showed that a sparse number of fluidic actuators positioned at the flap shoulder of a swept configuration could act as a fluidic fence that reduced the spanwise flow thereby increasing lift and reducing the nose up pitching moment. Other examples of AFC on swept wing configurations include the experimental and CFD studies focused on applying AFC on the CRM-SHL-AFC [1, 3]. These research efforts have provided further insight into control methods that are both effective and efficient.

SWJ actuators were previously demonstrated to control separation on the swept, semispan wing [13] of this study during an initial risk-reduction experiment supporting the CRM-SHL-AFC research. In subsequent risk-reduction experiments, we tested the NACA 0015 semispan wing in the unswept configuration and focused on comparing the relative effectiveness of various actuation concepts. The goal of the current research is to develop effective and efficient methods of controlling separation using active flow control that can be applied to swept wing configurations. During the experiment, we applied AFC using sweeping jet (SWJ) actuators on the deflected flap of the model and varied the deflection angle ($\delta_f = 20^\circ$ – 60°) and thus the adverse pressure gradient. The higher δ_f angles (40° and 60°) are similar to the CRM-SHL-AFC δ_f angles, studied in a prior wind tunnel test [1]. The smaller δ_f angle ($\delta_f = 20^\circ$) is in the range of deflection angles that were recently tested on the CRM-HL model. During this most recent wind tunnel experiment, AFC was applied on the deflected aileron of the 10% scale CRM-HL model. AFC on the deflected aileron is a concept recently explored by Shmilovich et al. [14] as a means of improving takeoff lift-to-drag ratio.

In this paper, we will present our progress in examining the interaction between the separated 3D flowfield, and the unsteady, SWJ excitation used for control. Surface static pressures, forces, particle image velocimetry (PIV), and flow visualization results are presented for $\delta_f = 0^\circ$ and $\delta_f = 20^\circ$.

II. Experiment Description

The experiments were conducted in the Basic Aerodynamics Research Tunnel (BART). This 11:1 contraction ratio, open-circuit tunnel has a test section that is 0.71 m high by 1.02 m wide by 3.05 m long. BART is used primarily as a flow physics facility; therefore, it has the instrumentation and optical access needed for measurement techniques such as laser Doppler velocimetry (LDV) and particle image velocimetry (PIV). A three-axis traverse system surrounds the test section of the facility and was used during the experiment to simplify the acquisition of multiple planes of PIV data. The maximum velocity of the tunnel is approximately 60 m/s and most of our testing was performed at a freestream velocity of 35 m/s corresponding to a chord Reynolds number, Re_c , of 750,000.

A. Semispan Swept NACA 0015 Model

The 30° swept wing, semispan model, with a 30% chord trailing edge flap, has an NACA 0015 cross-section normal to the leading edge. It was built for sidewall AFC testing in the Basic Aerodynamics Research Tunnel [4]. This left-handed model has a chord that is 0.3048 m and a semispan that is 0.68 m. The semispan of the unswept model (s) is 0.6096 m and is used as a reference for y locations. A 30° wedge (shown in Fig. 1) is inserted between the unswept model and the endplate (turntable) to achieve the swept configuration. The model was tested using a 0.6096 m span flap [15] with a deflection angle range of -10° to 60° in 10° increments. Our study was performed at $\delta_f = 0^\circ$ and 20° . Modeling clay was used to seal the gap between the deflected flap and the wedge. Forces and moments were measured by a 5-component (no side force) strain gauge balance located between the model turntable and the slew drive used to vary model angle of attack. The balance force and moment limits prevented testing at high angles of attack ($> 18^\circ$). Figure 1 shows the model layout and the pressure orifices. Sectional lift, drag, and pitching moment values can be obtained using data from the orifices at $y/s = 0.17, 0.50, 0.83$, and 0.99 (shown in Fig. 1) and compared to the balance results. There are 12 unsteady pressure transducers embedded in the model (Fig. 1). The model has a leading edge AFC excitation slot, which was unused but left open during this test, to promote transition. Additionally, transition dots with a height of 0.2 mm were applied to the upper surface of the model approximately 1.14 cm downstream of the leading edge to achieve a fully turbulent boundary layer on the upper surface. Sublimating chemicals and surface oil flow measurement have been used to verify the effectiveness of the open slot/transition dot combination. To minimize laser reflections during the particle image velocimetry (PIV) portion of the test, the model was painted black. Flow visualization results were obtained using fluorescent mini tufts and oil flow. A mixture of silicone oil with a viscosity of 5 centistokes and fluorescent pigment were used to visualize the surface flow patterns.

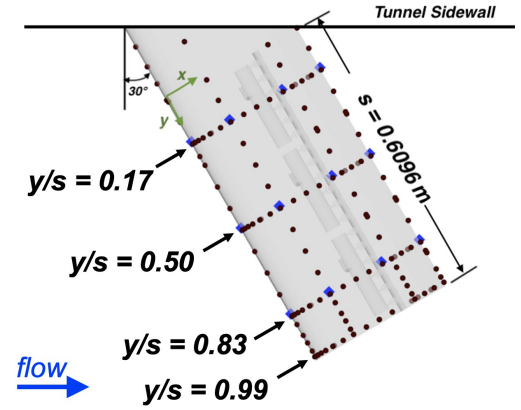


Fig. 1 CAD rendering with pressure orifice locations (circles - static, diamonds - unsteady).

B. Sweeping Jet Actuators

Three 0.2 m wide stereolithography SWJ actuator cartridges were integrated into the model upstream of the trailing edge flap. The SWJ actuators (Mod 2 design of Ref. [16]) used for the majority of the test had nozzles with a height of 1 mm, width of 2 mm, and spacing of 3.3 cm resulting in each cartridge containing 6 SWJ actuators. The diffuser length of the SWJ actuator was extended, which increased the sweep or spreading angle of the jet, due to jet attachment to the diffuser walls by a process referred to as a Coanda extension in Ref. [17]. As discussed in Ref. [16] when describing the unswept configuration, the height of the SWJ actuator changes the outer mold line (OML) of the model. For the swept configuration, a step exists between the outboard edge of the model and the wing tip and between the inboard edge of the model and the wedge used to sweep the model 30° . Additionally, the step between the trailing edge of the main

wing where the cartridges reside and the flap of the model is larger than the original model design of Greenblatt and Washburn [4]. We chose this actuator design because of the extensive data available on the unswept wing with this actuator design. A limited amount of testing, prior to this experiment, was performed using actuators that were 0.5 mm h by 2 mm w to obtain qualitative information (surface oil flow visualization). These actuators did not change the OML of the model. Future testing focused on AFC with $\delta_f \leq 20^\circ$ will include SWJ cartridges that don't affect the model OML.

Each of the three actuators cartridges was independently controlled by an electronic pressure regulator. Thermal mass flow meters in the three air supply lines were used to measure mass flow rate and each actuator plenum was instrumented with a static pressure orifice and a thermocouple for pressure and temperature measurements, respectively, which were used to compute density. The jet velocity is defined by Eq. 1, where, A_{jet} is the actuator nozzle area, 2 mm², and density is computed using isentropic relations. C_μ is defined by Eq. 2.

$$U_{jet} = \frac{\dot{m}}{\rho n_{jet} A_{jet}} \quad (1)$$

$$C_\mu = \frac{\dot{m} U_{jet}}{q S_{ref}} \quad (2)$$

C. Particle Image Velocimetry

A commercial stereoscopic PIV acquisition and analysis system [18] comprised of a pulsed Nd:YAG laser operated at frequencies in the range of 10 Hz to 15 Hz and two, 6 Megapixel (2752 pixel x 2200 pixel) CCD cameras with sensor sizes of 4.5 μ m by 4.5 μ m pixels was used to document the off-body flow above the flap. 105 mm lenses were used on both cameras. The cameras were rotated so that the model surface was horizontal in each camera view. Figures 2(a) and 2(b) show the orientation of the measurement planes and includes a description of the coordinate systems used to present the PIV results. An interrogation window size of 64 pixels x 64 pixels followed by an interrogation window size 32 pixels x 32 pixels with an overlap of 50% was used to process the $\delta_f = 0^\circ$ data. The interrogation window size for the $\delta_f = 20^\circ$ data was 48 pixels by 48 pixels with a 50% overlap followed by three passes using a window size of 24 pixels by 24 pixels with an overlap of 75%. Figures 3(a)–3(b) present the PIV regions for $\delta_f = 0^\circ$ and $\delta_f = 20^\circ$. A minimum of 1000 image pairs was used to compute the mean values that will be presented. Nine planes of data with a spacing of $\Delta y = 5.08$ mm were acquired with $\delta_f = 20^\circ$ (Fig. 3(b)) and the model angle of attack set at 4° . Five planes of data covering a measurement region in the spanwise direction of 38.1 mm were acquired at $\delta_f = 0^\circ$ and $\alpha = 14^\circ$ (Fig. 3(a)). The spanwise extent of the PIV planes for $\delta_f = 20^\circ$ was selected to be 4.06 cm so as to cover the output of one SWJ actuator, while the span of the PIV planes for $\delta_f = 0^\circ$ coincides with a region where oil flow interferometry measurements (not included) had been acquired. All PIV planes were acquired normal to the leading edge of the swept wing model with the components of the PIV system mounted to the 3-axis traverse of the BART facility. By using this setup, a stereoscopic PIV calibration was only required at the initial measurement plane for the $\delta_f = 0^\circ$ and $\delta_f = 20^\circ$ measurement regions. Data from the PIV planes with $\delta_f = 20^\circ$ were interpolated to obtain planes of data parallel to the leading along the flap in the measurement region.

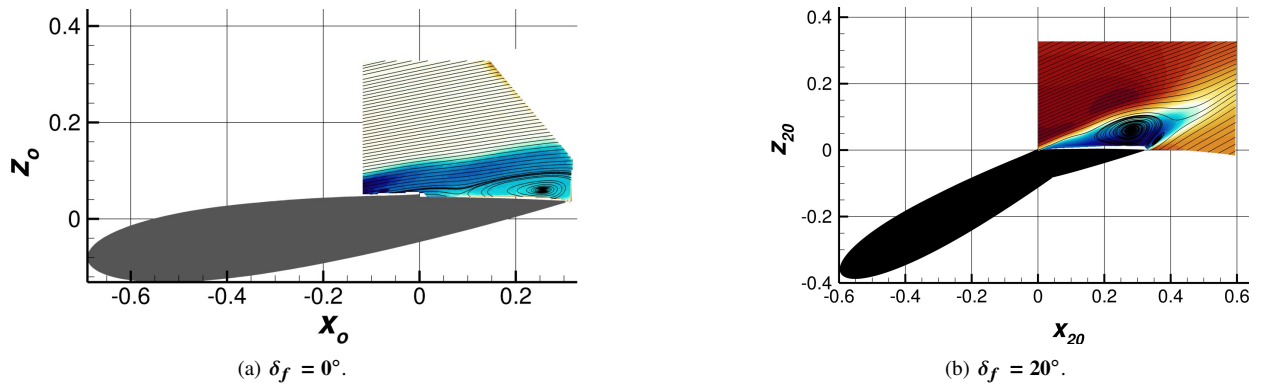


Fig. 2 PIV coordinate system descriptions.

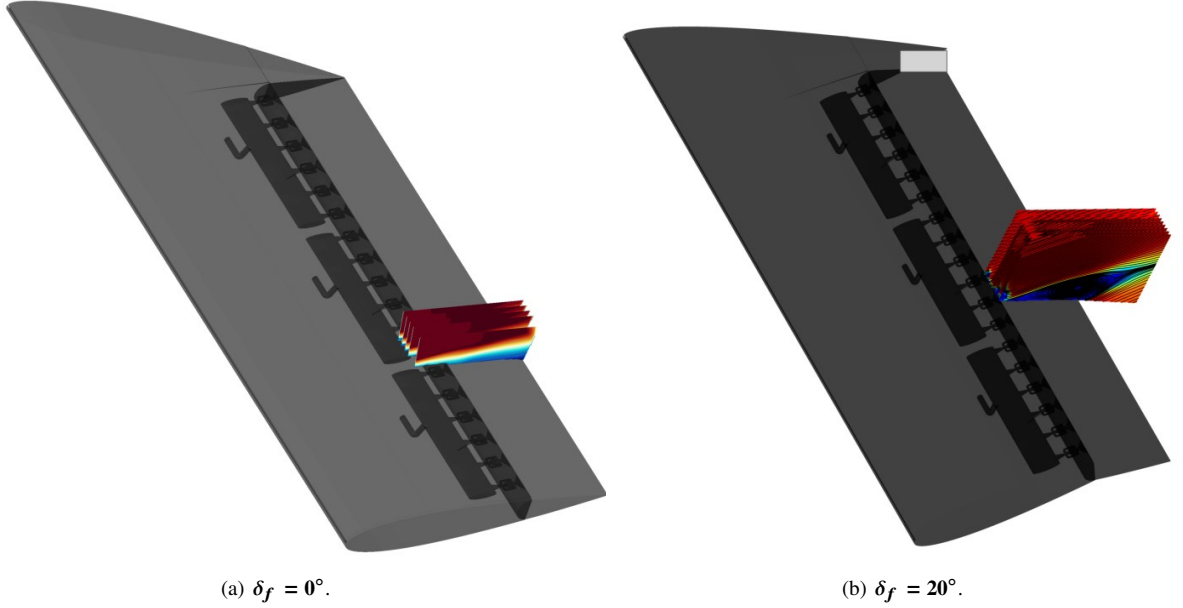


Fig. 3 PIV measurement locations.

III. Results

In the following sections, results are presented to describe the interaction of the sweeping jet actuators with the separated flowfield over the deflected trailing edge flap of the swept NACA 0015 wing. We begin by presenting results for $\delta_f = 0^\circ$ where there is no defined separation location like $\delta_f = 20^\circ$. This case is presented to illustrate how three-dimensional (3D) flow separation develops along the wing surface. Then, we present AFC results for $\delta_f = 20^\circ$ comparing the separated and SWJ controlled flap flowfields.

A. Flow Physics Results $\delta_f = 0^\circ$

Prior to the AFC studies, the model was tested over an α range that captured pre- and post-stall conditions on portions of the cruise configuration ($\delta_f = 0^\circ$). The purpose of the testing was to explore how stall occurred on the wing and to investigate the unsteady pressures when the flow was attached versus separated. Tuft flow visualization results from $\alpha = 0^\circ$, 8° , 14° , and 16° are presented in Figs. 4(a), 4(b), 4(c), and 4(d), respectively. Images have been cropped to show only the model surface visible in each image. Flow is from top to bottom. The right-hand side is at the tunnel wall, and the left-hand side is the wing tip. Rows of tufts, aligned parallel to the leading edge, were applied to the model with the last two rows of tufts on the flap. Results from $\alpha = 0^\circ$ and $\alpha = 8^\circ$, shown in Figs. 4(a) and 4(b), indicate that the flow is in the streamwise direction. At $\alpha = 14^\circ$ (Fig. 4(c)), the tuft patterns show that the flow is in the spanwise direction over a large portion of the wing when compared to the results obtained at $\alpha = 0^\circ$ (Fig. 4(a)) and $\alpha = 8^\circ$ (Fig. 4(b)). Oil flow visualization results (not presented) from testing that used SWJ actuators that did not change the model OML indicated that separation was present on the outboard portion of the wing at this α . In the present study, the spanwise direction of the tufts indicates that 3D flow separation may be present on the outboard region of the wing. Consequently, off-body measurements using PIV were acquired at $\alpha = 14^\circ$ to investigate the flap flowfield. As expected, stall on this swept, constant chord wing commenced outboard. This is evident by examining the tuft patterns/directions of Fig. 4(d) at $\alpha = 16^\circ$ where the outboard portion of the wing is massively separated while the inboard portion appears to be attached. When stall occurs on the outboard section of the wing, the flap tufts at $\alpha = 14^\circ$ and $\alpha = 16^\circ$ are similar except near the wing tip.

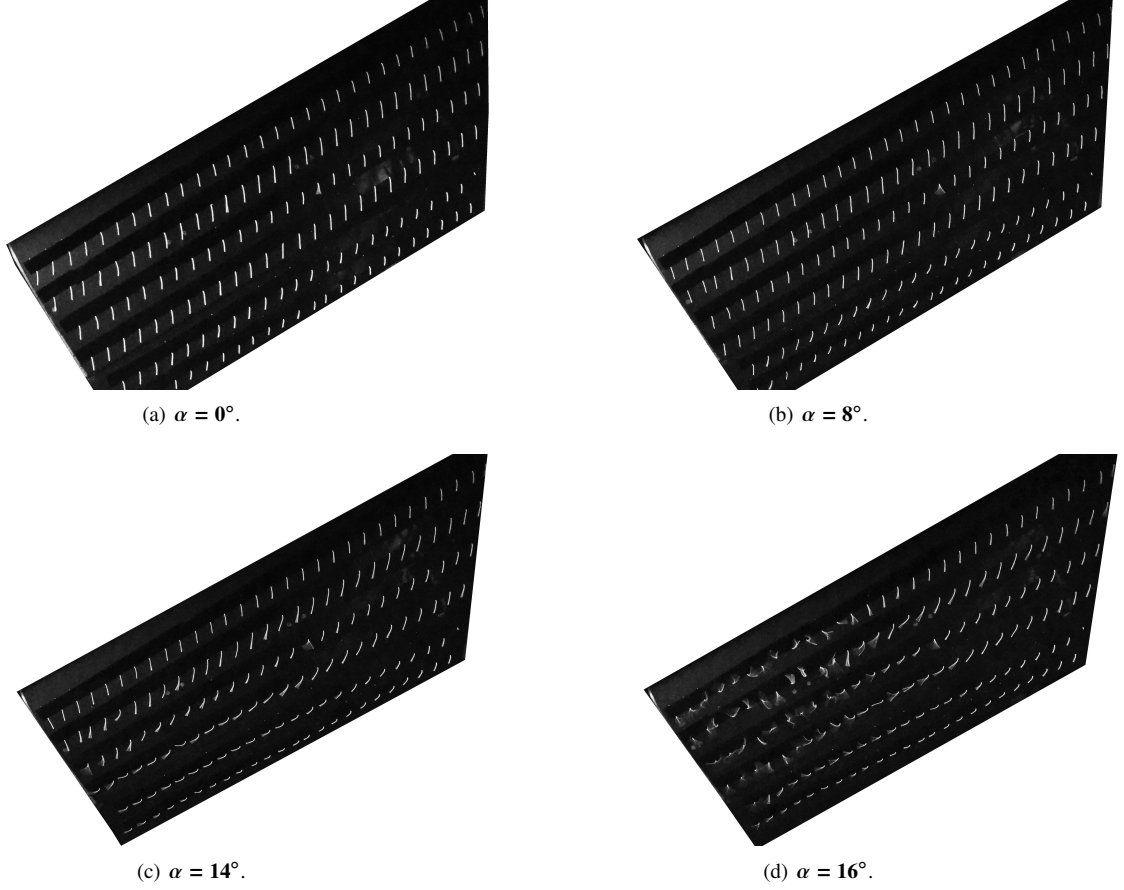


Fig. 4 Tuft flow visualization characterizing wing stall. $\delta_f = 0^\circ$, $Re_c = 750,000$.

C_p distributions corresponding to the flow visualization results of Fig. 4 are shown in Fig. 5(a)–Fig. 5(c). Note, the C_p values have been normalized using the dynamic pressure computed using the velocity component normal to the leading edge as described in Ref. [4]. Figure 5(a) depicts the C_p distribution of the wing at $y/s=0.17$. As α is increased, the suction peak increases for the four angles of attack indicating that stall has not occurred at this y/s location. At the center and outboard regions of the wing ($y/s=0.5$ and 0.83), the C_p distribution of Figs. 5(b) and 5(c), show that the suction peak at $\alpha = 16^\circ$ is lower than the suction peak at $\alpha = 14^\circ$ indicating that stall has occurred on these regions of the wing. In addition to the reduction in the suction peaks, the pressure recoveries shown in Figs. 5(b) and 5(c) also indicate that stall is occurring on these sections of the wing. The lift curves of Fig. 6(a) are shown for completeness and indicate that stall begins outboard while lift is still increasing at $y/s=0.17$. Stall is accompanied by a large increase in form drag (Fig. 6(b)) as shown by the c_{dp} results at $y/s=0.50$ and 0.83 . The pressure spectra provided in Figs. 7(a), 7(b), and 7(c) for the unsteady sensors embedded in the flap at $y/s = 0.17$, 0.5 , and 0.83 indicate that when separation occurs at a sensor location, large, low frequency pressure oscillations associated with the detached shear layer dominate the spectra. Using the increase in amplitude of the spectra at low frequencies as an indicator, the spectra of Figs. 7(b) and 7(c) show that separation has occurred by $\alpha = 16^\circ$ at these locations, while the spectra of Fig. 7(a) show no large changes in amplitude over the α range presented. Spectra for the two most outboard stations at $\alpha = 14^\circ$ indicate that the flow may be partially separated at these wing stations. The peak in the pressure spectra near a frequency, f , of 121 Hz is in the range of the blade pass frequency for this tunnel velocity.

Figure 8 presents PIV results obtained at $y/s=0.68$ with $\alpha = 14^\circ$. The result are presented in the rotated coordinate system described in Fig. 2(a) where positive velocity along x_o is toward the trailing edge, positive velocity in the y_o direction is toward the wing tip, and positive velocity in the z_o direction is away from the model surface. Although reflections from the laser light sheet influence the results near the wing surface, the off-body flowfield results aid in characterizing the 3D separation present on this portion of the wing. We present results from the most outboard measurement station from the five measurement planes acquired because the reflections are minimal. The u_{x_o} velocity

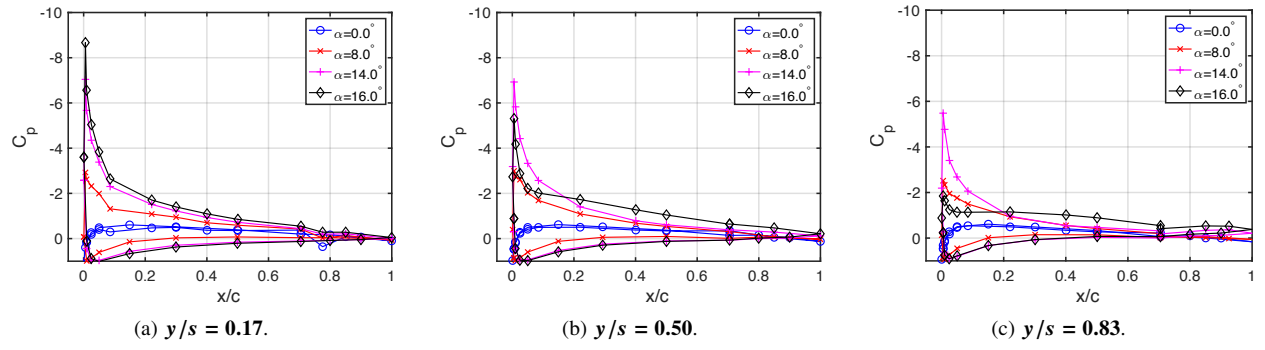


Fig. 5 C_p distributions characterizing wing stall. $\delta_f = 0^\circ$, $Re_c = 750,000$.

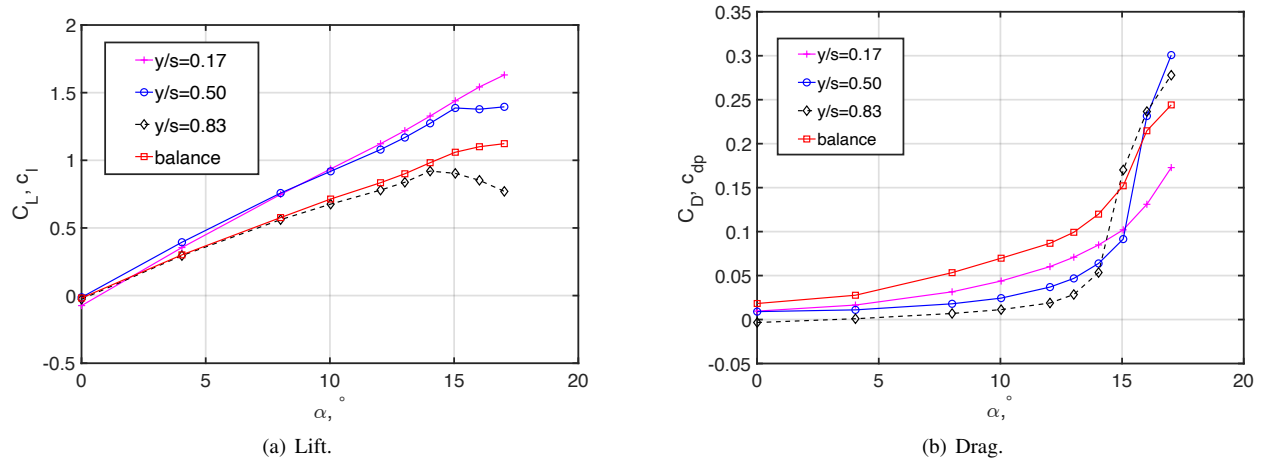


Fig. 6 Lift and drag characterizing wing stall. $\delta_f = 0^\circ$, $Re_c = 750,000$.

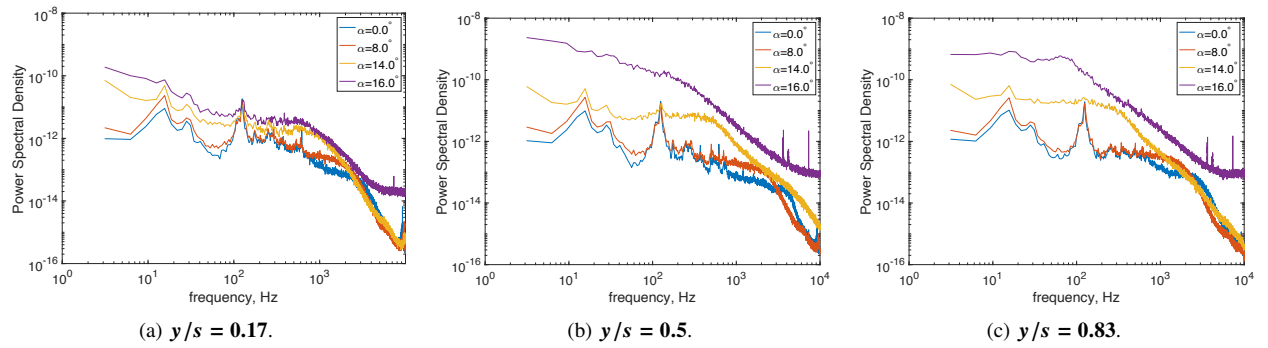


Fig. 7 Pressure spectra characterizing wing stall. $\delta_f = 0^\circ$, $Re_c = 750,000$, $x/c = 0.71$.

contours and streamlines of Fig. 8(a) show that there is a recirculation region on the flap surface beginning around $x_o \approx 0.09$. The recirculation region is bound by the separating streamline that is shown by the merging of streamlines at $x_o \approx 0.09$. When the streamlines merge, the y_o velocity component slows (compared to upstream values) and the region of lower velocity (u_{yo}) extends along the separating streamline (Fig. 8(b)). The negative u_{xo} values for $x_o > 0.09$, in the recirculation region, coincide with the velocity component in the y_o direction increasing (Fig. 8(b)). Consequently, the flow in this region should be directed upward and toward the wing tip. Two negative velocity regions, one centered at $x_o=0.05$ and the other at the trailing edge of the flap, are shown in Fig. 8(c) for u_{zo} . This component of velocity shown in Fig. 8(c) is directed toward the surface upstream of the location where separation occurs. Finally, the vorticity contours of Fig. 8(d) define the position of the shear layer (shown as the region of large negative vorticity, (Ω_{yo})) above the surface.

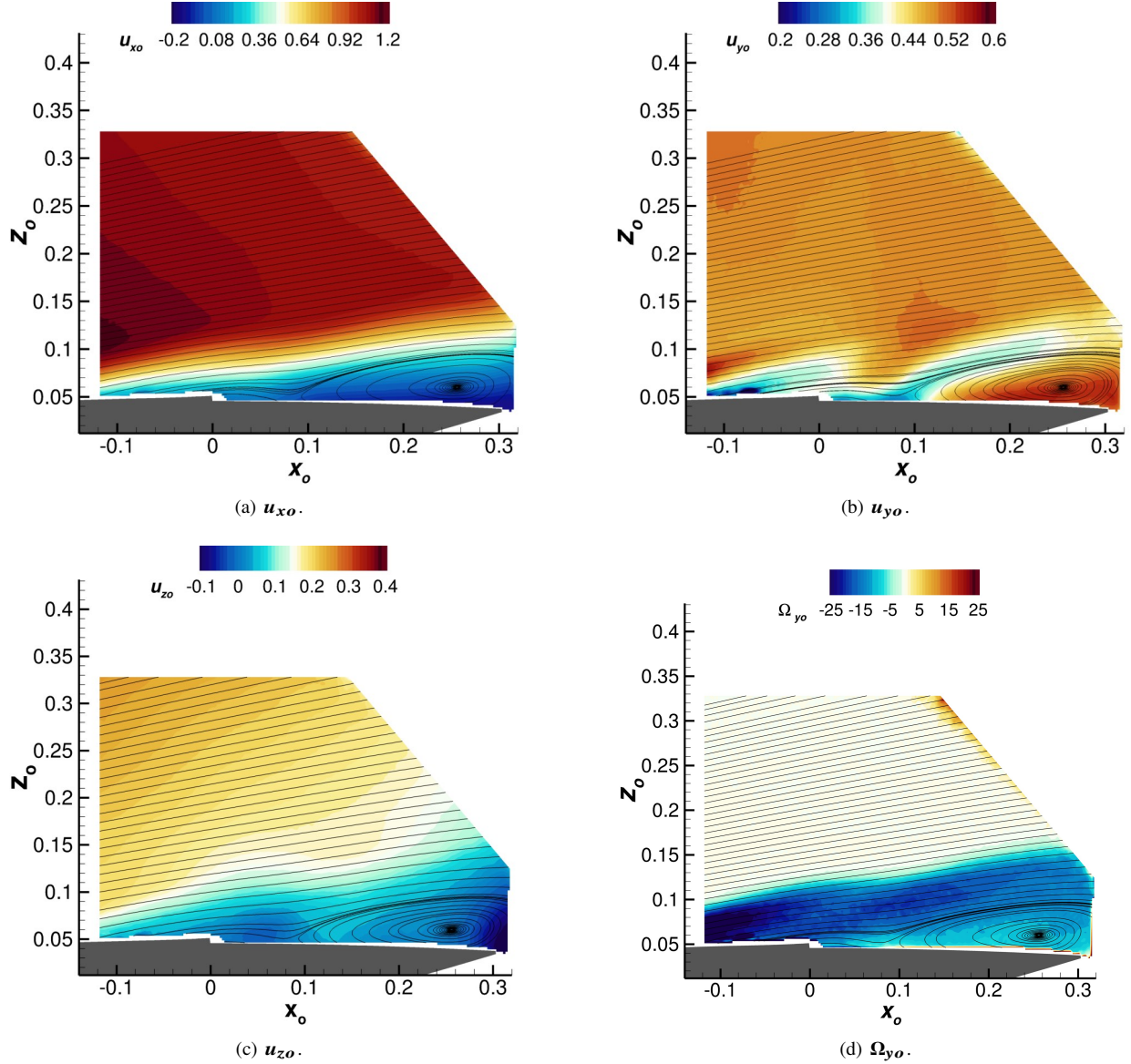


Fig. 8 Velocity and vorticity results from PIV. $\delta_f = 0^\circ$, $Re_c = 750,000$, $y/s = 0.68$, $\alpha = 14^\circ$.

B. AFC Results $\delta_f = 20^\circ$

With $\delta_f = 20^\circ$, the flap flowfield is separated for the α range (-4° to 16°) of this study. AFC using the selected SWJ actuators was capable of reattaching the separated shear layer to the flap surface even at the highest M number tested, $M = 0.15$. Unlike the 3D separation on the model with $\delta_f = 0^\circ$, separation is fixed at the shoulder of the simple-hinged flap. A summary of the lift increment, ΔC_L , obtained at $\alpha = 4^\circ$ when AFC is applied is given in Fig. 9(a) for $Re_c = 750,000$. Similar increments in lift are obtained for all α within the linear range of the lift curve. The plateau in the flap C_p results, presented in Fig. 9(b), confirms that the entire flap is separated with AFC off ($C_\mu = 0.0\%$). Using a trailing edge C_p ($C_{p,TE}$) value of 0 as an indicator of attached flow on the flap, we see that $C_\mu \approx 1.1\%$ reattaches the flow to the surface. The ΔC_L of 0.26 with attached flow represents a 26% improvement in C_L . For the remainder of the paper, we will focus on results obtained with the baseline (AFC-off) and the controlled (AFC-on) flowfields with $C_\mu = 1.1\%$.

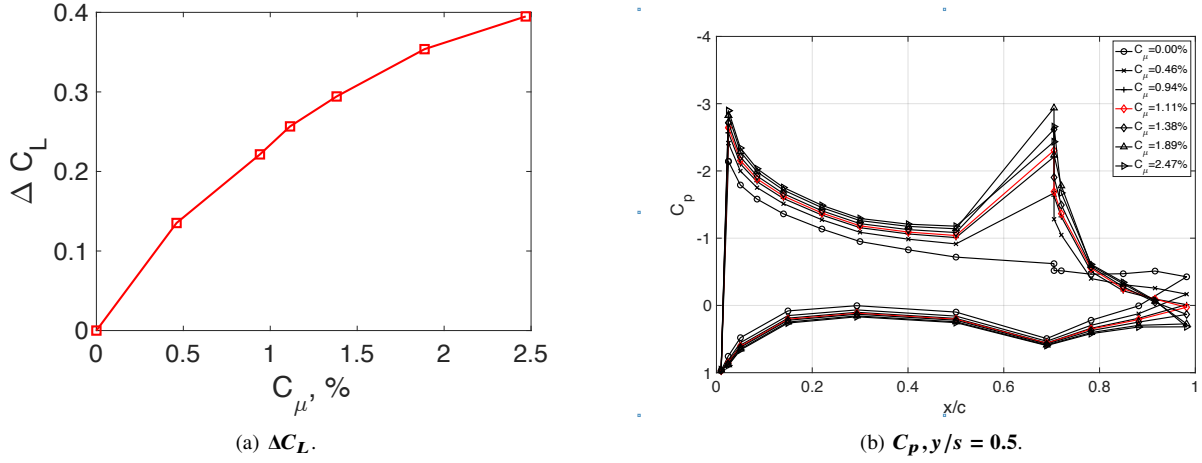
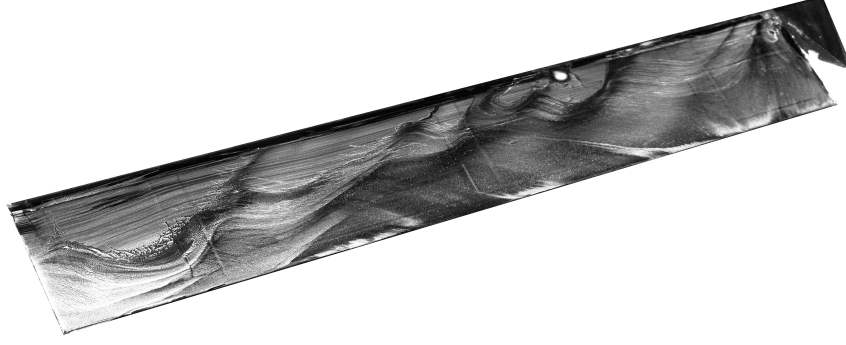


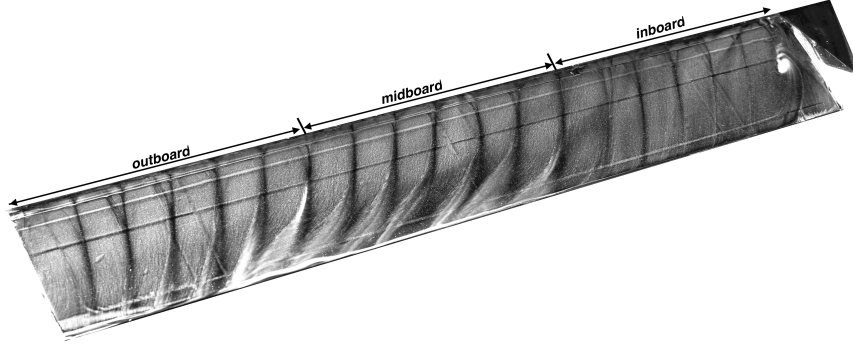
Fig. 9 Lift Increment and C_p . $Re_c = 750,000$, $\alpha = 4^\circ$, $M = 0.1$.

Figure 10 presents the oil flow visualization acquired on the flap with $\delta_f = 20^\circ$ and $\alpha = 4^\circ$ showing the baseline flowfield (Fig. 10(a)) and the SWJ controlled flow field (Fig. 10(b)). Again, the flow is from top to bottom and the upper edge in the image is the leading edge of the simple-hinged flap. Kapton tape was used to cover the spanwise and chordwise rows of pressure orifices and the unsteady pressure instrumentation. A sheet of mylar was then applied to cover the entire flap surface. The tape strips covering the chordwise pressure orifices at $y/s = 0.17$, $y/s = 0.5$, and $y/s = 0.83$ are evident in Fig. 10. In the AFC-off case of Fig. 10(a), the flow over the flap is separated. Immediately downstream of the SWJ actuators, near the leading edge of the simple hinged flap, the oil is stagnant (indicating that the flow velocity is very low in these regions). Further downstream, the flow recirculation region on the flap is characterized by the upstream and outboard motion of the flow, evident in the oil flow pattern. A small vortex, centered around the tape strip at $y/s = 0.5$, can be seen in Fig. 10(a). This vortex is in the region of the chord-normal PIV planes (Fig. 3(b)).

The AFC-on ($C_\mu = 1.1\%$) case shown in Fig. 10(b) was acquired using NPR levels that resulted in $C_{p,TE} = 0$. NPR is the ratio of the cavity pressure measured in each SWJ array to the tunnel static pressure. To achieve $C_{p,TE} = 0$, the inboard actuator was at an NPR of 2 (SWJ frequency 1330 Hz), while the midboard and outboard actuators were at an $NPR = 1.7$ (SWJ frequency 1250 Hz). Frequency of a SWJ actuator is dependent on actuator geometry and mass flow supplied to the actuator, therefore the actuators were not set to a prescribed frequency. Rather, the mass flow for each actuator cartridge was varied until $C_{p,TE} = 0$. The spatially oscillating jet produced by a SWJ actuator introduces a pair of counterrotating streamwise vortices into the flow that control separation by enhancing mixing. With attached flow over most of the flap surface, the spanwise extent of each of the 18 SWJ actuators installed upstream of the flap is clear in the oil flow pattern. At the border between actuators where opposite signed vortices from adjacent actuators meet, flow is lifted (upwash) from the surface producing the dark streak pattern shown in Fig. 10(b). In this swept wing flowfield, there is also an outward motion of the flow, especially noticeable downstream of the midboard actuator.



(a) $C_\mu = 0\%$, AFC off (baseline).



(b) $C_\mu = 1.1\%$, AFC on.

Fig. 10 Oil flow visualization comparing baseline and SWJ controlled flowfields. $Re_c = 750,000$, $M = 0.1$, $\delta_f = 20^\circ$, $\alpha = 4^\circ$.

Results from nine PIV measurement planes, beginning at $y/s = 0.53$, are used to compare the baseline and $C_\mu = 1.1\%$ controlled velocity fields downstream of a SWJ actuator. The results are presented in the flap-aligned coordinate system shown in Fig. 3(b). We begin by presenting results from a single measurement station ($y/s = 0.53$). This measurement location is the most inboard measurement station of Fig. 3(b) and coincides with the center of the fourth SWJ actuator in the midboard actuator cartridge. The baseline and controlled results at $\alpha = 4^\circ$ are presented in Fig. 11. There is a faint horizontal line, near the surface, present in the results due to a light sheet reflection. This horizontal line is most noticeable in the vorticity (Ω_{y20}) contours of Figs. 11(d) and 11(h).

For the baseline flowfield results presented in Figs. 11(a)–11(d), a large recirculation region residing on the flap is evident in the streamlines. Three distinct vortices are present in the recirculation region with one starting at $x_{20} \approx 0.15$ and extending to the trailing edge. Comparing the streamline patterns to the oil flow visualization results for the baseline flowfield (Fig. 10(a)), this vortex is downstream of the region where the oil was stagnant. The y_{20} component of velocity provided in Fig. 11(b) is larger than the x_{20} component of velocity (Fig. 11(a)), in this region, indicating the flow direction is upstream and toward the wing tip as shown in the oil flow results (Fig. 10(a)). Similar to the smooth body separation of Fig. 8(b), when separation occurs, u_{y20} has a local minimum that extends along a portion of the streamline enclosing the recirculation region. Downstream ($x_{20} \approx 0.15$) of the low velocity region, u_{y20} returns to levels similar to those above the recirculation region. The streamlines presented in Figs. 11(a)–11(d) also show the presence of a smaller clockwise vortex upstream of the vortex at $x_{20} \approx 0.15$. A local minimum in u_{z0} (Fig. 8(c)) coincides with the upstream vortex present in the flow as noted by the streamline patterns. The vortex may originate from a divot in the center actuator (third actuator) of the midboard cartridge. An oil stream in Fig. 10(a) travels from the center of the model and aligns with the location of the vortex of the baseline PIV results (Figs. 11(a)–11(d)). The vortex, largest at $y/s = 0.53$, is present in the results from the three most inboard PIV stations (not shown) and moves downstream as y/s increases. Downstream of the vortex caused by a surface imperfection, separation on the flap is characterized by a pair of counterrotating vortices enclosed in streamlines that merge in the wake. The detached shear layer of the flap upper surface has negative vorticity while positive vorticity emanates from the lower surface (Fig. 11(d)).

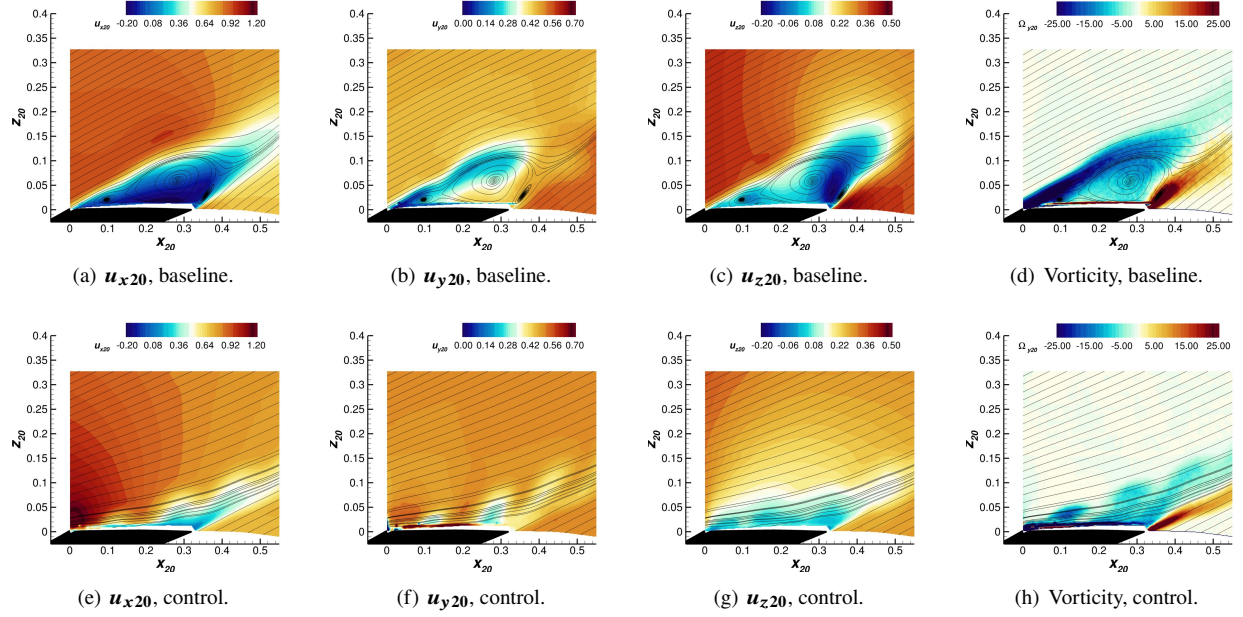


Fig. 11 Baseline and SWJ controlled PIV velocity and vorticity contours with streamlines. $\delta_f = 20^\circ$, $\alpha = 4^\circ$, $Re_c = 750,000$, $M = 0.1$, $y/s = 0.53$.

When SWJ AFC ($C_\mu = 1.1\%$) is applied, the flow is attached to the flap surface as shown in the oil flow visualization (Fig. 10(b)). Flow attachment is evident in the streamlines shown in Figs. 11(e)–11(h). With attached flow, three regions with lower momentum are evident in the u_{x20} , u_{y20} , u_{z20} contours of Figs. 11(e), 11(f), and 11(g), respectively. The Ω_{y20} results in Fig. 11(h) show that the AFC controlled flowfield has attached the shear layer, represented by the large negative values of Ω_{y20} in close proximity to the surface. The Ω_{y20} results show the attached flowfield has a pattern similar to that of the velocity vectors shown in Figs. 11(e) and 11(f). In Fig. 10(b) the patterns in the oil flow representing the streamwise vortices produced by the SWJ are shown to be inclined toward the wing tip. Vortices from SWJ actuators inboard of our chord-normal planes of PIV intersect the $y/s = 0.53$ plane at the locations indicated in Figs. 11(e), 11(f), and 11(h).

1. Composite of Flap Flowfield Downstream of SWJ

In this final section, preliminary results are presented for data obtained by interpolating nine, chord-normal PIV planes from measurements downstream of a SWJ actuator on the flap to provide a composite view of the baseline and controlled ($C_\mu = 1.1\%$) flowfields. An initial spacing of $\Delta y = 10.16$ mm was selected for chord-normal PIV planes. Four additional planes were acquired to reduce the spacing to $\Delta y = 5.08$. The schedule for PIV acquisition during this test prevented the acquisition of planes of PIV on the flap surface, parallel to the leading edge like those of Ref. [15] which took advantage of the alignment between the wing and tunnel 3-axis traverse system.

In Fig. 12 contours of the three velocity components and vorticity are presented at $x_{20} = 0.1$. As a reminder, $y_{20} = 0$ is at the center of the fourth SWJ actuator in the midboard cartridge and the actuator spacing is $\Delta y_{20} = 0.108$. The baseline flowfield results are presented in Figs. 12(a)–12(d) for u_{x20} , u_{y20} , u_{z20} and Ω_{x20} , respectively. The streamlines given in these y_{20} – z_{20} planes indicate that near the flap surface, where all velocity components are near zero, the streamlines have a slope near zero. The slope changes as the velocity in the boundary layer increases with the u_{y20} and u_{z20} components being almost identical. The results for u_{y20} (Fig. 12(b)) show variations across the span that seem to coincide with the way that the data were acquired. The reason for this is unknown. The boundary thickness of the baseline results is constant over this y/s section, as indicated by the velocity variation in the boundary layer and the concentration of negative vorticity that represents the shear layer being at the same height. In contrast to the baseline flowfield, the streamline pattern for the SWJ controlled flowfield (Fig. 12(e)–12(h)) is more uniform over the measurement region. The streamwise vortices introduced by the SWJ actuator have attached the flow to the flap surface. Near the flap surface, there are local minimums in the flow that matches the spacing of the SWJ actuators.

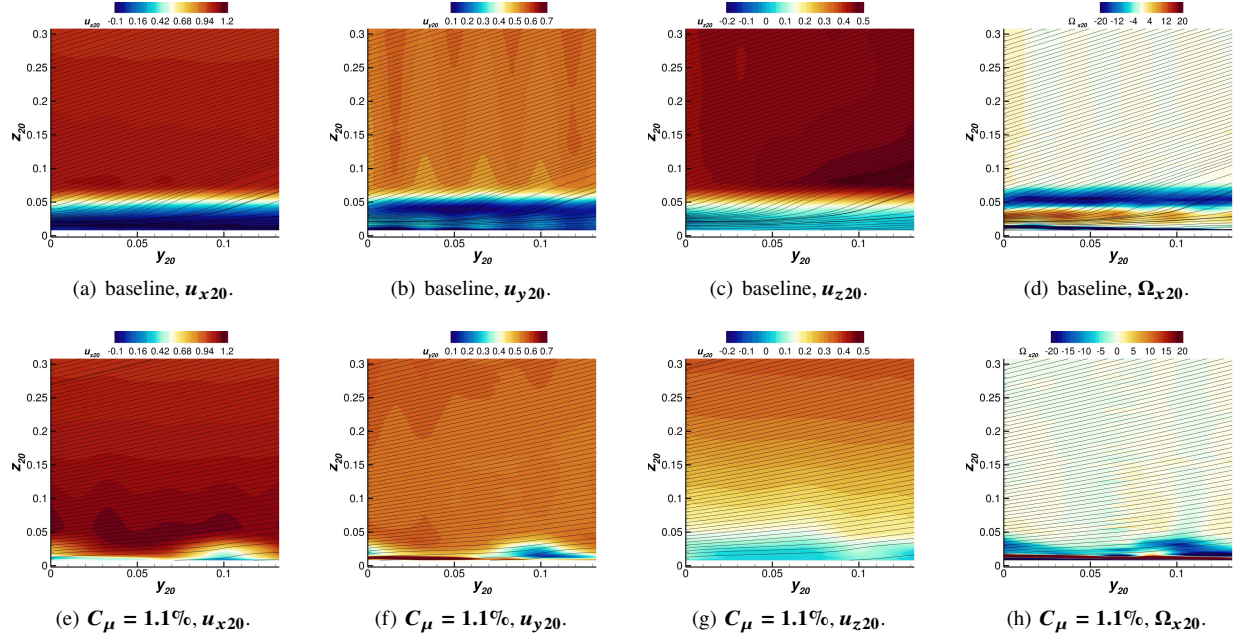


Fig. 12 Velocity field at $x_{20} = 0.11$. $\delta_f = 20^\circ$, $\alpha = 4^\circ$, $Re_c = 750,000$, $M = 0.1$.

These regions coincide with the SWJ actuator spacing and are due to the upwash produced by the streamwise vortices as noted in the oil flow results of Fig. 10(b). At x_{20} , the local minimum in u_{x20} (Fig. 12(e)) are close to the centerlines of the SWJ actuators. The SWJ controlled u_{y20} flowfield has a local minimum at the same location as the u_{x20} contours of Fig. 12(e). With control, the u_{y20} contours do not show patterns that would align with the spacing of the PIV acquisition planes like that of the baseline u_{y20} contours of Fig. 12(b). The Ω_{x20} results of Fig. 12(h) show a pair of opposite signed vorticity concentrations centered around $y_{20} = 0.1$ and a portion of a negative vorticity concentration at $y_{20} = 0$, which would be the approximate spacing of the SWJ actuator. The SWJ actuators introduce a pair of opposite sign vortices into the flowfield. In the swept wing flowfield, the PIV results indicate the position of the vortices varies with increasing downstream distance, consistent with the oil flow results (Fig. 10(b)).

Farther downstream on the flap at $x_{20} = 0.19$, the results presented in Fig. 13 indicate that the baseline, separated boundary layer has increased in height. The streamlines have a slope near zero in the stagnant flow region close to the flap surface that has increased in z_{20} at this location compared to $x_{20} = 0.1$ (Figs 11(a), 11(a) and 11(a)). The baseline u_{y20} contours presented in Figs. 13(b) indicate that in the low momentum region near the flap surface the structures shown in Fig. 12(b), aligned with the PIV plane location have increased in height with downstream distance. Vorticity contours presented in Fig. 13(d) show the shear layer at $z_{20} \approx 0.1$. The SWJ controlled flowfields with $C_\mu = 1.1\%$, as show in Fig. 13 indicate that with flow attachment, the streamlines have similar slopes throughout the measurement region. The regions of low velocity in the u_{x20} and u_{y20} contours (Figs. 13(e) and 13(f)) denote the regions where the SWJ vortices are larger and have shifted in y_{20} compared to the results at $x_{20} = 0.1$ (Figs. 12(e) and 12(f)). Similar to the results for $x_{20} = 0.1$, the SWJ controlled flowfield of Fig. 12(f) does not have not features that are related to how the data were acquired. Finally, the vorticity contours of Fig. 13(h) show that the vortex pairs introduced by the SWJ have expanded with distance from the SWJ exit and are skewed due to the spanwise flow of this swept wing configuration.

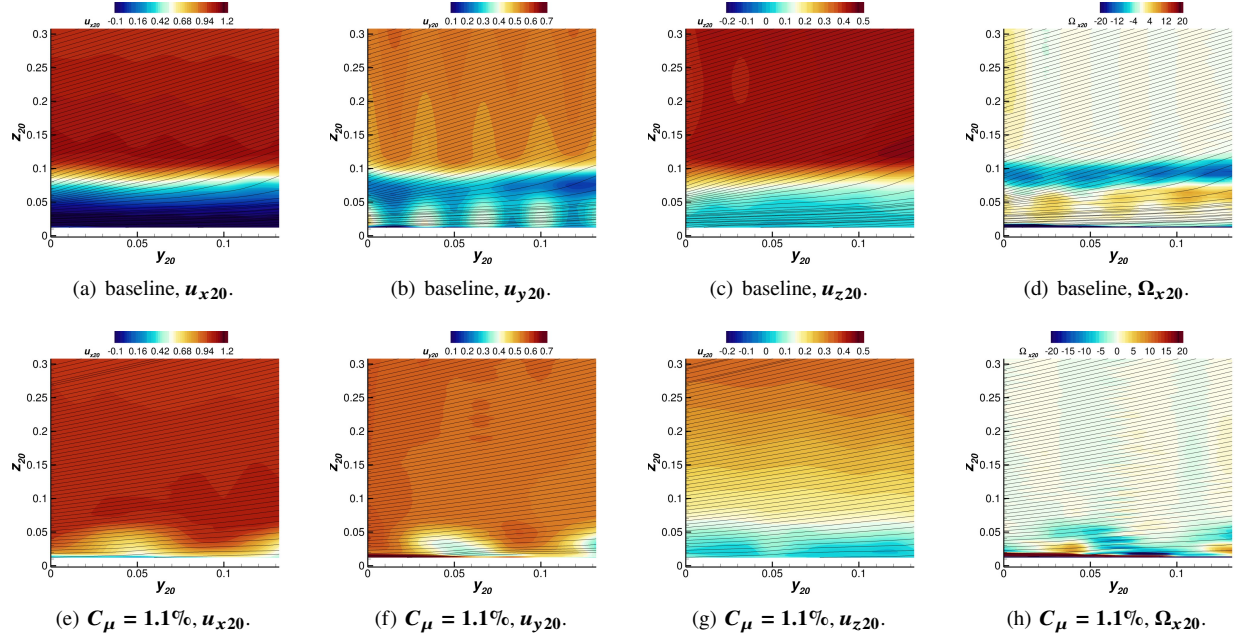


Fig. 13 Velocity field at $x_{20} = 0.19$. $\delta_f = 20^\circ$, $\alpha = 4^\circ$, $Re_c = 750,000$, $M = 0.1$.

IV. Summary

Flow separation and reattachment on a 30° , swept wing model with an aspect ratio of 4.35 were studied using quantitative and qualitative measurement techniques that provided insight into the global flowfield over the wing. The model used for the experiment has a 30% chord trailing edge flap and results were presented for flap deflection angles of 0° and 20° . Although our focus was control of the separated flow field when the flap deflection was 20° , we also presented results describing the separation that occurs on the wing near stall with $\delta_f = 0^\circ$. This flow physics study was undertaken after the completion of the active flow control testing on the simplified high-lift version of the Common Research Model (CRM-SHL-AFC) where AFC was applied on a simple-hinged flap with $\delta_f \geq 50^\circ$. The CRM-SHL-AFC research highlighted a need for AFC testing focused on maximizing the efficiency of AFC actuation systems for use in swept wing applications. The $\delta_f = 20^\circ$ used in this study is of interest because of the AFC research underway investigating AFC on a drooped aileron to increase lift-to-drag ratio during takeoff.

Results for the $\delta_f = 0^\circ$ case focused on the flowfield prior to wing stall in a region where some separation was present on the flap of the wing. Fluorescent tuft flow visualization results are presented comparing pre- and post-stall flowfields to show the onset of separation on the outboard portion of the swept wing. Through a combination of surface pressure results (steady and unsteady) and particle image velocimetry (PIV), a visual and quantitative measure of the changes in velocity during separation are presented. With the $\delta_f = 20^\circ$, a momentum coefficient, C_μ , of 1.1% reattached the flap flow increasing the lift by ≈ 0.26 . PIV results acquired at multiple spanwise locations covering a region 4.06 cm wide were discussed. These results are used, along with oil flow visualization, to compare the separated and SWJ controlled flow fields downstream of a single SWJ actuator located near the center span. The spanwise velocity component when separation is present results in the separated flow being directed toward the wing tip. The streamwise vortices introduced into the flowfield with the SWJ actuators reattach the flow to the flap surface and are seen in both the oil flow and the spanwise planes reconstructed from the PIV data acquired normal to the wing leading edge. In the swept wing flowfield, vortices produced by the actuators are inclined toward the wing tip.

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References

- [1] Lin, J. C., Melton, L. P., Hannon, J. A., Andino, M. Y., Koklu, M., Paschal, K. B., and Vatsa, V. N., “Testing of High-Lift Common Research Model with Integrated Active Flow Control,” *Journal of Aircraft*, Vol. 57, No. 6, 2020, pp. 1121–1133. doi:<https://doi.org/10.2514/1.C035906>.
- [2] Vatsa, V. N., Lin, J. C., Melton, L. P., Lockard, D. P., and Ferris, R., “Computational Investigation of Conventional and Active-Flow-Control-Enabled High-Lift Configurations,” *Journal of Aircraft*, Vol. 58, No. 5, 2021, pp. 1137–1153. doi:<https://doi.org/10.2514/1.C036233>.
- [3] Lin, J. C., Melton, L. P., Hannon, J. A., Andino, M. Y., Koklu, M., Paschal, K. B., and Vatsa, V. N., “Wind Tunnel Testing of Active Flow Control on High Lift Common Research Model,” AIAA Paper 2019-3723, AIAA, 2019. doi:<https://doi.org/10.2514/6.2019-3723>.
- [4] Greenblatt, D., and Washburn, A., “Influence of Finite Span and Sweep on Active Flow Control Efficacy,” *AIAA Journal*, Vol. 46, No. 7, 2008, pp. 1675–1694. doi:<https://doi.org/10.2514/1.33809>.
- [5] Naveh, T., Seifert, A., Tumin, A., and Wygnanski, I., “Sweep Effect on Parameters Governing Control of Separation by Periodic Excitation,” *Journal of Aircraft*, Vol. 35, No. 3, 1998, pp. 510–512. doi:<https://doi.org/10.2514/2.2332>.
- [6] Seifert, A., and Pack, L. G., “Effects of Sweep on Active Separation Control at High Reynoldods Numbers,” *Journal of Aircraft*, Vol. 40, No. 1, 2003, pp. 120–126. doi:<https://doi.org/10.2514/2.3066>.
- [7] Whalen, E. A., Shmilovich, A., Spoor, M., Tran, J., Vijgen, P., Lin, J. C., and Andino, M. Y., “Flight Test of an Active Flow Control Enhanced Vertical Tail,” *AIAA Journal*, Vol. 56, No. 9, 2018, pp. 3393–3398. doi:<https://doi.org/10.2514/1.J056959>.
- [8] Lin, J. C., Whalen, E. A., Andino, M. Y., Graff, E. C., Lacy, D. S., Washburn, A. E., Gharib, M., and Wygnanski, I. J., “Full-Scale Testing of Active Flow Control Applied to a Vertical Tail,” *Journal of Aircraft*, Vol. 56, No. 4, 2019, pp. 1376–1386. doi:<https://doi.org/10.2514/1.C034907>.
- [9] Andino, M. Y., Lin, J. C., Seele, R., Graff, E. C., Gharib, M., Whalen, E. A., and Wygnanski, I. J., “Active Flow Control on Vertical Tail Models,” *AIAA Journal*, Vol. 57, No. 8, 2019, pp. 3322–3338. doi:<https://doi.org/10.2514/1.J057876>.
- [10] Seele, R., Graff, E., Gharib, M., Taubert, L., Lin, J., and Wygnanski, I., “Improving Rudder Effectiveness with Sweeping Jet Actuators,” AIAA Paper 2012-0417, Jun. 2012. doi:<https://doi.org/10.2514/6.2012-3244>.
- [11] Rathay, N. W., Boucher, M. J., and Amitay, M., “Performance Enhancement of a Vertical Tail Model Using Synthetic Jet Actuators,” *AIAA Journal*, Vol. 52, No. 4, 2014, pp. 810–820. doi:<https://doi.org/10.2514/1.J052645>.
- [12] Tewes, P., Taubert, L., and Wygnanski, I., “On the Effect of Sweep on Separation Control,” AIAA Paper 2014-2513, June 2014. doi:<https://doi.org/10.2514/6.2014-2513>.
- [13] Melton, L. P., “Active Flow Separation Control on a NACA 0015 Wing using Fluidic Actuators,” AIAA Paper 2014-2364, Jun. 2014. doi:<https://doi.org/10.2514/6.2014-2364>.
- [14] Shmilovich, A., Stauffer, M., Wozidlo, R., and Vijgen, P., “Low-Speed Performance Enhancement using Localized Active Flow Control –Simulations, Scaling and Design of Localized Active Flow Control on the Common Research Model,” Tech. Rep. 20220006736, NASA Technical Reports Server, 2022. URL <https://ntrs.nasa.gov/citations/20220006736>.
- [15] Melton, L. P., Koklu, M., Andino, M. Y., and Lin, J. C., “Active Flow Control via Discrete Sweeping and Steady Jets on a Simple-Hinged Flap,” *AIAA Journal*, Vol. 56, No. 8, 2018, pp. 2961–2973. doi:<https://doi.org/10.2514/1.J056841>.
- [16] Melton, L. P., Koklu, M., Andino, M., Lin, J. C., and Edelman, L. M., “Sweeping Jet Optimization Studies,” AIAA Paper 2016-4233, Jun. 2016. doi:<https://doi.org/10.2514/6.2016-4233>.
- [17] Koklu, M., “Effect of a Coanda Extension on the Performance of a Sweeping-Jet Actuator,” *AIAA Journal*, Vol. 54, No. 3, 2016, pp. 1131–1134. doi:<https://doi.org/10.2514/1.J054448>.
- [18] Scarano, F., and Riethmuller, M., “Advances in Iterative Multigrid PIV Image Processing,” *Experiments in Fluids Supplemental*, Vol. 29, 2000, pp. S51–S60. doi:<https://doi.org/10.1007/s003480070007>.