

Active Flow Control Enhanced Aileron of the High-Lift Common Research Model at Takeoff Condition

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An experimental investigation was conducted in the NASA Langley 14- by 22-Foot Subsonic Tunnel on the NASA 10% scale High-Lift Common Research Model (CRM-HL) to improve the high-lift aerodynamic performance of the takeoff configuration. Active flow control (AFC) was applied at the aileron hinge line to control flow separation at high aileron deflection angles (δ_a) to increase lift-to-drag ratio (L/D). Improvements in low speed L/D can increase vehicle payload and/or range resulting in a more efficient vehicle. Aileron deflection angles of 0° , 7.5° , 16° , and 25° were investigated. Flow control was applied to the two largest aileron deflections, which are considered the high-lift (HL) improved takeoff configurations. A companion paper will discuss baseline flow characteristics of the CRM-HL at the three takeoff conditions: reference, nominal, and HL-improved. In this paper, we focus on the aerodynamic improvement obtained when AFC was applied to $\delta_a = 16^\circ$ relative to the nominal configuration, $\delta_a = 7.5^\circ$. Multiple flow control parameters, including actuator type, spacing, and intensity, were investigated to evaluate the efficiency of the actuation system. The different AFC configurations tested were assessed with tuft visualization, steady surface pressure data, and force and moment data. The results indicated that all actuation types and spacings examined led to an increase in lift across the range of angles of attack investigated. Flow separation was mitigated with the injection of momentum at the aileron hinge line. The configurations with the smallest spacing produced the highest improvement in L/D . Steady jet actuation showed higher efficiency but similar aerodynamic performance when compared to the sweeping jet actuators. This work was performed in support of the NASA Advanced Air Transport Technology (AATT) Project.

Nomenclature

A_{jet}	single actuator exit area
A_n	total active actuator exit area
b	wing semispan
c	mean aerodynamic chord, 27.58 inches at $y = 46.875$ inches
C_D	drag coefficient
C_L	lift coefficient
c_L	sectional lift coefficient
C_μ	actuator momentum coefficient, $\dot{m}^2/(\bar{\rho} A_n q_\infty S_{ref})$
C_p	pressure coefficient, $(P - P_\infty)/q_\infty$
C_π	power coefficient, $C_Q * P_s/q_\infty$
C_Q	mass flow coefficient, $\dot{m}/(\rho U_\infty S_{ref})$
h	height of actuator nozzle
L/D	lift-to-drag ratio, lift/drag
M	Mach number
$\dot{m}$	mass flow rate, $\rho U_{jet} A_{jet} n_{jet}$
n_{jet}	total number of actuators
NPR	nozzle pressure ratio, P_s/P_∞
P	pressure

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P_∞	freestream static pressure
P_s	actuator inlet static pressure
q_∞	freestream dynamic pressure, $\rho_\infty U_\infty^2/2$
Re_c	Reynolds number based on mean aerodynamic chord (c)
S_{ref}	reference surface area
U_{jet}	actuator nozzle velocity
U_∞	freestream velocity
w	width of actuator nozzle
x, y, z	model coordinate system
α	angle of attack, degrees
δ_f	flap deflection angle, degrees
δ_s	slat deflection angle, degrees
δ_a	aileron deflection angle, degrees
η	normalized semispan, y/b
Λ	sweep angle, degrees
ρ_∞	free stream air density
$\bar{\rho}$	supply air density weighted average

Abbreviations

14x22	14- by 22-Foot Subsonic Tunnel
3D	three dimensional
AFC	active flow control
AATT	Advanced Air Transport Technology
CD	convergent-divergent nozzle
CHL	conventional high lift
CRA	Computational Reference Aircraft
CRM-HL	High-Lift version of the Common Research Model
CRM-SHL-AFC	Simplified High-Lift version of the Common Research Model
LaRC	Langley Research Center
lbs	pounds
psia	pounds per square inch, absolute
nm	nautical miles
psf	pounds per square foot
SLA	stereolithography
STJ	steady jet
SWJ	sweeping jet
SHL	simplified high lift
sp	spacing
VSTOL	vertical short takeoff and landing

I. Introduction

Active flow control (AFC) has been demonstrated to be effective in improving the aerodynamic performance of high-lift systems on commercial transports. Previous studies with higher technology readiness levels (TRL) [1, 2] have shown promising results indicating AFC can significantly enhance the performance of high-lift devices by delaying flow separation and increasing lift. For this reason, AFC has been a technology investment area for the NASA Advanced Air Transport Technology (AATT) Project. AATT focuses on advancing technologies that may improve the energy efficiency and environmental compatibility of future commercial transports. AFC is considered as one of the technologies that may contribute to reaching net zero greenhouse gas emissions by 2050. However, a challenge often faced by promising AFC applications is the impact or cost of the technology when integrated into an aircraft. The current experimental campaign leverages the 10% scale high-lift version of the Common Research

(CRM-HL), a relevant high-lift configuration originally built for AFC testing, and the lessons learned from that AFC research. Additionally, the initial AFC research on the CRM-HL model was a joint NASA/Boeing effort, with discussions about future applications and research opportunities. These discussions helped lay the groundwork for the current research effort.

The 10% scale CRM-HL semispan model was designed as a test article to assess the viability of various AFC approaches. Testing of the 10% scale CRM-HL model with AFC on the aileron follows the successful wind tunnel test campaign during which AFC was applied upstream of a simple-hinged flap (CRM-SHL-AFC configuration) [3, 4]. In that first AFC test using the 10% scale CRM-HL [4, 5], simple-hinged inboard and outboard flaps with various types of pneumatic actuators near the flap hinge line were evaluated to determine the aerodynamic feasibility of replacing the Fowler flaps. Replacing the conventional Fowler flaps with simple-hinged flaps augmented by AFC was shown by Hartwich et al. [6] to reduce fuel burn by up to 2.25%. This reduction in fuel burn was attributed primarily to eliminating the flap track fairings associated with the Fowler flaps. Results of the CRM-SHL-AFC test campaign indicated that simple-hinged flaps could be used to match the lift performance of a conventional high-lift configuration with slotted Fowler flaps. Several candidate actuator configurations were tested in an attempt to achieve the targeted lift performance. The large adverse pressure gradient present on the CRM-SHL-AFC with 50° inboard and 55° outboard flaps required the use of an actuation concept called the High Efficiency Low Power (HELP) actuator [3, 4]. Although the actuation in conjunction with the flap configuration was successful in recovering the lift, the changes to the wing geometry and the significant amount of AFC momentum required to control flow separation made the CRM-SHL-AFC configuration a far-term technology for improving fuel burn on a commercial transport.

Following the AFC studies using the CRM-SHL-AFC model, our AFC research pivoted to possible localized applications of AFC that could be integrated into an existing aircraft design and powered by onboard air sources. Shmilovich et al. [7-9] explored several localized applications of active flow control capable of improving L/D by increasing the lift (L) and/or reducing the drag (D) at takeoff and/or landing conditions. Based on the results of these studies, the application of AFC to the aileron was selected to be implemented on the 10% scale CRM-HL model in the NASA Langley 14- by 22-Foot Subsonic Tunnel (14x22). During takeoff, the ailerons are typically deflected symmetrically to a nominal deflection angle of 7.5°. Computational Fluid Dynamic (CFD) simulations indicated that applying AFC to the aileron during takeoff could potentially improve L/D by as much as 5%. A 1% improvement in L/D has been estimated by Garner et al. [10] to be equivalent to a 2,800 lb increase in payload or a 150 nm increase in range for a large, generic twin engine transport aircraft. These potential improvements in the efficiency of a commercial transport motivated the AFC aileron experimental wind tunnel test campaign.

The application of AFC on the “drooped” aileron is similar to the AFC research on the “drooped” flap of the CRM-SHL-AFC configuration in that momentum is introduced into the flowfield upstream of the natural separation point in an attempt to reduce flow separation. Several studies have shown that this approach is successful in reducing or eliminating flow separation, thereby increasing lift. Unlike the CRM-SHL-AFC configuration, the aileron deflection angles, and hence the adverse pressure gradient, are much smaller. These small deflection angles, when compared to the SHL deflection angles, result in separated flowfields that require less momentum input to control. Shmilovich et al. [7, 8] examined several types of actuation ranging from steady blowing through a continuous spanwise slot to discrete ducts on the aileron of a computational reference aircraft (CRA). The CRA used for the study is representative of a conceptual future short/medium range, twin-engine transonic airplane. A system integration study by Vijgen et al. [11, 12] took the CRA results and translated them onto a performance reference configuration to determine the benefit after the AFC system was integrated into the vehicle. They explored the use of the auxiliary power unit (APU), engine bleed, and auxiliary compressors as options for the pneumatic sources required for the AFC system. They concluded with a ranking of each option considering availability, practicality, and weight. Supplying air to the AFC aileron system using the APU (with engine bleed backup) was an option that received a high rating in terms of overall practicality.

The goal of our experimental study was to determine the increment in L/D that can be achieved when applying AFC to the aileron of the 10% scale CRM-HL model. After describing the test facility, model geometry, and installation, we present results, starting with the effects of AFC on the aileron at a deflection angle (δ_a) of 16°. Each subsection begins with an analysis of AFC’s impact on aerodynamic performance characteristics, using the nominal takeoff configuration of the CRM-HL model at $\delta_a = 7.5^\circ$ as a reference for performance improvements. We assess the benefits of the AFC aileron using surface static pressure measurements, balance force and moment results, and mini tuft flow visualization.

II. Experiment and Model Description

The experiment was conducted in the NASA Langley Research Center (LaRC) 14x22. The 14x22 is a closed-circuit wind tunnel with a 9:1 contraction ratio that was built for VSTOL testing in 1970. The test section has multiple configuration options that include closed, slotted, partially open, and open [13]. Reference [13] provides an overview of the facility capabilities that include a boundary layer removal system and optical access for measurement techniques such as Particle Image Velocimetry (PIV), Laser Doppler Velocimetry, and photogrammetry. For the current CRM-HL AFC experiment, we tested with the closed configuration, and the boundary layer removal system was not used. In this tunnel configuration, the test section is 14.5 ft high by 21.75 ft wide by 50 ft long and the maximum speed is 338 ft/sec. The tunnel test section consists of two streamwise bays into which various facility model support carts are installed. Semispan models like the CRM-HL are floor-mounted on a cart in the forward part of the test section [13]. The turbulence intensity in the tunnel is between 0.07 and 0.08 percent at a dynamic pressure (q_∞) of 60 psf; however, it varies with q_∞ and with location [14]. All data presented were acquired at a Mach number of $M = 0.2$ ($q_\infty \approx 60$ psf) resulting in a Reynolds number based on the mean aerodynamic chord (Re_c) of approximately 3.0×10^6 . Temperature is not controlled in the 14x22, so with M fixed, the Re_c varies slightly due to temperature variations. Facility data can be corrected using classical correction methods, the Heyson method [15], and the Transonic Wall Interference Correction System (TWICS), which is based on a wall signature method [16]. Data presented in this paper were corrected using the TWICS method, as were wall corrected data from the CRM-SHL-AFC tests in the 14x22 [3, 4].

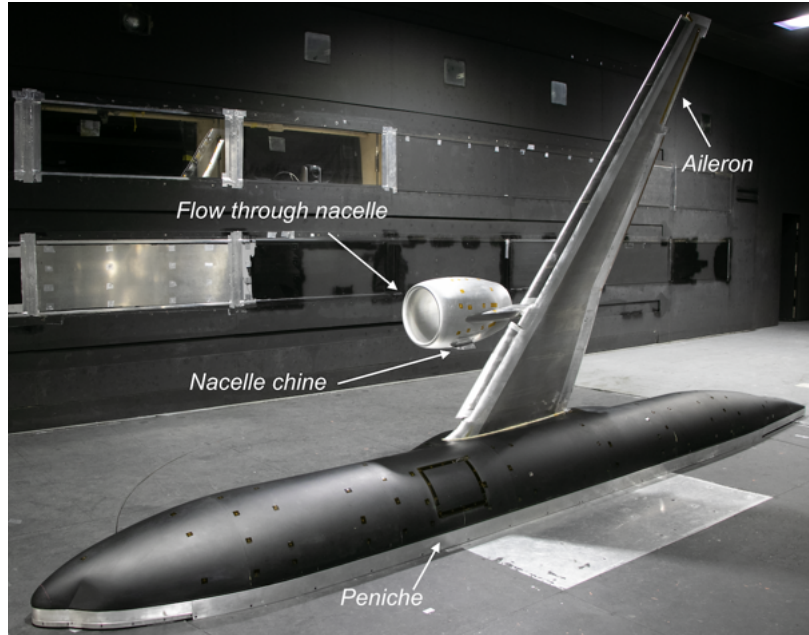


Fig. 1 CRM-HL model in the 14x22 [Source: NASA].

A. CRM-HL Model

The 10% scale semispan CRM-HL model (Fig. 1) was originally built for aeroacoustic and active flow control testing [3, 4, 17]. A new outboard wing section was built and tested in the reference takeoff configuration as defined by Lacy and Clark [18]. Table I summarizes the model dimensions. In the takeoff configuration, the leading edge slat deflection is 22° and the trailing edge flap deflections are 25° for both the inboard and outboard flaps. Additionally, the leading edge slat is sealed [18]. To secure the slat to the wing under slat surface (WUSS), 15 slat brackets, three for the inboard slat and 12 for the outboard slat, were manufactured using direct metal laser sintering. The slat brackets were designed with channels for routing pressure tubing to the WUSS, eliminating the need to route tubing bundles external to the brackets. Two brackets, one internal and one external, connect the inboard flap to the main element and two external brackets support the outboard flap. These brackets are covered by

polycarbonate flap fairings that also cover the outboard flap pressure tubing that is routed through the main wing. The model is mounted on top of a 3.5 inch peniche and includes a strake at the junction between the fuselage and wing leading edge. Similar to the landing configuration [19], the takeoff configuration includes a nacelle chine. The nacelle has the original inlet lip and does not have the modification referred to in Ref. [18]. Transition dots with a height of 0.254 mm (0.01 inches) and a diameter of 1.27 mm (0.05 inches) were installed on the model following the trip dot installation description available for the fourth High-Lift Prediction Workshop [20] that used the results of Lacy and Clark [18] and Evans et al. [21]. Figure 2 shows the pressure orifice layout of the 10% scale CRM-HL model in the takeoff configuration with the AFC aileron installed. Compared to the original outboard section, there are fewer pressure orifices due to the addition of the AFC air supply lines that will be discussed in the next section. Streamwise pressures at $\eta = 0.82$ and $\eta = 0.91$ are labeled in Fig. 2 since these two locations are most affected by aileron AFC.

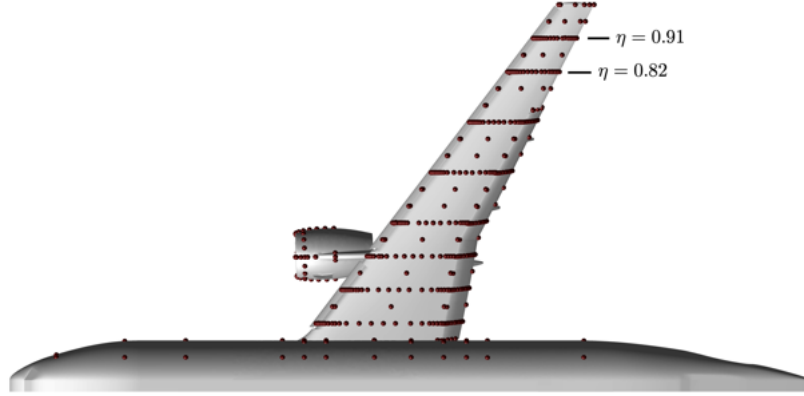


Fig. 2 CAD model with pressure orifices denoted by dots.

Table 1 10% scale CRM-HL model geometry.

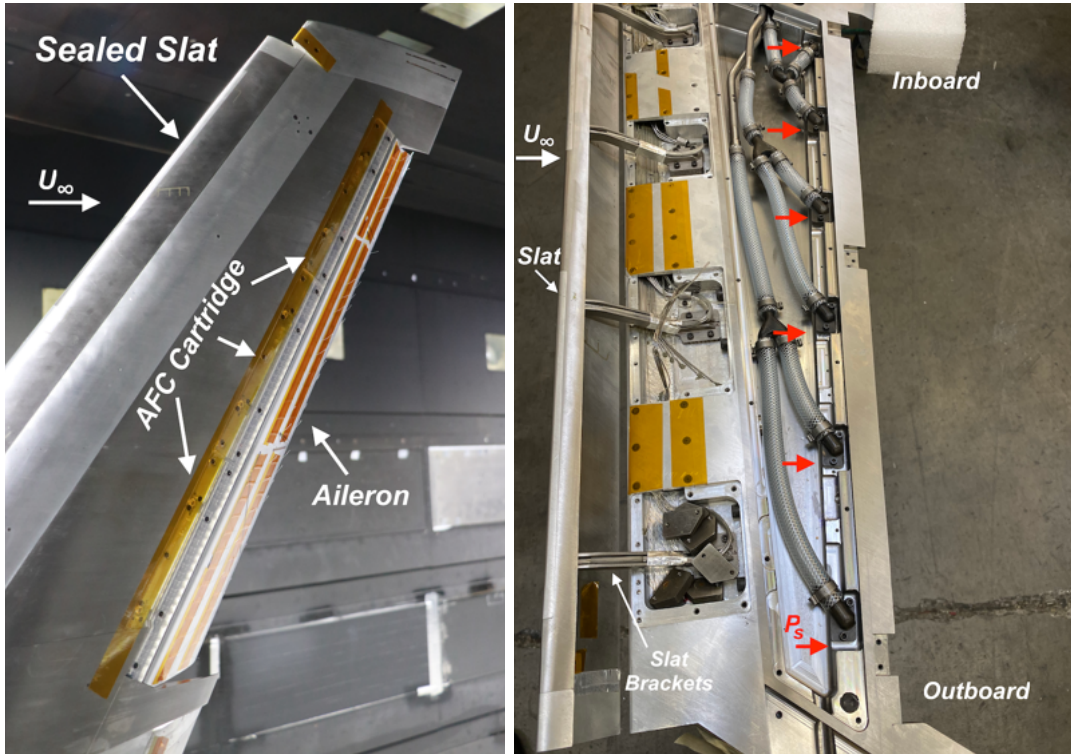
Parameter	Symbol	Value	
		SI	English
Mean aerodynamic chord	c	701 mm	27.6 in
Wing semispan	b	2938 mm	115.7 in
Reference area of semispan wing	S_{ref}	1.918 m ²	2973.6 in ²
Sweep angle at wing quarter chord	Λ	35°	
Aspect Ratio	AR	9	

B. AFC-Aileron

The 10% scale CRM-HL model was designed to be modular to accommodate options such as a future aileron design (Fig. 3a). At the junction between the inboard (just outboard of the outboard flap) and the outboard wing sections, a 25.4 mm (1 inch) diameter hole/passage way was included to route instrumentation and AFC air lines for flow control. Boeing defined an aileron for the CRM-HL planform [8], and the wind tunnel hardware was designed at LaRC. The new outboard wing section of the CRM-HL was designed to include an aileron with fixed brackets for aileron deflection angles of 0°, 7.5°, 16°, and 25°. The aileron at a deflection angle of 0° is defined as the reference takeoff configuration for the CRM-HL ecosystem. The CRM-HL nominal takeoff configuration used for this study has an aileron deflection angle of 7.5°. CFD simulations indicated a potential benefit in L/D by using AFC to control separation on ailerons deflected beyond the nominal deflection angle of 7.5° [7, 8]. Similar to the CRM-SHL-AFC model design [3, 4], the aileron design included a region where AFC actuator cartridges, manufactured using stereolithography, could be installed. Using lessons learned from the 2018 CRM-SHL-AFC test,

the cartridges did not include pressure or thermocouple instrumentation. This instrumentation was included in other regions of the wing that were fixed throughout the test. The red arrows shown in Fig. 3b indicate the fixed locations where the pressures, P_s , used to compute NPR for each actuator cartridge were measured. Thermocouples were installed in the supply lines closer to the valves used to control mass flow rate. Both sweeping jet actuators (SWJ) and convergent-divergent (CD) steady jet actuators were manufactured and tested. Parameters investigated included actuator spacing, mass flow rate, and NPR . The design and installation of the AFC cartridge for the aileron allowed multiple passive and active flow control actuator configurations to be evaluated. Three actuator cartridges (Fig. 3a), covering the span of the aileron, were used for AFC. The mass flow rate to each cartridge could be independently controlled. Figure 3b shows the internal routing of the plumbing used for control. Each actuator cartridge has two air inlets. Actuator inlet static pressure, P_s , was measured in each input port and the average was used to compute NPR for each cartridge.

Due to the smaller adverse pressure gradient generated by deflecting the aileron when compared to CRM-SHL-AFC configuration [3, 4], the mass flow requirements were significantly reduced. An upstream Venturi flowmeter was used to measure total mass flow rate. Additionally, three thermal mass flow meters installed downstream of the control valves for the three AFC actuator cartridges were used to measure the mass flow rate supplied to each AFC cartridge. The AFC air supply system was relocated relative to the layout tested in Ref. [22]. Additionally, the hoses used for the AFC air delivery system were flexible and were routed through the center of the balance to minimize hose and tare interference. The 2-inch diameter high volume shop air line served as the supply air source for the aileron actuator cartridges.



(a) Close-up, top view of aileron [Source: NASA]. (b) Internal cavity view of outboard wing lower surface (aileron and lower surface hatch cover not installed). Red arrows denote P_s measurement locations [Source: NASA].

Fig. 3 Images of CRM-HL model outboard wing section with AFC-enhanced aileron.

Both the SWJ and CD actuators used for the investigation had the exit width-to-height ratios of 2:1 and all actuator orifice dimensions ($w = 1.12 \text{ mm} \times h = 0.55 \text{ mm}$) were identical. The actuator height was limited by the outer mold line (OML) of the CRM-HL model at the trailing edge of the main element. With this limit on actuator height, the width was selected based on the study of Koklu [23] who found 2:1 to be the optimal aspect ratio for a

sweeping jet actuator. Shmilovich et al. [8] also recommended this aspect ratio for the aileron AFC actuators on the CRM-HL model. Spacing of SWJ and CD actuators was varied with spacings (sp) 1, 2, and 3, corresponding to 69, 35, and 18 actuators, respectively. Table 2 summarizes the actuator configurations that were evaluated. Results for SWJ1, SWJ2, SWJ3, CD1, and CD2 actuators are presented in this paper.

Table 2 Aileron actuator cartridge configurations.

Actuator Designation	Actuator Type	Inboard Quantity	Midboard Quantity	Outboard Quantity	Total nozzle area, mm ²
SWJ1	SWJ	23	23	23	43.1
SWJ2	SWJ	12	11	12	21.9
SWJ3	SWJ	6	6	6	11.2
CD1	STJ	23	23	23	43.1
CD2	STJ	12	11	12	21.9

III. Experimental Results

In this section, we present results from the wind tunnel test campaign focused on applying AFC to the drooped aileron of the 10% scale CRM-HL model in the 14x22. During this test campaign, aileron deflection angles, δ_a , of 0°, 7.5°, 16°, and 25° were investigated. A companion paper [24] includes a discussion of three different takeoff configurations, namely, reference ($\delta_a = 0^\circ$), nominal ($\delta_a = 7.5^\circ$), and HL-improved ($\delta_a = 16^\circ$ or 25°), all without AFC. When the aileron is deflected beyond its nominal deflection angle, there is further increase in wing camber that results in the development of a large adverse pressure gradient accompanied by aileron flow separation and an increase in drag. Flow control cases with aileron deflection angle of 16° are investigated and compared to the takeoff aileron nominal deflection angle of 7.5° following the CFD study of Shmilovich et al. [8]. Improvements in L/D are possible at both aileron deflection angles, but higher trim drag penalties are found at larger aileron deflection angles. All data presented here have been corrected for wind tunnel wall interference. The actuators were tested over an NPR range of 1 to 3. The upper NPR limit of 3 was exceeded for some of the cartridges, especially when the number of actuators was reduced for the $sp2$ and $sp3$ actuator configurations of Table 2. All actuator cartridges were evaluated over an abbreviated angle of attack range (0° – 11°) at fixed NPR values to obtain the data needed to assess the L/D benefit of AFC on the drooped aileron. In addition to the α sweeps at a fixed NPR , testing was also performed at a fixed α with NPR varied.

A. Sweeping jet actuators

Sweeping jet actuators have proven to be effective in enhancing aerodynamic performance by suppressing flow separation. Their effectiveness has been demonstrated in numerous experiments with higher technology readiness level (TRL) including flight demonstration of the AFC-enhanced vertical tail [2]. One of the advantages of this type of actuator is the generation of unsteady streamwise vortices, which vary in the spanwise direction, introduced by the natural oscillation of the exit jet [23].

We begin by examining the aerodynamic performance characteristics for an aileron deflected at an angle of 16° using SWJ with three different spacings (SWJ1, SWJ2, and SWJ3) and with NPR levels varied from 1 to 3. The aileron has three individual actuator cartridges used for the evaluation of flow control at the same actuation amplitude for each of the cases presented. Fig. 4a shows lift characteristics referenced to the nominal takeoff configuration, $\delta_a = 7.5^\circ$, over an abbreviated range of angles of attack and selected AFC cases with fixed NPR values for all three spacings tested. In Figs. 4a and 4b, the uncontrolled ($NPR = 1$) HL-improved takeoff configuration, $\delta_a = 16^\circ$, shows a lift coefficient (C_L) increment of approximately of 0.02. Lift increases above the lift level of the nominal takeoff configuration for all NPR levels presented. Applying flow control starting with SWJ1, the most dense distribution of actuators, provides the largest C_L improvement ($\Delta C_L \approx 0.06$ to 0.08) at an NPR of 3. SWJ2 at NPR of 3 results in a lift coefficient increase similar to that of SWJ1 at NPR of 2. The use of either of these configurations, compared to the most effective configuration (SWJ1 at NPR of 3), would result in a slight decrease

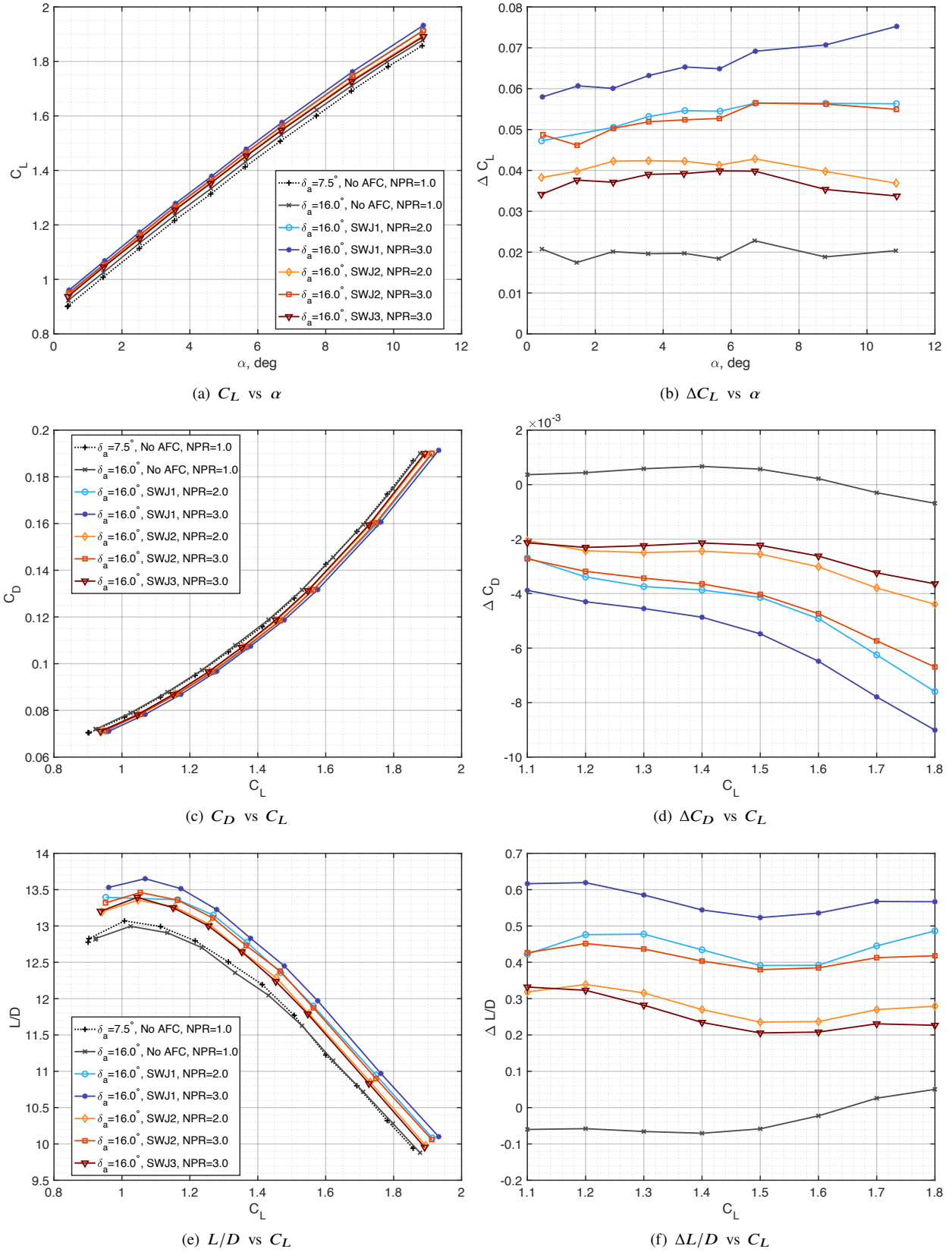


Fig. 4 Aerodynamic performance effects of sweeping jets, SWJ, at various actuation intensities and spacings for an aileron deflected at 16° ($Re_c = 3.0 \times 10^6$, $M = 0.2$).

in the C_L performance improvement. Using SWJ2 at NPR of 3 would reduce the required actuation by half, at the cost of higher input pressure (NPR). SWJ3 at NPR of 3 results in a lift coefficient improvement similar to that of SWJ2 at NPR of 2 for all angles of attack. The effect of sweeping jet actuation effectively increases lift coefficient for the range of angles of attack presented. Fig. 4b is included to enhance the discussion of actuation effects as compared to the nominal takeoff configuration. Increments in lift are clear and consistent across the range presented. Localized AFC applied to the deflected aileron produces small increments in C_L when compared to the improvements to sectional lift due to controlling flow separation resulting from the drooped aileron. Tuft flow visualization and surface static pressure results, presented in later sections of the paper, will illustrate the local effect of AFC on the model.

Fig. 4c shows the drag coefficient (C_D) for SWJ controlled flow fields versus C_L for the NPR levels examined in Fig. 4a. As mentioned previously, with $\delta_a = 16^\circ$ flow separation develops on the aileron, resulting in an increase in C_D with AFC off ($NPR = 1$). Fig. 4c shows a reduction in C_D for a constant lift coefficient for all SWJs at select NPR values over the range presented. Furthermore, as C_L increases, C_D decreases by a greater magnitude as compared to the nominal takeoff aileron deflection angle of $\delta_a = 7.5^\circ$. Fig. 4d shows the reduction in drag coefficient achieved with AFC using our nominal takeoff configuration, $\delta_a = 7.5^\circ$, as a reference. All cases presented with the SWJ actuators active ($NPR > 1$) produced a reduction in drag for a given C_L . Depending on the ΔC_D required, similar C_D performance can be obtained using either SWJ1 at NPR of 2 or SWJ2 at NPR of 3. C_D results for SWJ3 at NPR of 3 are also similar to those obtained with SW2 at NPR of 2. Presenting the data in this manner demonstrates AFC contributions to drag reduction.

Results in Figs. 4e and 4f show the combined contribution of AFC in L/D for a range of C_L . L/D is increased over the abbreviated α range presented. It is interesting to note that when we look at the increments compared to the nominal takeoff case, the L/D improvement is not constant, but it is sustained through the C_L range. With SWJ AFC, the high-lift performance of the CRM-HL model is improved as evidenced by the increments in L/D obtained over the C_L range of Fig. 4f. L/D increases for a given actuator spacing as NPR increases and thus input momentum is increased. In agreement with the C_L and C_D results of Figs. 4b and 4d, respectively, the number of SWJ actuators can be traded against input pressure (NPR) to obtain a given $\Delta L/D$. The improvements in L/D shown in Fig. 4e are similar to the computational results of Shmilovich [25] performed on the CRM-HL model. During takeoff, a symmetric deflection of the ailerons is used to increase L/D . A small aileron deflection angle that increases wing camber without generating a large separated flow region on the aileron is used to increase L/D . For the drooped aileron with AFC, the aileron droop or deflection angle is increased to a point where separation is present on the aileron. AFC in combination with the higher δ_a maintains attached flow on the aileron. Shmilovich notes that the improvements in L/D with the AFC aileron are due to a reduction in form drag and an increase in induced drag. These result from changes in span loading due to the increase in sectional lift on the outboard wing section, which in turn generates a more elliptical lift distribution.

Flow visualization was performed by applying fluorescent minitufts over the aileron. Fig. 5 shows seven images of different sweeping jet spacings and actuation amplitudes at $\alpha = 4.6^\circ$. The first image on the left shows the AFC reference case with the aileron at its nominal takeoff deflection angle of $\delta_a = 7.5^\circ$. Here a small separation bubble is observed near the trailing edge. Crossflow is starting to develop along the span of the aileron, and it is more pronounced outboard of $\eta = 0.82$ all the way to its tip. Next we have $\delta_a = 16^\circ$ at NPR of 1. The tufts are now pointed upstream and unsteady, which seems to clearly indicate massive separation on the aileron at $\delta_a = 16^\circ$. This correlates well with the increase in lift and drag results. There is a strong unsteady spanwise flow where the tufts are oscillating (noted by the “fan-like” shape of the tufts) in the direction of the aileron’s tip. When actuation is applied with SWJ1 at NPR of 2, the flow seems to be attached. The spanwise flow is eliminated at the TE of the aileron. From the flow visualization alone, there is no significant improvement when the actuation amplitude is increased from $NPR = 2$ to $NPR = 3$ for SWJ1. Images 5-7 show the effects of increased spacing between actuators. In images 5 and 6, the number of actuators was reduced by half. For this configuration, starting with SWJ2 with an NPR of 2, flow separation is reduced but not eliminated. This is shown by the streamlined tufts near the LE of the aileron (i.e. attached flow) but separated flow near the TE of aileron. There is a reduction in crossflow when compared to the uncontrolled $\delta_a = 16^\circ$ case. For SWJ2 at NPR of 3, the flow is mostly attached, but there are a few local flow separations (such as one inboard of $\eta = 0.82$ and one outboard of $\eta = 0.91$) due to increased actuator spacing caused by cartridge mounting screws. An increase in the flow unsteadiness is captured by the long exposure of the image and is represented by the blurry movement of the tufts. On our last image, SWJ3 at NPR of 3, actuator spacing was increased and the number of actuators reduced to 26% compared with the most dense case, SWJ1. For this spacing, we observe unsteadiness and the flow is separated, but it is different

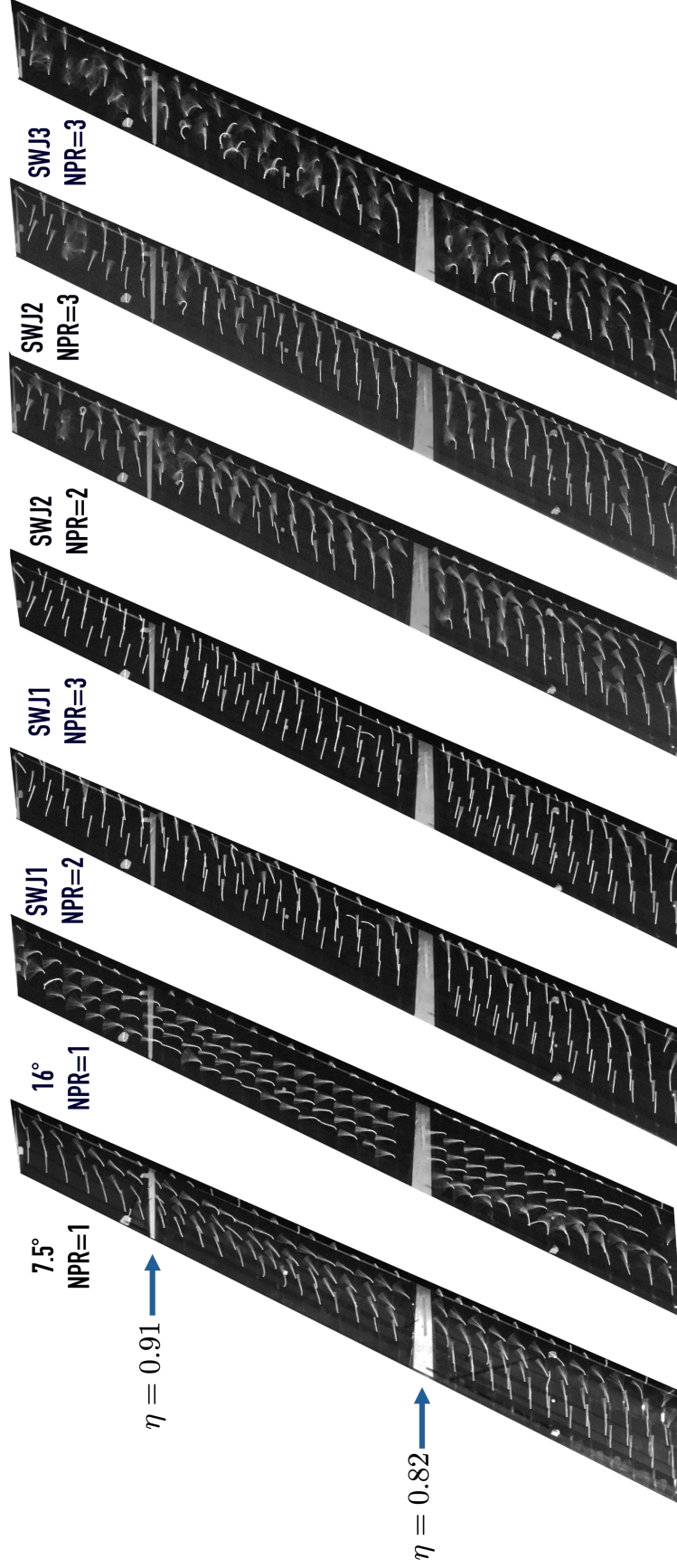


Fig. 5 Flow visualization for an aileron deflected at 16° using SWJ for different spacings at selected NPR values ($Re_c = 3.0 \times 10^6$, $M = 0.2$, $\alpha = 4.6^\circ$).

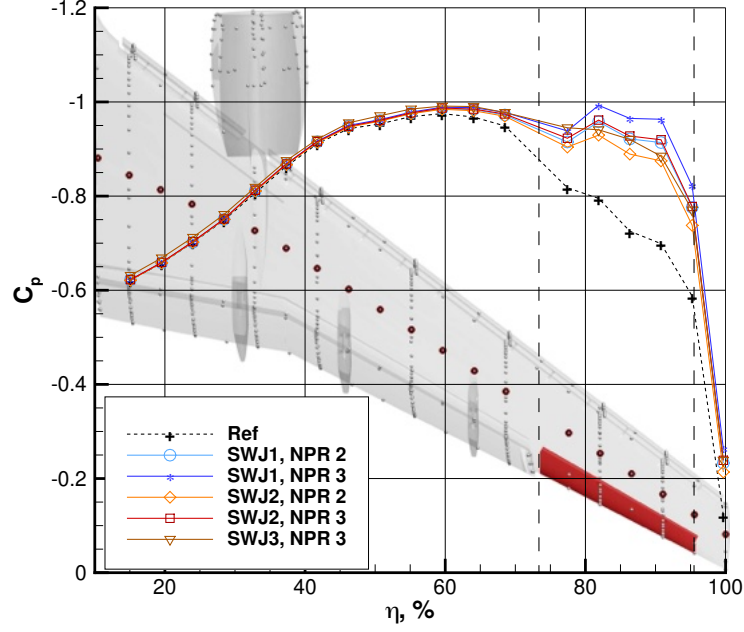
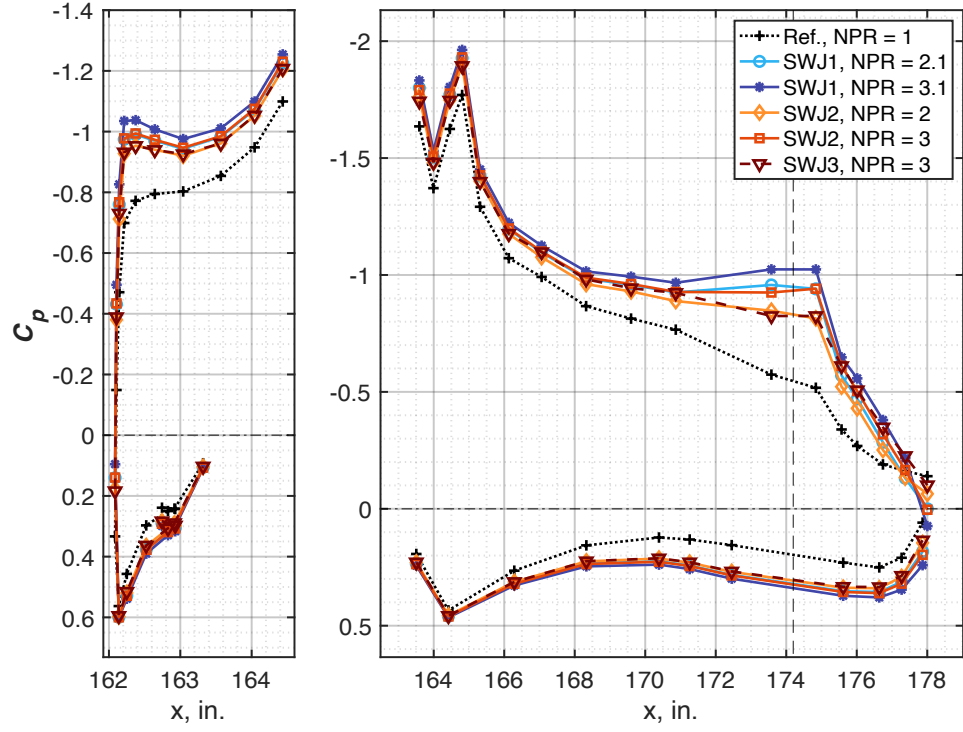


Fig. 6 Effect of SWJs on pressure coefficient along a spanwise location for various actuation intensities and spacings for an aileron deflected at 16° ($Re_c = 3.0 \times 10^6$, $M = 0.2$, $\alpha = 4.6^\circ$).

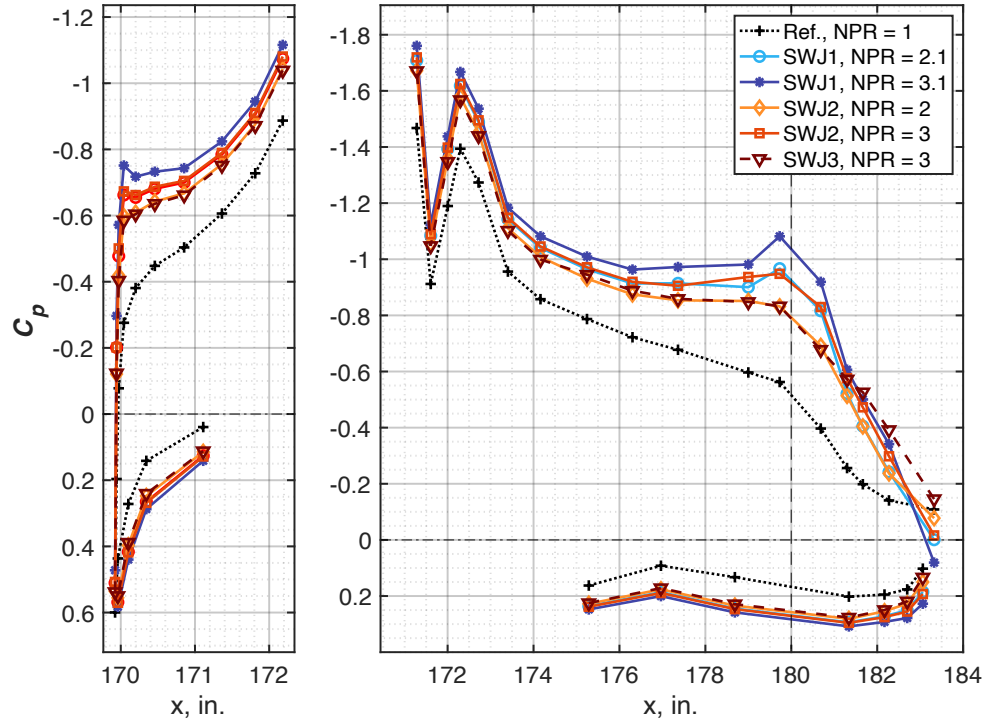
than our uncontrolled case of NPR of 1. In this case, each cartridge has 6 jets and we can deduce where some of the jet exits are by following rows of tufts that go along a line.

Local changes to the flowfield over the wing can be determined by an examination of the pressure distributions. First, we observe the spanwise pressure distribution over the main element in Fig. 6 at $\alpha = 4.6^\circ$. Static pressure ports and the aileron are highlighted in red. Application of AFC causes an increase in suction pressure across the aileron section. Its effects are noticeable in pressure ports inboard of the aileron, starting near $\eta = 0.60$. As we saw with the aerodynamic coefficients, the effects of SWJ1 at NPR of 2 are similar to SWJ2 at NPR of 3. Suction pressure increases with the increase of actuation amplitude for each spacing shown.

Now we examine C_p distributions at two spanwise locations ($\eta = 0.82$ and $\eta = 0.91$, labeled in Fig. 2) on the aileron at $\alpha = 4.6^\circ$ in Fig. 7. As before, the uncontrolled case presented is the nominal takeoff configuration, $\delta_a = 7.5^\circ$, shown by the dotted line. In Fig. 7a at $\eta = 0.82$, the C_p distribution indicates the flow over the aileron's trailing edge is separated. For all actuated cases, the suction pressure is increased on the slat and main element. The C_p distribution confirms what we observed in the flow visualization. SWJ1 at NPR of 2 and SWJ2 at NPR of 3 attach the separation present towards the trailing edge of the aileron at its nominal deflection. The pressure distribution near the trailing edge for SWJ2 at NPR of 2 is slightly more attached than the uncontrolled case. Fig. 7b shows the C_p distributions at $\eta = 0.91$. SWJ3 for an NPR of 3 at this location has more separation than the uncontrolled case. SWJ1 at NPR of 2 and SWJ2 at NPR of 3 show attached flow. The improvements in the C_p distribution are consistent with the increased lift coefficient for the AFC cases.



(a) $\eta = 0.82$



(b) $\eta = 0.91$

Fig. 7 Effect of SWJs on pressure coefficient at two locations on the aileron at various actuation intensities and spacings for an aileron deflected at 16° ($Re_c = 3.0 \times 10^6$, $M = 0.2$, $\alpha = 4.6^\circ$).

B. CD steady jet actuators

The use of steady blowing for flow control has been shown to effectively control separation [26]. Previous studies indicate that steady jets, when properly oriented, can outperform sweeping jets [27]. In this study, the exits for both actuator types are identical in size, location, and orientation. Fig. 8a and 8b show the lift coefficient over a limited range of α for selected AFC cases in which CD steady jets were used. Two different spacings (CD1 and CD2) were investigated. The CD actuators showed an increase in lift coefficient when compared to both the nominal takeoff configuration ($\delta_a = 7.5^\circ$) and HL-improved takeoff configuration ($\delta_a = 16^\circ$). CD1, which has the densest jet distribution, at an NPR of 3 shows the largest performance improvement compared to the uncontrolled cases. Notably, CD1 at NPR of 2 produced similar performance gains compared to CD2 at NPR of 3. In the CD2 configuration, the actuator number was reduced by half. Reducing the nozzle exit area to half could be beneficial, though it requires higher pressure ratios. Design limitations will ultimately dictate the trade-offs made in selecting a final design.

Fig. 8c and 8d present the drag polars, covering the same range of α as shown in Fig. 8a. To better understand the effect of the selected AFC cases on the drag coefficient, the data are plotted in this format. Note that both uncontrolled cases show similar drag values. All steady CD jet cases resulted in a reduction in drag coefficient for a given lift coefficient, particularly when compared to the nominal ($\delta_a = 7.5^\circ$) and HL-improved ($\delta_a = 16^\circ$) takeoff configurations. This reduction becomes more pronounced as C_L increases.

The AFC increases in lift-to-drag ratio are presented in Fig. 8e and 8f. CD1, at an NPR of 3, provides the largest improvement in L/D . Increasing the spacing, CD2 at $NPR = 3$ produces similar improvements to CD1 at an $NPR = 2$. Overall, the increases in L/D are evident across the range of C_L values presented.

Fig. 9 shows tuft flow visualization results for $\delta_a = 16^\circ$, demonstrating the effect of AFC using CD steady jets. Each image is labeled with its corresponding AFC parameter to the left. First, we show the flow field for the nominal takeoff configuration ($\delta_a = 7.5^\circ$, $NPR = 1$), followed by the HL-improved takeoff configuration ($\delta_a = 16^\circ$, $NPR = 1$). Next, we present the first CD1 case at $NPR = 2$, where the flow field exhibits a noticeable change in behavior. A reduction in crossflow is the most significant difference compared to the uncontrolled case at $\delta_a = 16^\circ$. Although there is some unsteady spanwise flow, the flow visualization indicates predominantly attached flow. When the actuation amplitude is increased to $NPR = 3$, we observe that the slight unsteadiness of the tufts close to the trailing edge is reduced or eliminated in some areas. These behaviors are similar to those observed for sweeping jet actuators. Next, reducing the number of actuators and increasing their spacing takes us to the CD2 configuration. A slight difference is observed at CD2 for both $NPR = 2$ and $NPR = 3$, where in the region between $\eta = 0.82$ and $\eta = 0.91$, a group of tufts behaves differently from the rest. The steady jets seem unable to affect this region, whereas for SWJ2 at $NPR = 3$, an effect was noticed. One positive effect of the CD2 configurations is that the crossflow is reduced as the actuation amplitude increases.

Fig. 10 presents the local changes to the flowfield over the main element from a spanwise pressure distribution at $\alpha = 4.6^\circ$. The application of AFC results in an increase in suction pressure across the aileron section. This effect is noticeable even inboard of the aileron, starting near $\eta = 0.60$. As seen in the aerodynamic characteristics, the effects of CD1 at $NPR = 2$ are similar to those of CD2 at $NPR = 3$. Suction pressure increases with the actuation amplitude for each spacing.

Streamwise C_p pressure distributions for two locations ($\eta = 0.82$ and $\eta = 0.91$) on the aileron at $\alpha = 4.6^\circ$ are shown in Fig. 11. The CD steady jets produce an increase in suction pressure over the slat and main element at both streamwise locations (Fig. 11a and 11b). CD1 at $NPR = 2$ and CD2 at $NPR = 3$ indicate attached flow over the aileron. Flow separation is significantly reduced for CD2 at $NPR = 2$ compared to the nominal takeoff configuration of $\delta_a = 7.5^\circ$ at $\eta = 0.82$. The maximum increase in suction pressure is near the aileron's hinge line and is obtained for CD1 at $NPR = 3$. Similar behaviors are observed for the results at $\eta = 0.91$, shown in Fig. 11b. At this location, there are higher suction peaks around the aileron's hinge line and slightly smaller values over the slat and main element, when compared to the levels found at $\eta = 0.82$. CD2 at $NPR = 2$ produces similar C_p values at the aileron trailing edge compared to the nominal takeoff $\delta_a = 7.5^\circ$.

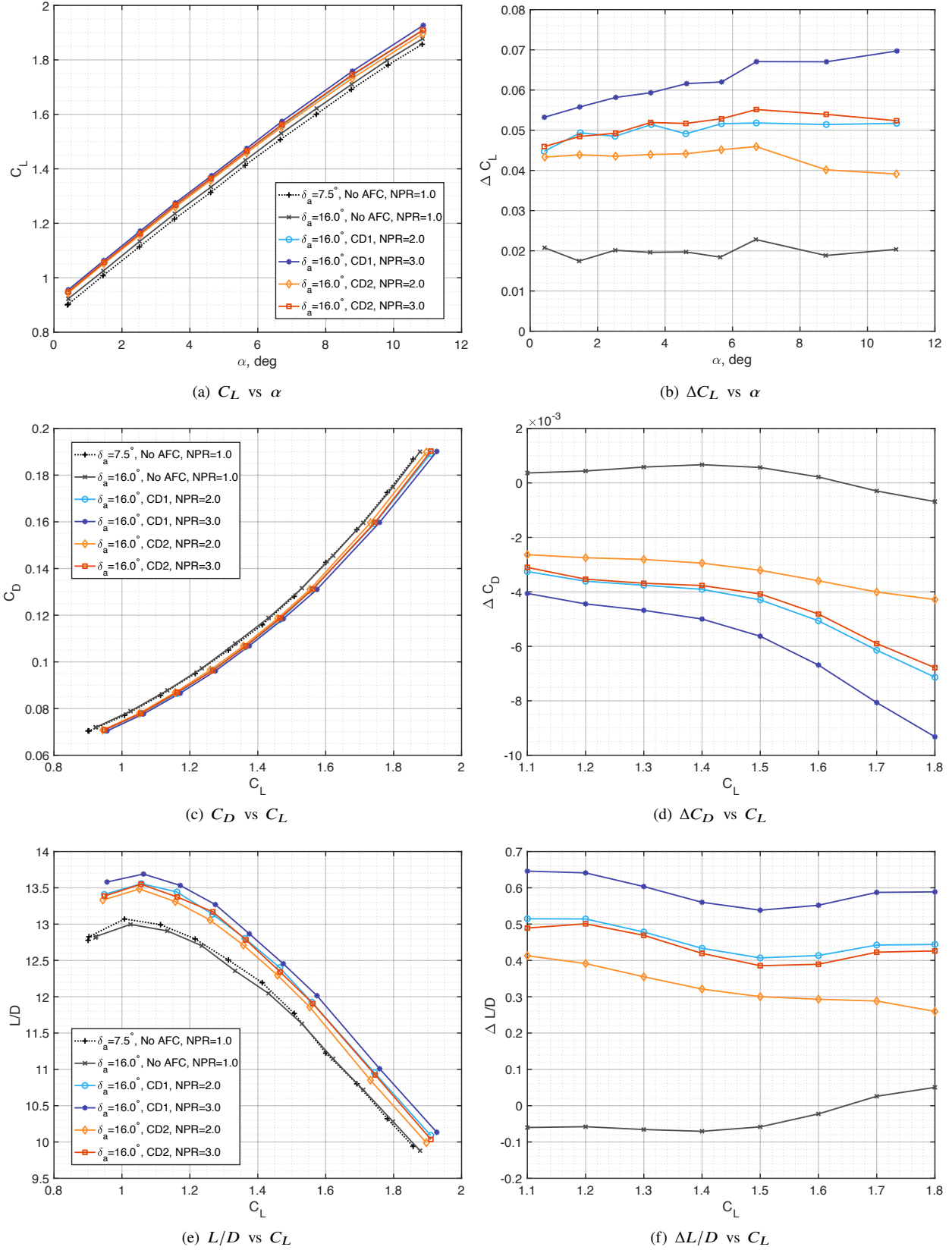


Fig. 8 Aerodynamic performance effects of convergent divergent, CD, steady jets at various actuation intensities and spacings for an aileron deflected at 16° ($Re_c = 3.0 \times 10^6$, $M = 0.2$, $\alpha = 4.6^\circ$).

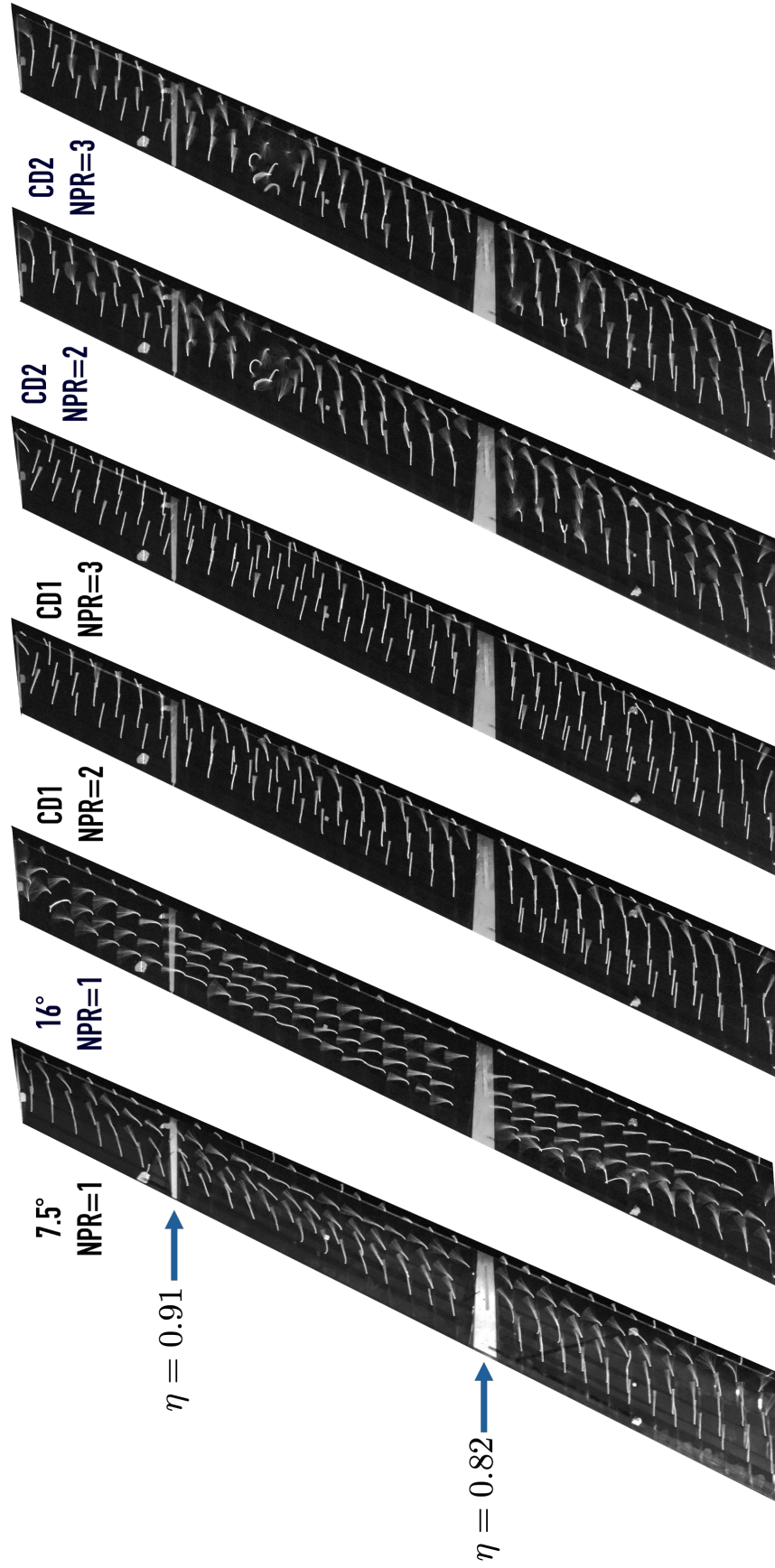


Fig. 9 Flow visualization for an aileron deflected at 16° using CD steady jets for different spacings at selected NPR values ($Re_c = 3.0 \times 10^6$, $M = 0.2$, $\alpha = 4.6^\circ$).

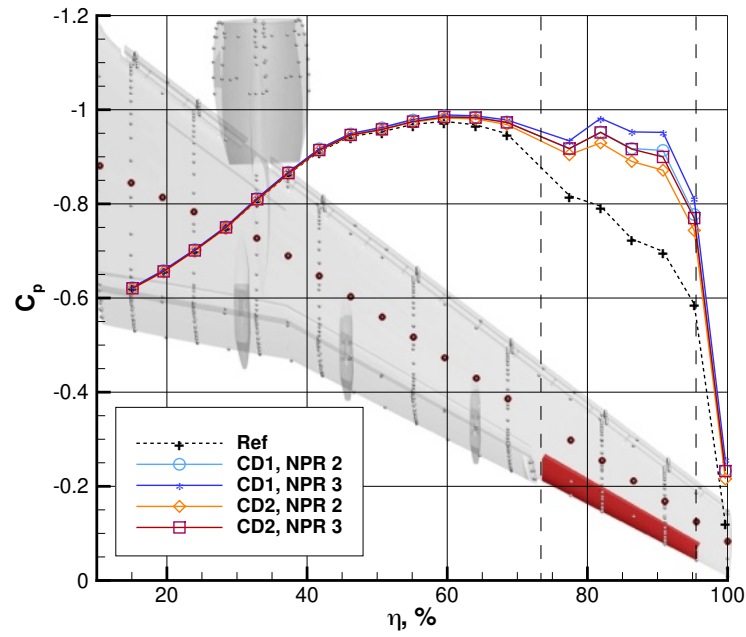
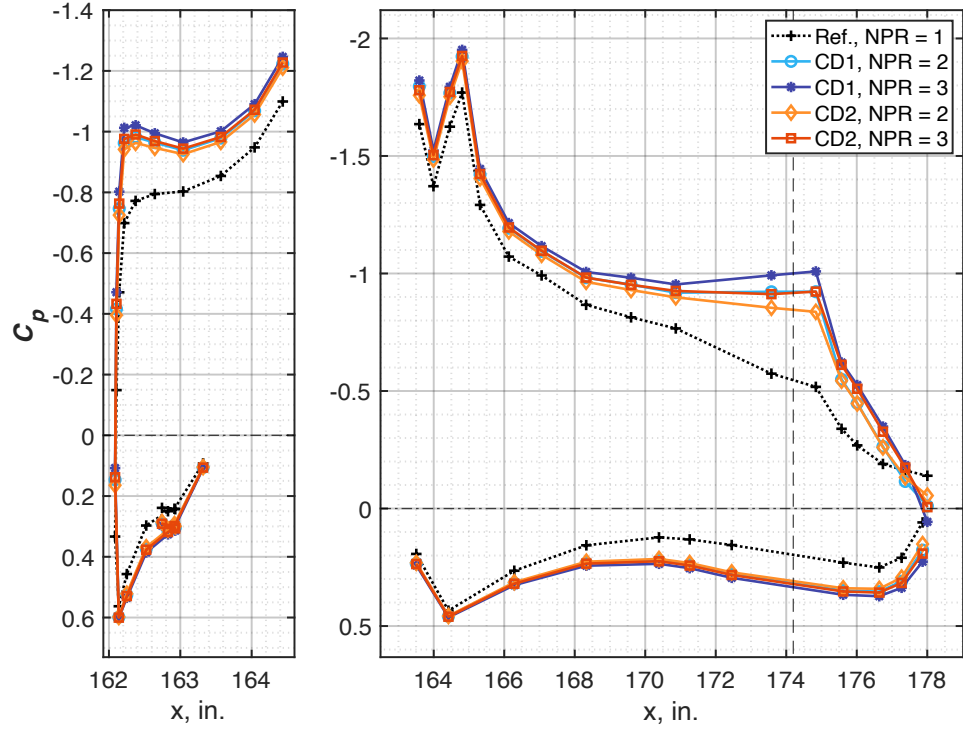
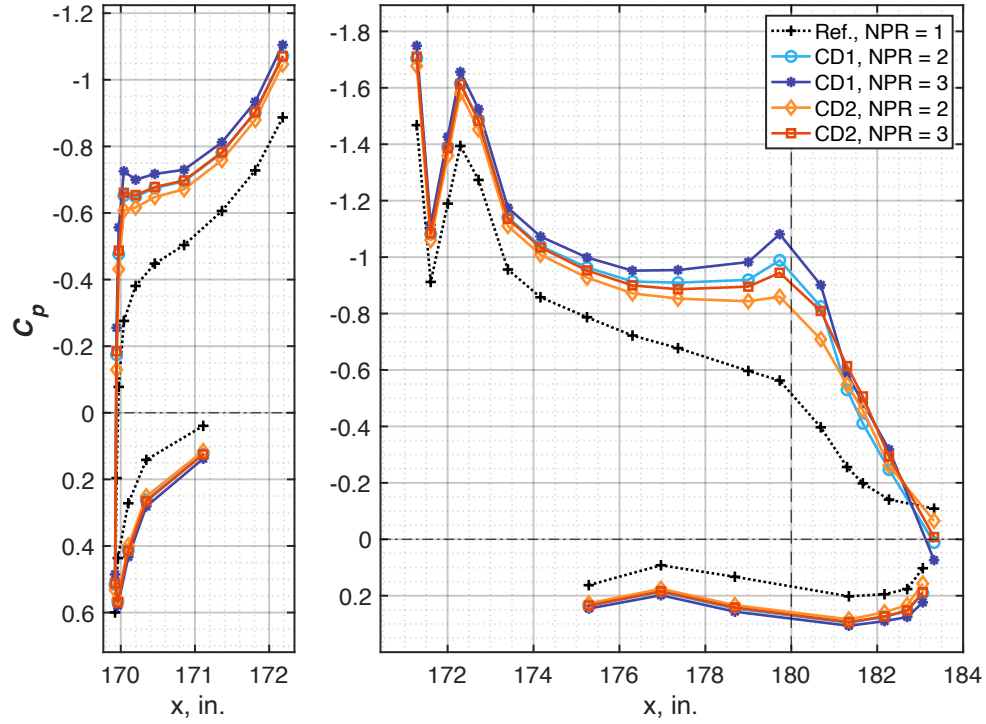


Fig. 10 Effect of CD steady jets on pressure coefficient along a spanwise location for various actuation intensities and spacings for an aileron deflected at 16° ($Re_c = 3.0 \times 10^6$, $M = 0.2$, $\alpha = 4.6^\circ$).



(a) $\eta = 0.82$



(b) $\eta = 0.91$

Fig. 11 Effect of CD steady jets on pressure coefficient at two locations on the aileron at various actuation intensities and spacings for an aileron deflected at 16° ($Re_c = 3.0 \times 10^6$, $M = 0.2$, $\alpha = 4.6^\circ$).

C. AFC Evaluation Parameters

Another important aspect of this study is evaluating the efficiency of the selected flow control device. To do so, we examine the dependence of lift-to-drag ratio (L/D) on four AFC performance parameters. The data were acquired at fixed angle of attack ($\alpha = 4.6^\circ$) by performing an amplitude sweep for each spacing and actuation type tested. The increments in L/D were calculated using the uncontrolled HL-improved takeoff configuration ($\delta_a = 16^\circ$) as the reference for the results discussed in this subsection. Cavity pressures are measured just upstream of each cartridge input port. To assess the effect of spacing and actuation type, we tested each configuration at the same NPR values.

First, in Fig. 12a, we present the range of NPR tested against the percentage increments in L/D . We found that for $sp1$ and an NPR of 2, both types of actuation are successful at attaching the flow. The improvements from the CDs seem to level off at an NPR of 2.5 for $sp1$. The maximum increase in L/D from the SWJs reached 4.5% at an NPR of 3, while the CDs reached 3.8% at the same NPR. The two $sp2$ devices produced somewhat lower but similar L/D improvements across the same amplitude range.

The dependence of L/D on the power coefficient, C_π , is shown in Fig. 12b. Comparing CD2 and SWJ2 at an NPR of 2, each has a similar increase in $\Delta L/D$ and power coefficient. However, for larger NPRs, CD2 has a slightly lower increase in $\Delta L/D$ ($\approx 0.2\%$) and power coefficient ($\approx 0.1E - 4$) than SWJ2. Now comparing CD1 and SWJ1 at an NPR of 2, each produces a similar increase in $\Delta L/D$, but CD1 has a lower power coefficient ($\approx 0.1E - 4$) than SWJ1. For NPR of 2.5 the power coefficient needed by CD1 is smaller than for the SWJ1. At each NPR, CD1 has a lower C_π than SWJ1 for the same actuation amplitude.

In Fig. 12c we show the improvements in $\Delta L/D$ against the momentum coefficient, C_μ . Comparing $sp1$ configurations, we find that CD1 is more efficient than SWJ1 at an NPR of 1.5 because a lower momentum coefficient is required for the same $\Delta L/D$ increase. At larger NPR values, CD1 levels off in $\Delta L/D$ performance improvement while SWJ1 continues to increase in performance and the momentum coefficient needed. For the $sp2$ configurations, there is a similar trend, however, the performance improvement differences are smaller. Results show that CDs are more efficient than SWJs for this 3D flow field.

Finally, Fig. 12d compares the $\Delta L/D$ increase against the mass flow coefficient, C_Q . Results demonstrate similar behaviors to those found for the momentum coefficient, C_μ . In this evaluation, the CD actuation type is more efficient because it requires a lower mass flow coefficient for a given $\Delta L/D$; however, SWJ actuation provides the highest performance improvements in L/D .

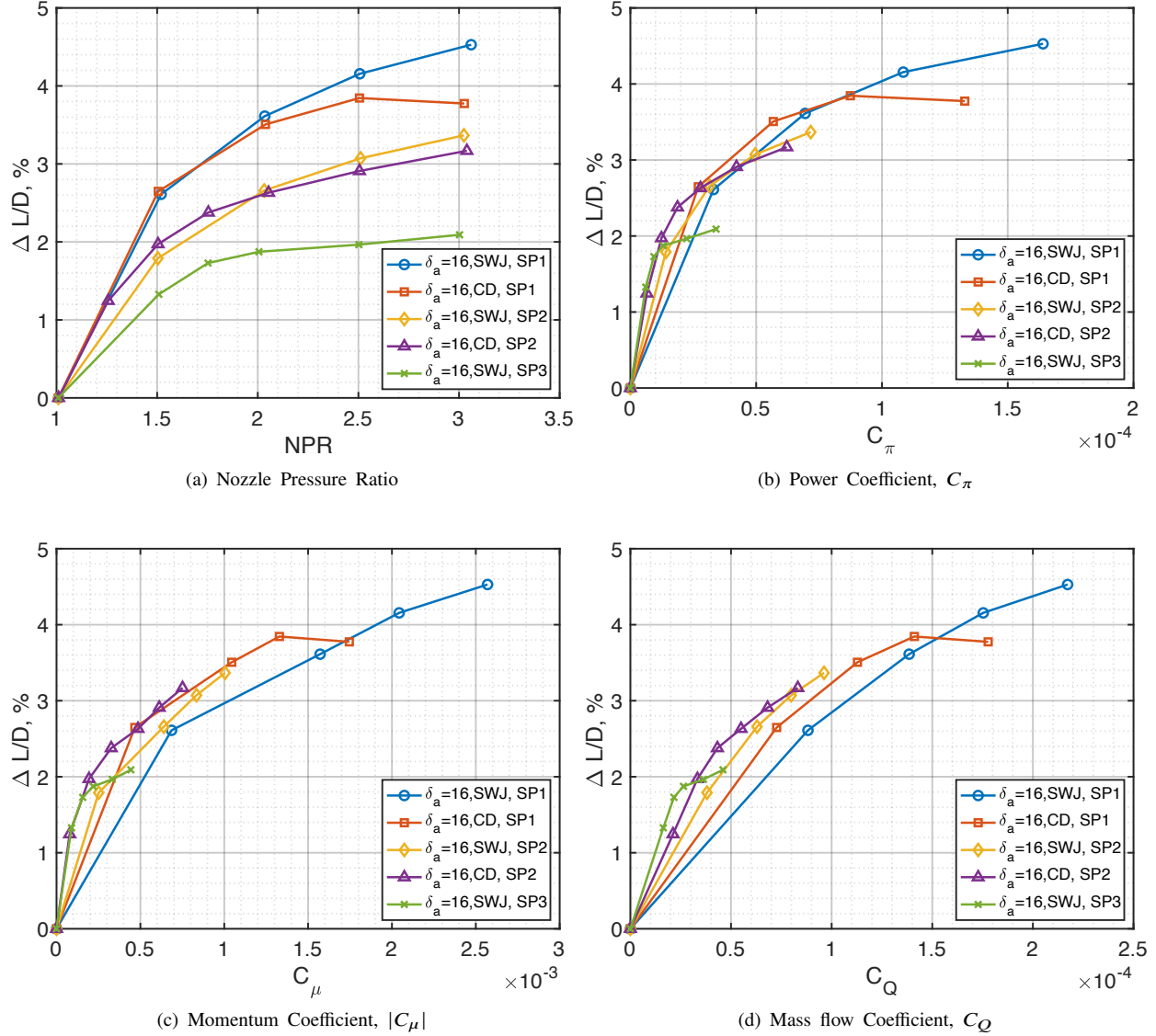


Fig. 12 Dependence of L/D on NPR , C_π , C_μ , and C_Q at various actuation intensities and spacings for an aileron deflected at 16° ($Re_c = 3.0 \times 10^6$, $M = 0.2$, $\alpha = 4.6^\circ$).

IV. Summary

An experimental investigation was conducted in the NASA Langley 14- by 22-Foot Subsonic Tunnel on the NASA 10% scale High-Lift Common Research Model (CRM-HL) to improve its high-lift aerodynamic performance in the takeoff configuration. Active flow control (AFC) was applied to the aileron to enhance the lift-to-drag ratio (L/D). The study investigated aileron deflection angles of 0° , 7.5° , 16° , and 25° , with AFC applied at 16° and 25° deflections. Aileron deflection angles of 16° and 25° with AFC applied represent the high-lift (HL) improved takeoff configurations. These configurations were compared to the nominal takeoff aileron deflection of 7.5° .

A companion paper [24] discussed baseline flow characteristics for the CRM-HL under three takeoff conditions: reference, nominal, and HL-improved. To accommodate this study, a new aileron was designed with three interchangeable flow control cartridges at the hinge line, enabling the investigation of various flow control parameters, including actuator type, spacing, and intensity.

The performance of the different AFC configurations was assessed using tuft visualization, steady surface pressure measurements, and force and moment data. Results demonstrated that all AFC configurations increased the lift coefficient (C_L) across all angles of attack studied. Flow separation was mitigated by the injection of momentum at the aileron hinge line. The configurations with the smallest actuator spacing provided the highest aerodynamic improvements in L/D . Steady jet actuation demonstrated higher efficiency, with similar overall aerodynamic performance compared to sweeping jet actuators. Sweeping jet actuators produced the highest aerodynamic performance at the cost of larger power coefficient (C_π), momentum coefficient (C_μ), and mass flow coefficient (C_Q).

For the HL-improved takeoff configuration at an aileron deflection of 16° , all AFC cases resulted in increases in lift coefficient (C_L) and reductions in drag coefficient (C_D) over a limited range of angles of attack. These improvements led to higher L/D ratios for both sweeping jet (SWJ) and converging diverging (CD) steady jet actuation types. When the number of actuators was reduced by half, both actuation types produced similar improvements in L/D , suggesting that reduced actuation could still maintain the aerodynamic benefits. Flow visualization provided qualitative confirmation of the aerodynamic performance improvements observed in the surface pressure and force results.

One of the primary objectives of this project was to use localized AFC to achieve drag reduction. The results confirmed that all AFC strategies led to drag reduction within a specific range of constant lift coefficient. This research supports the NASA Advanced Air Transport Technology (AATT) Project, contributing to the development of more efficient high-lift systems for future aircraft.

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