



Aerodynamic Performance Improvement: Active Flow Control Application on the NASA CRM-HL Aileron

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**3rd Colloquium on Separation Control in High-Speed Flows – mechanisms,
methods, and application**

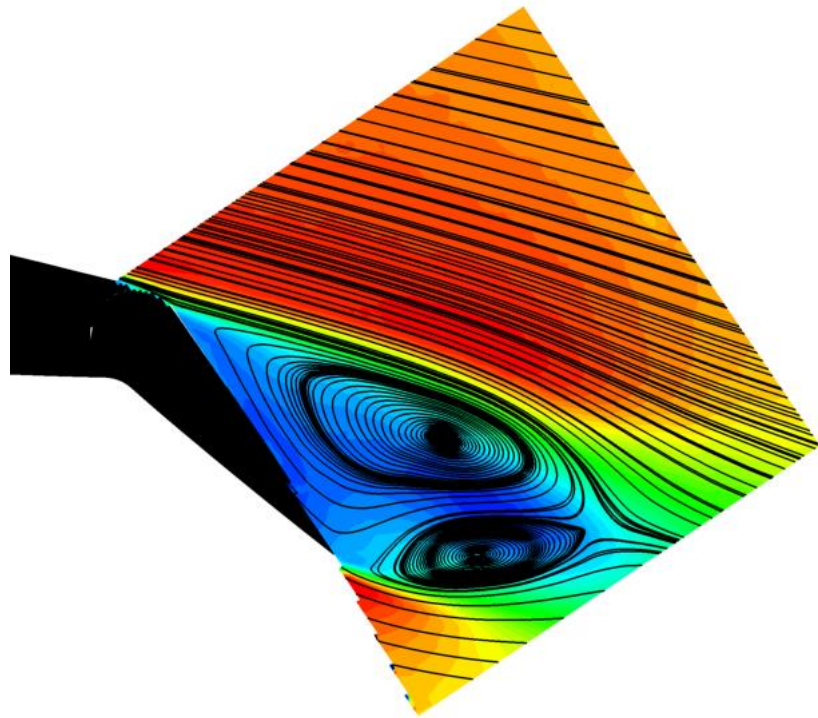
Research funded by Airframe Technologies (AT) Subproject of the Advanced Air Transport Technology (AATT) Project

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Active Flow Control



“The ability to actively manipulate a flow field to bring about a desired change ...”
from Gad-el-Hak **Flow Control: Passive, Active, and Reactive Flow Management**



AFC-off

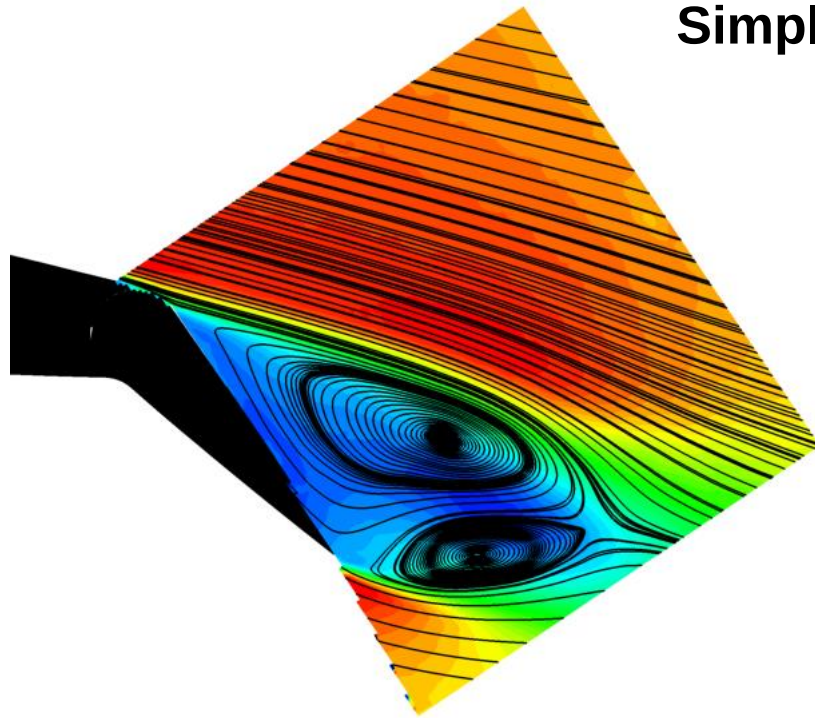
Melton, et al., <https://doi.org/10.2514/1.J056841>

Active Flow Control

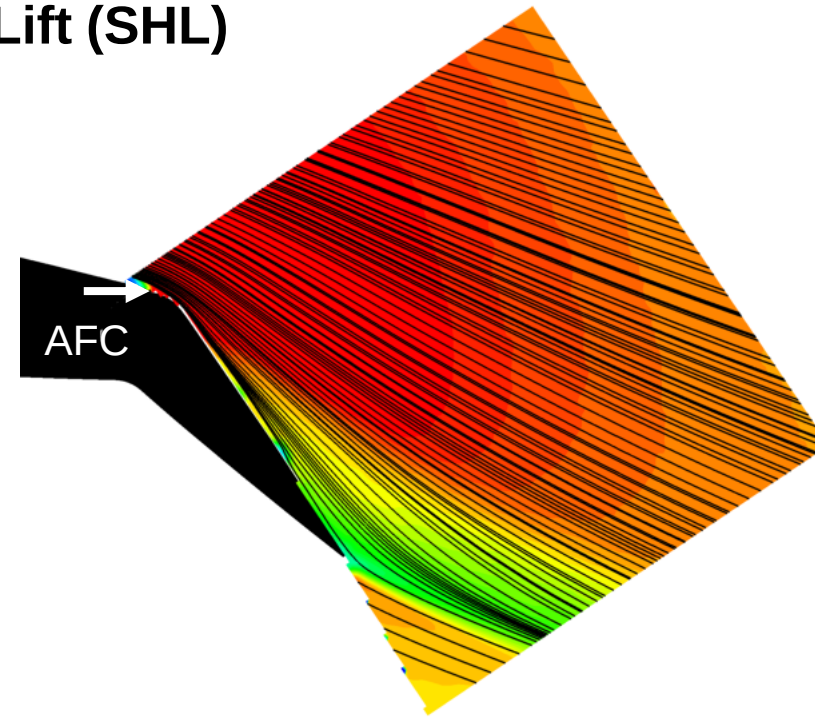


“The ability to actively manipulate a flow field to bring about a desired change ...”
from Gad-el-Hak **Flow Control: Passive, Active, and Reactive Flow Management**

Simplified High-Lift (SHL)



AFC-off



AFC-on



Active Flow Control (AFC) has proven effective in enhancing the aerodynamic performance of high-lift systems on commercial transport aircraft.

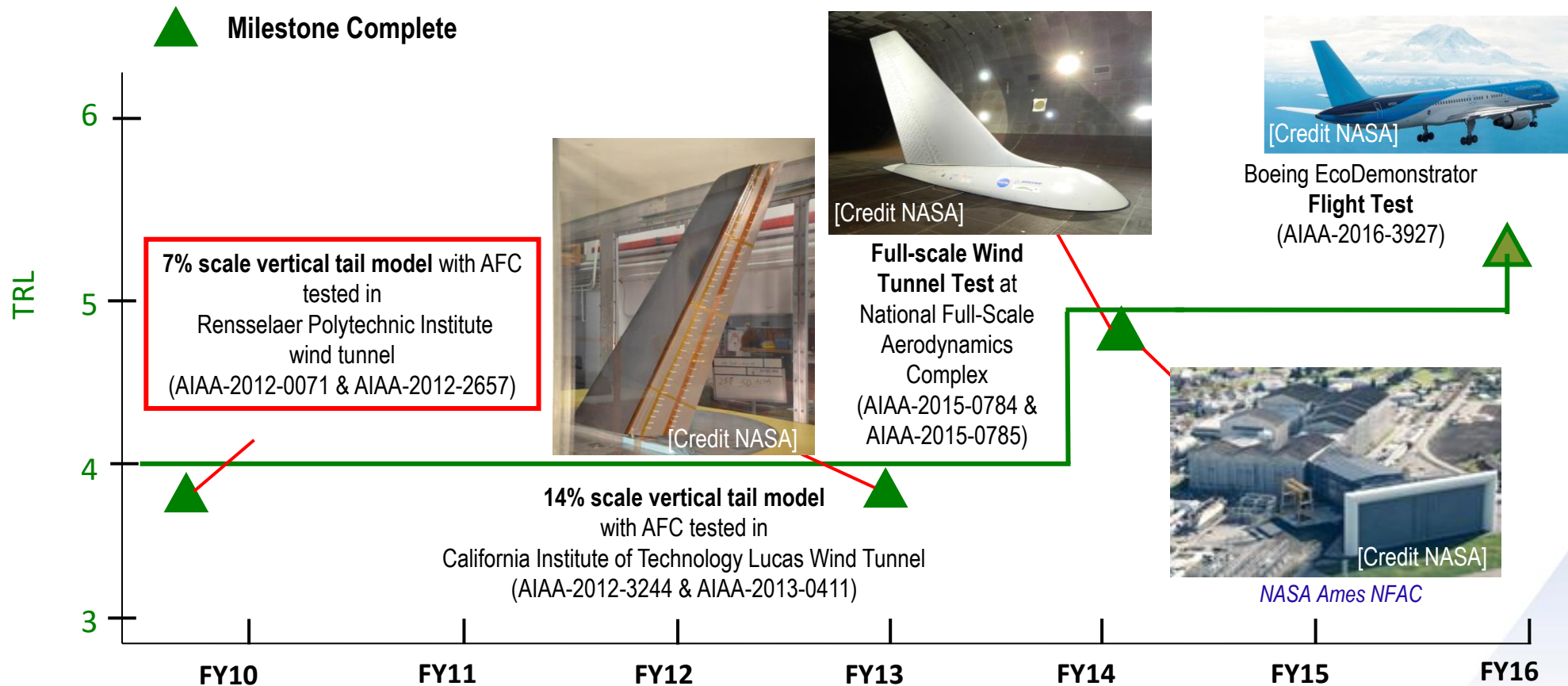
- AFC has been a technology investment area for NASA programs
- Environmentally Responsible Aviation program goals
 - Flow Control concepts for drag reduction
 - Advanced composites for weight reduction
 - Advanced Ultra High Bypass engine: fuel burn and noise reduction
 - Airframe and engine integration concepts: community noise and fuel burn reduction

Separation Control: Previous work



- AFC technology fits within NASA's Environmentally Responsible Aviation goals of 8% drag reduction for airframe technology
- Boeing system study estimated fuel burn reduction of 15,500 gallon/airplane/year for AFC enhanced vertical tail using sweeping jets to achieve 20% side force enhancement

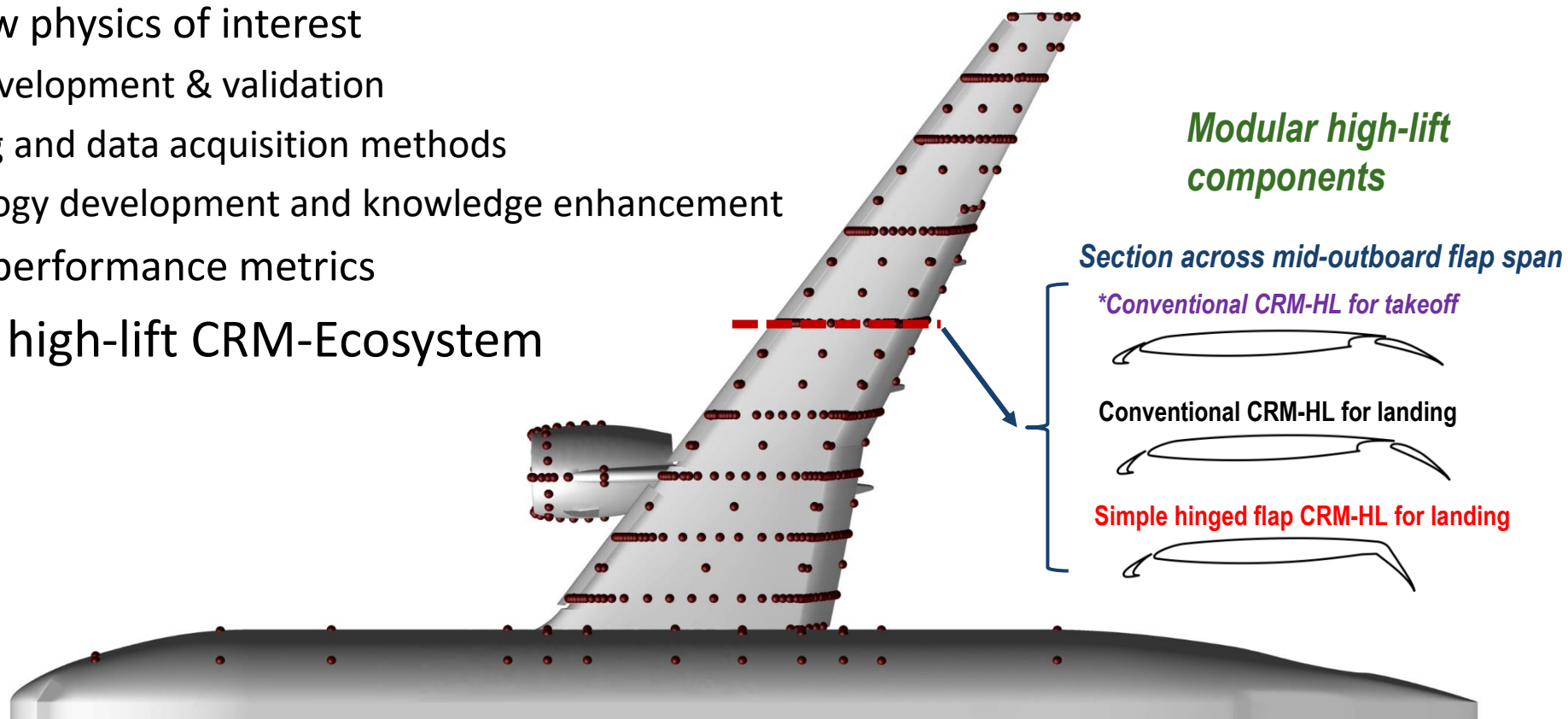
TRL Maturation and Benefit Timeline for Drag Reduction



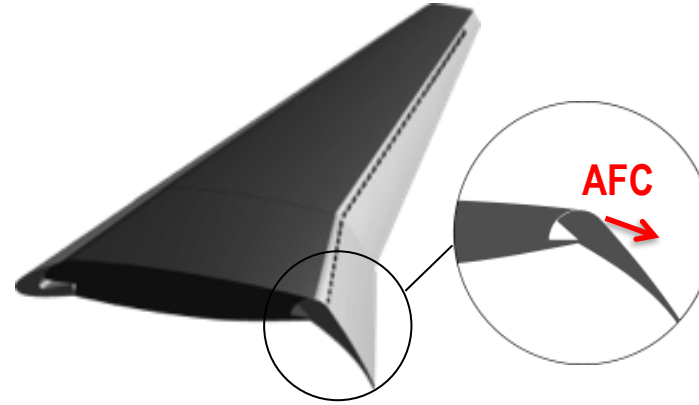
NASA 10% scale High-Lift Common Research Model



- Reference configuration: CRM-HL open/relevant (NASA/Boeing)
 - Based on the original CRM for high-speed
 - Representative flow physics of interest
 - CFD methods development & validation
 - Improved testing and data acquisition methods
 - High-lift technology development and knowledge enhancement
 - Provide reference performance metrics
- Predecessor of the high-lift CRM-Ecosystem



Separation Control: Previous work



- A simple-hinged flap high-lift wing using AFC to recover lift and reduce cruise drag.
- Overall fuel savings of 2.25% (825.5 gal/mission for ERA-0003 twin-aisle, 275 passenger, concept aircraft; Hartwich et al., AIAA Paper 2017-0321).

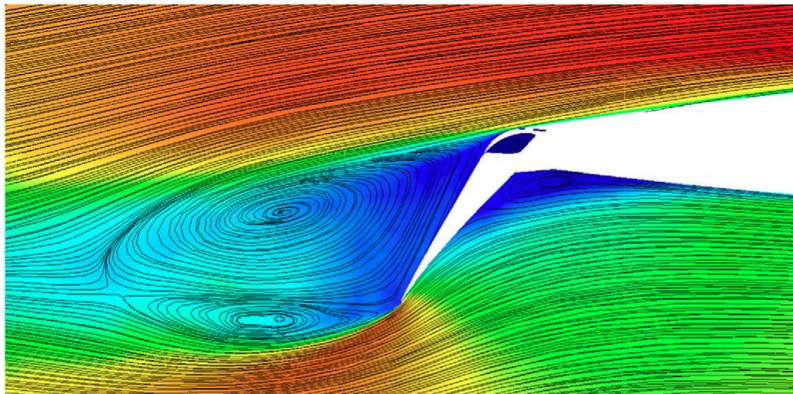
Test Objective: to produce the same lift level as the conventional (Fowler flap) high-lift case while minimizing AFC power requirement.

Separation Control: Previous work

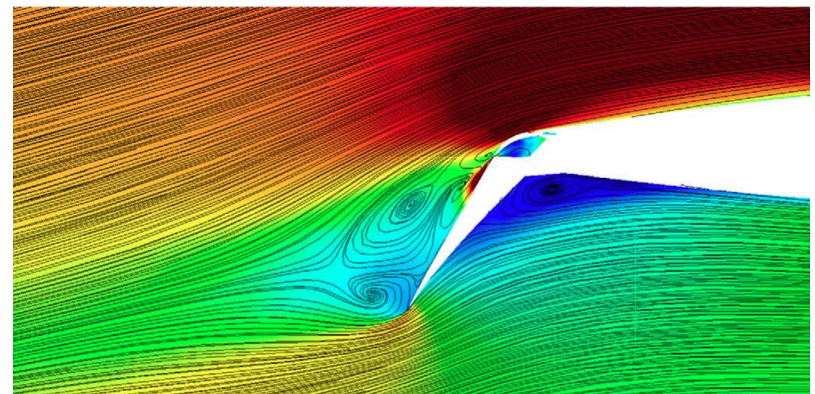


- Large flap deflection leads to massive flow separation
- AFC used to reduce flow separation on flap, increasing C_L

AFC off



AFC on



$M_\infty = 0.2, \alpha = 8^\circ$



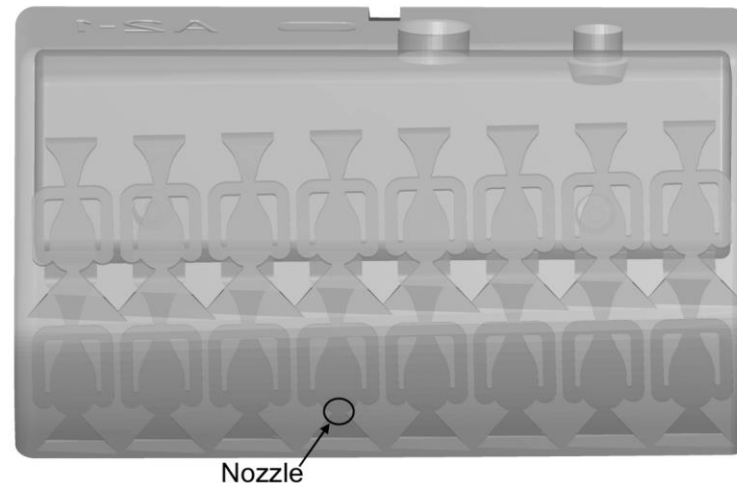
Separation Control: Previous work



Candidate actuators

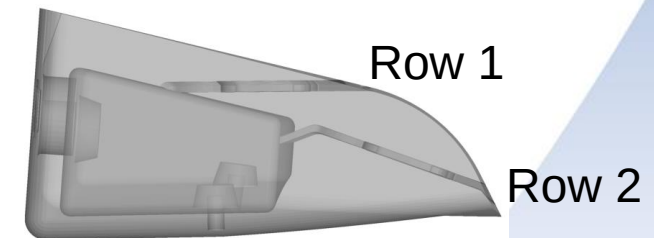
- Double Row Sweeping Jet (DRSWJ)
- Alternating Pulsed Jet (APJ)
- High Efficiency Lower Power (HELP)

Cartridge 1
Top view

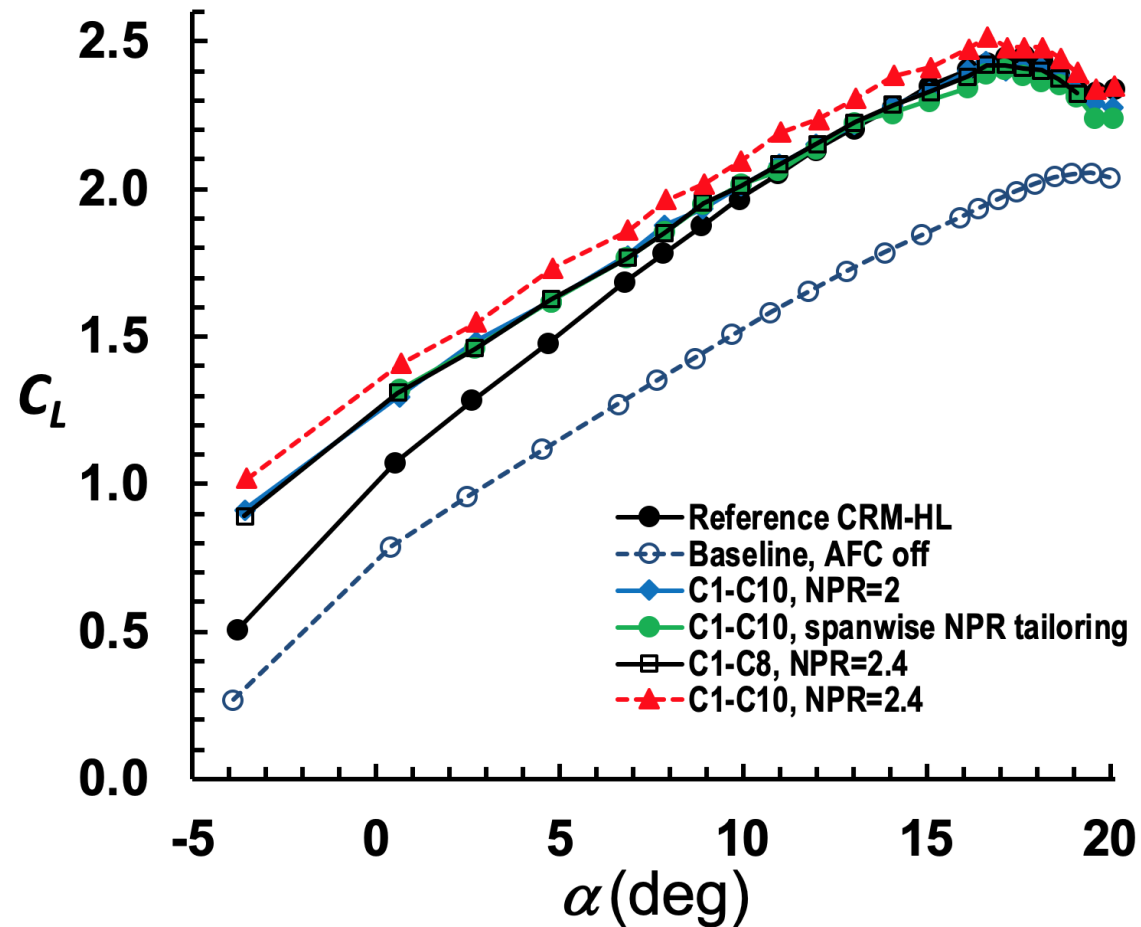


Double-Row Sweeping Jet (DRSWJ)

Cartridge 1
Side view

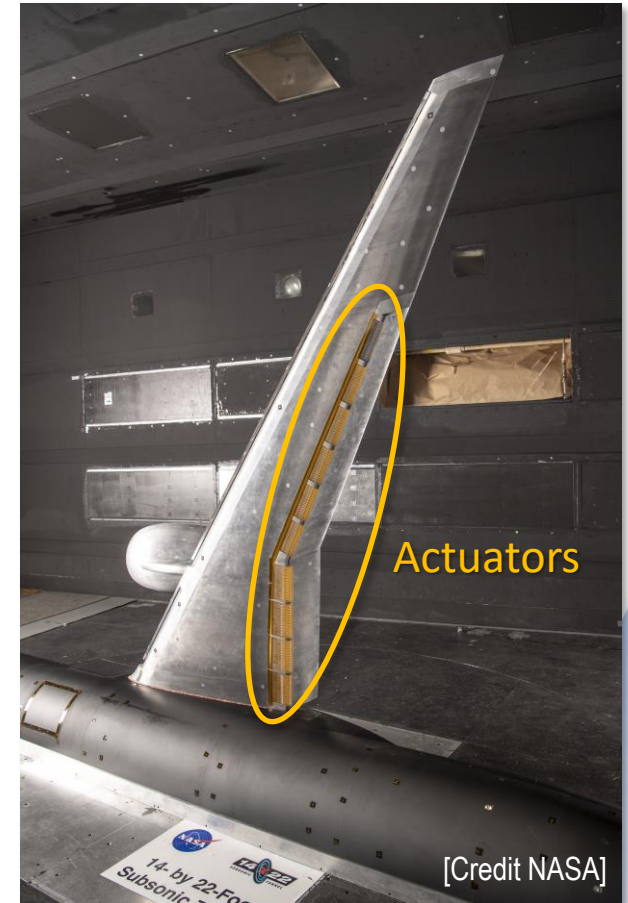


Separation Control: Previous work



High Efficiency Lower Power (HELP) actuators (red triangles) for an NPR=2.4 achieve the performance target (solid black circles) over the range of angle of attack.

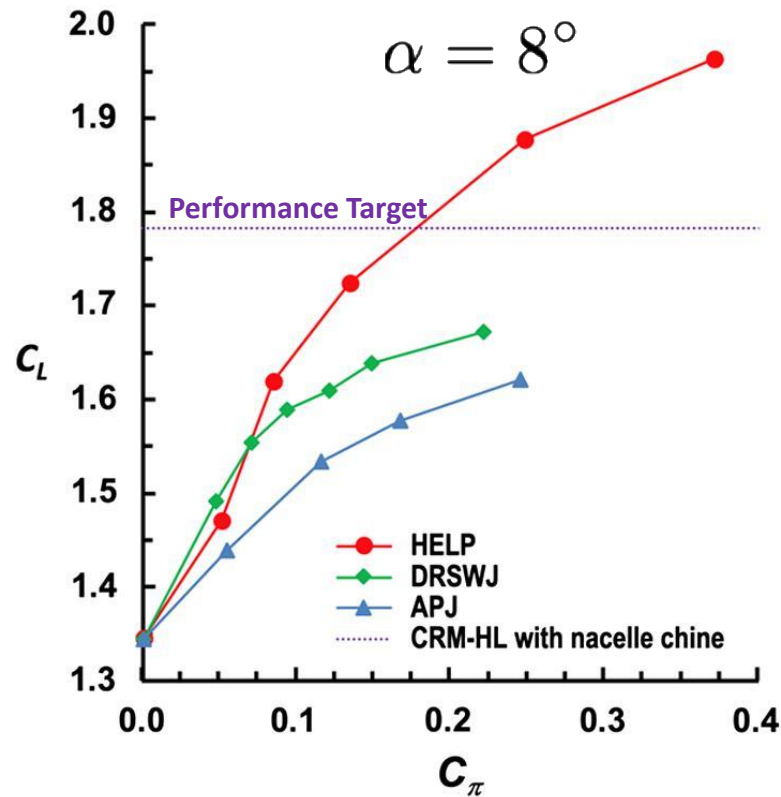
2018



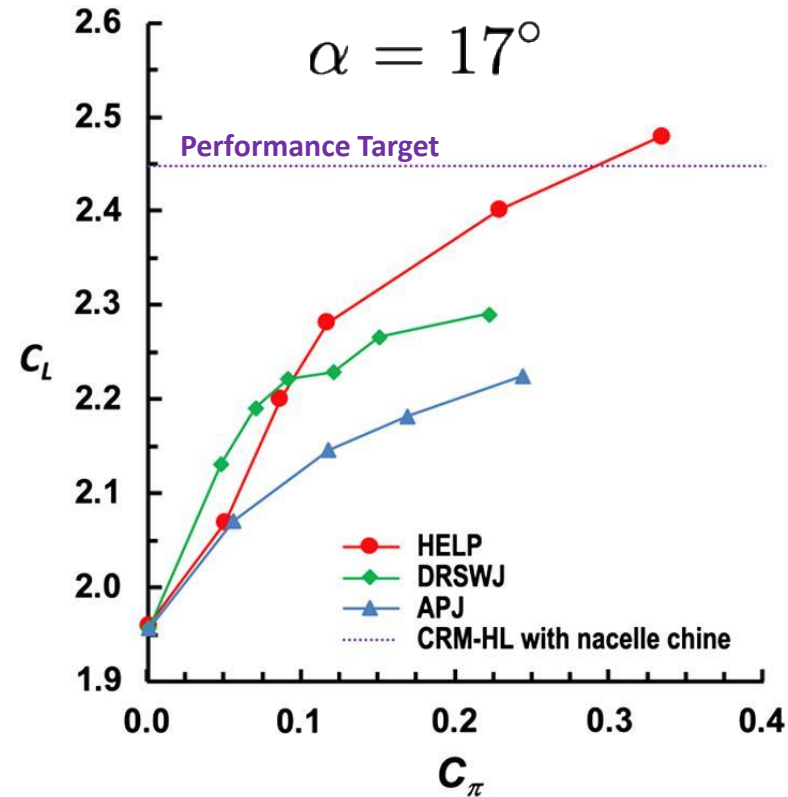
Cruise Drag Reduction

Source: Lin et al., AIAA Paper 2020-0783
<https://doi.org/10.2514/6.2020-0783>

Separation Control: Previous work



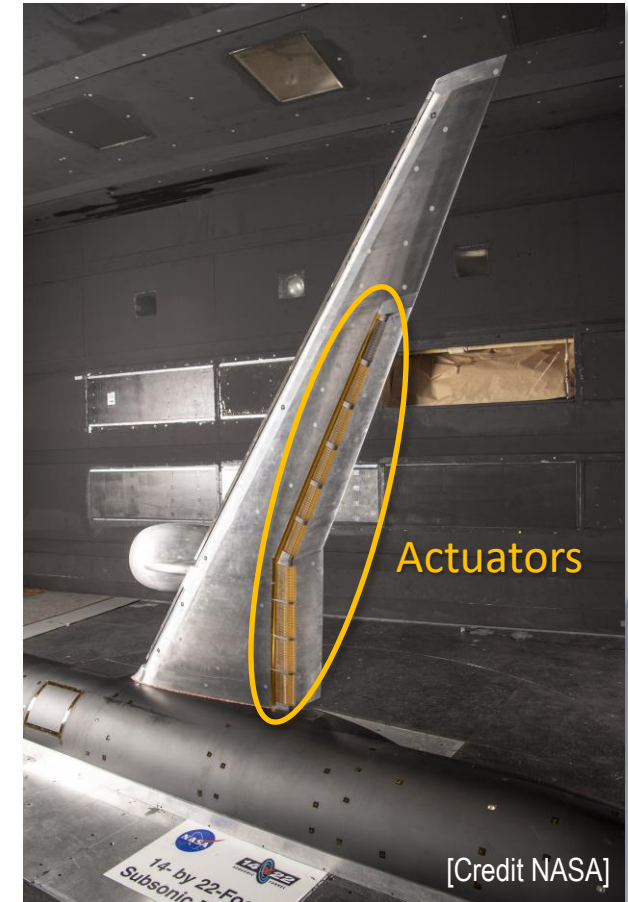
$$C_Q = \frac{\dot{m}}{\rho_\infty U_\infty S_{ref}}$$



$$C_\pi = \frac{C_Q \overline{P_{oi}}}{q_\infty}$$

- Power coefficient, C_π , is used to assess AFC performance
- C_π can be used to scale up pneumatic-based AFC systems

2018



Cruise Drag Reduction

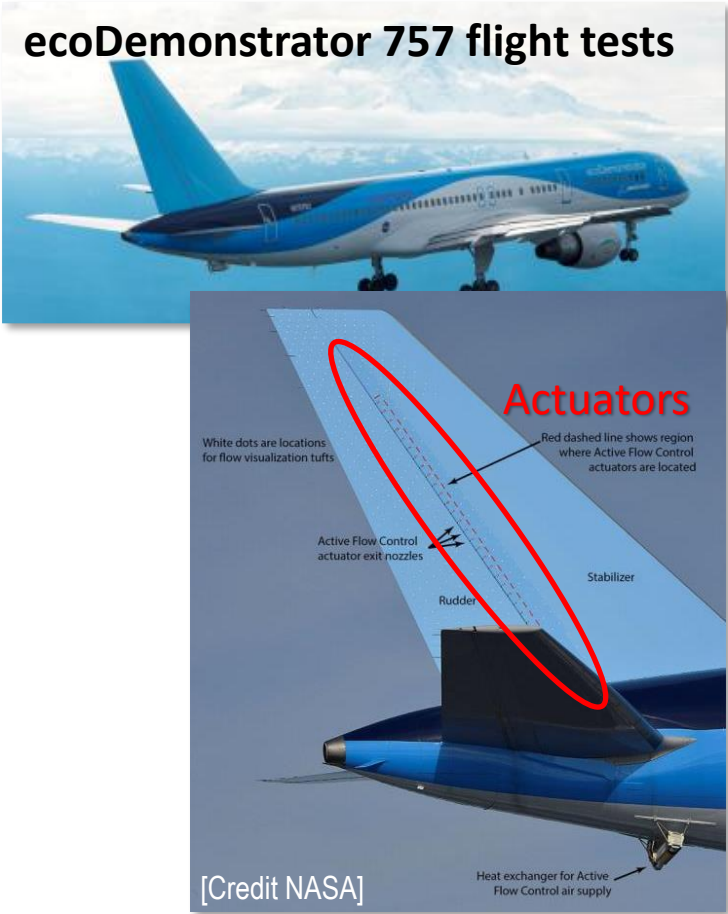
Source: Lin et al., 2020, Journal of Aircraft, Vol. 57, No. 6, <https://doi.org/10.2514/1.C035906>.

Recent Research Activities



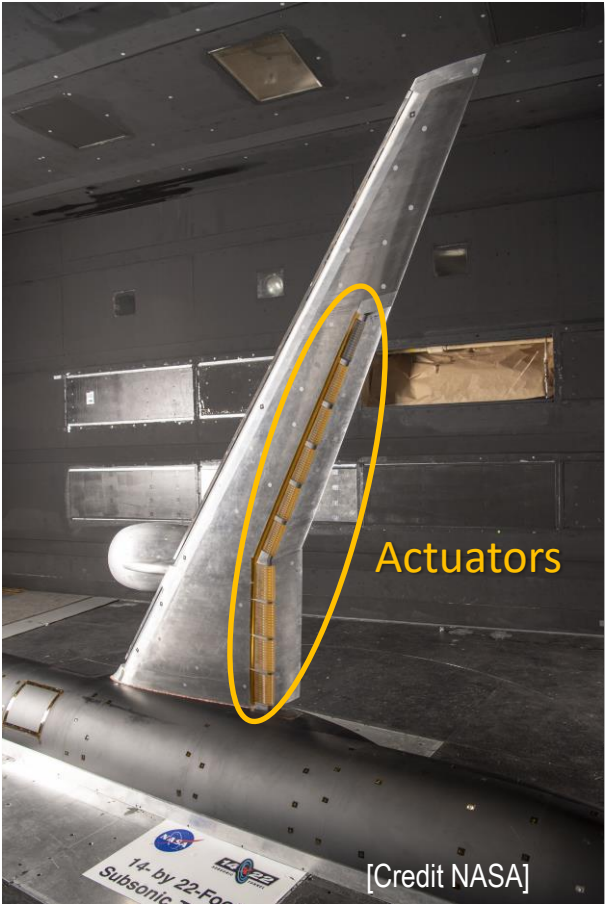
2015

ecoDemonstrator 757 flight tests



AFC-Enhanced Vertical Tail
Reduce weight, drag and rate of fuel burn

2018



Simplified High-Lift
Reduce Cruise Drag

2024



AFC-Enhanced Aileron
Increase L/D

Motivation

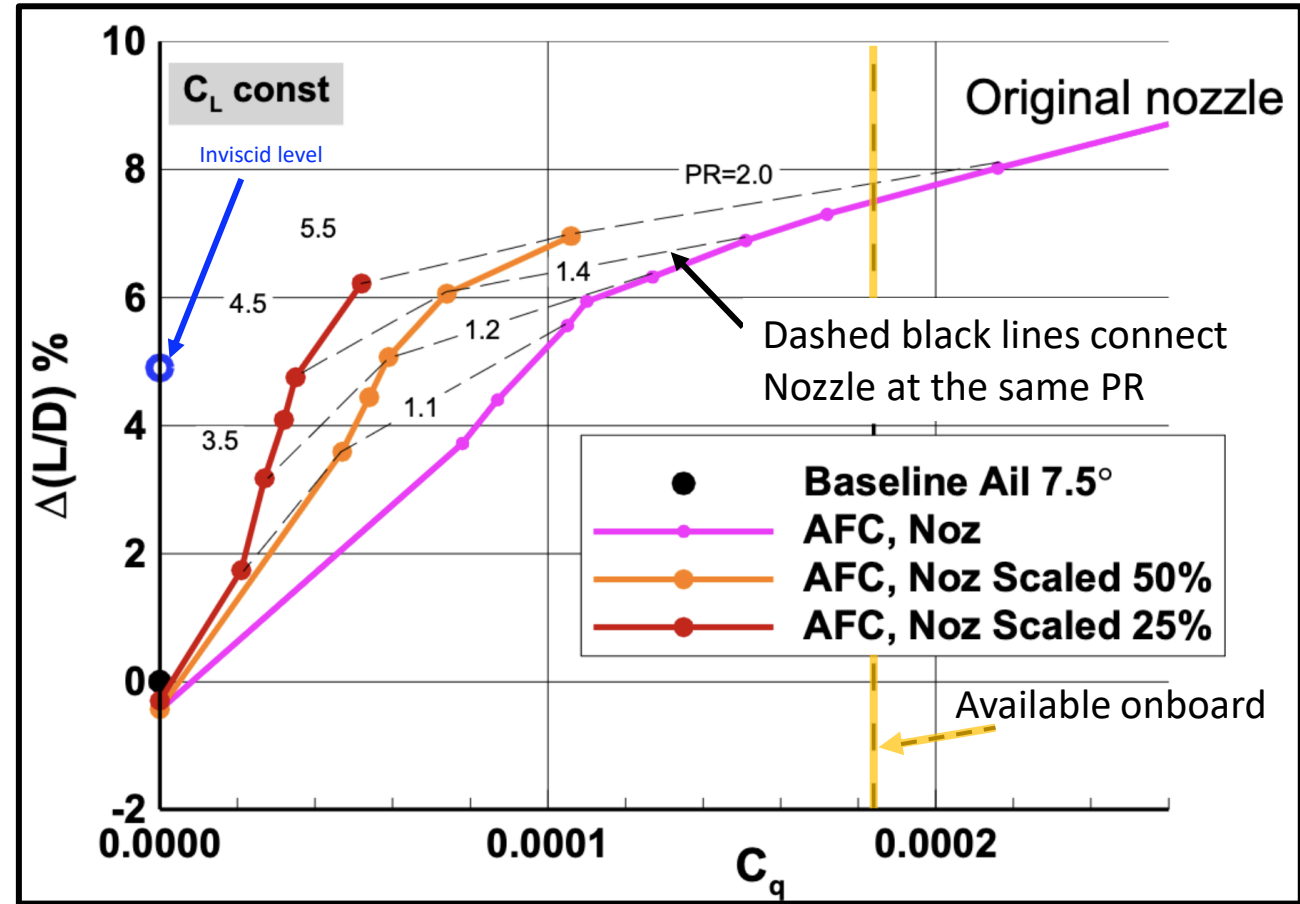


Garner et al.

- 1% Improvement in L/D for a large, generic twin engine transport is equivalent to
 - 1270 kg increase in payload or
 - 277.8 km increase in range

Garner et al., AIAA Paper 1991-1527,
doi.org/10.2514/6.1991-1527

Can it be achieved experimentally with available onboard resources?



Effect of nozzle size on aerodynamic performance, aileron 25°, PR=2.

Source: Shmilovich et al., AIAA Paper 2023-0655,
doi.org/10.2514/6.2023-0655

Objectives



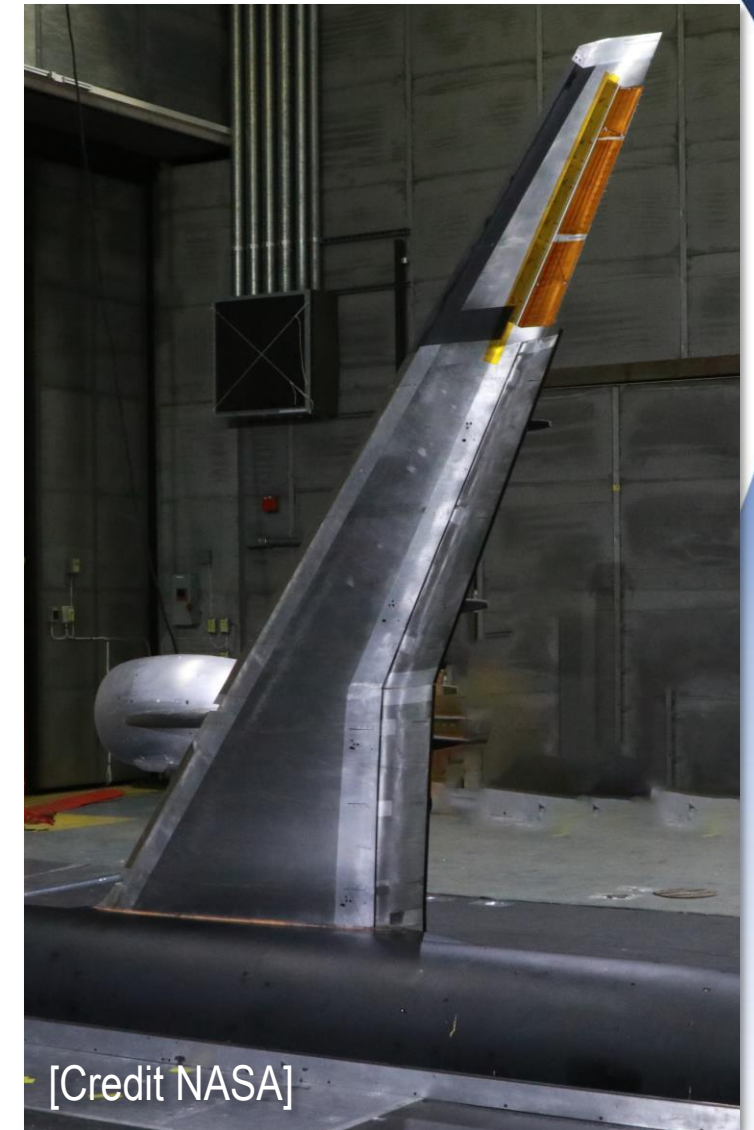
- A test at the NASA Langley 14- by 22-Foot Subsonic Tunnel to assess the performance improvement of localized AFC on the aileron of the 10% scale, semispan CRM-HL model
- A new outboard wing section with an adjustable aileron
 - Different takeoff configurations
 - AFC actuator integration
- Obtain a reference for the localized AFC research



CRM-HL Model Geometry



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



CRM-HL Model: Takeoff Configuration



AFC Angle of attack range

$$\alpha = 0^\circ - 11^\circ$$

Reynolds number

$$Re_c = 3 \times 10^6$$

Mach number

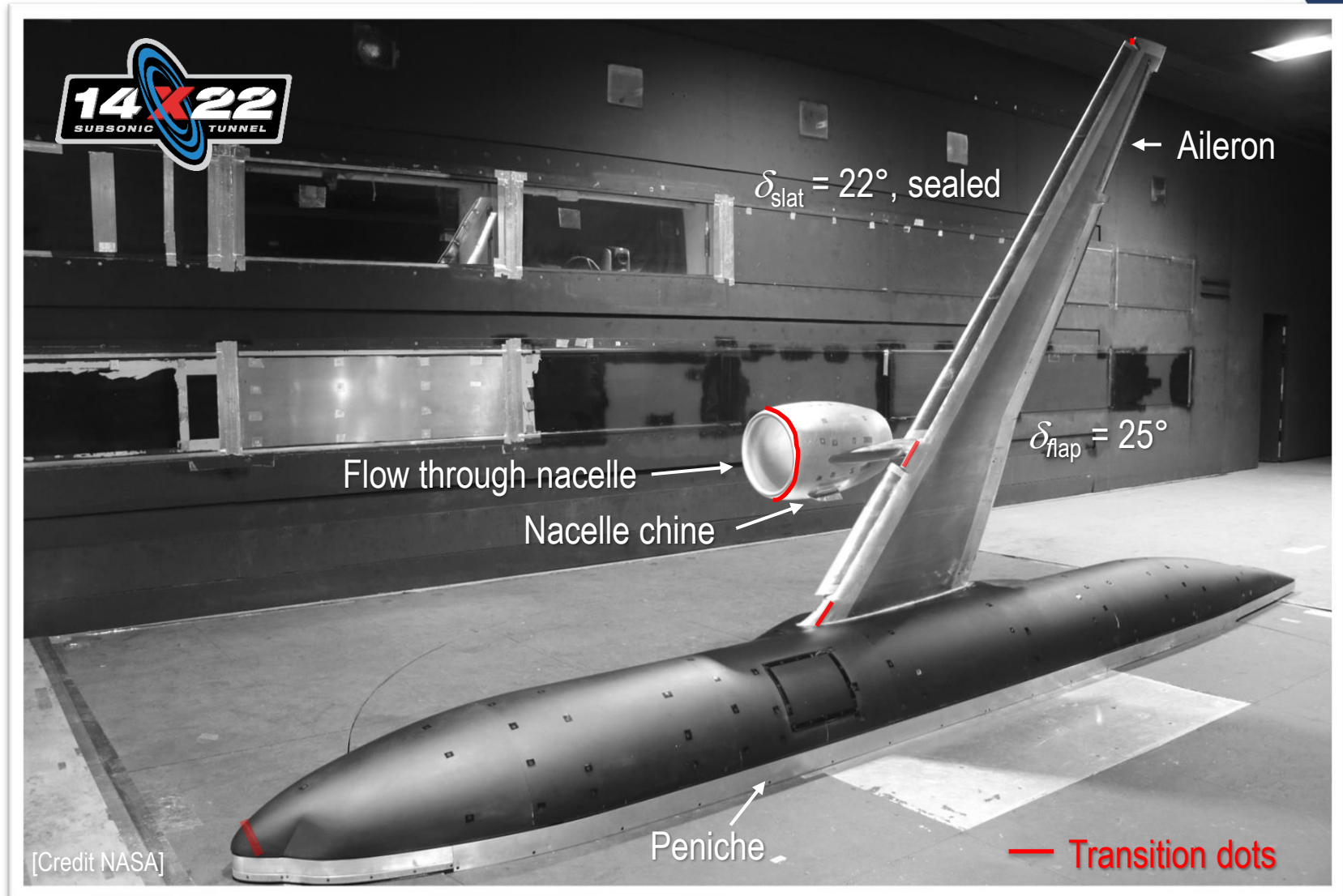
$$M = 0.2$$

Sealed Slat

$$\delta_{slat} = 22^\circ$$

Inboard and Outboard flap

$$\delta_{flap} = 25^\circ$$



CRM-HL Model: Takeoff Configurations



➤ Reference takeoff configuration

- 25° flaps and 22° slats with sealed slat gap
- Non-deflected aileron, $\delta_a = 0^\circ$
- Lacy et al., AIAA Paper 2020-2771, doi.org/10.2514/6.2020-2771



0°

➤ Nominal takeoff configuration

- Airplanes benefit by deflecting the aileron during takeoff
- Nominal aileron deflection, $\delta_a = 7.5^\circ$



7.5°

➤ High-lift improved takeoff configuration

- Achieved by deflecting the aileron further
- $\delta_a = 16^\circ$ and $\delta_a = 25^\circ$
- Intended to be used with AFC

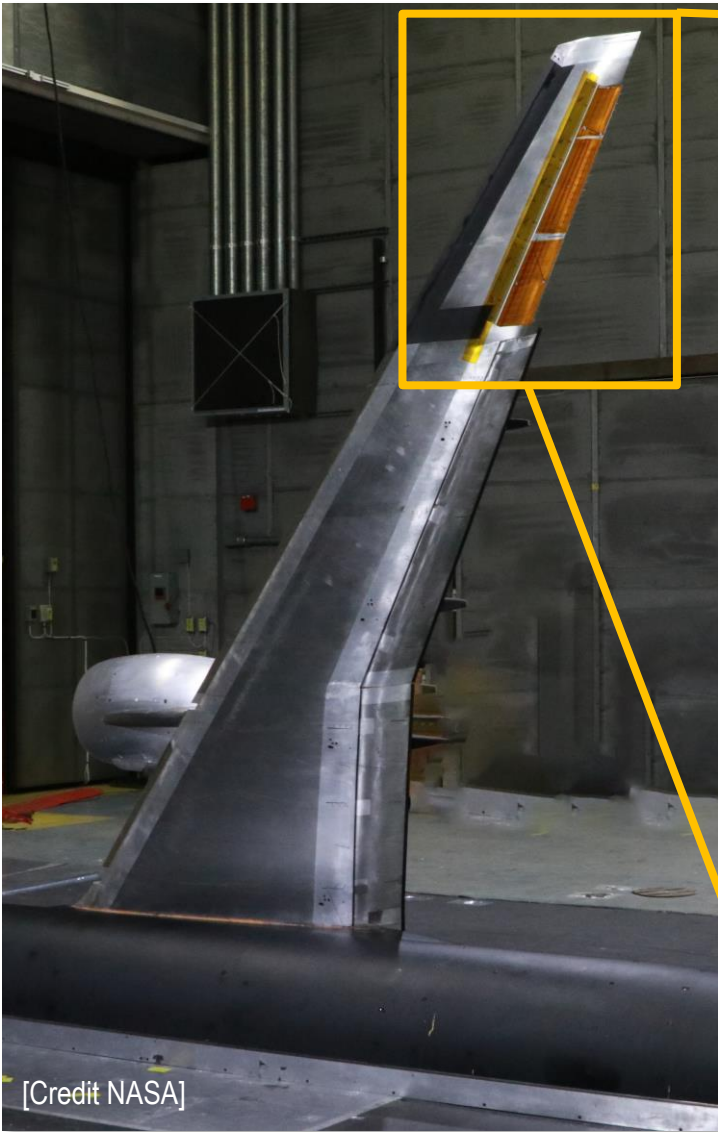


16°

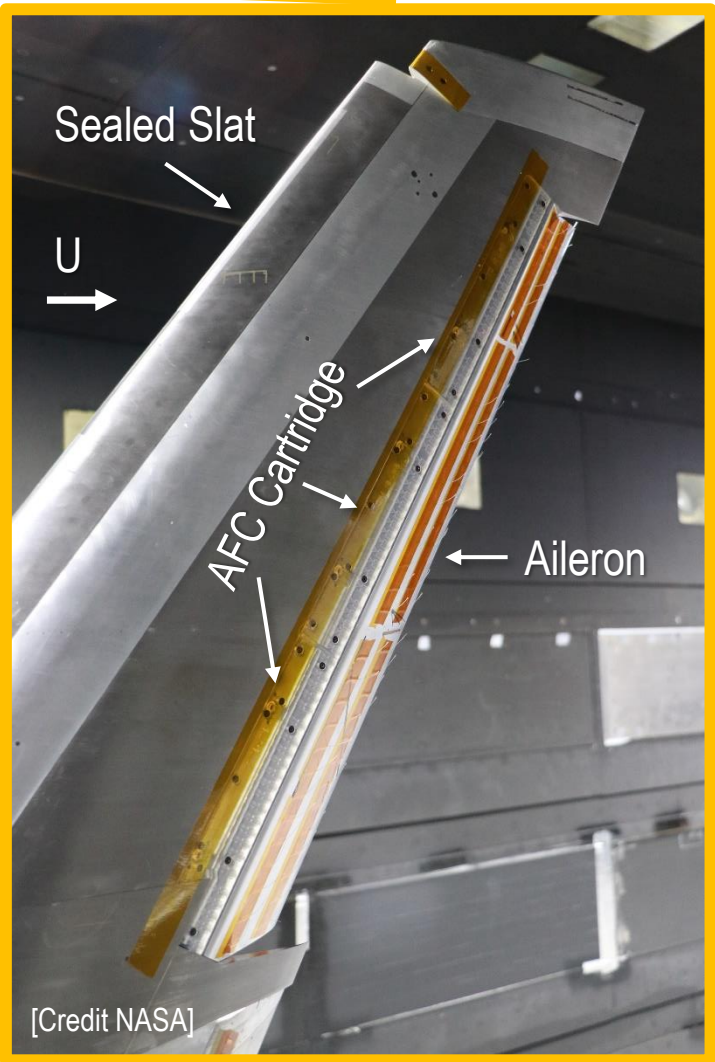


25°

CRM-HL Model: Aileron

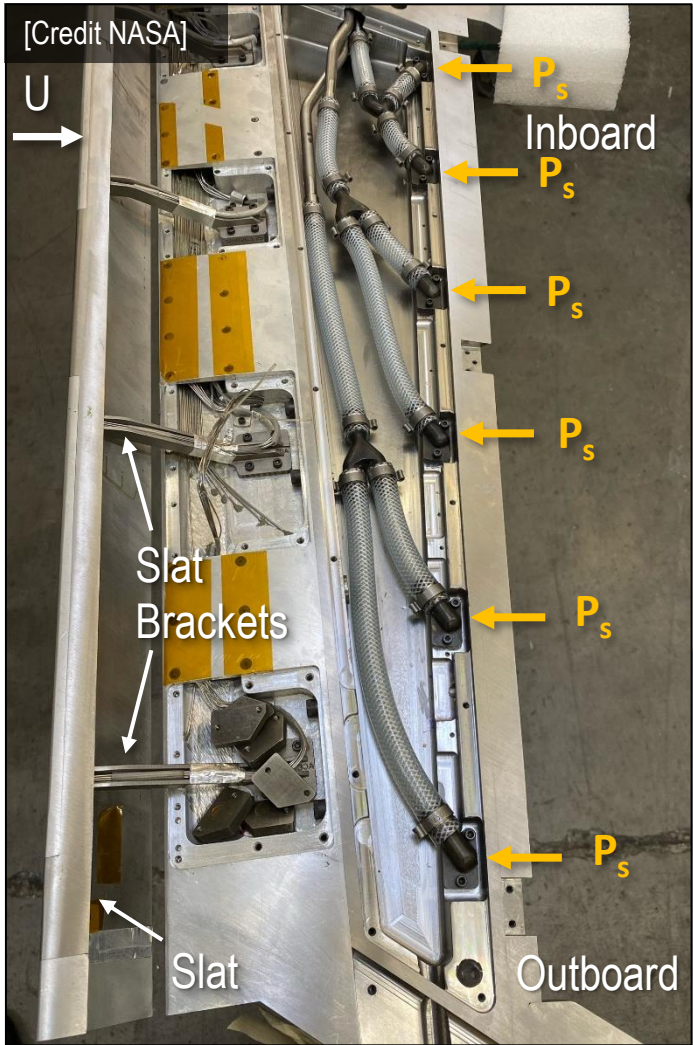


[Credit NASA]



[Credit NASA]

Upper Surface



[Credit NASA]

Lower Surface without aileron

AFC Service Air Supply System Configuration

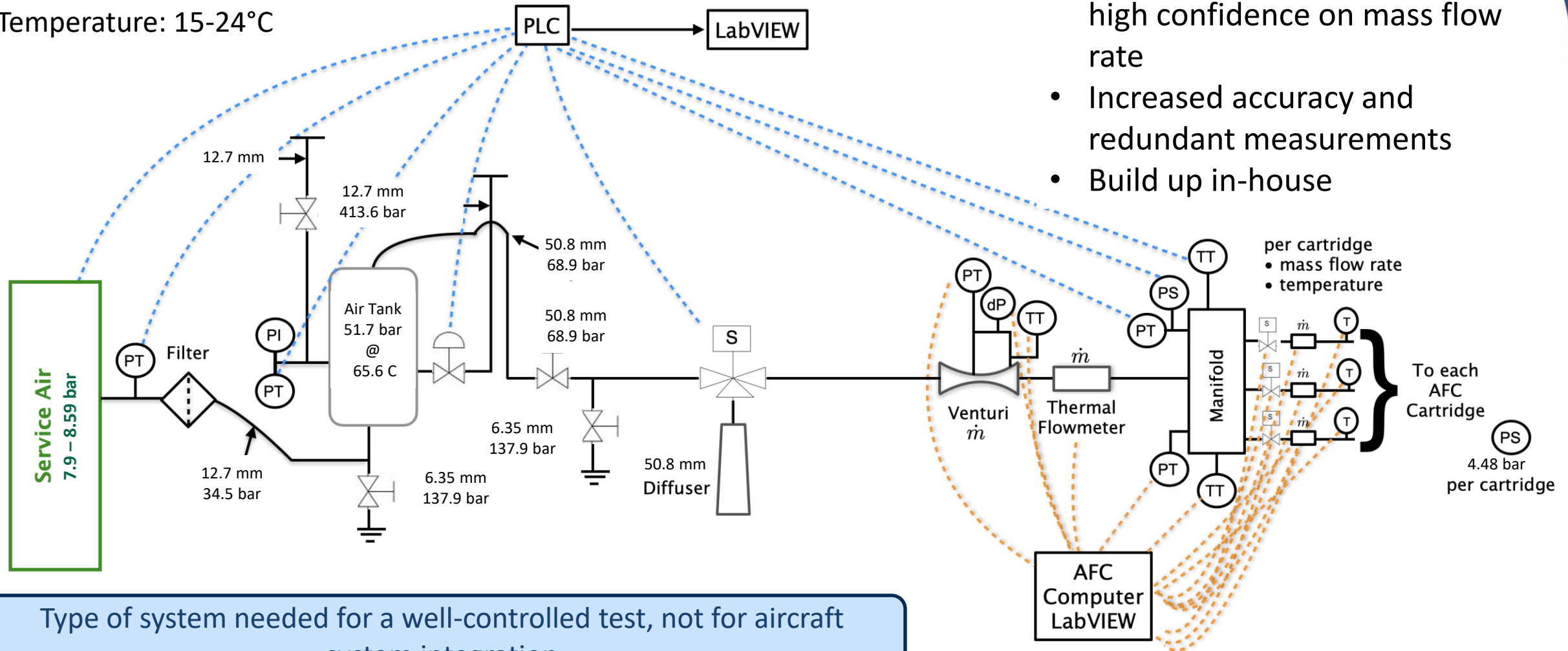


Test Conditions:

Supply Pressure range 8.60 bar

Temperature: 15-24°C

- Repeatable measurements, high confidence on mass flow rate
- Increased accuracy and redundant measurements
- Build up in-house

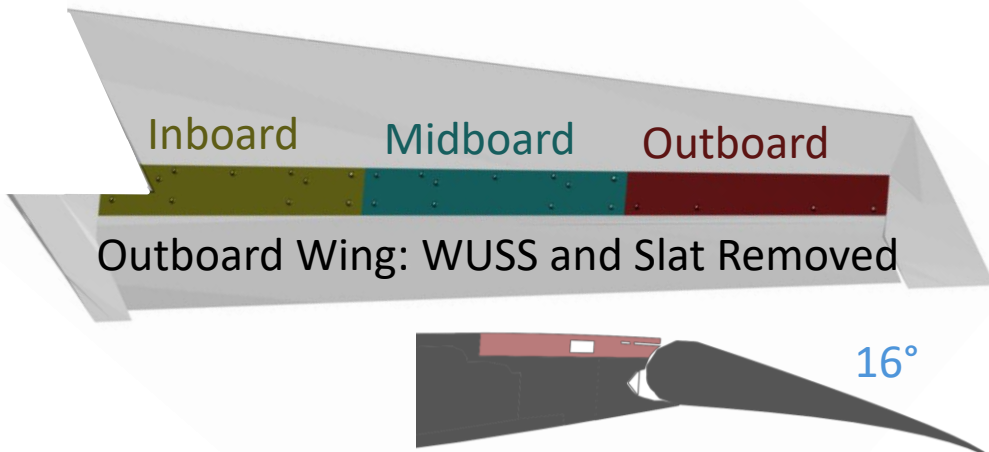


AFC Actuators Spacing

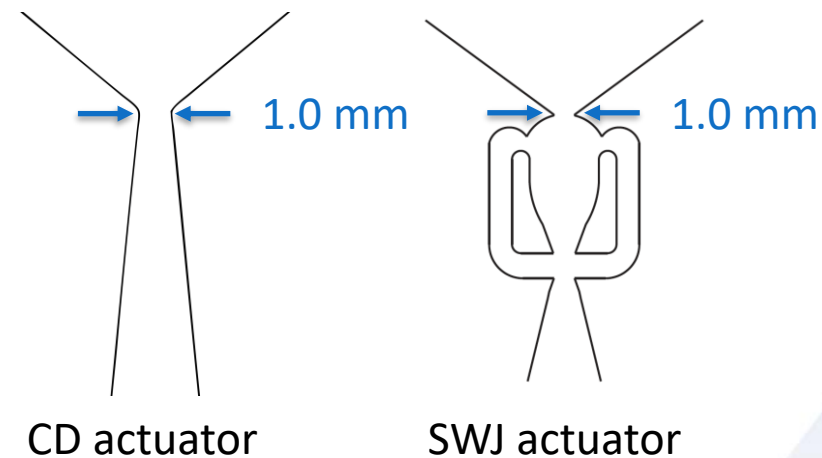


Type		Inboard Qty	Midboard Qty	Outboard Qty	Total nozzle area, mm ²
Sweeping Jet (SWJ)	SWJ1	23	23	23	43
	SWJ2	12	11	12	22
	SWJ3	6	6	6	12
Convergent Divergent Jet (CD)	CD1	23	23	23	43
	CD2	12	11	12	22

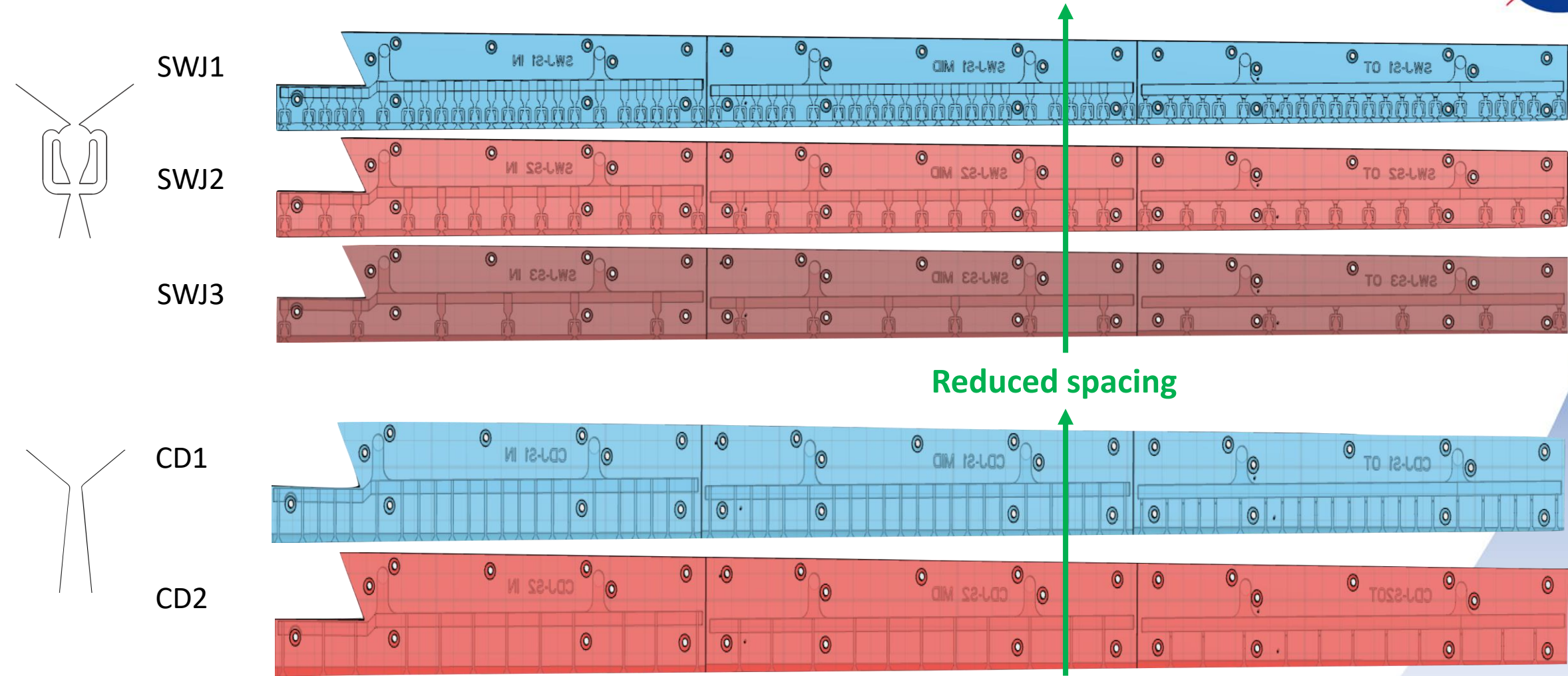
Reduced
spacing



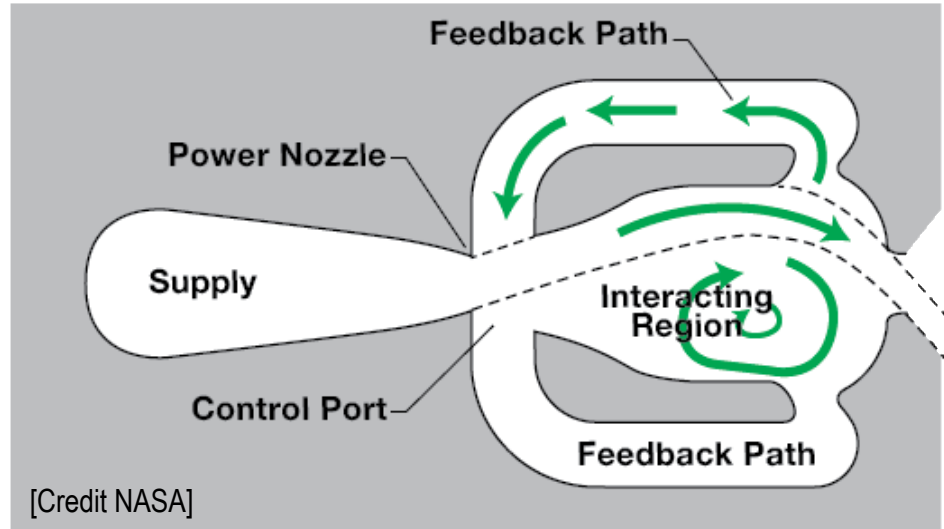
All actuator nozzle exits were 0.5 mm H x1.0 mm W



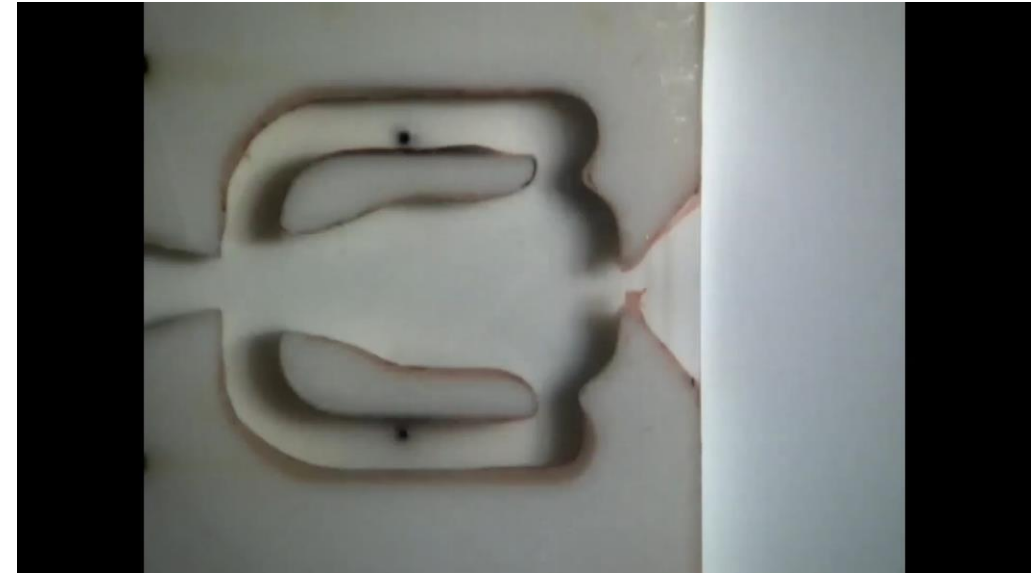
AFC Actuators



Sweeping Jet Actuators



- Flow oscillating based on bi-stable mode of wall attachment with feedback loop
- No moving parts

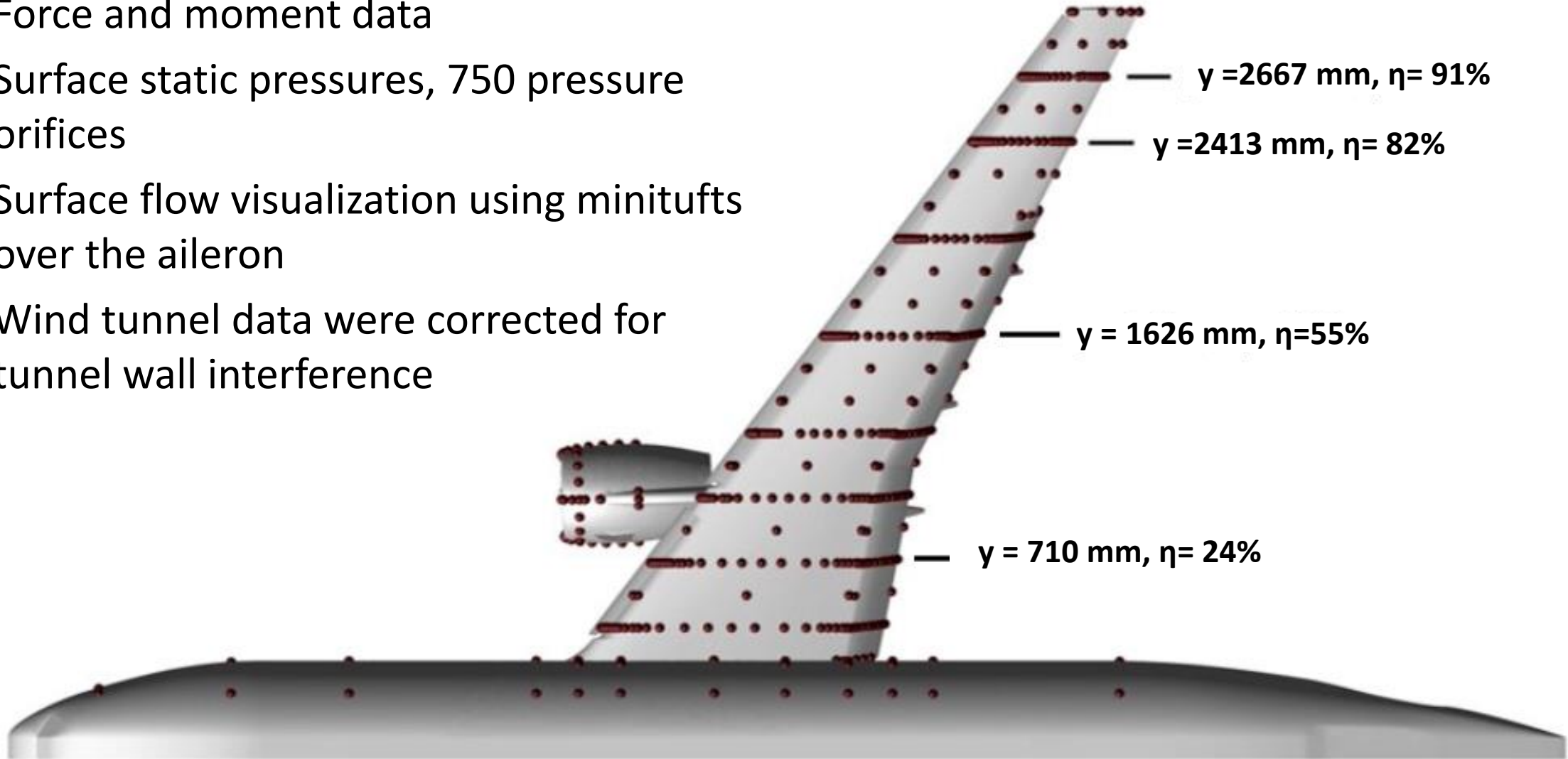


Credit: NASA
Brian Chang, Michale Leonetti
(LARSS Graduate Students)
Mentors: Dr. Brian Allan, Dr. Greg Jones

Wind Tunnel Measurements



- Force and moment data
- Surface static pressures, 750 pressure orifices
- Surface flow visualization using minitufts over the aileron
- Wind tunnel data were corrected for tunnel wall interference



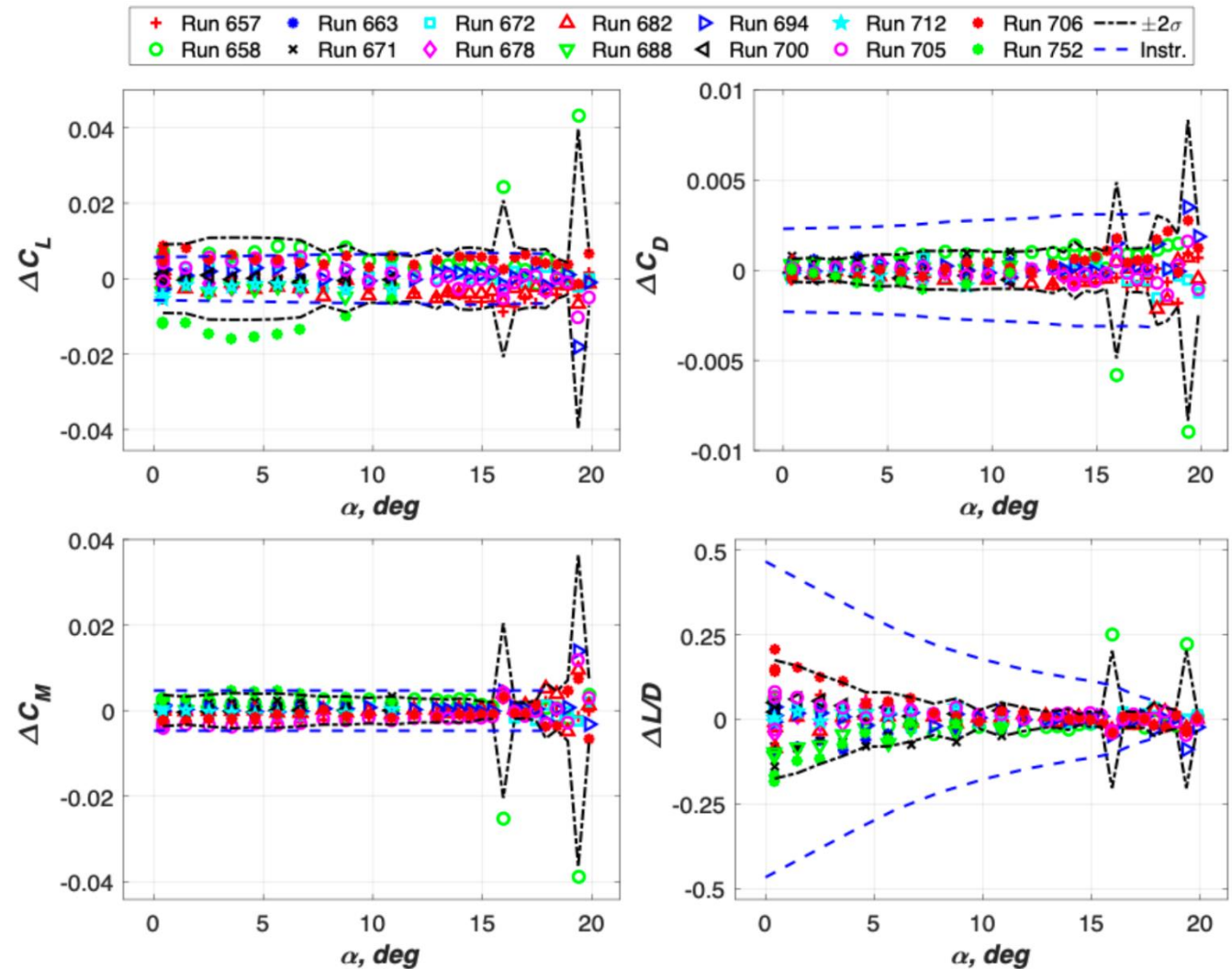
Repeatability



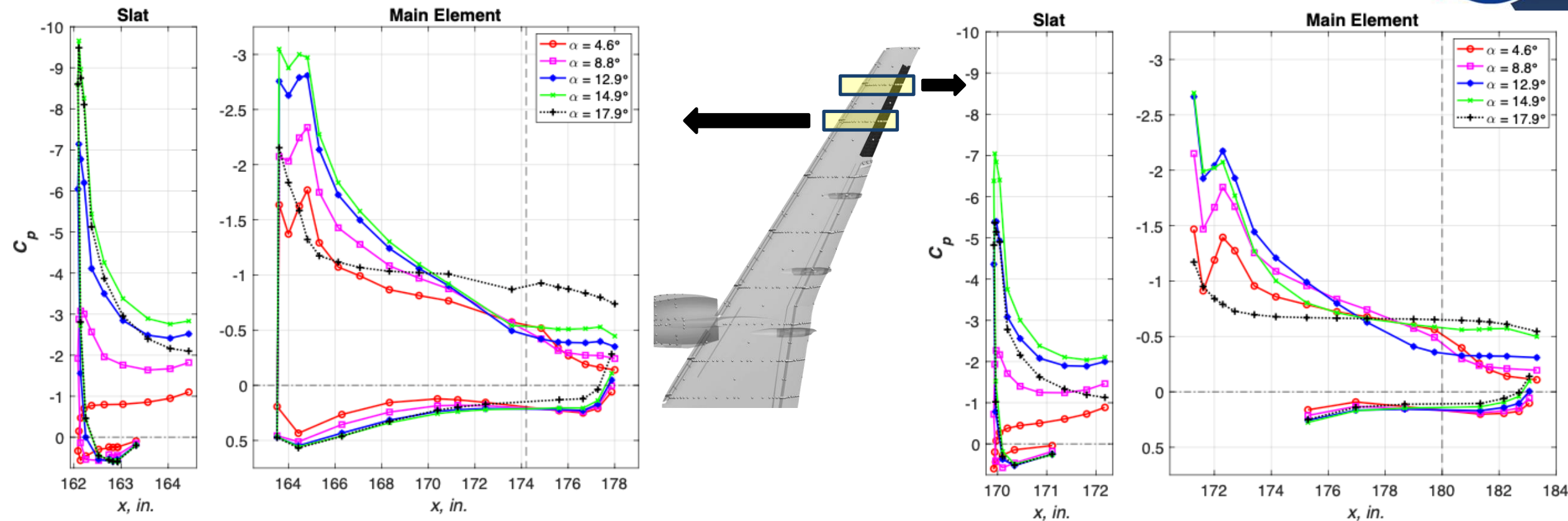
- Calculated residuals for the HL-improved takeoff configuration

$$M_{\infty} = 0.2, \delta_a = 16^{\circ}$$

- Black dash line indicates $\pm 2\sigma$ values
- Blue dash line indicates expected instrumentation uncertainty
- These plots indicate that the variation in the C_L , C_D , C_M , L/D are in general within the instrumentation uncertainty



Reference Takeoff Configuration: Outboard Wing



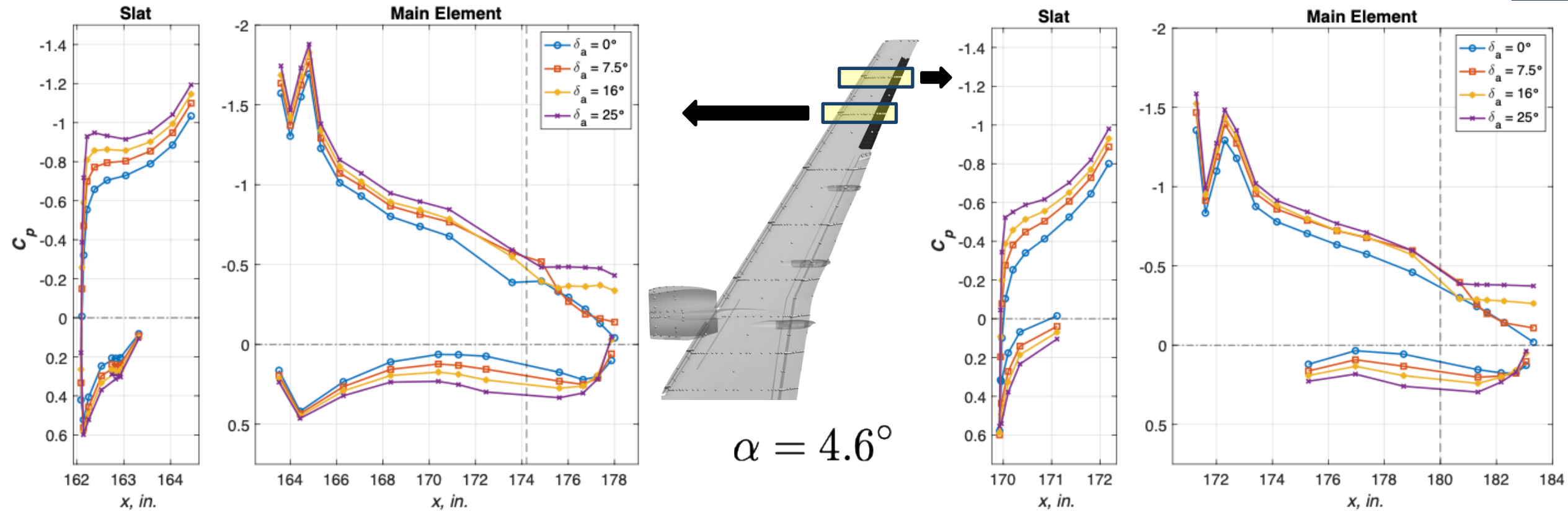
- Increasing α results in higher suction pressures
- Flow near the aileron trailing edge appears attached for $\alpha = 4.6^\circ$
- Entire main element is separated for $\alpha = 17.9^\circ$
- Flow over the main element separates earlier for most outboard location, $\alpha \leq 14.9^\circ$

$$M_\infty = 0.2, \delta_a = 0^\circ$$

$$Re_c = 3 \times 10^6$$

Effect of Aileron deflection

$$M_\infty = 0.2, Re_c = 3 \times 10^6$$



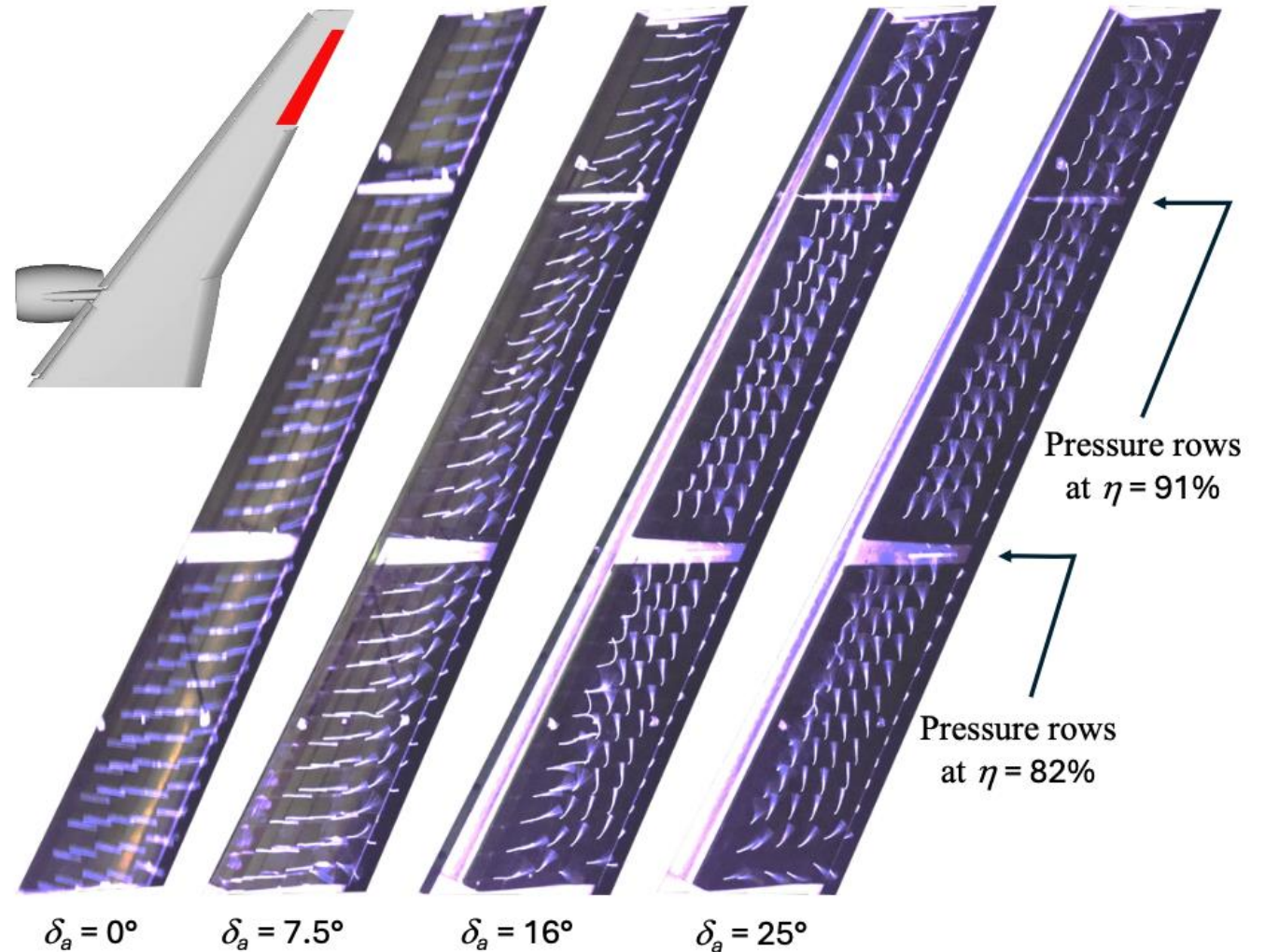
- Increasing aileron deflection angle improves C_p on both suction and pressure surfaces
- C_p distribution indicates attached flow for $\delta_a = 0^\circ$ for the two outboard locations
- Flow separation moves upstream as δ_a increases

Effect of Aileron deflection



$$M_{\infty} = 0.2, Re_c = 3 \times 10^6 \quad \alpha = 4.6^{\circ}$$

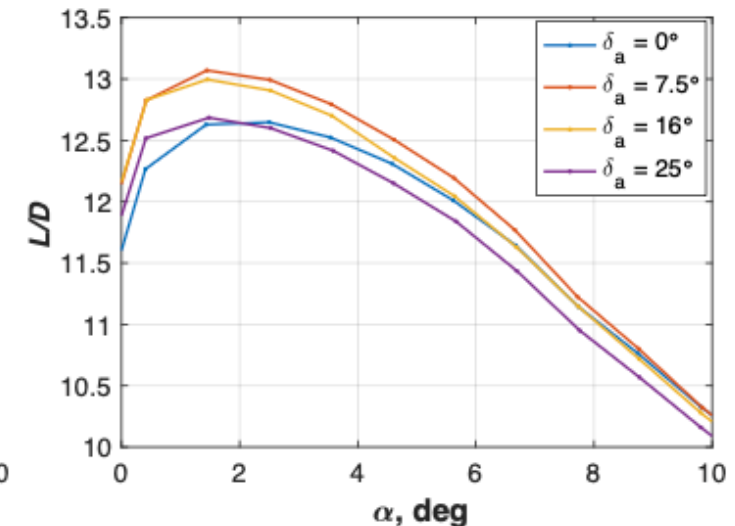
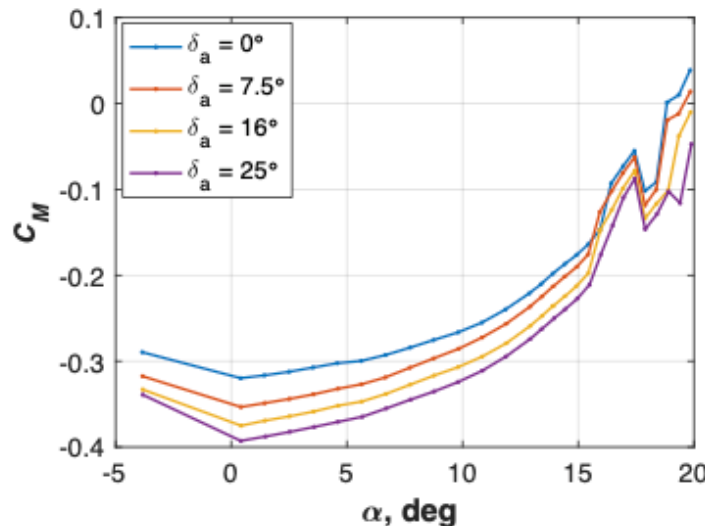
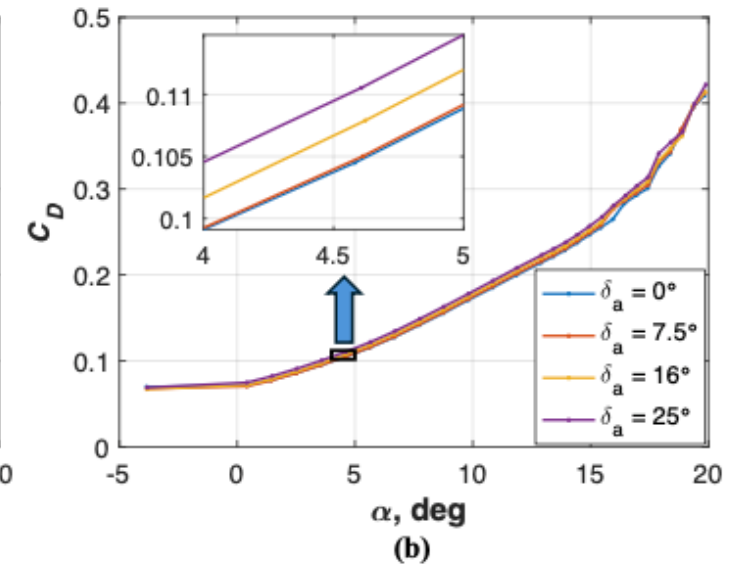
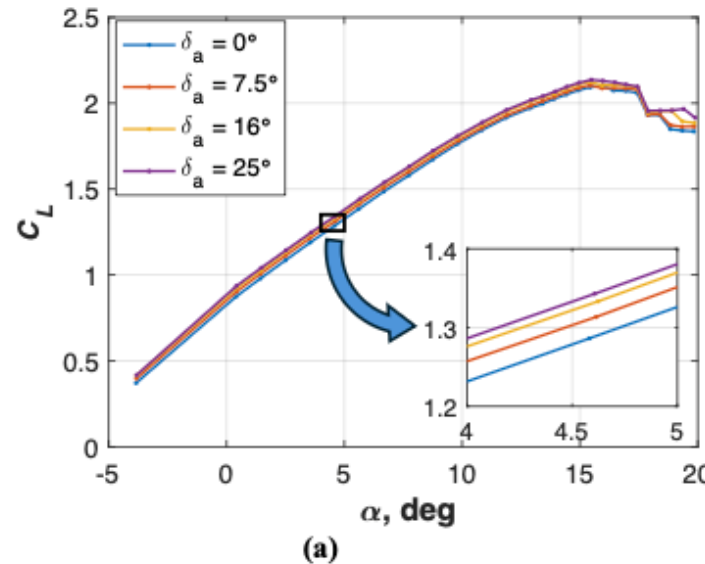
- Attached flow for $\delta_a = 0^{\circ}$
- Small separation bubble near TE for $\delta_a = 7.5^{\circ}$
- Separated flow over the entire aileron for $\delta_a \geq 16^{\circ}$

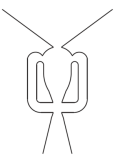


Effect of Aileron deflection



- Lift coefficient increases with δ_a
- The improvement is as much as ~ 0.06 at lower α and resulted in C_{Lmax} of 2.137 for $\delta_a = 25^\circ$
- The flow separation over the aileron ($\delta_a \geq 7.5^\circ$) mainly affects C_D (50 drag counts)

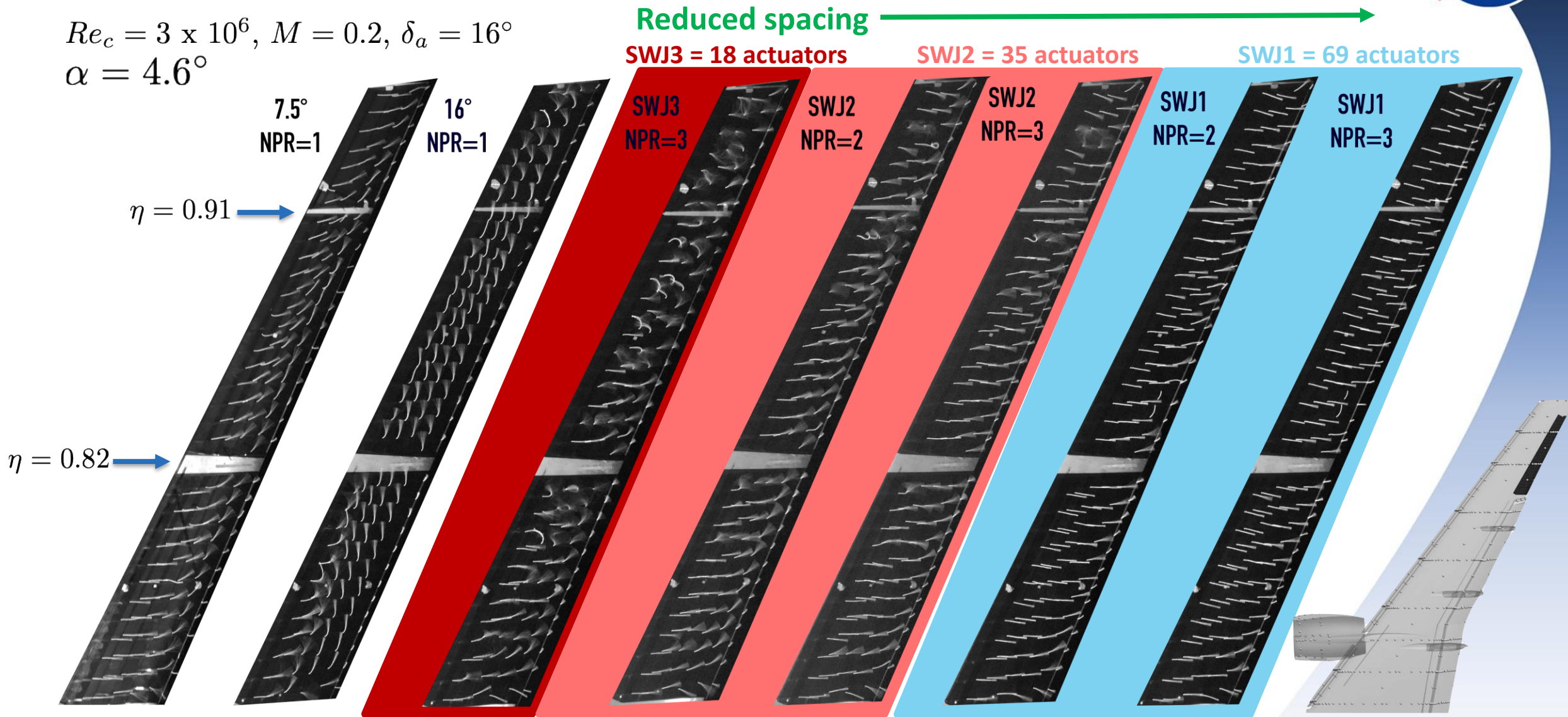


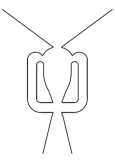


Sweeping Jets Flow Visualization at 16°



$$Re_c = 3 \times 10^6, M = 0.2, \delta_a = 16^\circ$$
$$\alpha = 4.6^\circ$$



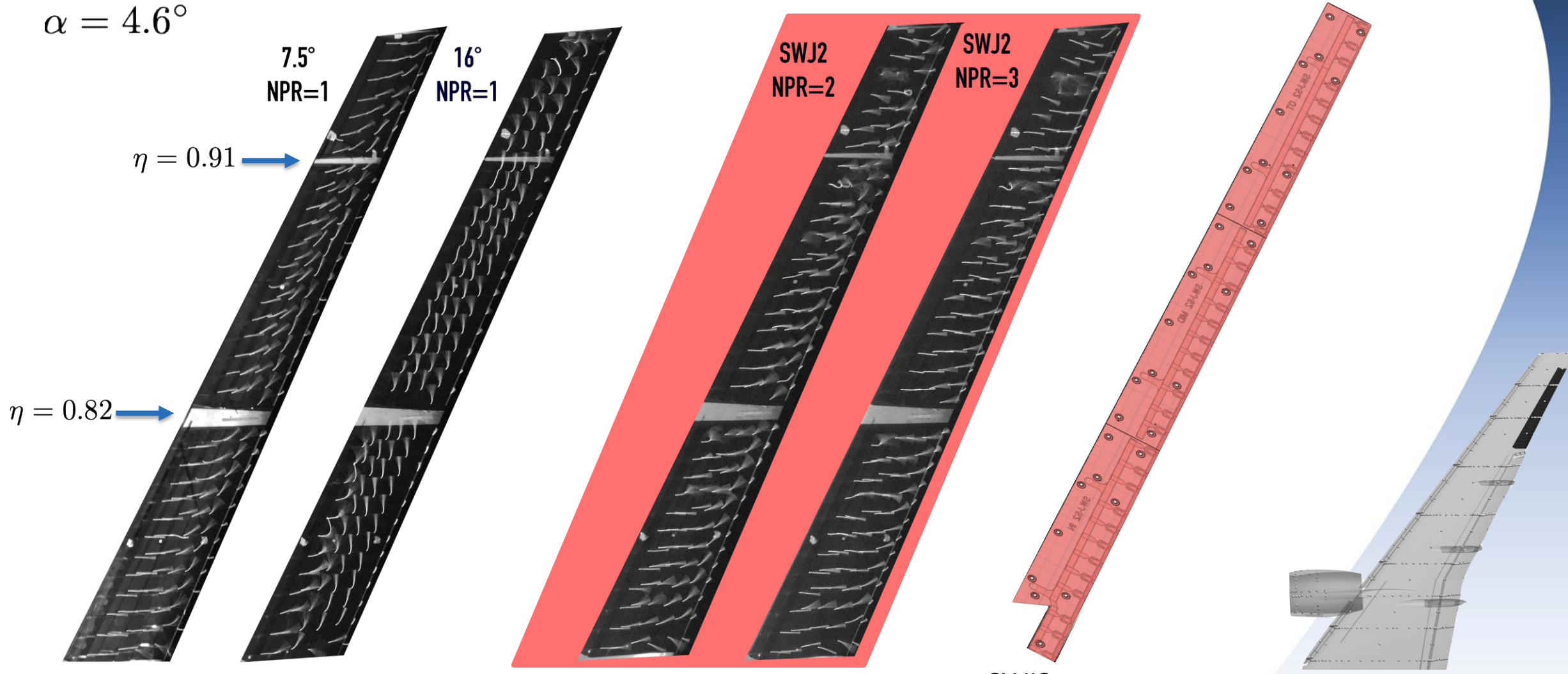


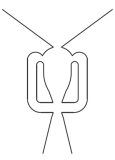
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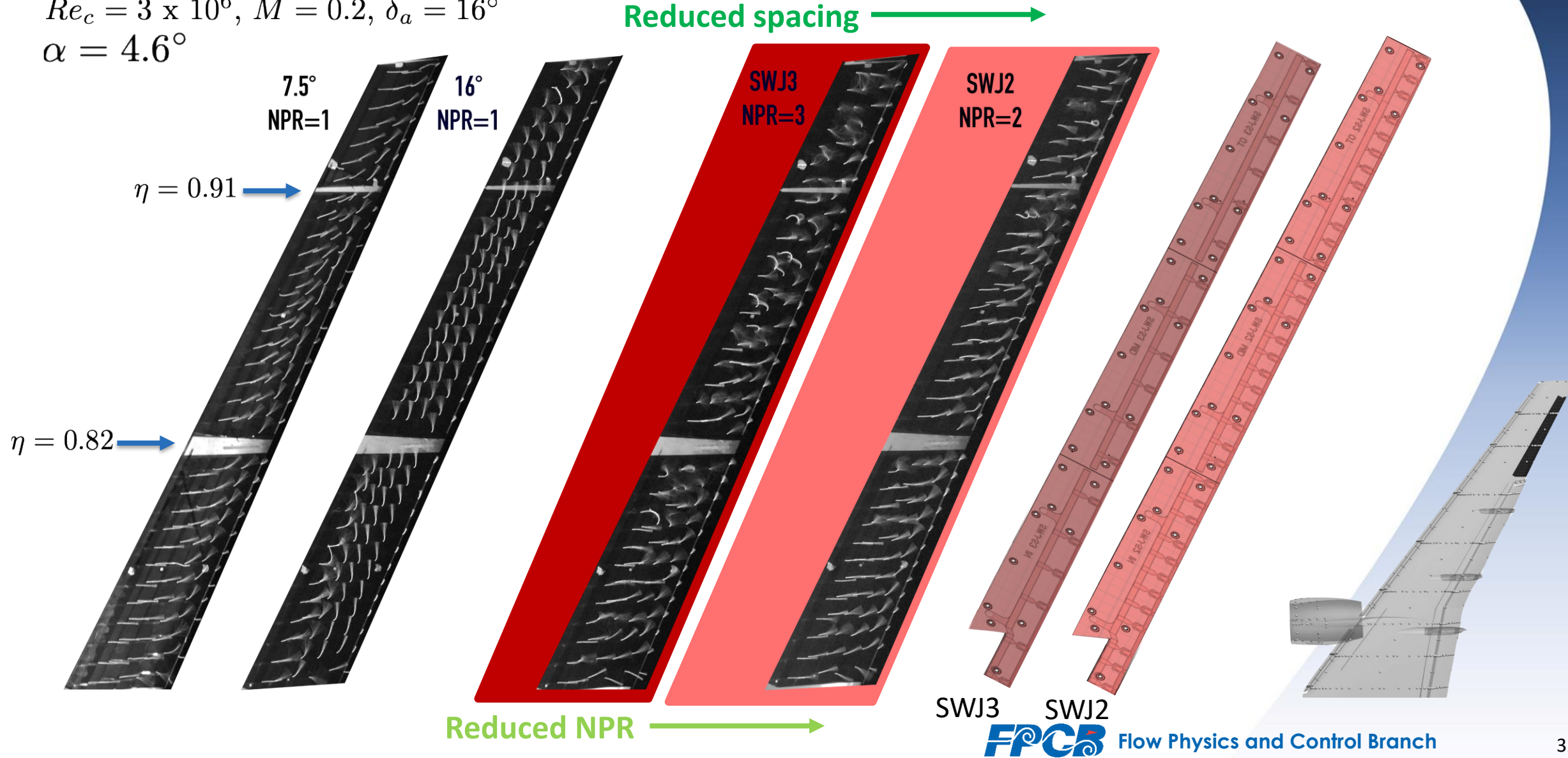


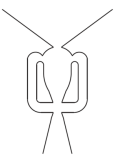


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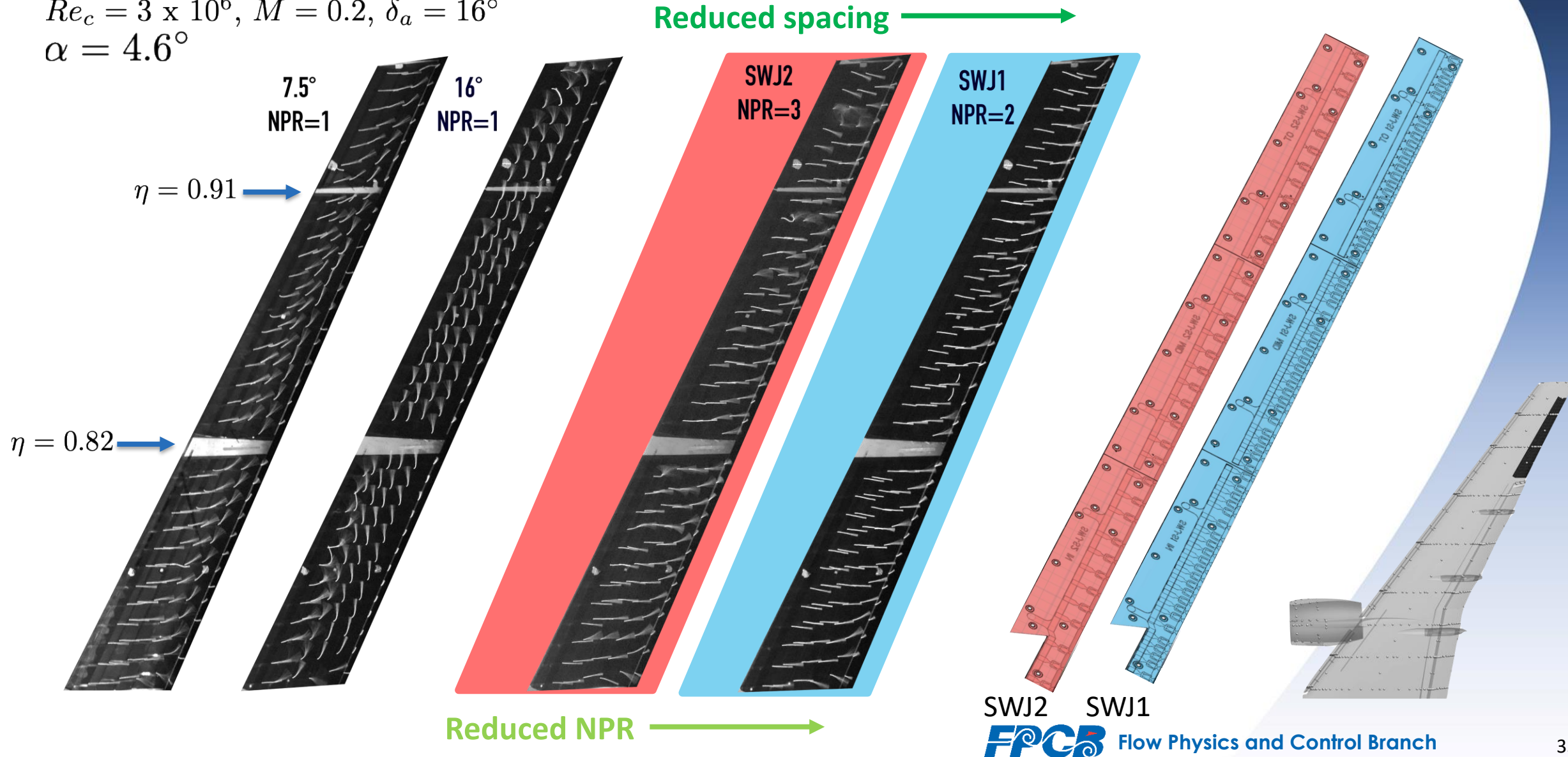


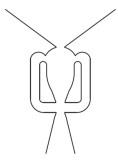


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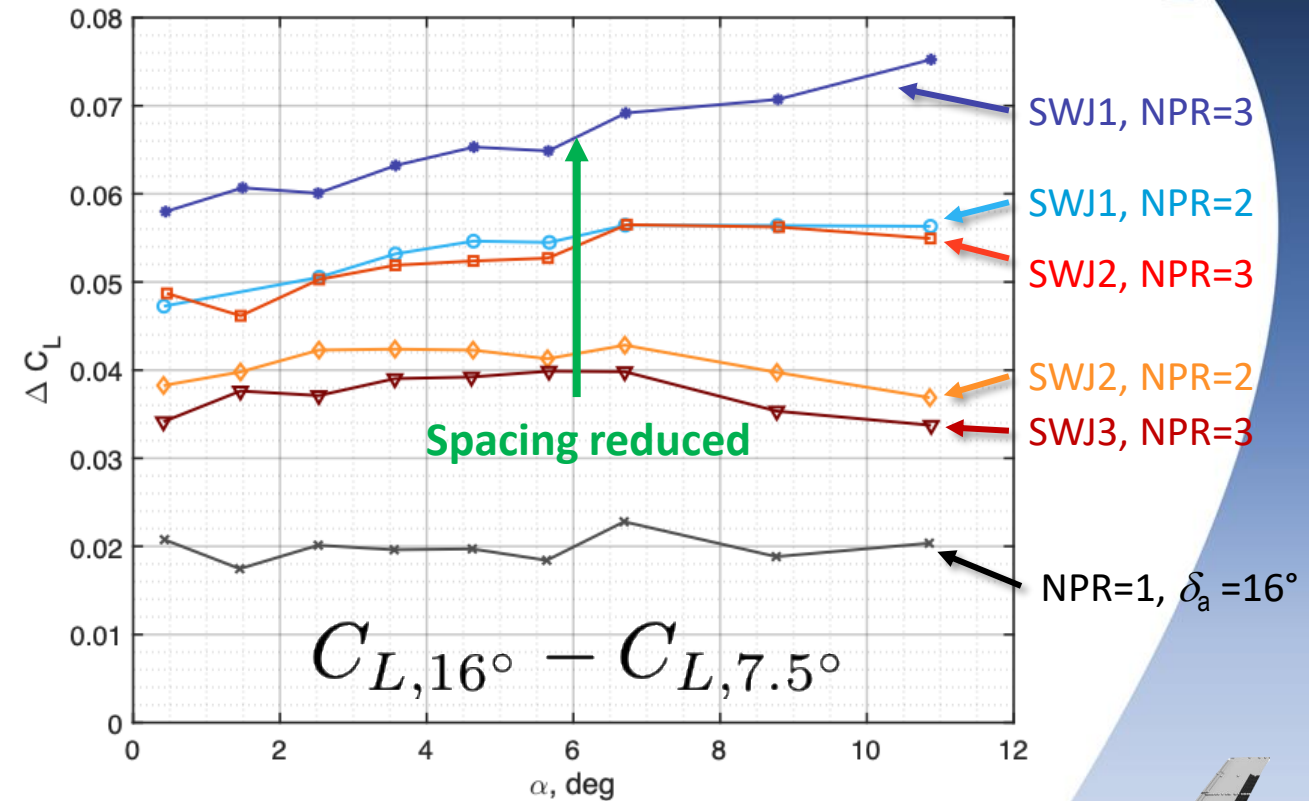
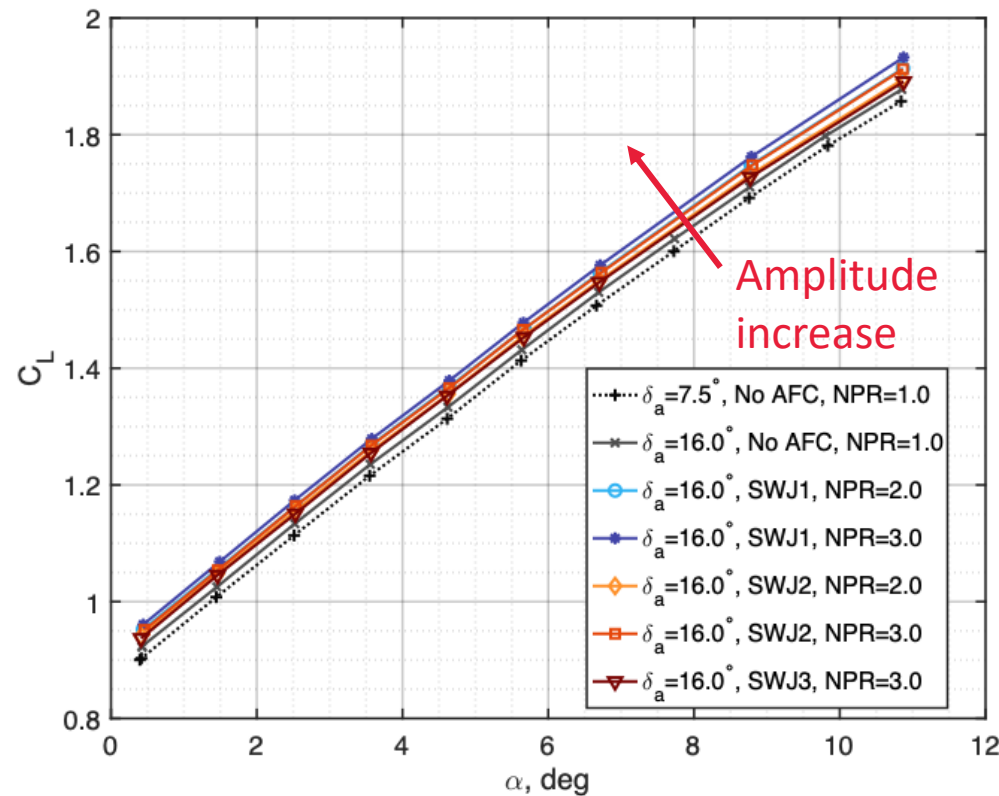
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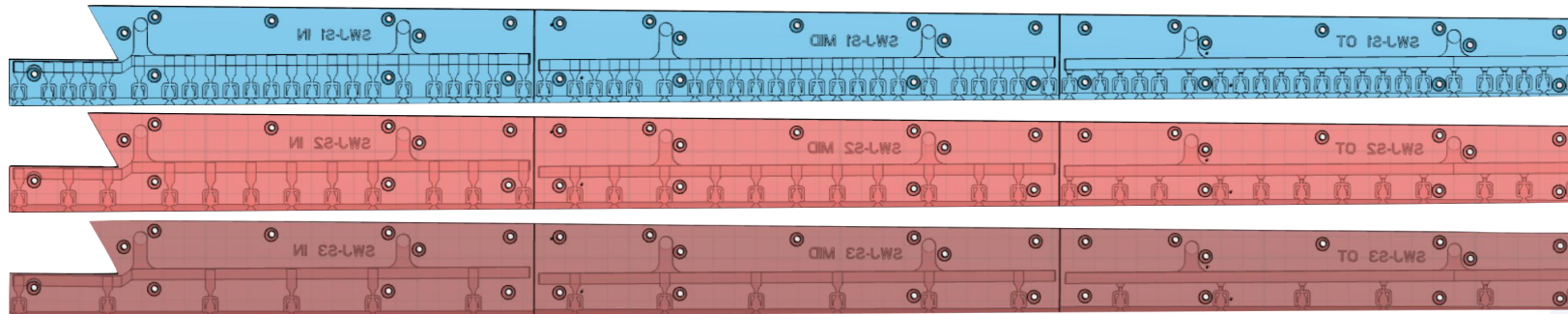


Sweeping Jets: Lift Coefficient

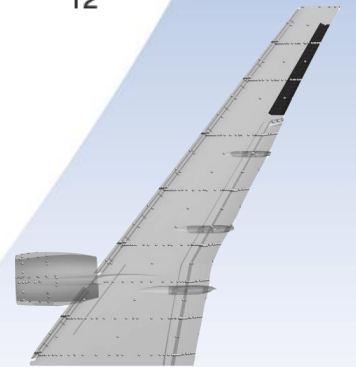
$$Re_c = 3 \times 10^6, M = 0.2, \delta_a = 16^\circ$$

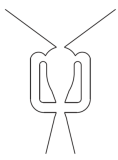


SWJ1
SWJ2
SWJ3



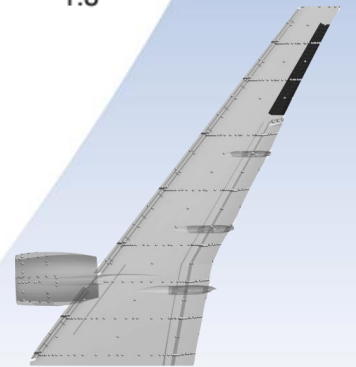
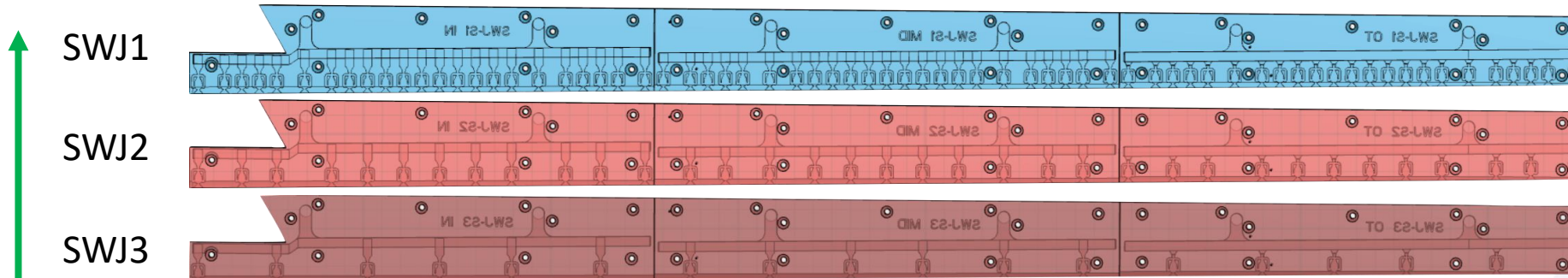
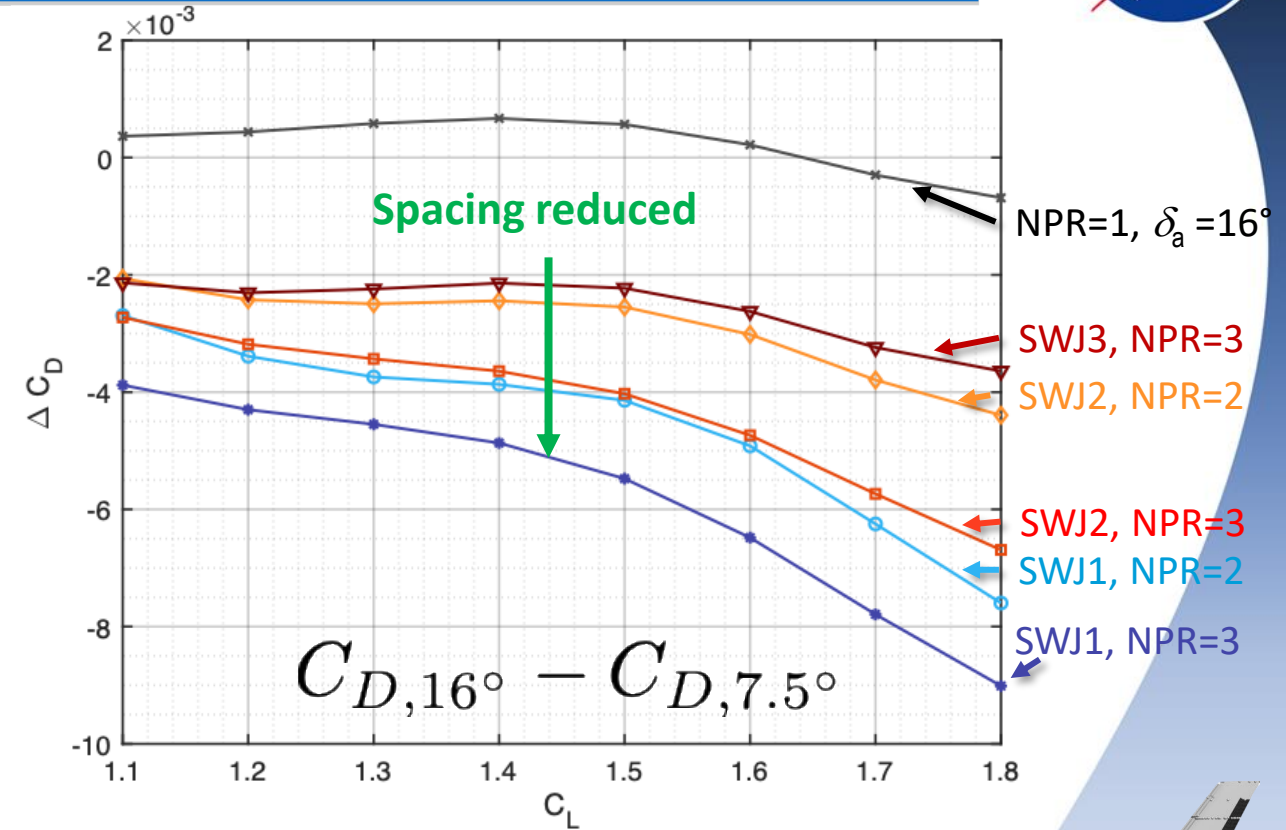
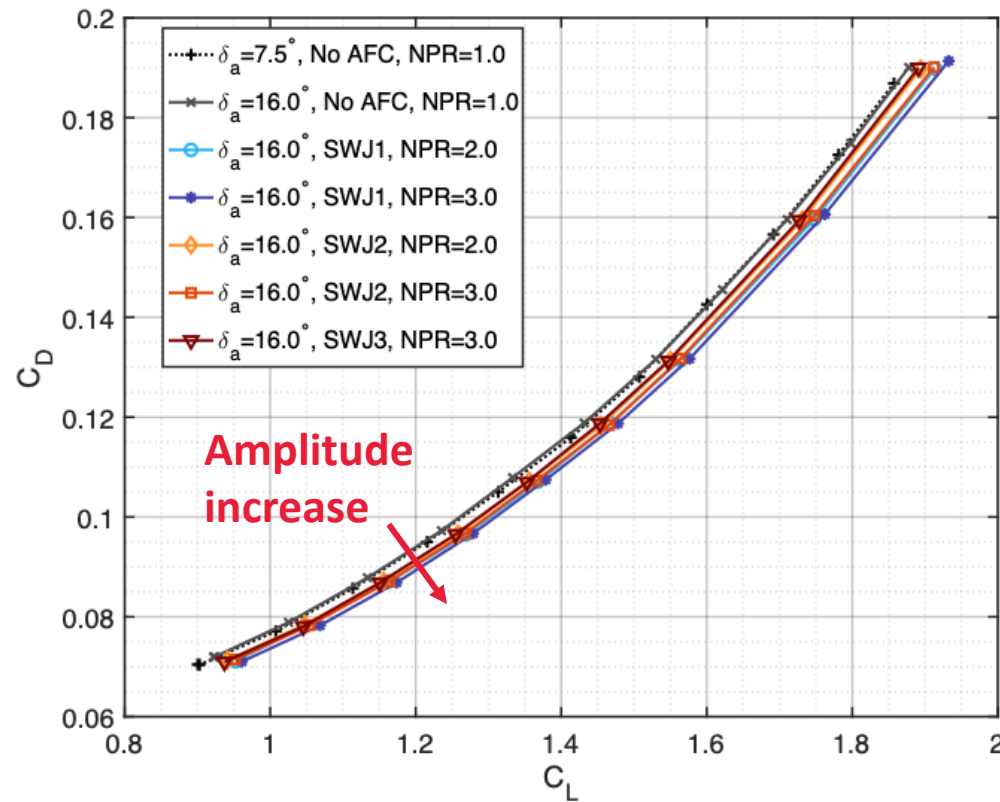
Spacing reduced



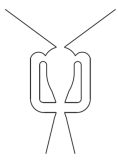


Sweeping Jets: Drag Coefficient

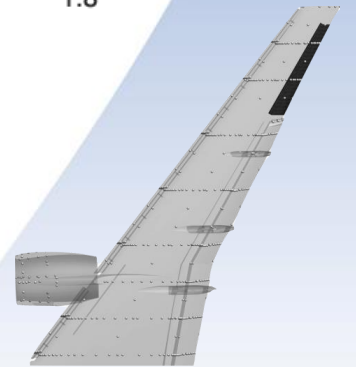
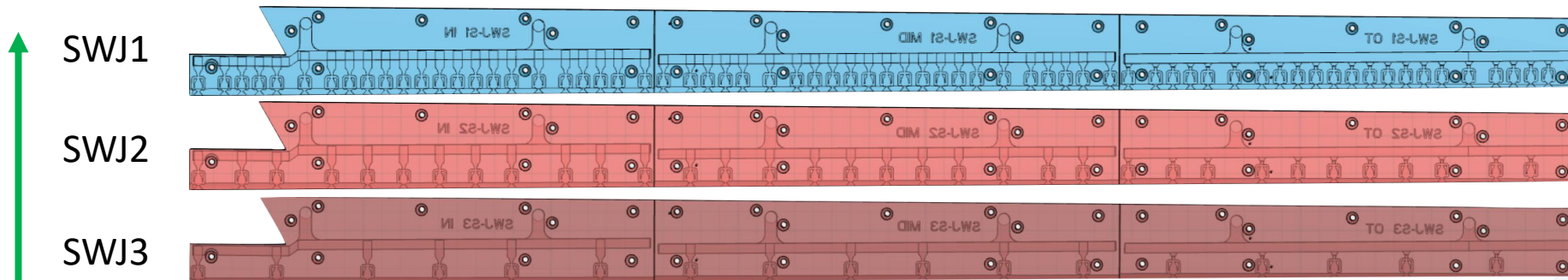
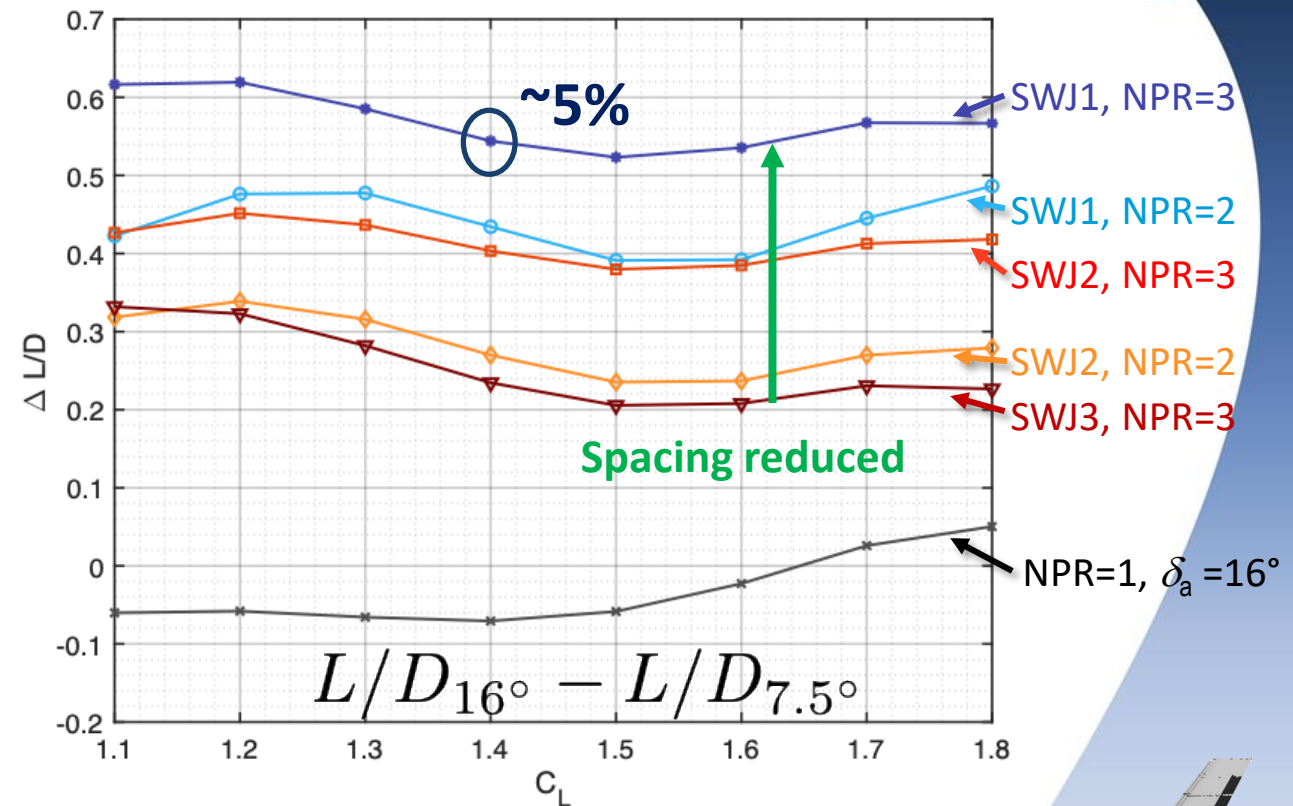
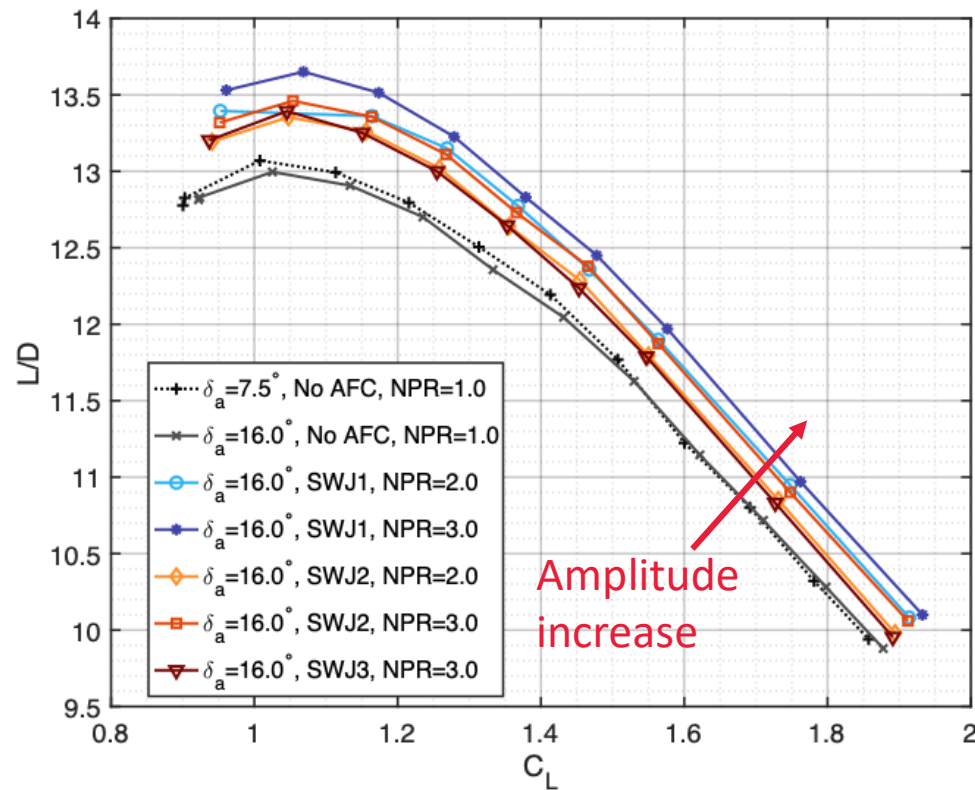
$$Re_c = 3 \times 10^6, M = 0.2, \delta_a = 16^\circ$$



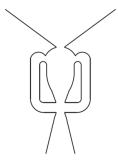
Spacing reduced



Sweeping Jets: Lift-to-Drag ratio $Re_c = 3 \times 10^6$, $M = 0.2$, $\delta_a = 16^\circ$

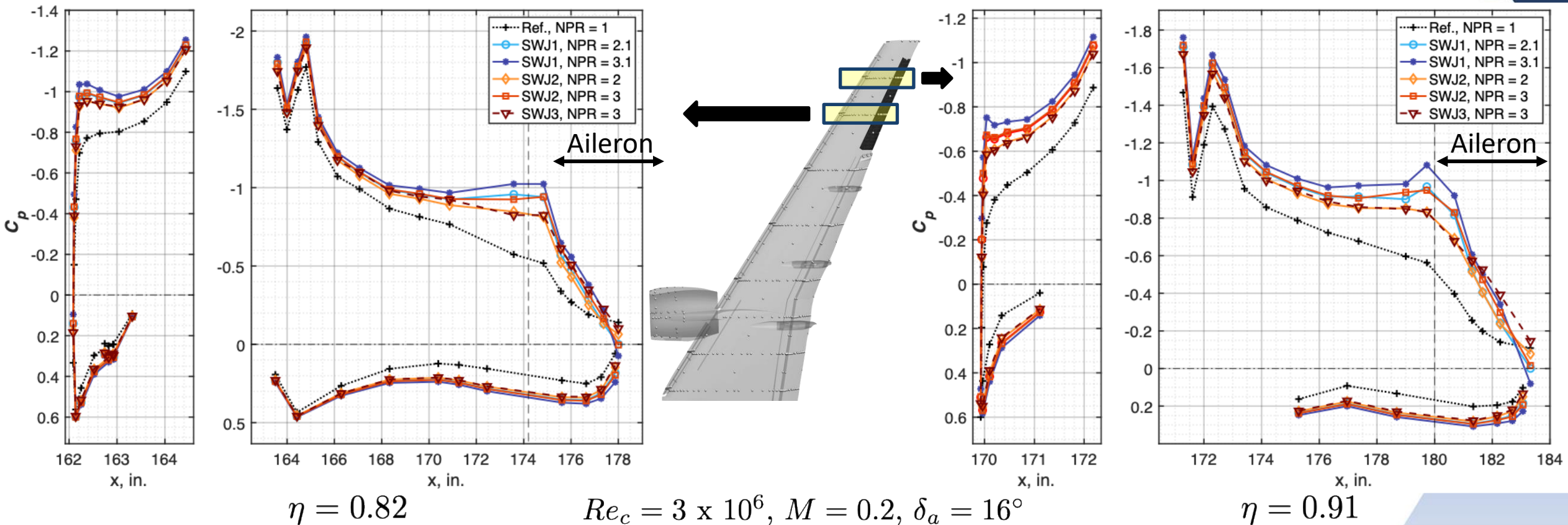


Spacing reduced

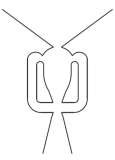


Sweeping Jets: Streamwise C_p Distributions

$$\alpha = 4.6^\circ$$



- NPR=1, flow separation at the aileron's TE
- AFC cases: Suction pressure increased: slat + main element
- Flow attached: SWJ1 at NPR=2 and SWJ2 at NPR=3
- C_p distribution improvements are consistent with C_L increase

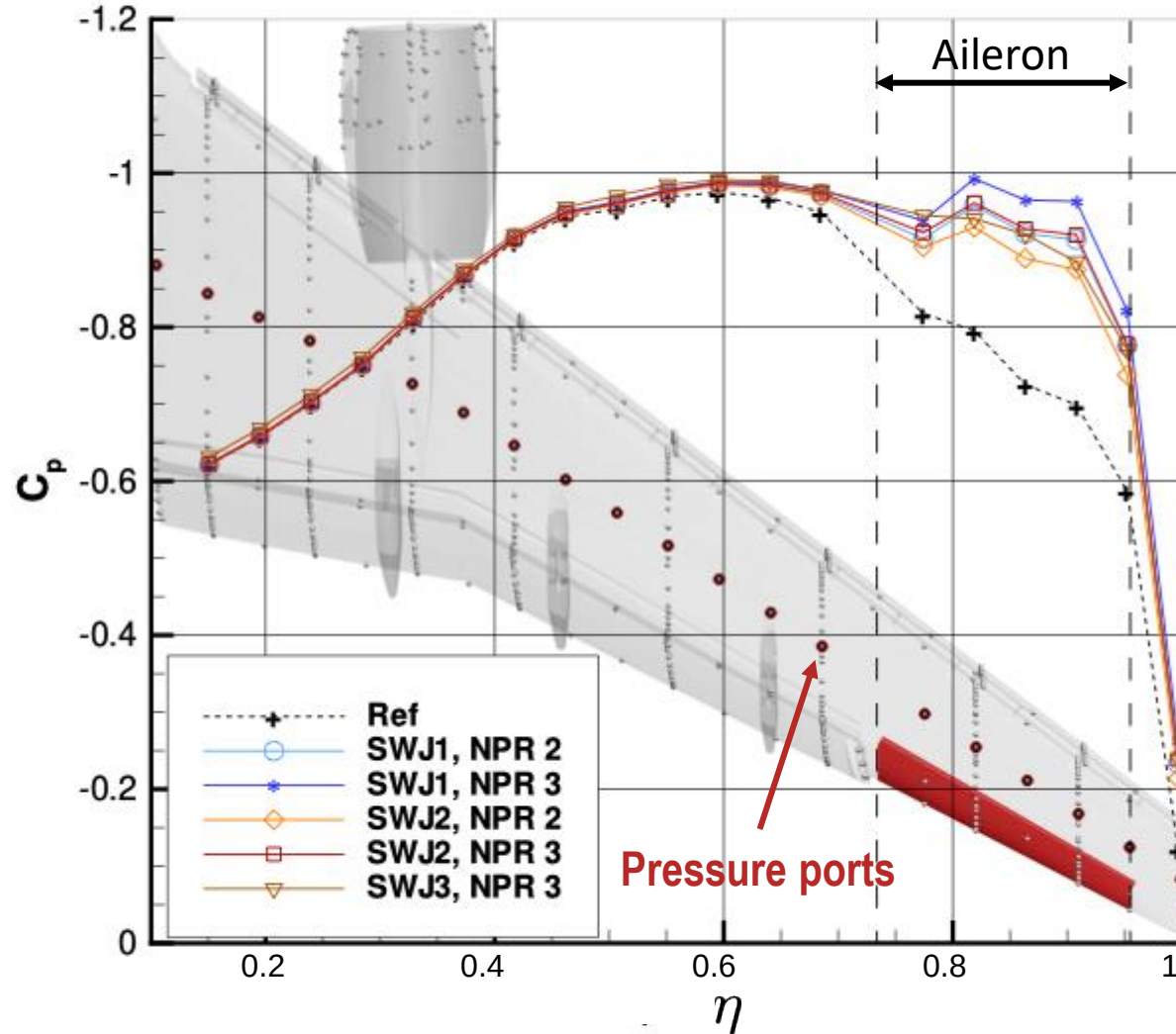


Sweeping Jets: Spanwise C_p Distributions



$$Re_c = 3 \times 10^6, M = 0.2, \delta_\alpha = 16^\circ$$

$$\alpha = 4.6^\circ$$



- Increased suction pressure upstream of the aileron section
- Suction pressure increases with actuation amplitude
- AFC effects are noticeable inboard of the aileron
- SWJ1 at NPR=2 similar performance to SWJ2 at NPR=3

AFC Evaluation Parameters



➤ Momentum coefficient

$$C_{\mu} = \frac{\dot{m}^2}{\bar{\rho} A_n q_{\infty} S_{ref}}$$

$$C_{\mu} = f(\dot{m}, \bar{\rho}, A_n, q_{\infty}, S_{ref})$$

➤ Mass flow rate coefficient

$$C_Q = \frac{\dot{m}}{\rho_{\infty} U_{\infty} S_{ref}}$$

$$C_Q = f(\dot{m}, \rho_{\infty}, U_{\infty}, S_{ref})$$

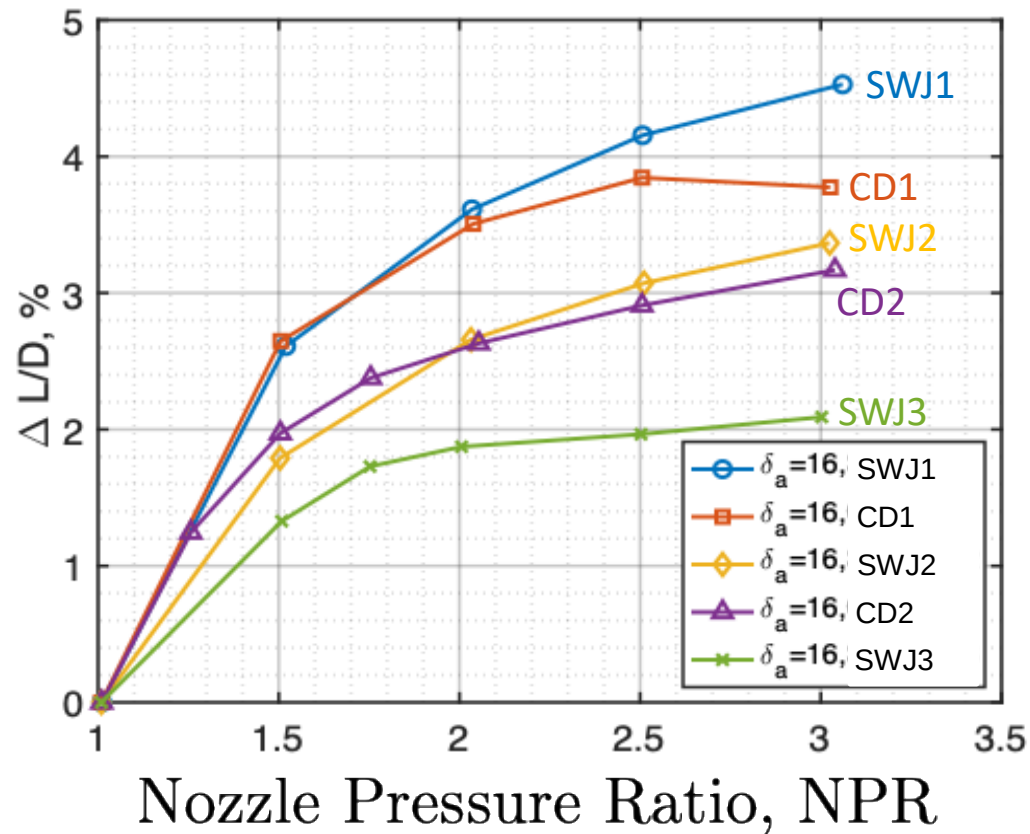
➤ Power Coefficient

$$C_{\pi} = \frac{C_Q \overline{P_o}_i}{q_{\infty}}$$

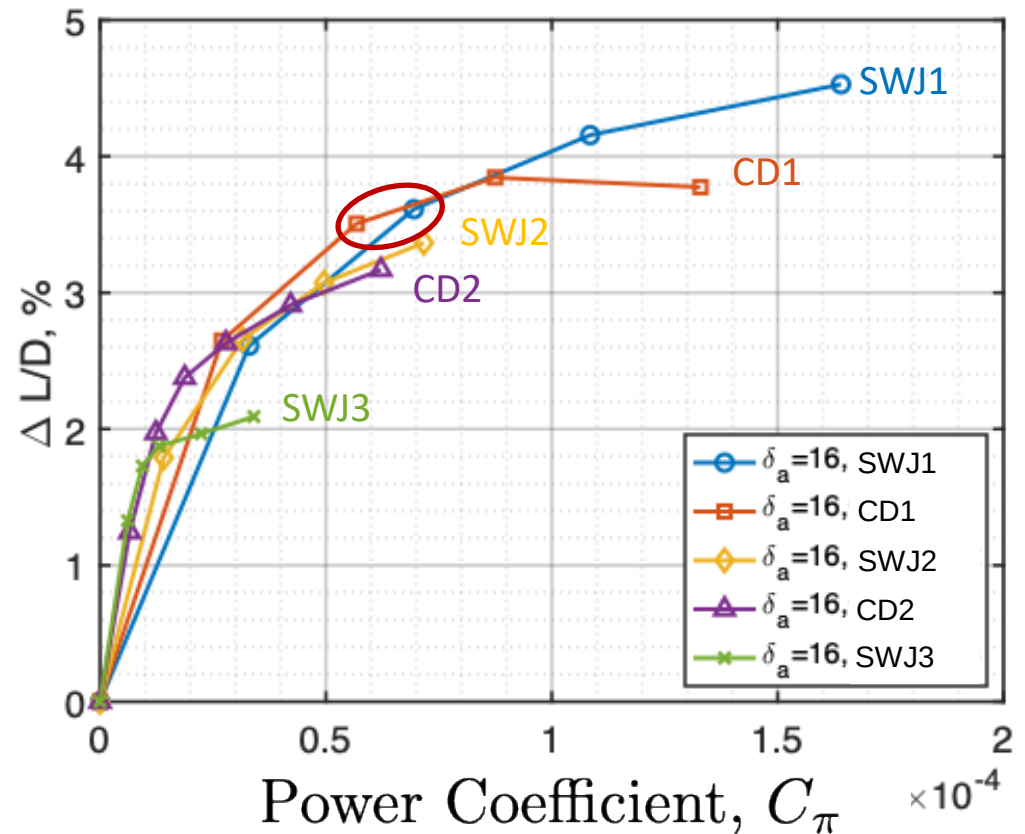
$$C_{\pi} = f(\dot{m}, \rho_{\infty}, U_{\infty}, S_{ref}, \overline{P_o}, q_{\infty})$$

AFC Evaluation Parameters

$$Re_c = 3 \times 10^6, M = 0.2, \delta_a = 16^\circ$$



$$\alpha = 4.6^\circ$$

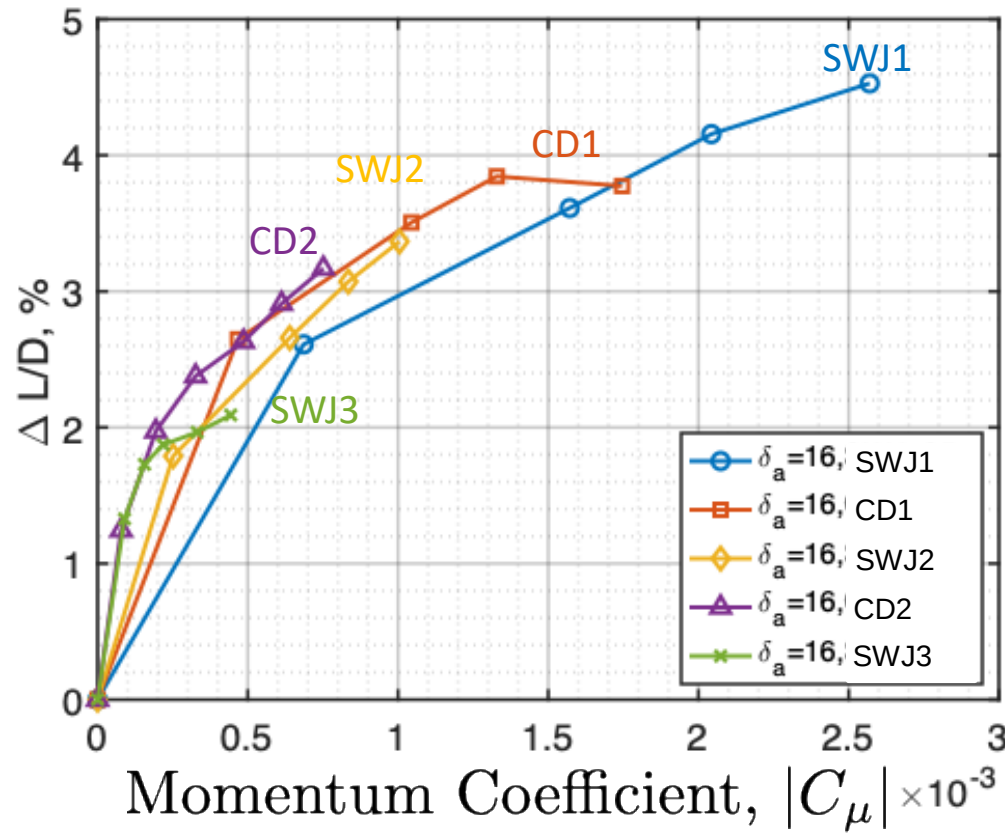


- CDs more efficient than SWJs for this 3D flow field
- SWJ2 and CD2 have similar performance improvements
- At NPR=2, CD1: CD1 has lower C_π than SWJ1 (red oval)

$$\frac{L/D_{16^\circ} - L/D_{16^\circ, noAFC}}{L/D_{16^\circ, noAFC}}$$

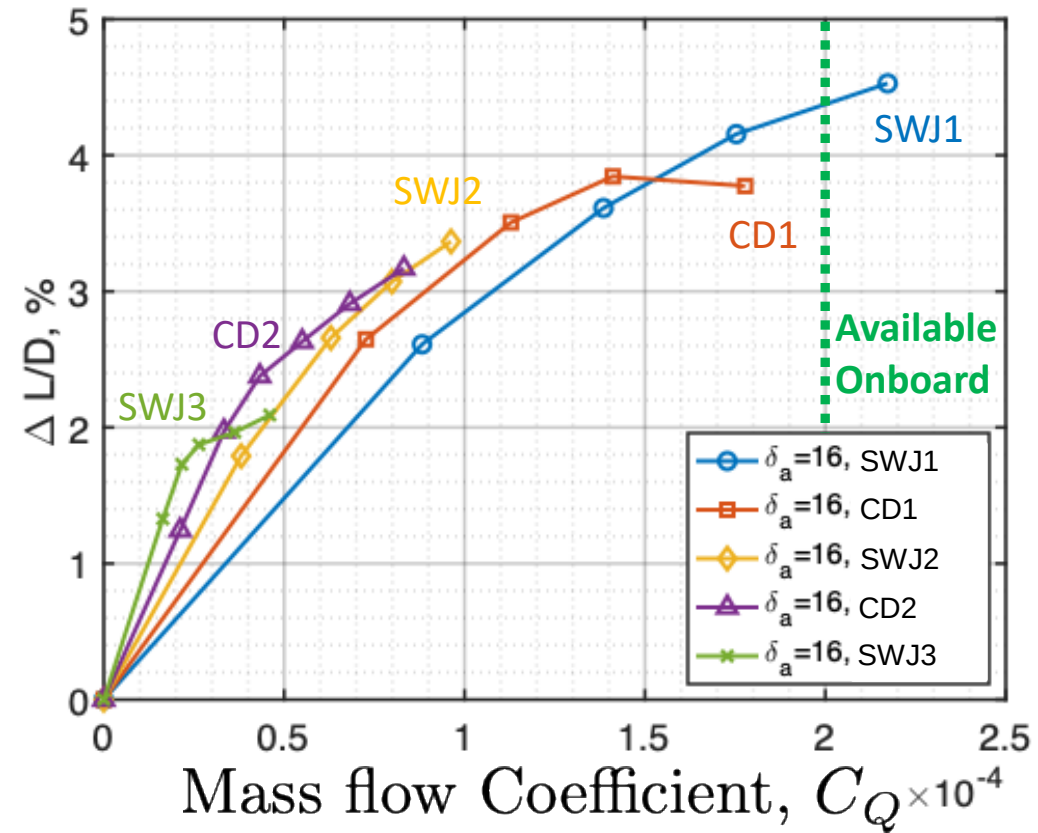
AFC Evaluation Parameters

$$Re_c = 3 \times 10^6, M = 0.2, \delta_a = 16^\circ$$



$$\alpha = 4.6^\circ$$

- Maximum performance improvement SWJ1
- CD2 and SWJ2 have similar performance levels



$$\frac{L/D_{16^\circ} - L/D_{16^\circ, noAFC}}{L/D_{16^\circ, noAFC}}$$

Summary



- An experimental investigation was conducted at the NASA Langley 14- by 22-Foot Subsonic Tunnel on the NASA 10% scale High-Lift Common Research Model in the takeoff configuration.
- AFC was applied to the aileron to enhance the L/D ratio for an aileron deflection angle of 16 degrees, HL-improved takeoff configuration.
- AFC performance was assessed using tuft visualization, steady surface pressure measurements, and force and moment data.
- All AFC cases resulted in increased C_L and reduced C_D , resulting in higher L/D ratios for both SWJs and CDs.

*AFC applied to an aileron achieved a **5% improvement in L/D** using available onboard resources*

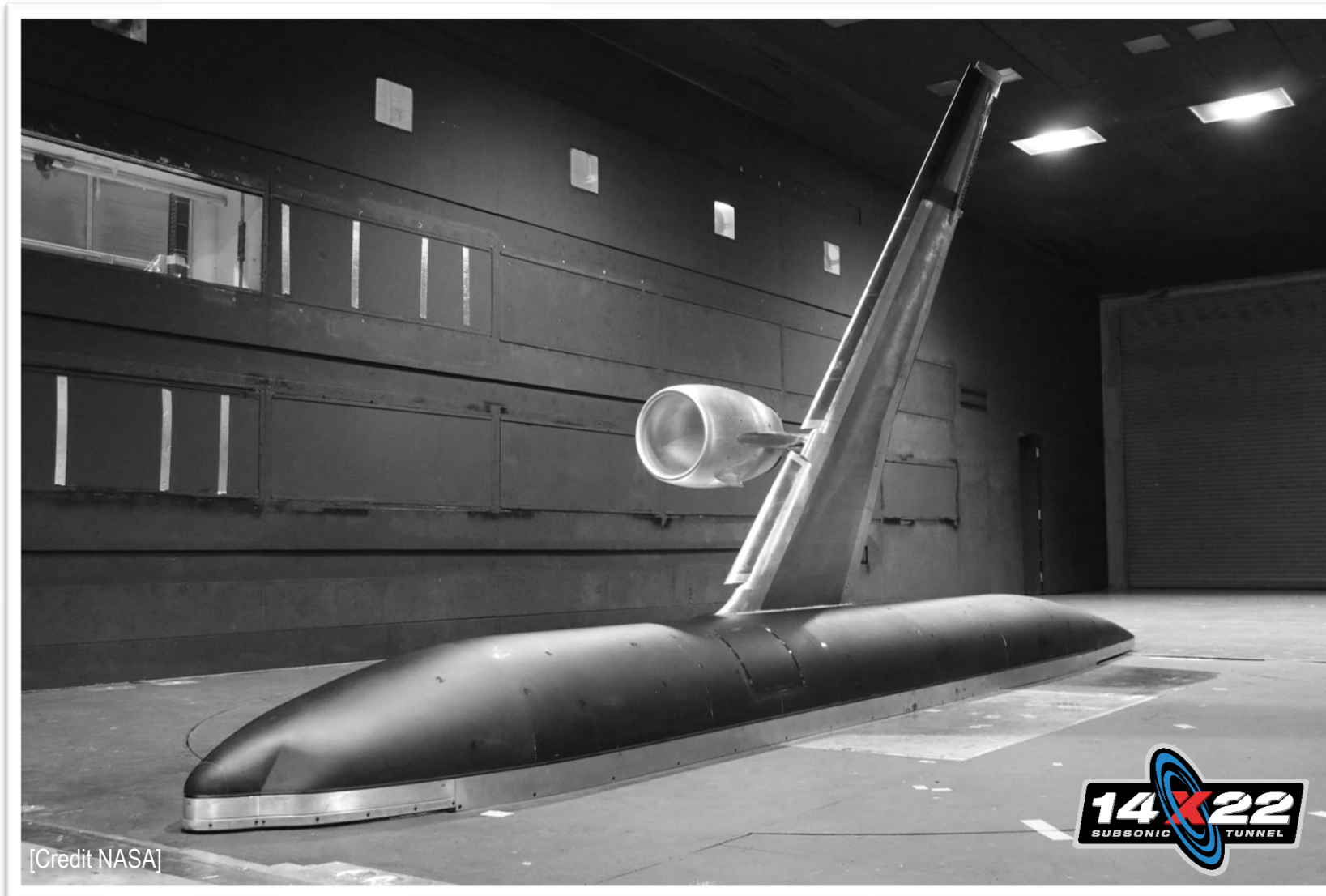
Acknowledgements



- Airframe Technologies Subproject of the Advanced Air Transport Technology Project in the NASA Advanced Air Vehicles Program for funding this research.
- 14x22-Foot Subsonic Wind Tunnel Staff for their support.
- NASA Langley machine shop



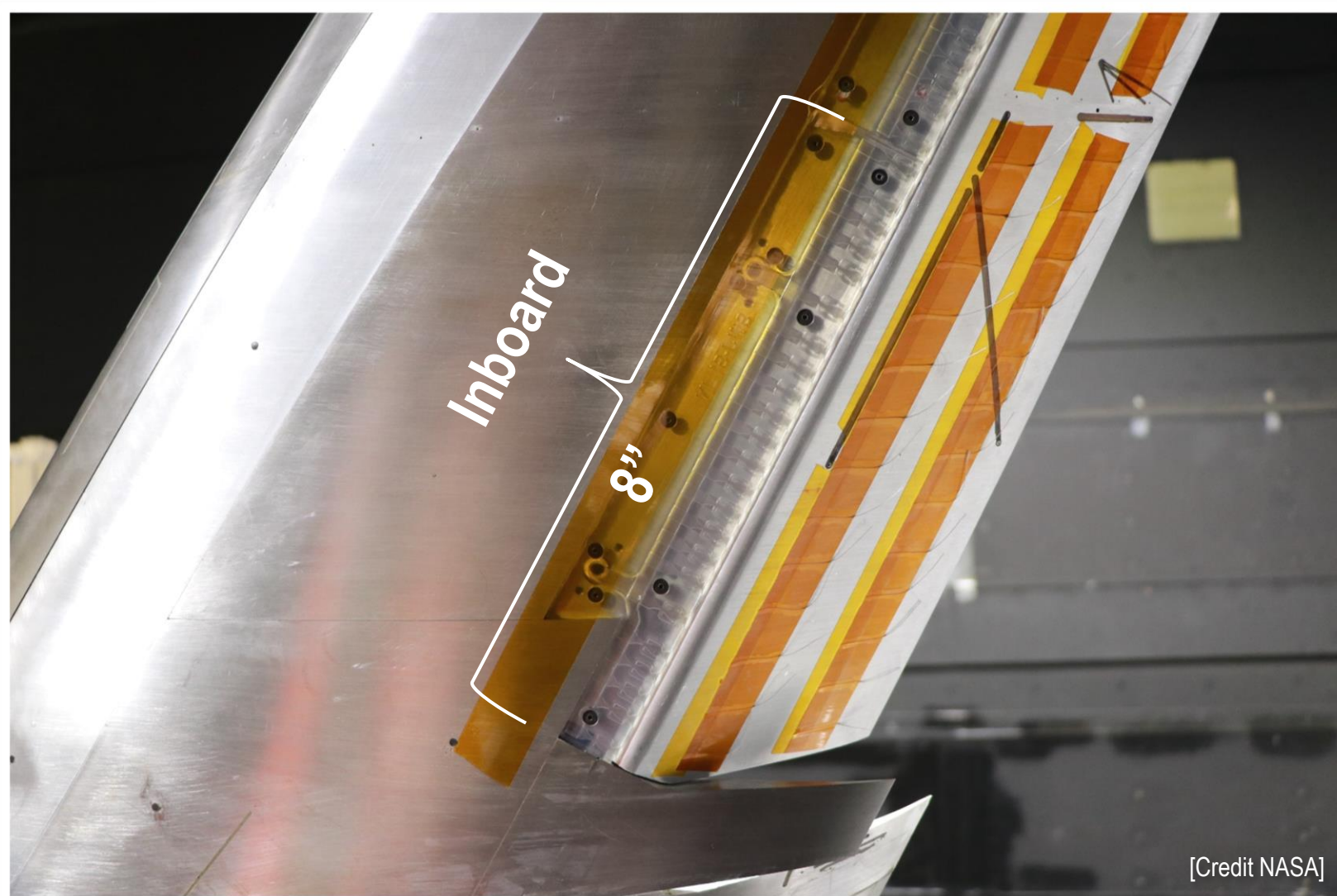
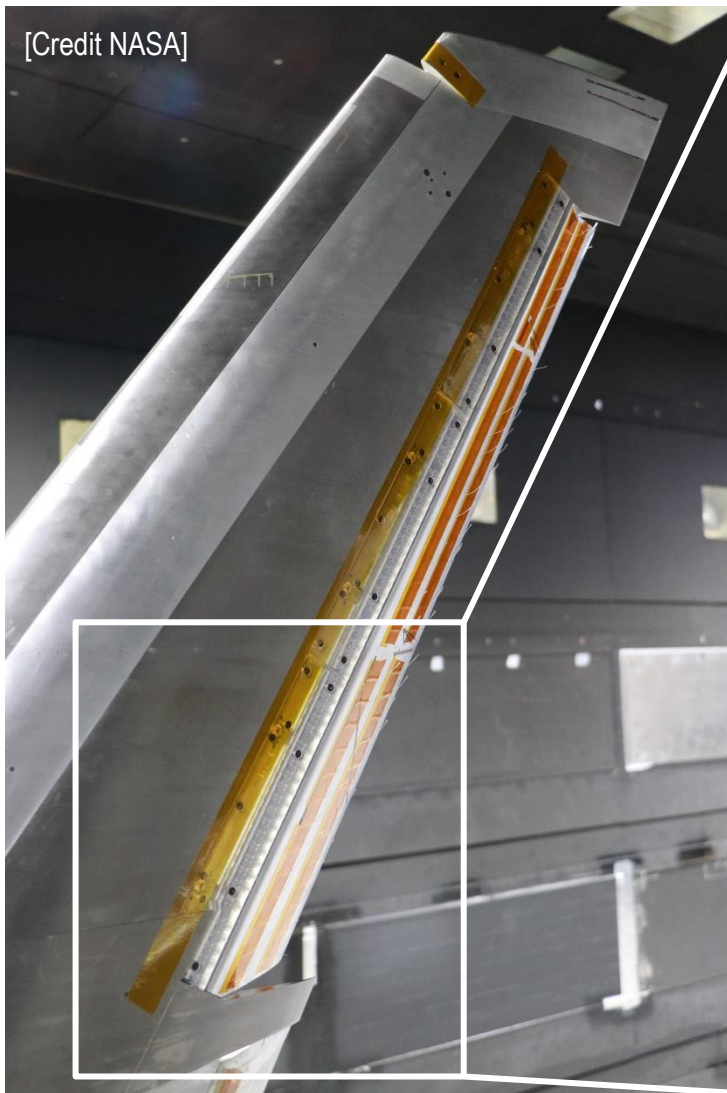
Questions



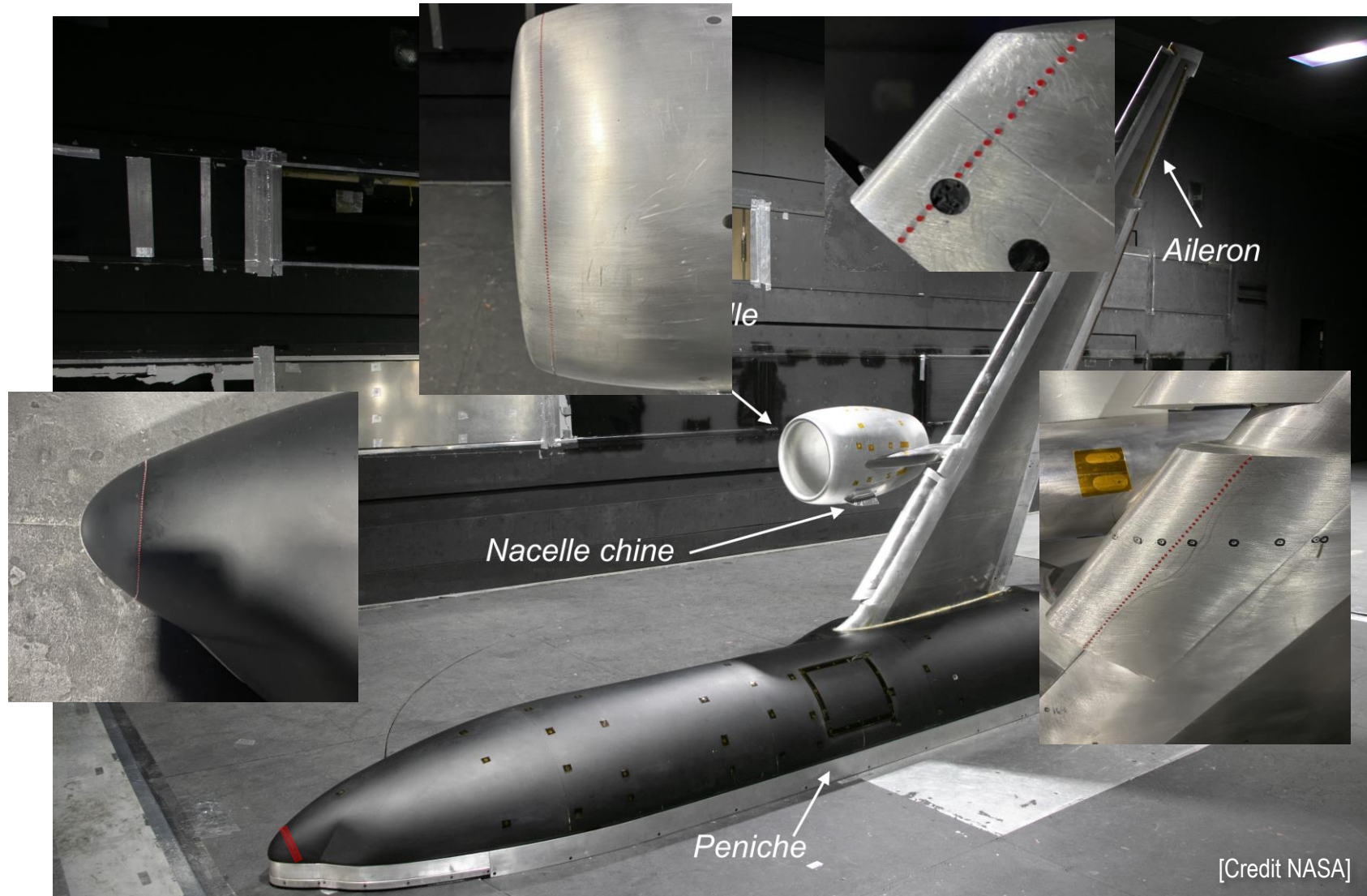
SWJ1 Actuators close-up



[Credit NASA]



CRM-HL Trip Locations



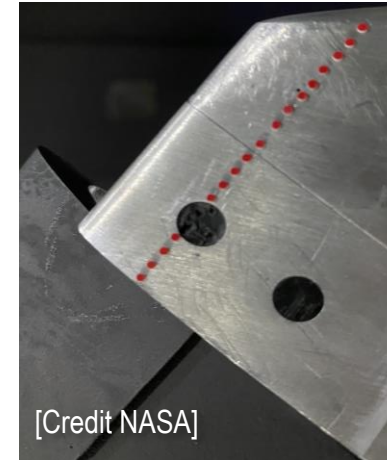
CRM-HL Trip Locations



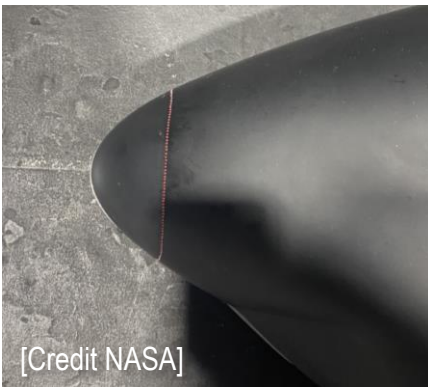
nacelle



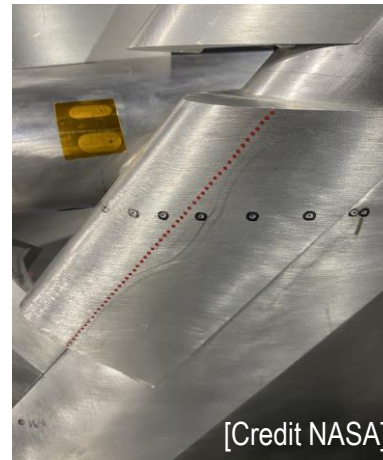
wing tip



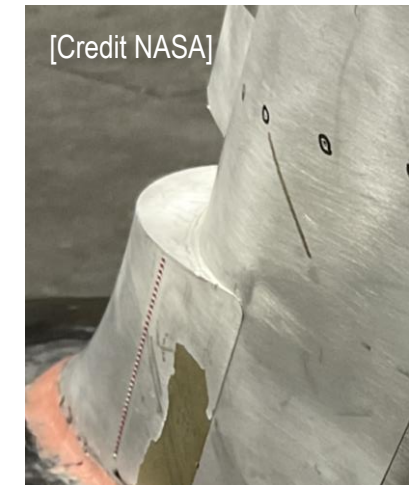
fuselage nose



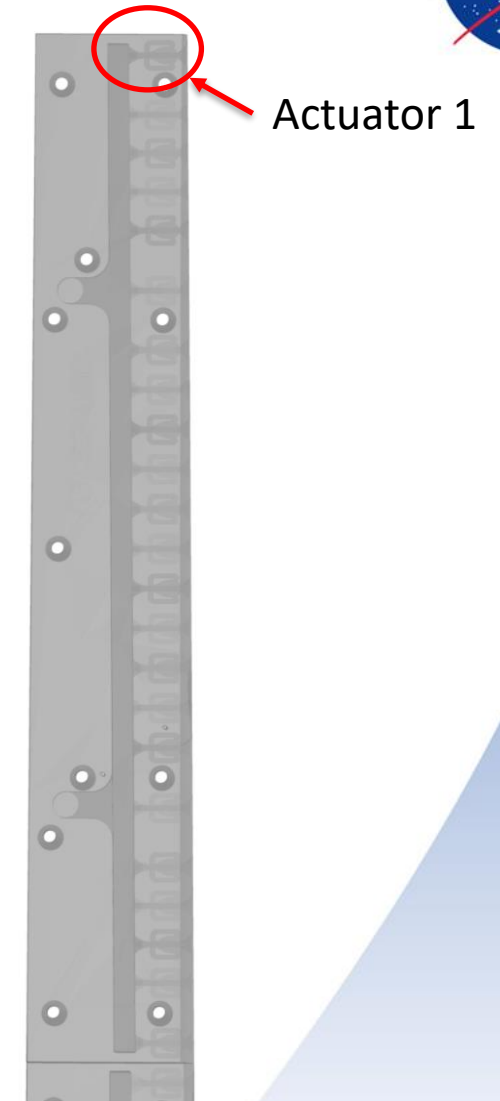
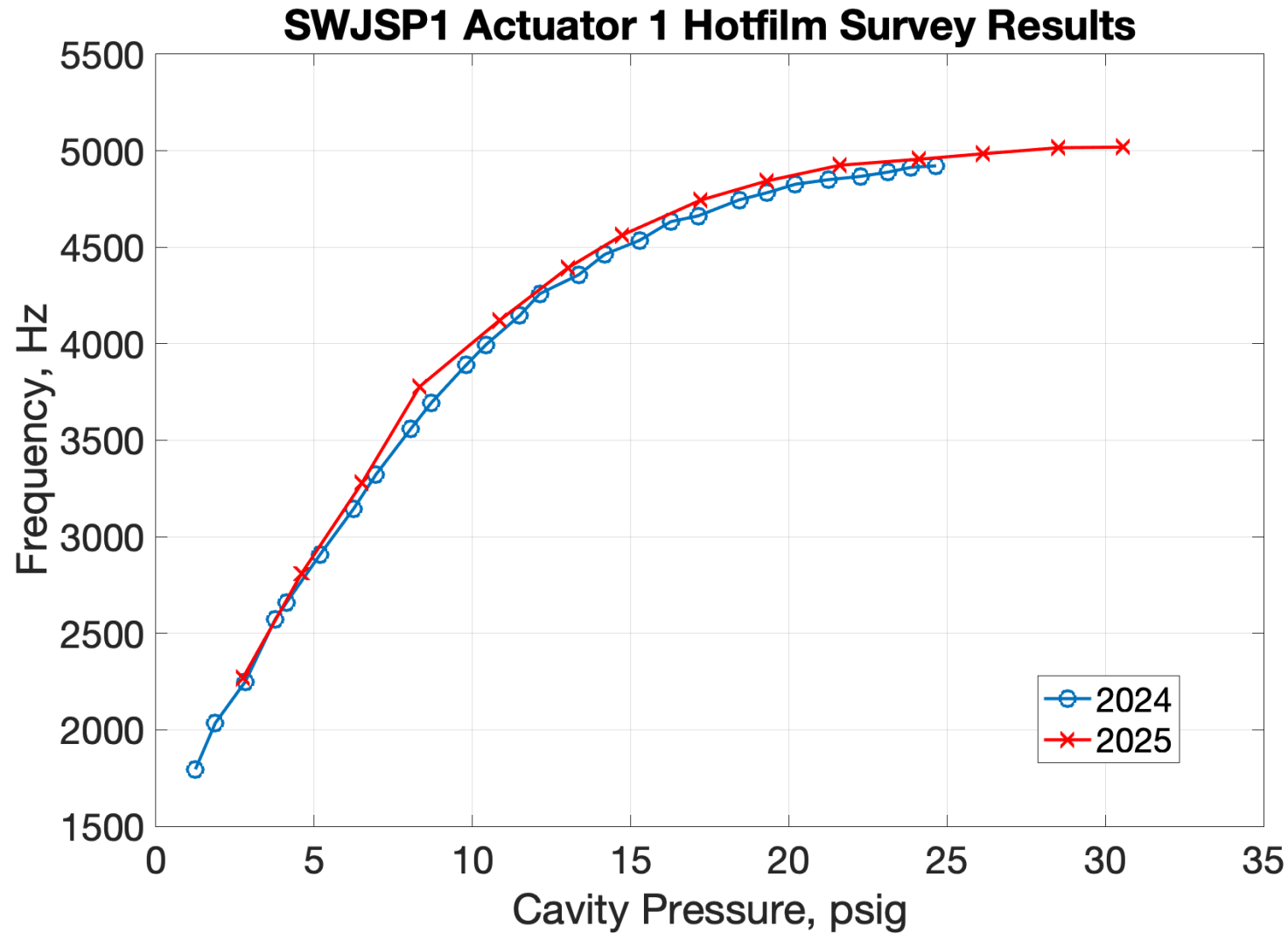
“slatless” WUSS



strake



Comparing measurements 2024 vs. 2025



AFC Service Air Supply System Configuration



Test Conditions:

Supply Pressure range 110 psig

Temperature: 60-75 deg F

