Computational Investigation of Active Aerodynamic Load Control for Multi-Element Airfoils

Sheida Hosseini†, ‡
Co-authors:
Professor Case van Dam†
Dr. Shishir Pandya‡

†University of California, Davis
‡NASA Ames Research Center

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Acknowledgment

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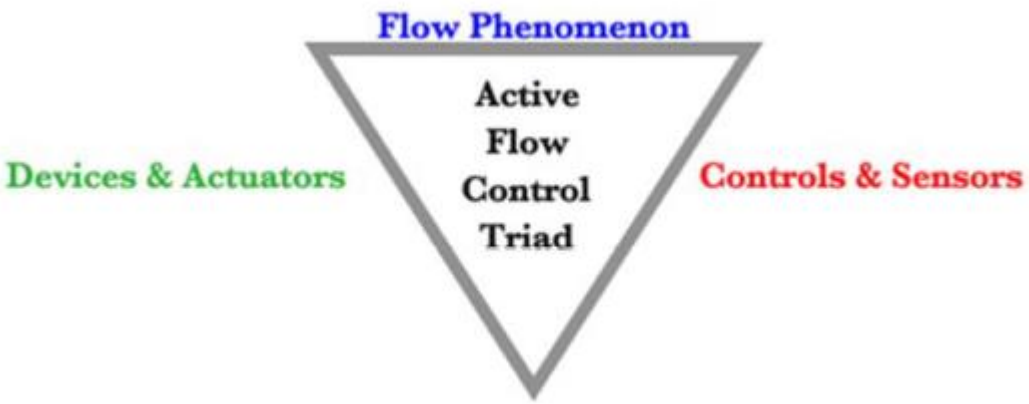
Motivation

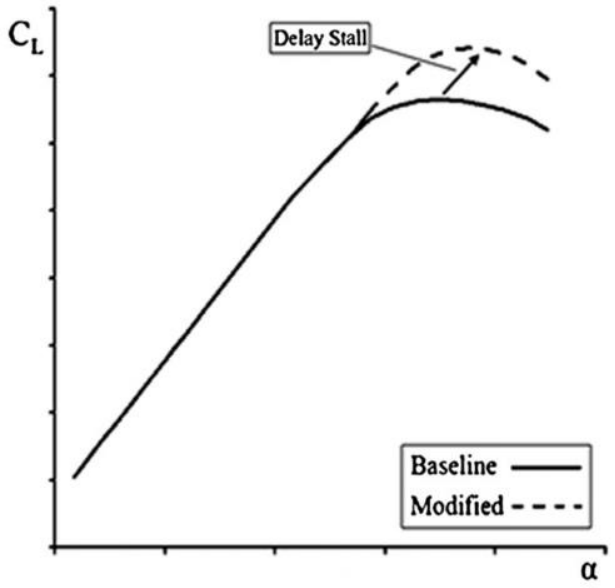
Active Flow Control for high-lift systems

- $C_{L_{max}}$
- L/D
- Lift in the linear region

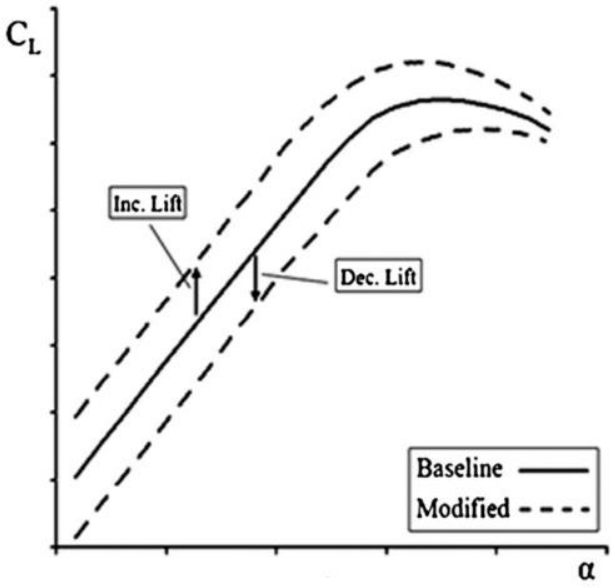
Active Flow Control (AFC)



Separation Mitigation



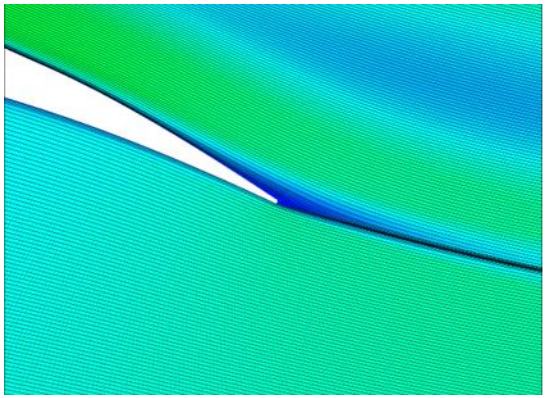
Load Control



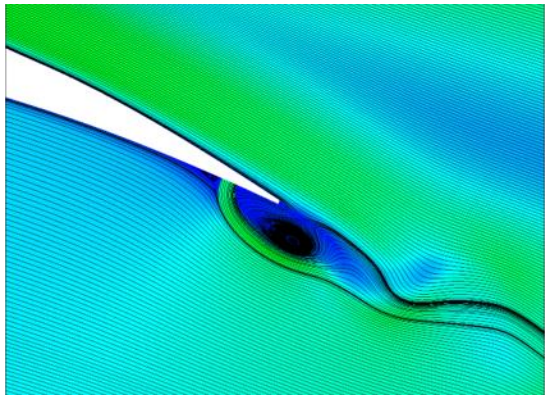
Kral 1998
Johnson et al. 2008

Outline

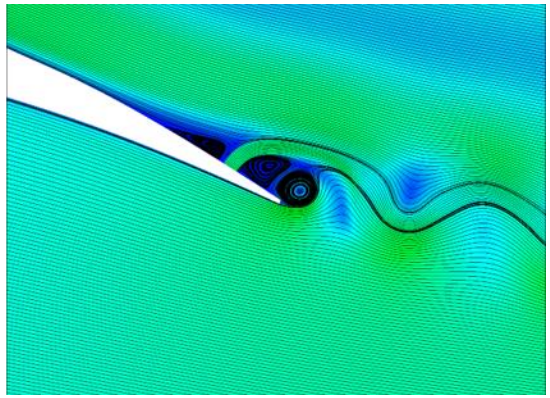
- Overview
- Computational setup on baseline multi-element airfoil NLR7301
  - Various grid sensitivities
- Investigation of flap microjet on NLR7301
  - Sensitivities of lift and drag to microjet settings
  - Microjet definition sensitivity
- Summary and Conclusions



Baseline (no jet)



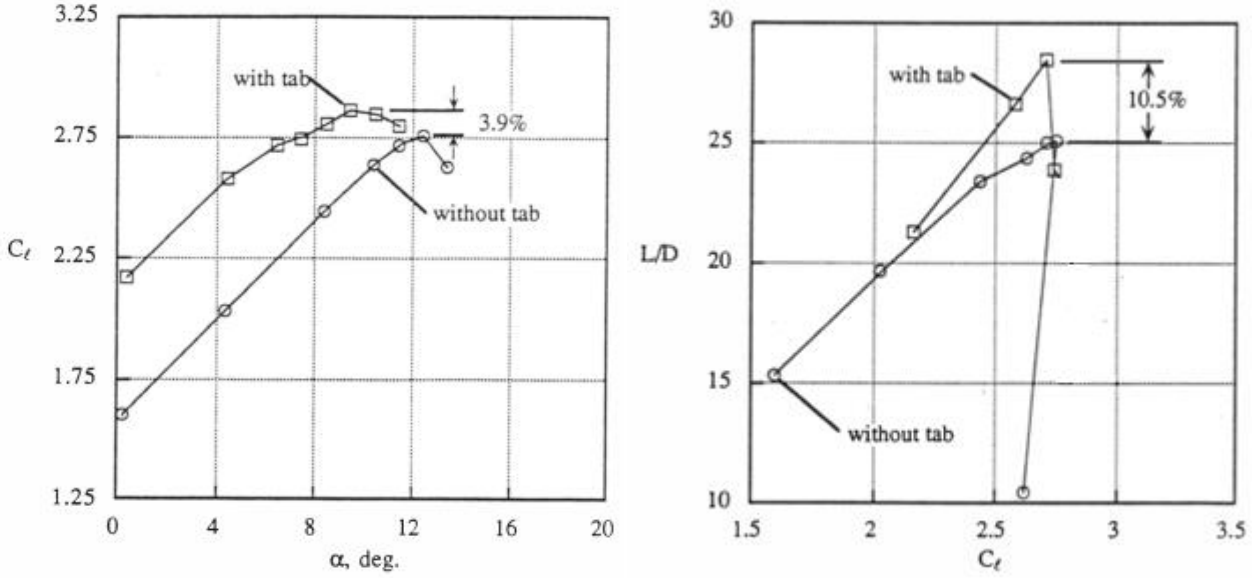
Baseline + lower surface jet

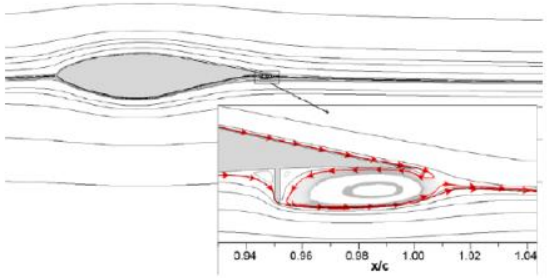


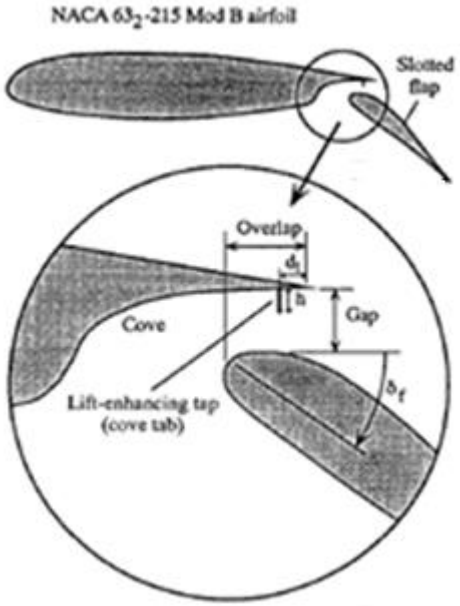
Baseline + upper surface jet

Microtab AFC Load Control

1%c tab located at 1%c upstream of trailing edge







- Vertical tabs (Gurney flaps) can increase L/D
- Geometric tabs increase loads (actuation force/torque)
- Tabs require physical space
- Tabs are not necessarily continuous spanwise once activated
- Quick movement of tab is desirable – AFC allows rapid activation

Storms and Ross, 1995
Johnson et al. 2010

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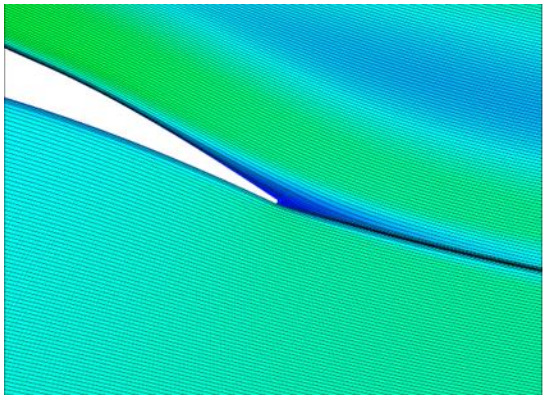
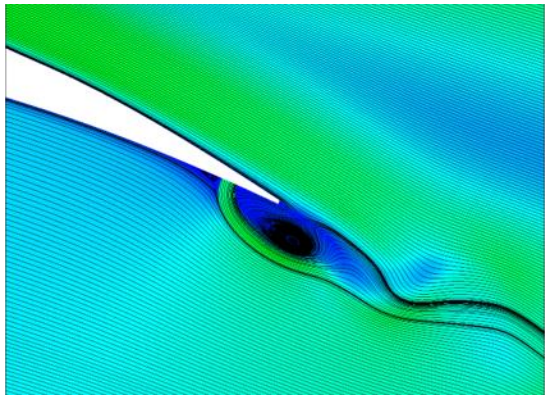
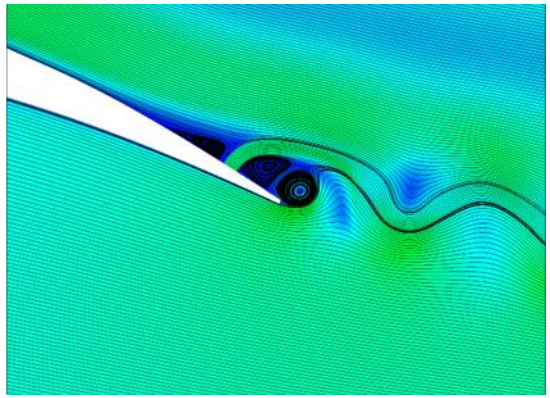


Baseline (no jet)



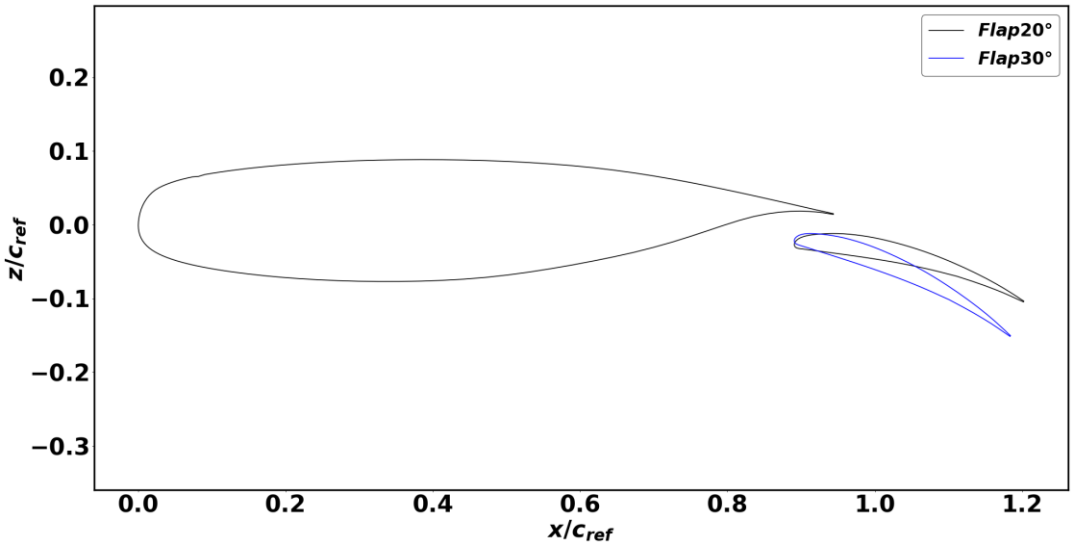
Baseline + lower surface jet



Baseline + upper surface jet

Airfoil Definition

- NLR7301: flap chord is 32%c_{ref}
  - Flap deflection 20°, overlap 0.053 c_{ref}, gap 0.026 c_{ref}. Experimental 2-D data is available at $\alpha = 6°$, $Re = 2.51E6$, and $M = 0.185$
  - Flap 30° is set up with the same overlap and gap as flap 20°
    - No experimental data



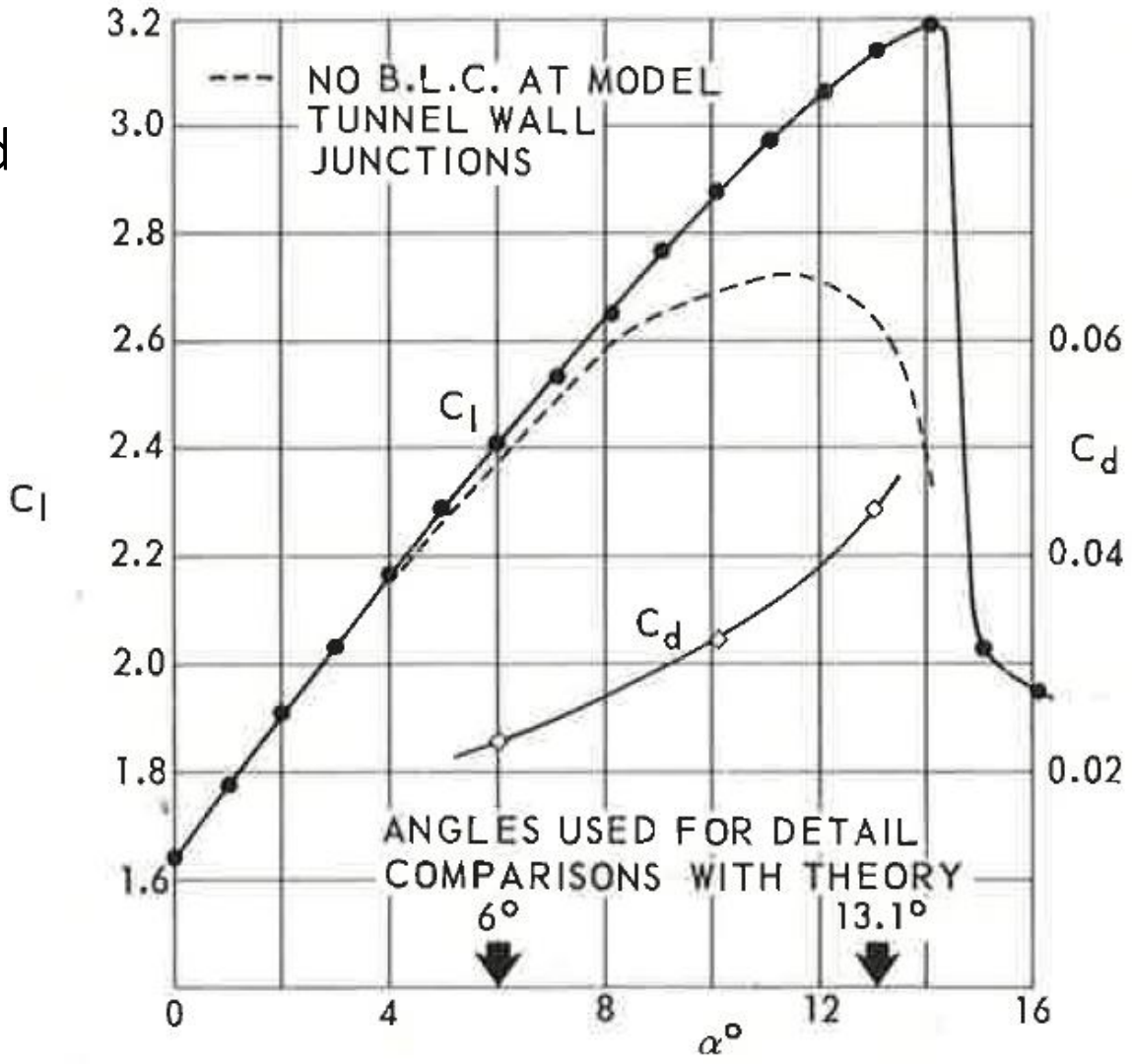
Vandenberg and Oskam 1980

NLR7301 Experimental Data

Reported accuracy at

$\alpha = 6°,\ Re = 2.51E6$, and $M = 0.185$

- C_l within ±0.4%
- C_d within ±2%
- C_p within ±0.5%
- α within ±0.05 °



Vandenberg and Oskam 1980

NLR7301 Experimental Data

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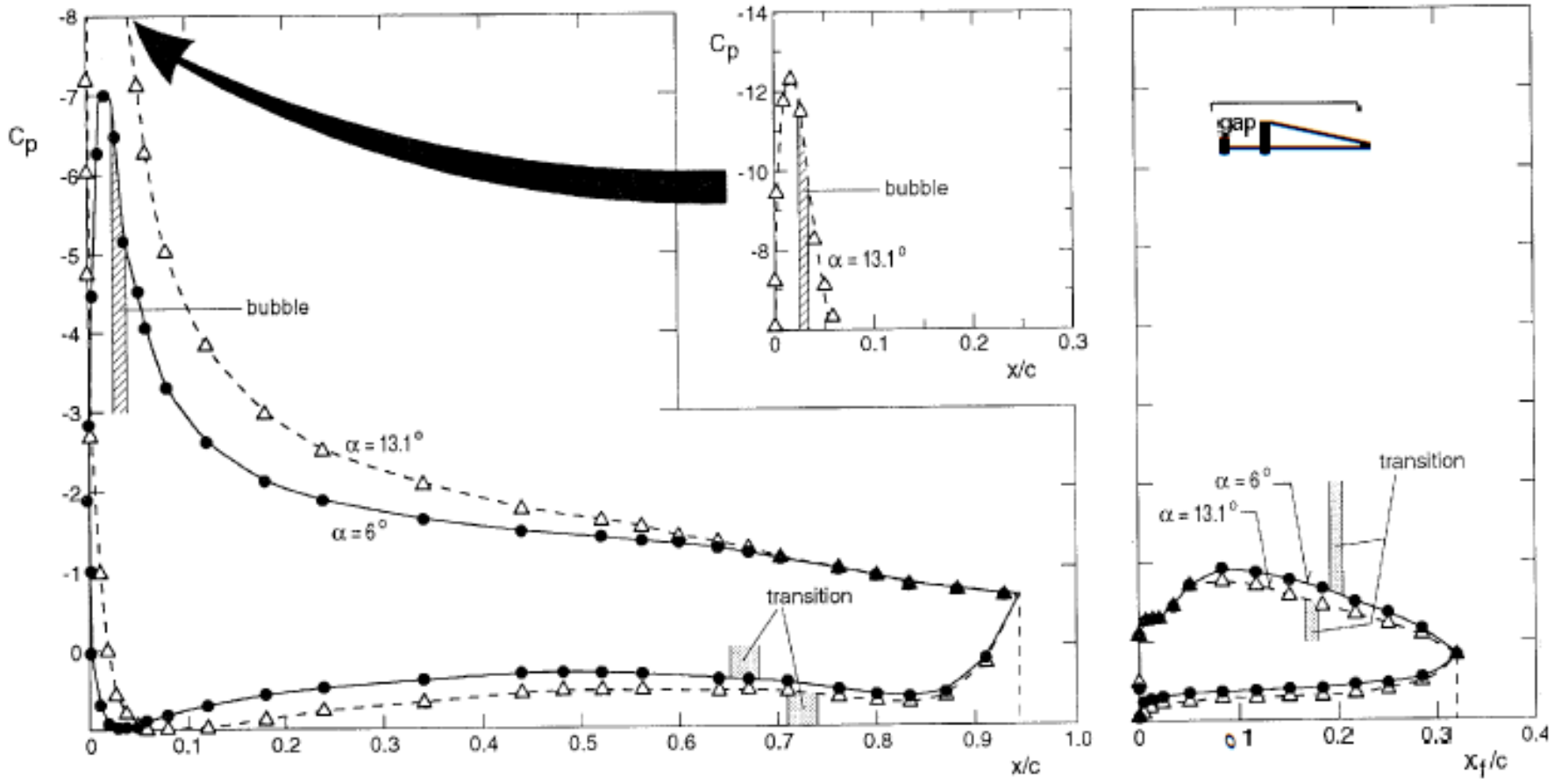
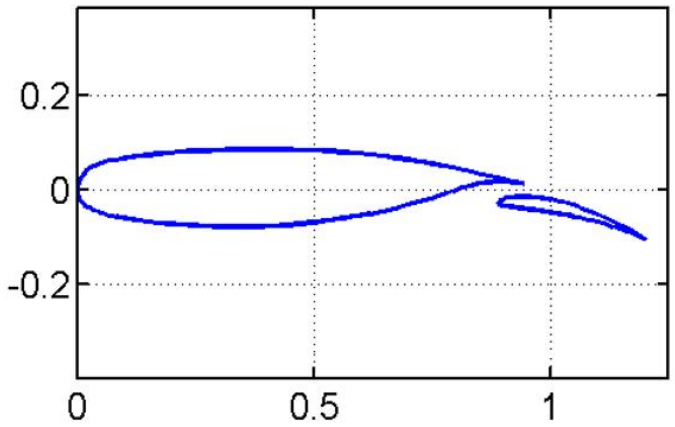
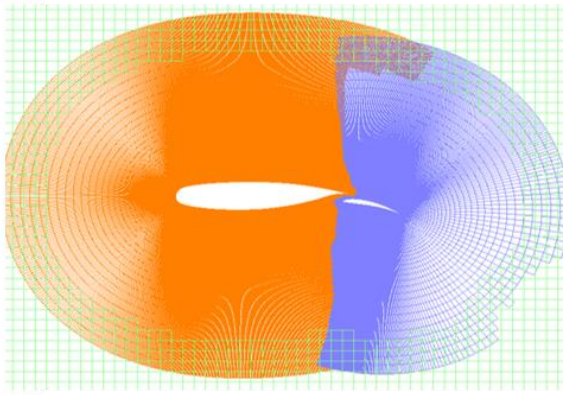


Vandenberg and Oskam 1980

Initial Computational Setup: 2D Studies

- Chimera Grid Tools: Overset grid technology
  - O-grid topology growing 50c away
  - PEGASUS mesh connectivity
- RANS OVERFLOW 2
  - 4^{th} order central difference and ARC3D diagonalized approximate factorization with matrix artificial dissipation
  - SA turbulence model
  - Fully turbulent simulations





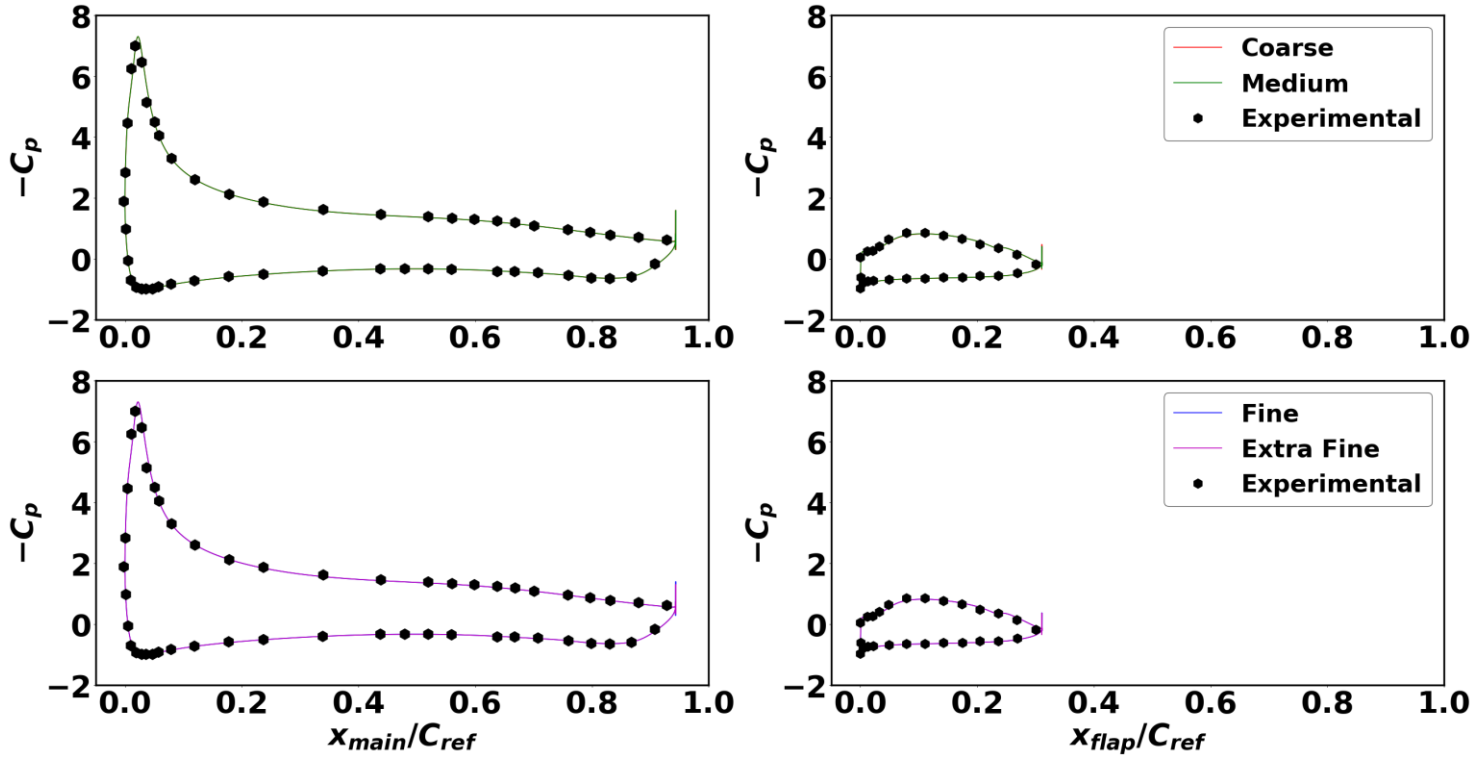
More details can be found at: Hosseini, S. S., van Dam, C. P., and Pandya, S. A., "Computational investigation of nominally-orthogonal pneumatic active flow control for high-lift systems," 2018 AIAA Aerospace Sciences Meeting, AIAA Paper2018-0559, Kissimmee, Florida, 2018. doi:10.2514/6.2018-0559.

Surface Grid Sensitivity: 2D Studies

Number of Points on	Main Element	Flap Element
Coarse	600	300
Medium	800	400
Fine	1000	500
Extra-fine	1200	600

α=6°, Re = 2.51E6, and Ma = 0.185

Main TE thickness: 0.0009c_ref
Flap TE thickness: 0.00115c_ref



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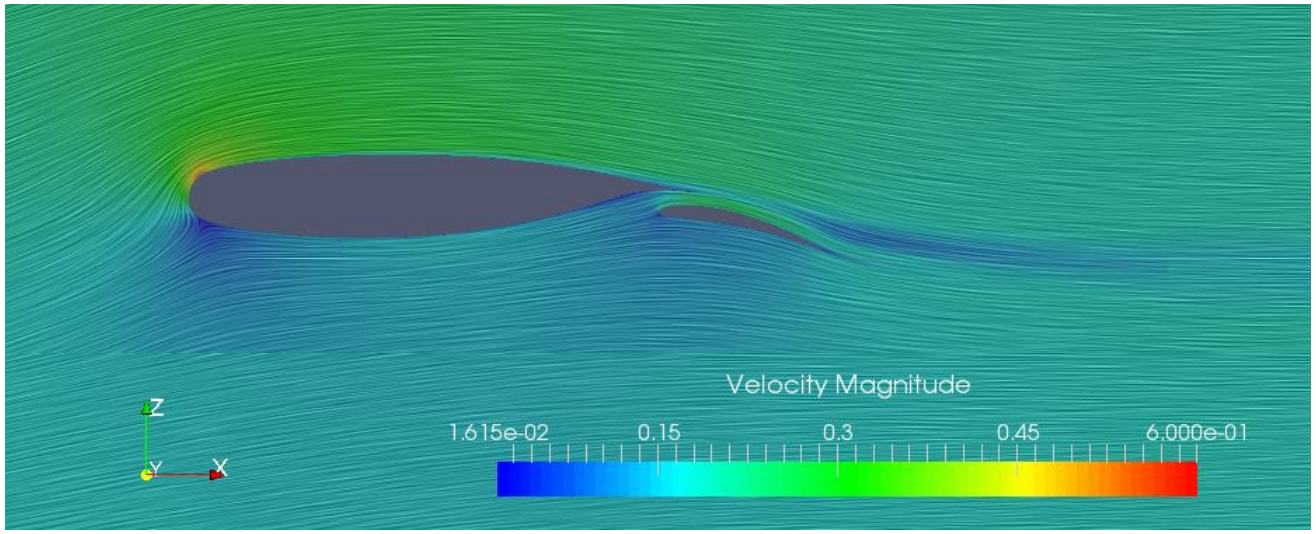
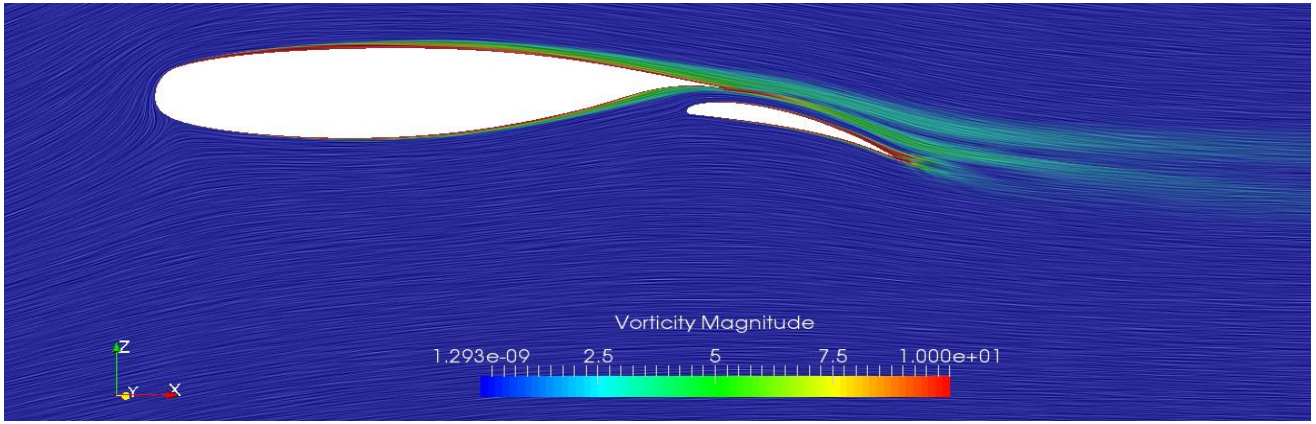
Volume Grid Sensitivity

α=6°, Re = 2.51E6, and Ma = 0.185





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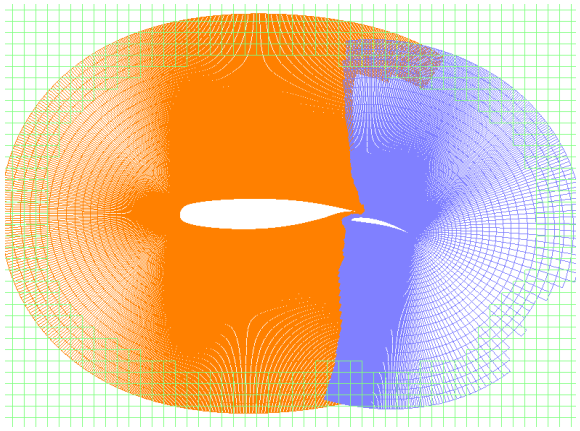
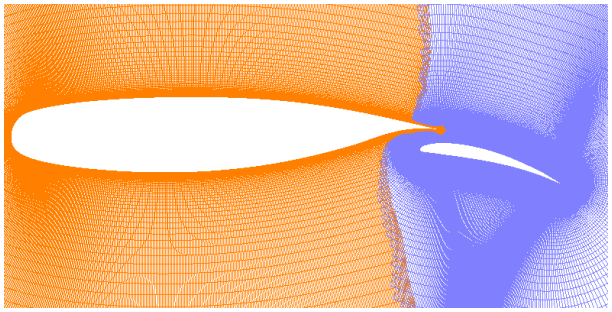
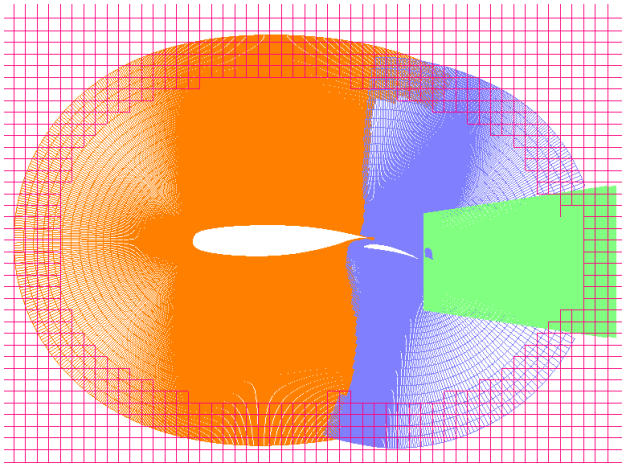


Lift improves :
0.14% < 0.4% exp_accuracy
Drag improves:
1.48% < 2.0% exp_accuracy

Flap grid refinement to capture the shear layer leaving the main element TE



Wake grid addition to capture flap element TE wake



	C_l	C_d
Baseline	2.4321	0.0270
Grid refinement for shear layer	2.4371	0.0267
Wake layer grid addition	2.4325	0.0268
Both grid addition	2.4356	0.0266
Experimental	2.42	0.0229

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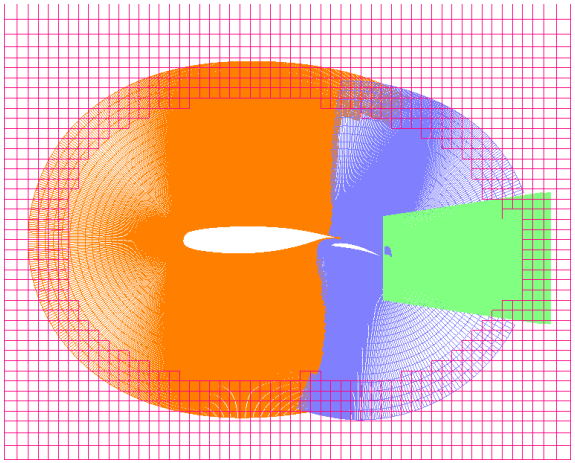
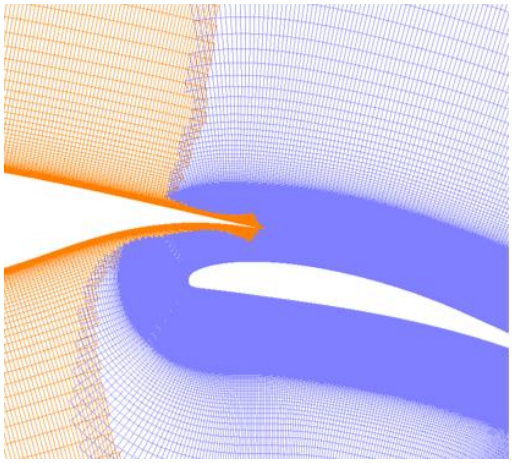
Grid Connectivity Study

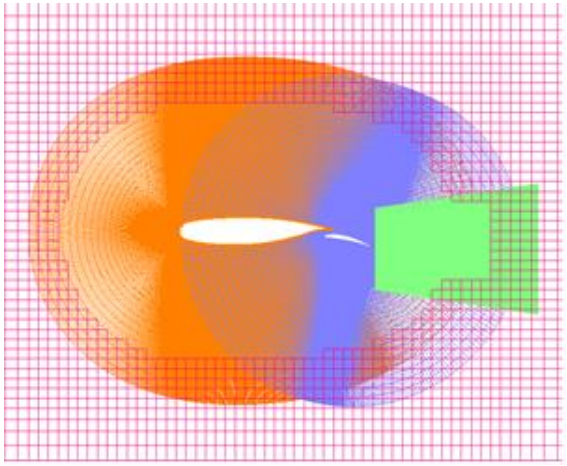
- PEGASUS: Outside of OVERFLOW

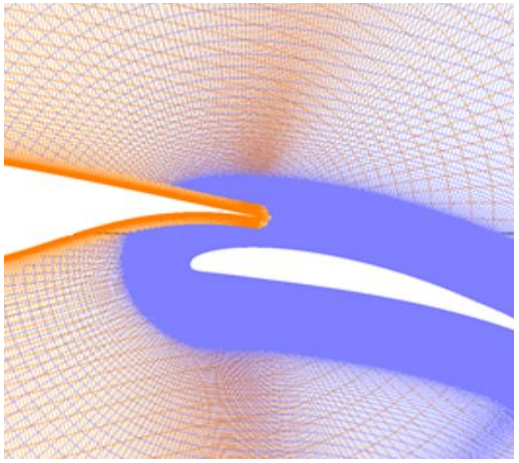
α=6°, Re = 2.51E6, and Ma = 0.185





- Domain Connectivity Function (DCF): Built-in in OVERFLOW





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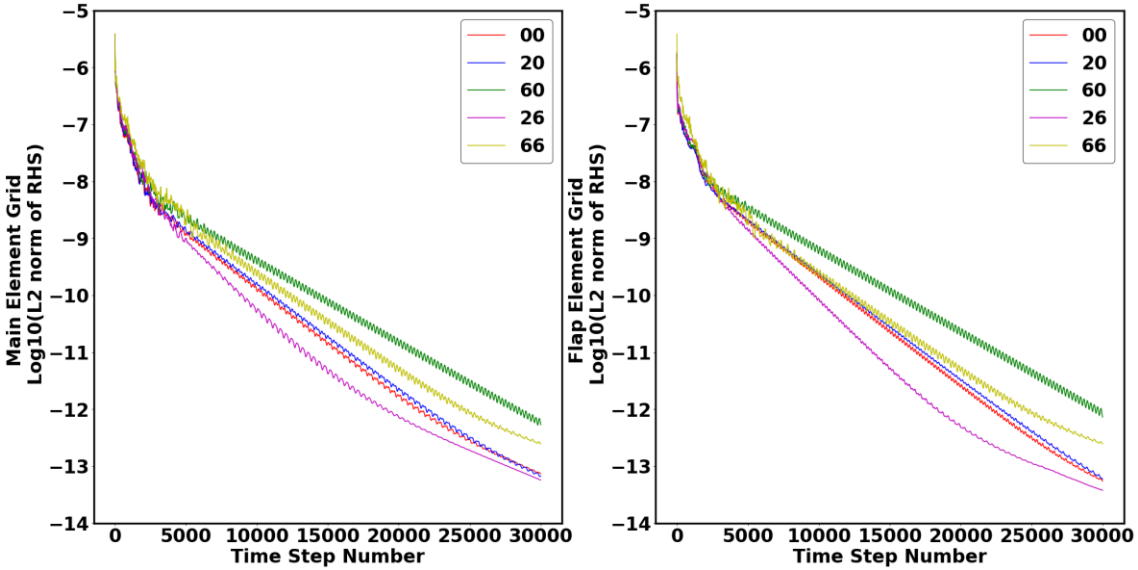
Solver Study

α=6°, Re_c = 2.51E6 and Ma = 0.185, Steady State

	LHS	RHS	Clock Time[min]	C_l	ΔC_l% error	C_d	ΔC_d% error
00	ARC3D approx. factor.	Central diff.	27.30	2.4159	0.16%	0.0284	24.0%
20	ARC3D diag. approx. factor.	Central diff.	16.38	2.4159	0.16%	0.0284	24.0%
60	SSOR	Central diff.	39.11	2.4159	0.16%	0.0284	24.0%
26	ARC3D diag. approx. factor.	HLLE++ upwind	23.21	2.4276	0.31%	0.0286	24.9%
66	SSOR	HLLE++ upwind	42.14	2.4276	0.31%	0.0286	24.9%

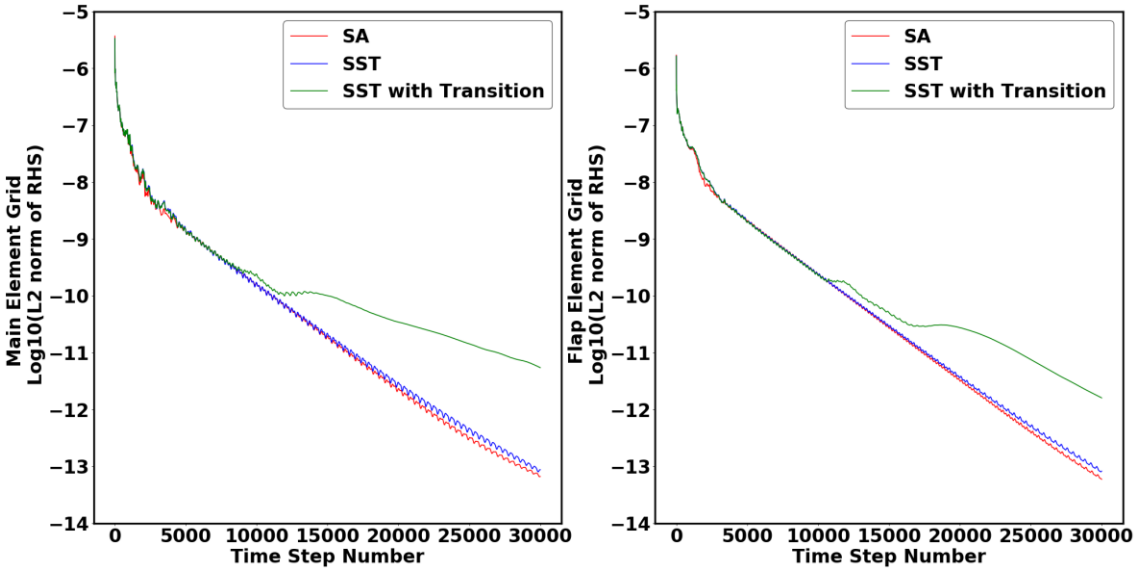


Turbulent Model Study

α=6°, Re_c = 2.51E6 and Ma = 0.185, Steady State

Experiment accuracy: Cl: ±0.4% Cd: ±2.0%

Turbulence Model	Clock Time[min]	C_l	ΔC_l% error	C_d	ΔC_d% error
SA	16.38	2.4159	0.16%	0.0284	24.0%
SST	32.08	2.3946	1.05%	0.0301	31.4%
SST with Langtry-Menter transition	52.35	2.4609	1.69%	0.0260	13.5%

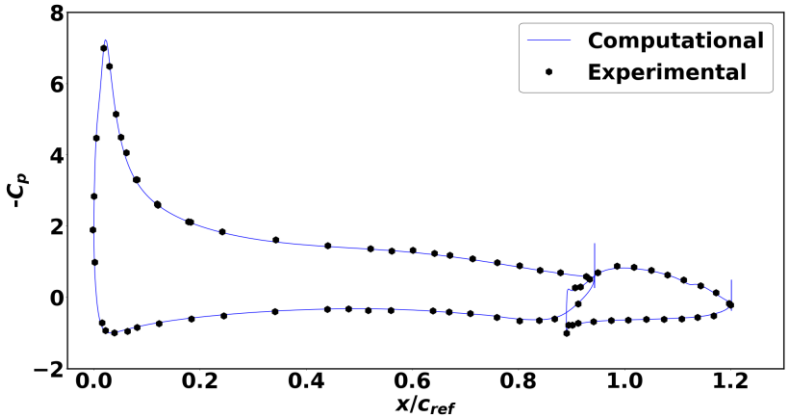


Future studies will implement SST with transition

2-D CFD Setup Summary

- Extensive CFD sensitivity study (solver, grid) conducted in 2018
- Overset grid technology
  - O-grid topology growing 50c away
  - DCF mesh connectivity
- RANS OVERFLOW 2
  - 4th order central difference and ARC3D diagonalized approximate factorization with matrix artificial dissipation
  - SST turbulence model

ΔCd discrepancy transition related
CFD – fully turbulent
Exp – transition free



Flap 20˚

Clock Time[min] on 48 Haswell Processors	C_l	ΔC_l% w/t resp. exp.	C_d	ΔC_d% w/t resp. exp.
32.08	2.3946	1.05%	0.0301	31.4%

More details can be found at: Hosseini, S. S., van Dam, C. P., and Pandya, S. A., "Computational investigation of nominally-orthogonal pneumatic active flow control for high-lift systems," 2018 AIAA Aerospace Sciences Meeting, AIAA Paper2018-0559, Kissimmee, Florida, 2018. doi:10.2514/6.2018-0559.

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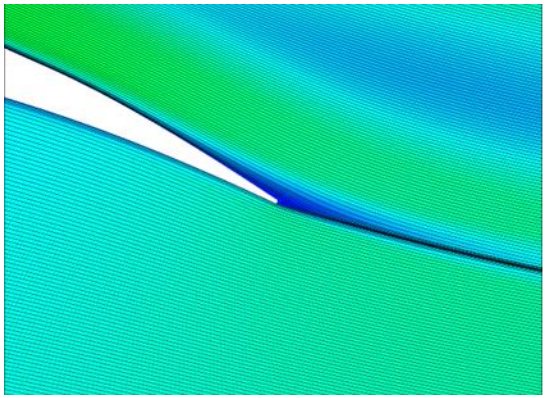
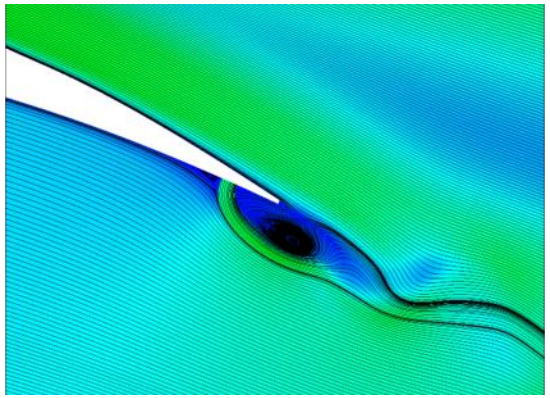
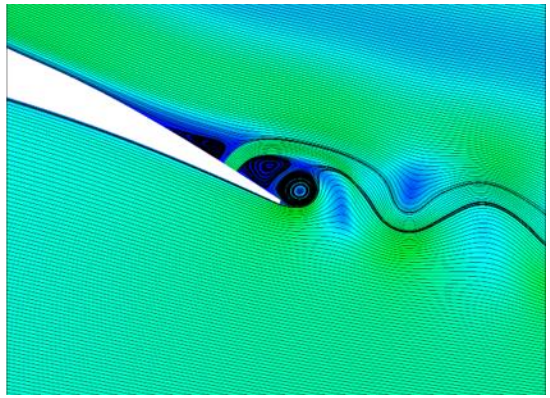


Baseline (no jet)



Baseline + lower surface jet

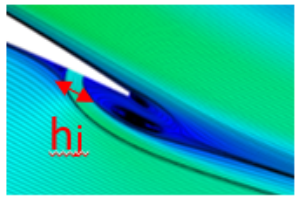


Baseline + upper surface jet

Microjet Momentum Coefficient

α=6°, Re = 2.51E6, and Ma = 0.185

$$C\mu = \frac{\dot{m}_j U_j}{\frac{1}{2}\rho_\infty U_\infty^2 S_{ref}} \xrightarrow{\dot{m}_j = (\rho U A)_j} C\mu = \frac{\rho_j U_j^2 h_j b}{\frac{1}{2}\rho_\infty U_\infty^2 b\, c} \xrightarrow{Incompressible} C\mu = 2\frac{U_j^2}{U_\infty^2}\frac{h_j}{c}$$



C_μ range: 0.0004-0.04 corresponding to $\frac{U_j}{U_\infty}$: 0.2-2.0 for the jet exit $h_j = 0.005 c_{ref}$

- $C_\mu < 0.01$ Steady state simulations provide results within a few percentage of the time-accurate simulations
- $C_\mu \geq 0.01$ required time-accurate simulations
- For consistency all studies are done time-accurate

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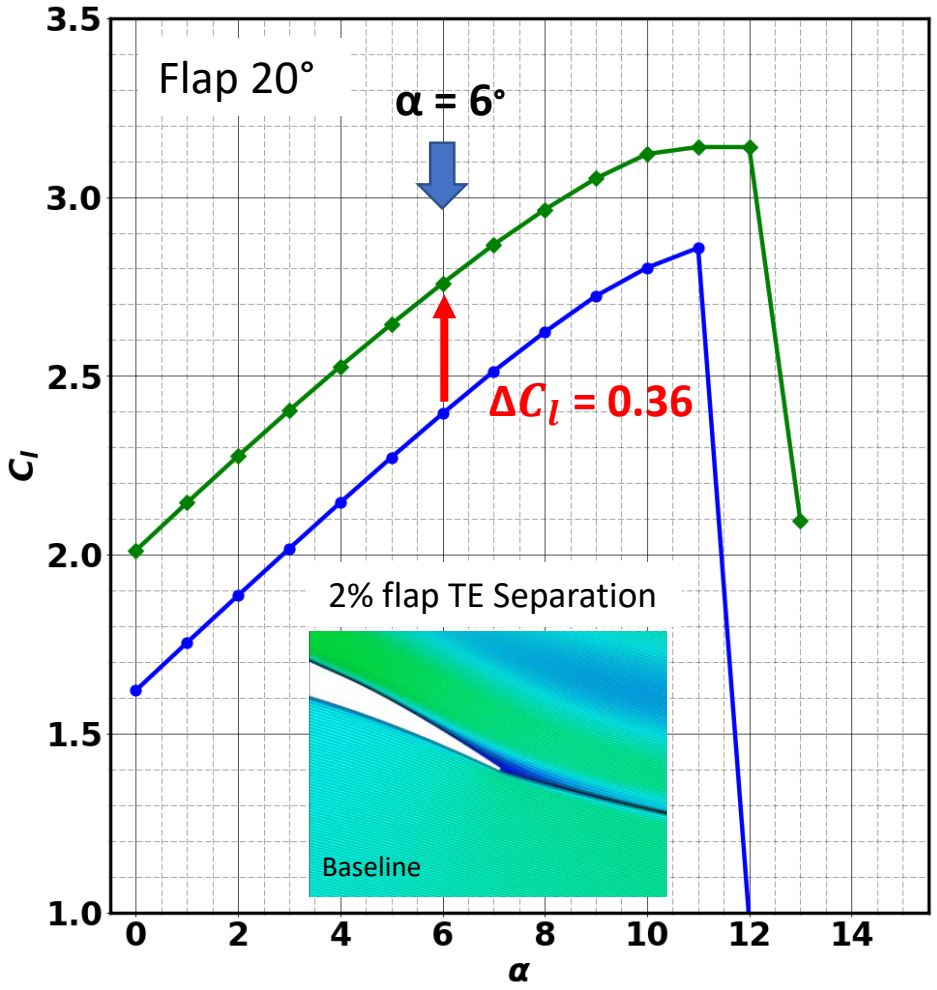
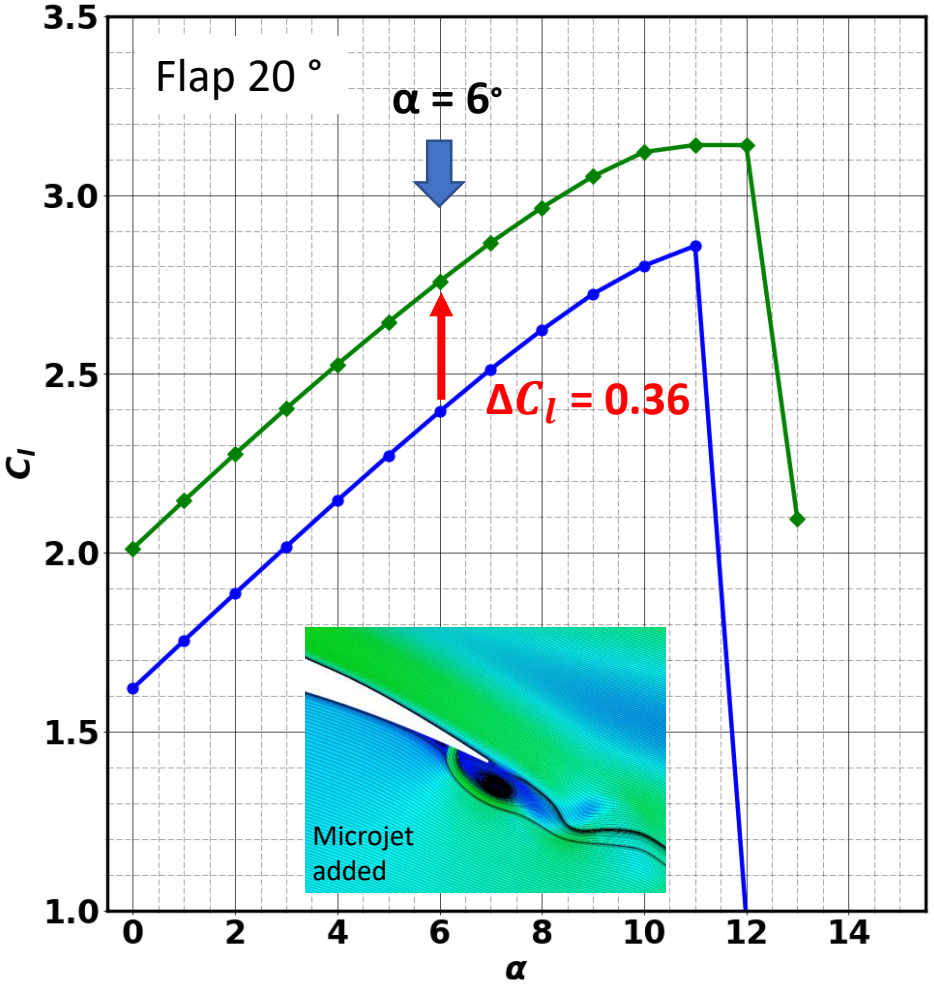
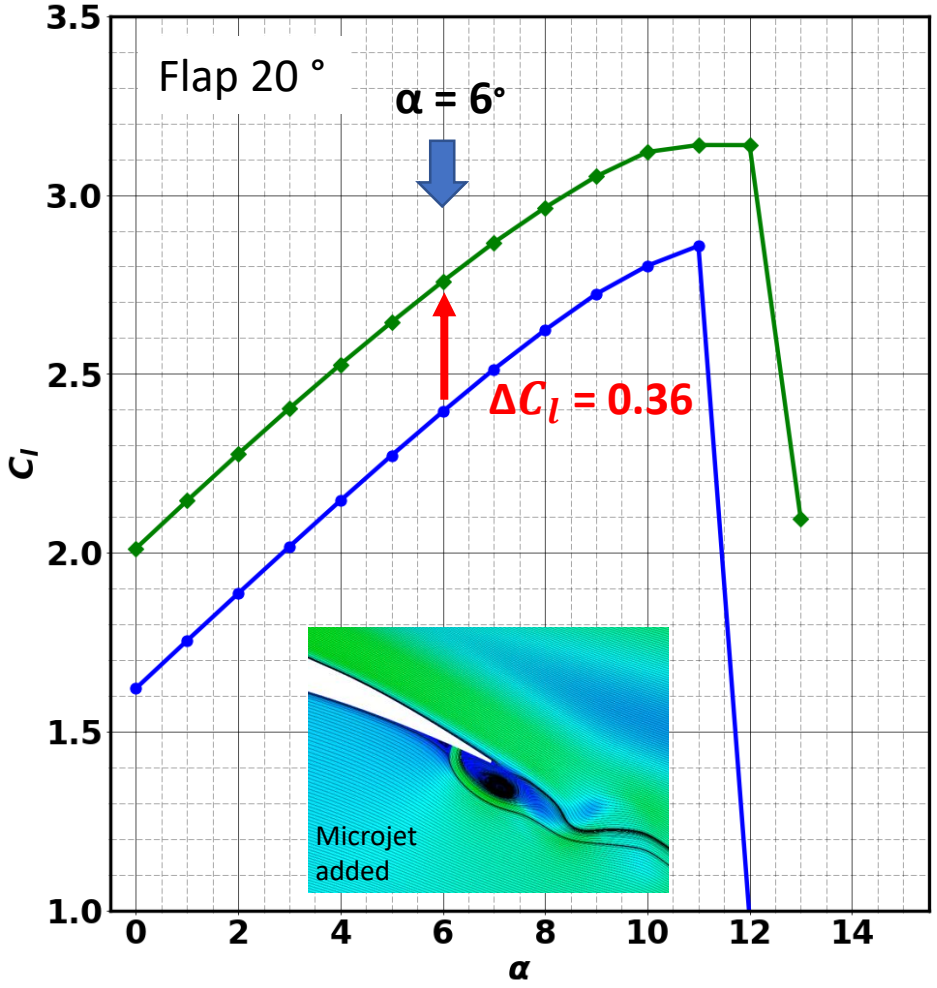
Microjet Lift Enhancement

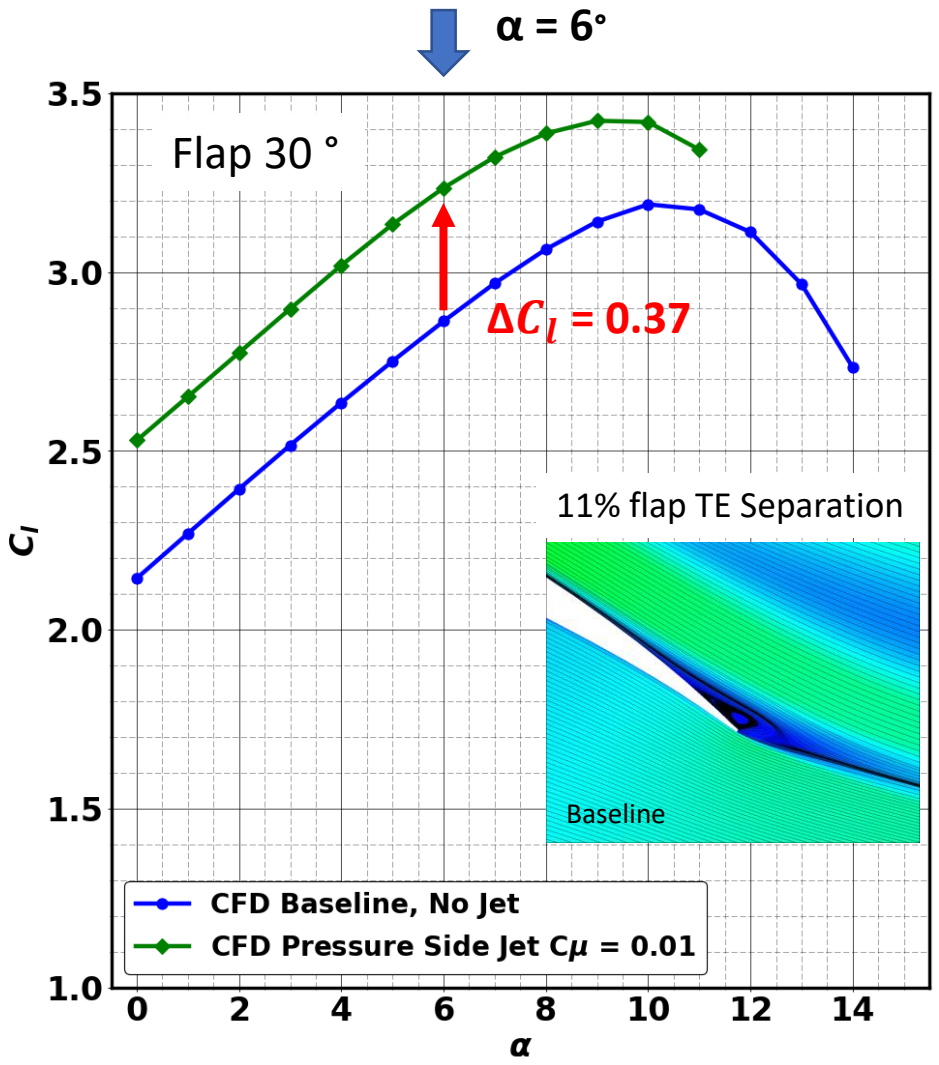


Microjet Lift Enhancement

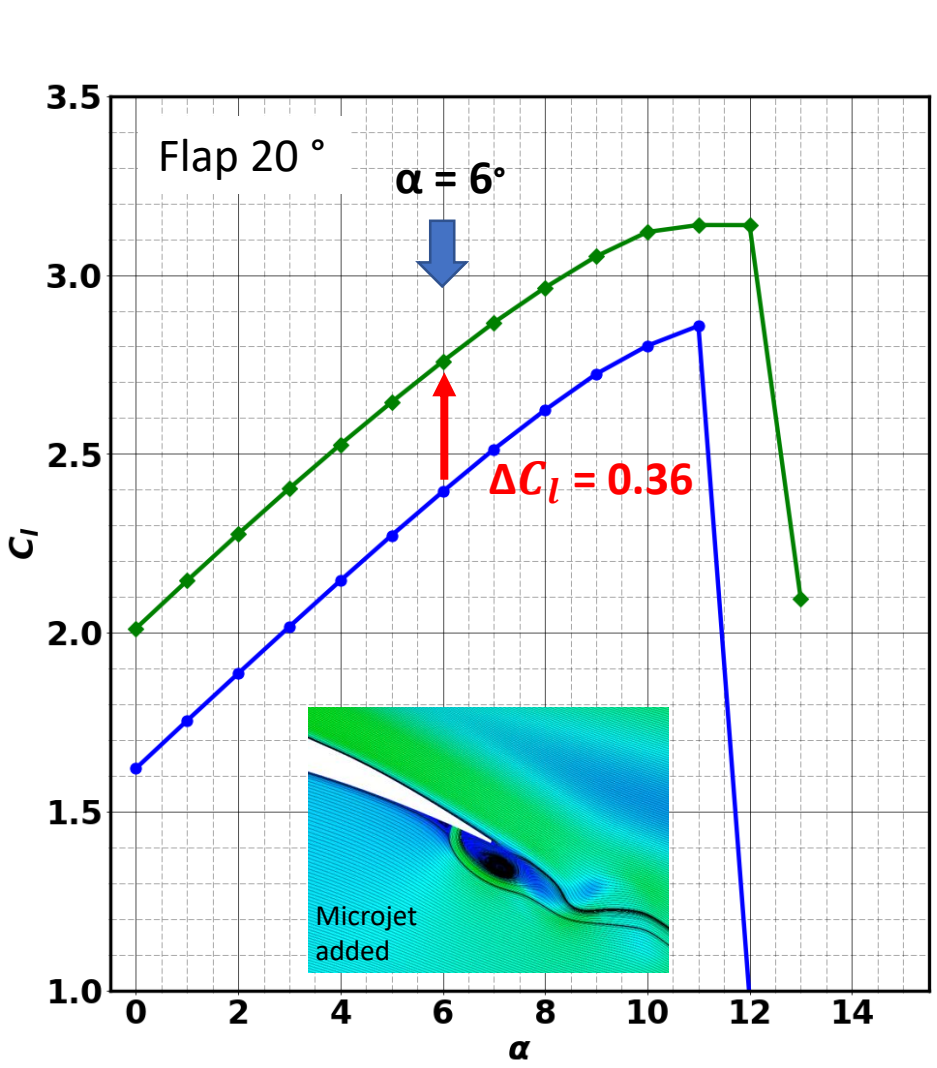


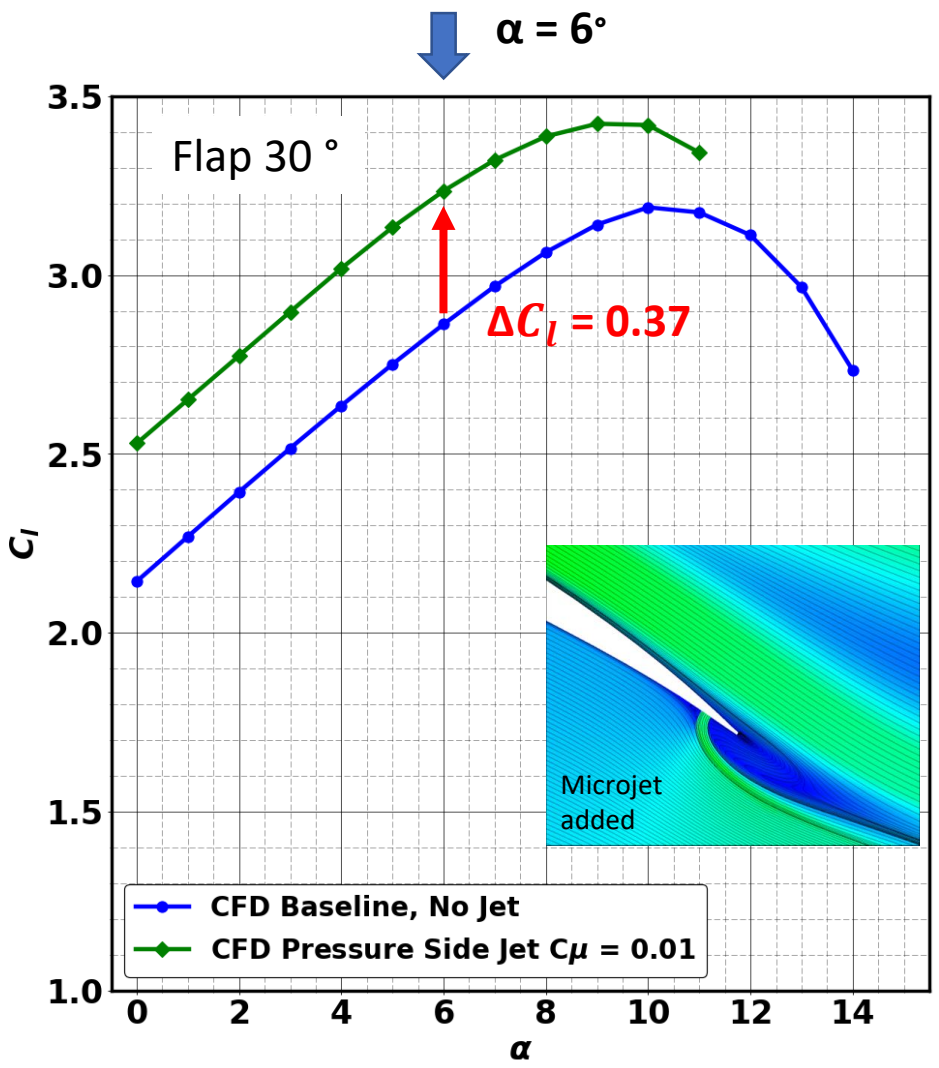
Microjet Lift Enhancement



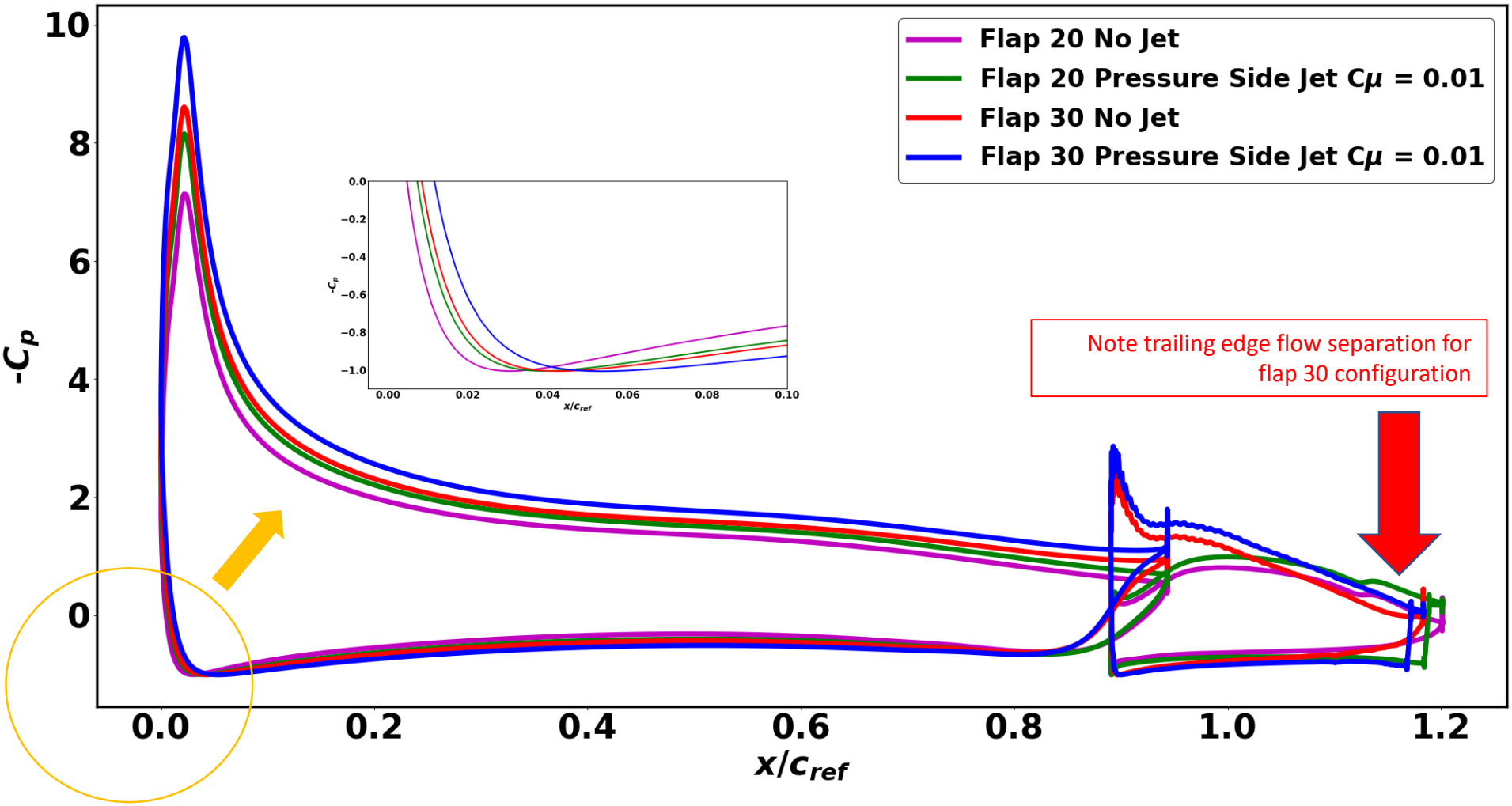


Microjet Lift Enhancement



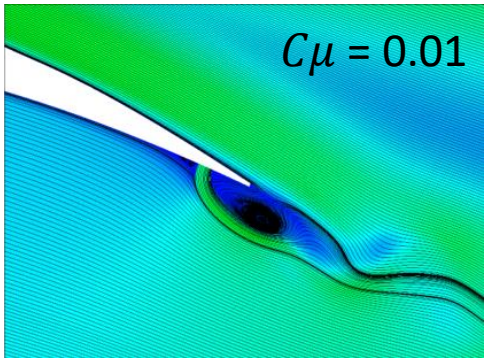


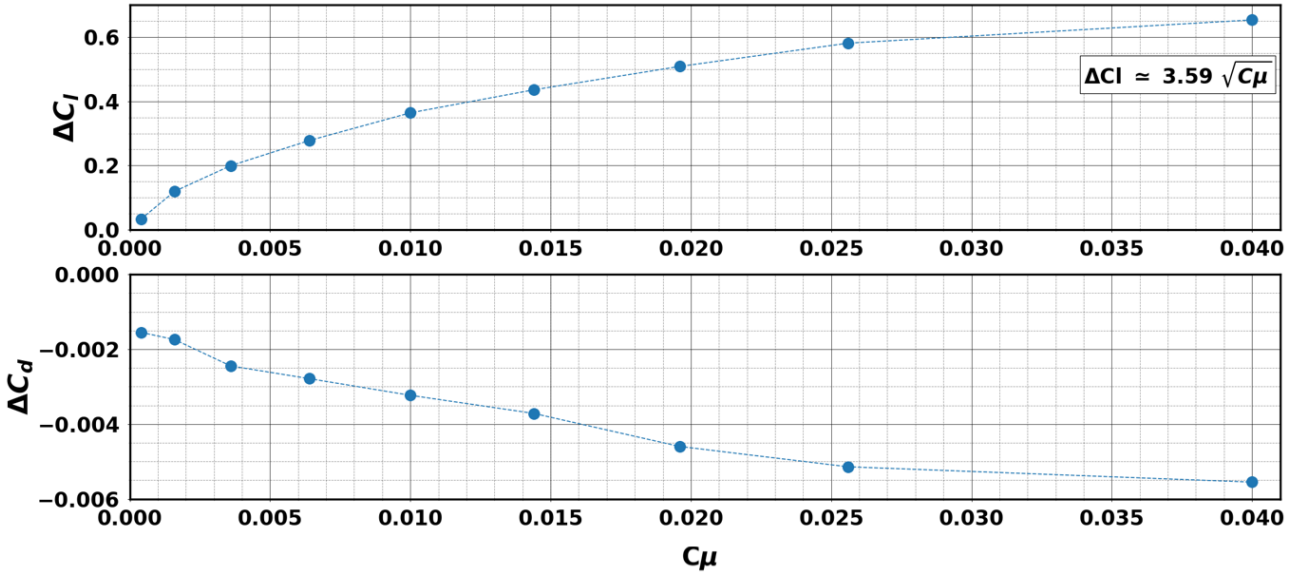
α=6°, Re = 2.51E6, Ma = 0.185



α=6°, Re = 2.51E6, Ma = 0.185

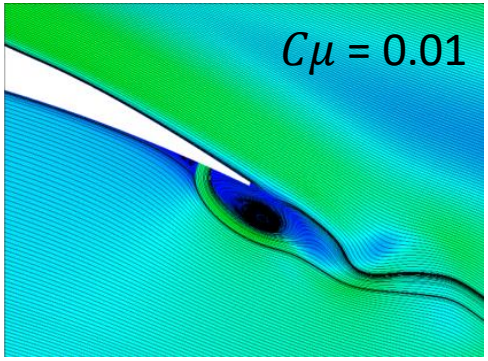
Flap 20˚

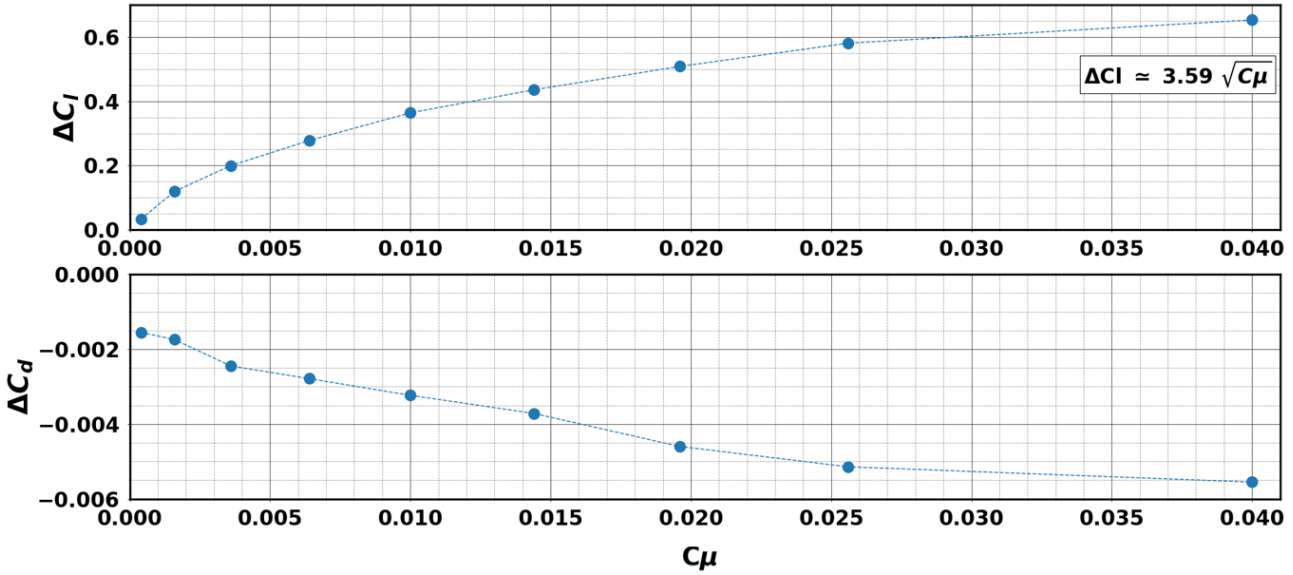




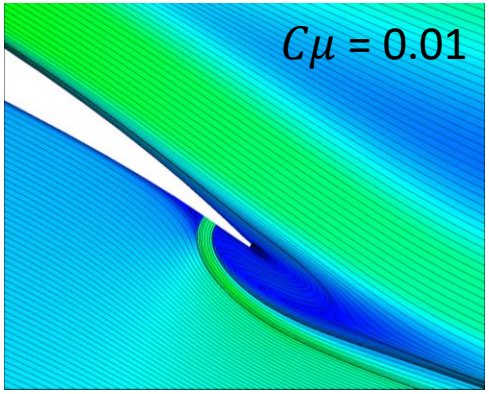
α=6°, Re = 2.51E6, Ma = 0.185

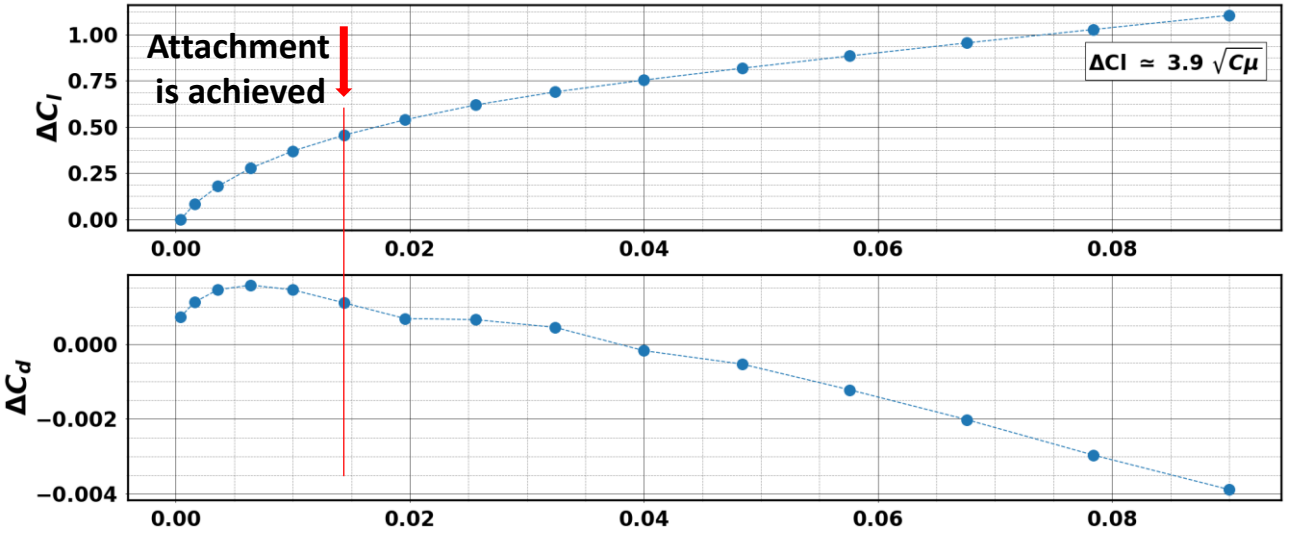
Flap 20°





Flap 30°

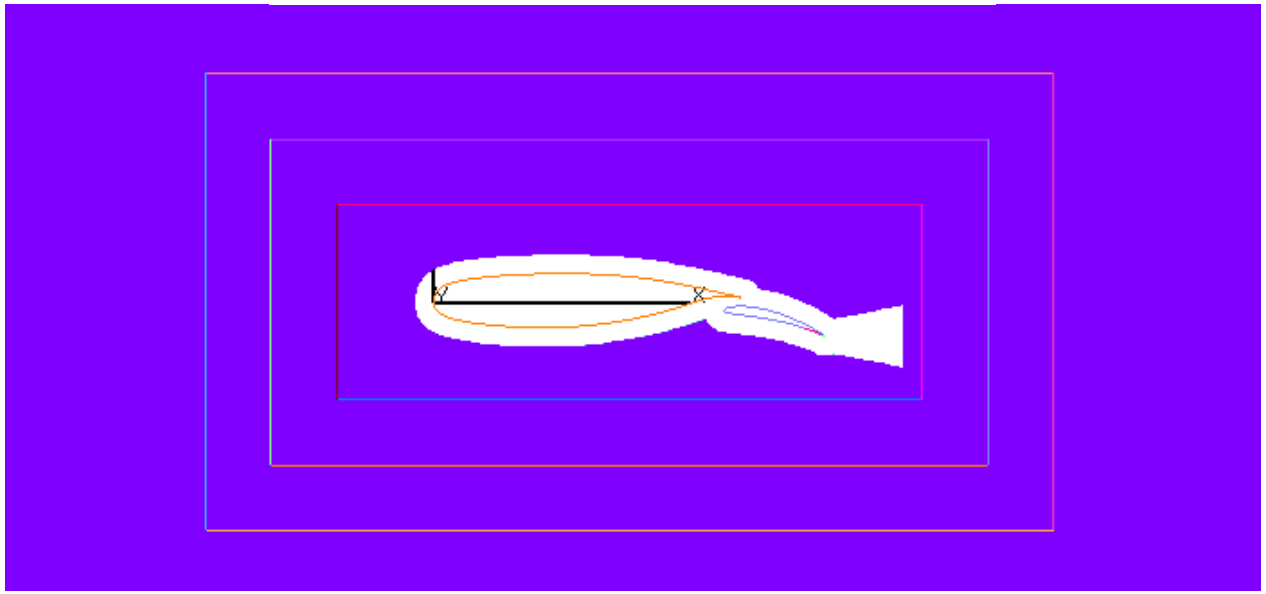




Verification

α=0°, Re = 2.51E6, and Ma = 0.185

Case	Integration at	C_l	C_d
Pressure side jet	surface	2.011	0.01550
Pressure side jet	0.3c far-field	2.011	0.01551
Pressure side jet	0.5c far-field	2.011	0.01551
Pressure side jet	0.7c far-field	2.011	0.01551



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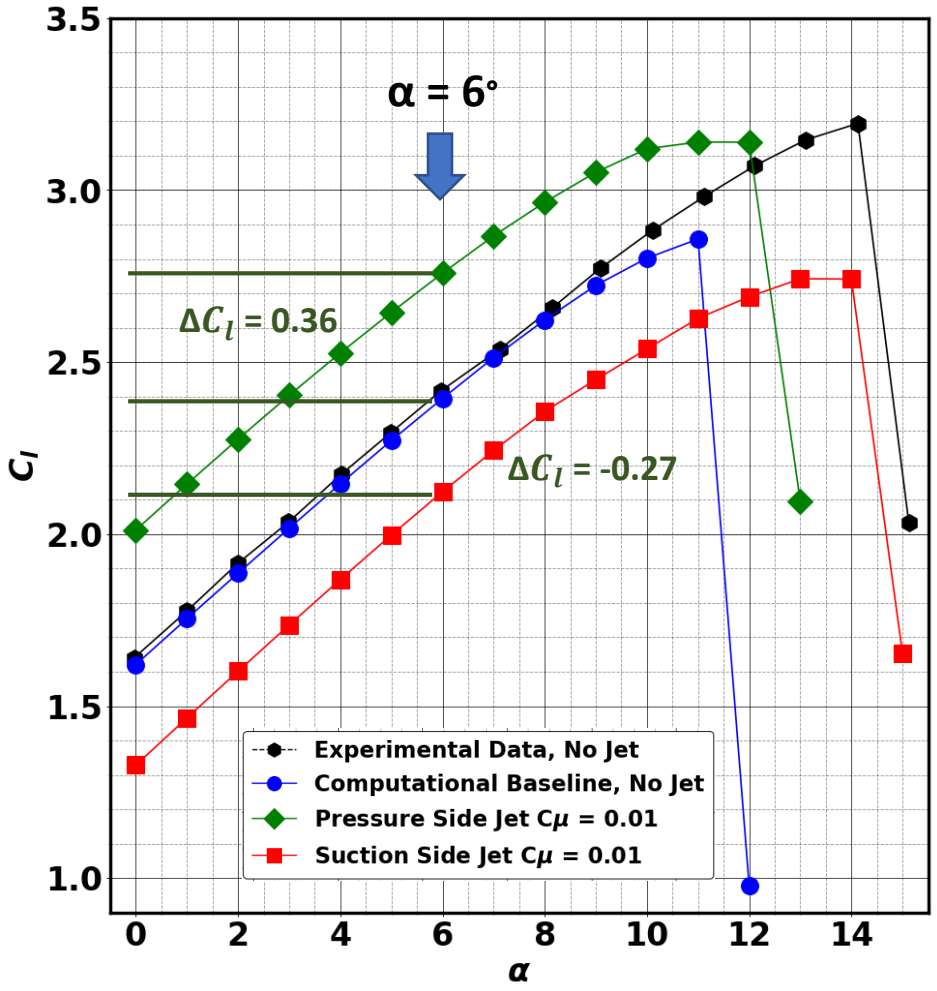
Flap 20˚: Effects on Lift



α=6°, Re = 2.51E6, Ma = 0.185, $C\mu$ = 0.01

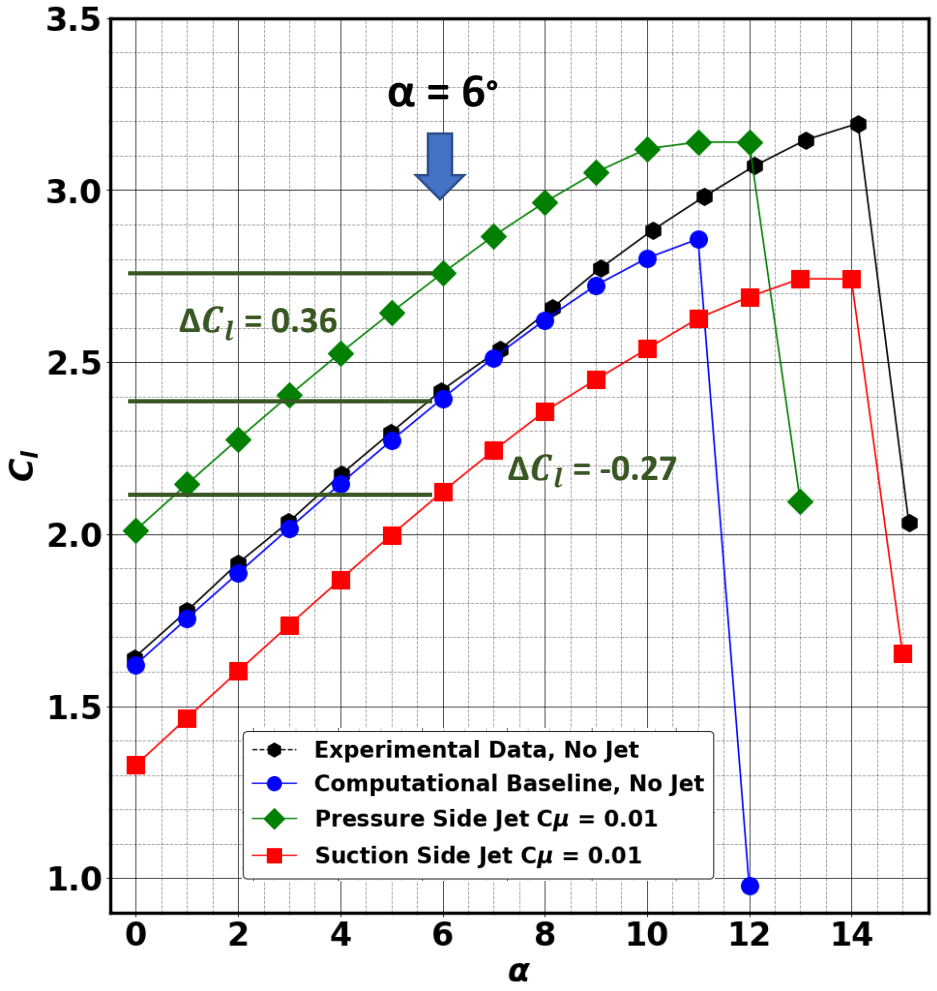
Lift due to Pressure is 2 orders of magnitude higher than due to added momentum

C_l at α=6°	Baseline No jet	Pressure side jet	Suction side jet
Pressure	2.39414	2.75046	2.13282
Viscous	0.00048	0.00076	0.00038
Momentum	0	0.00839	-0.00760
Total	2.39466	2.75961	2.12260

$$\boldsymbol{F} = \int (-P\delta_{ij} + \tau_{ij})\, n_j\, dA + \int \rho u_i u_j\, n_j dA$$

$$L = -F_x sin\alpha + F_z cos\alpha$$

Flap 20˚: Effects on Lift



α=6°, Re = 2.51E6, Ma = 0.185, $C\mu$ = 0.01

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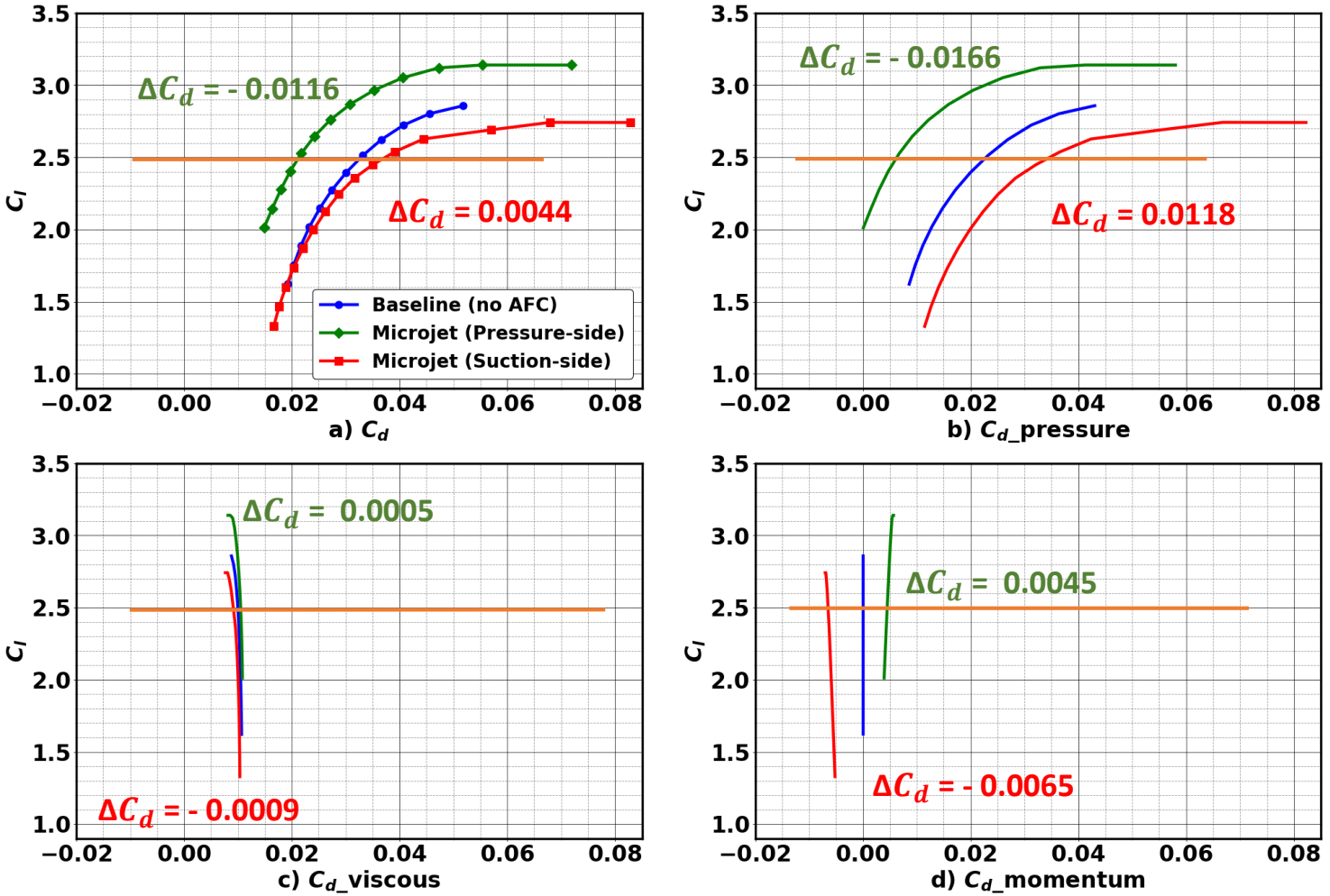
Flap 20˚: Drag Decomposition

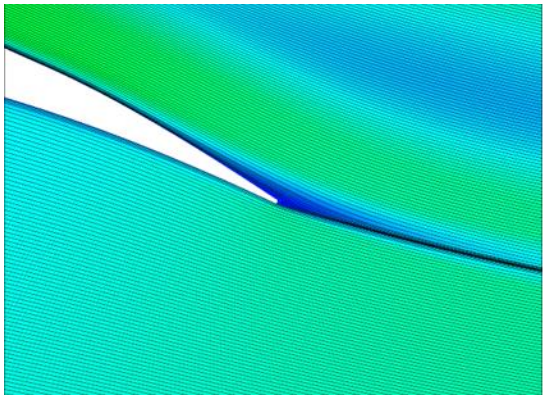
α=6˚, Re = 2.51E6, Ma = 0.185, $C\mu$ = 0.01

$$\boldsymbol{F} = \int (-P\delta_{ij} + \tau_{ij})\, n_j\, dA + \int \rho u_i u_j\, n_j dA \quad \Rightarrow \quad D = F_x cos\alpha + F_z sin\alpha$$

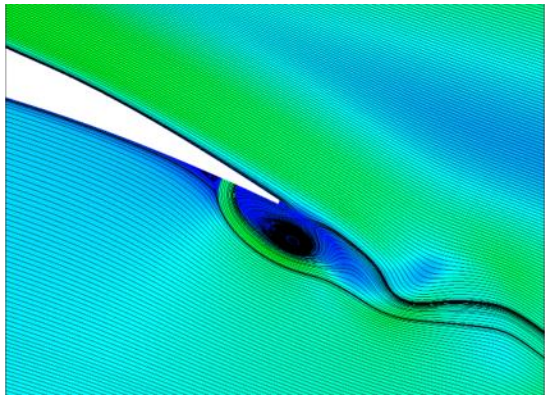


Outline

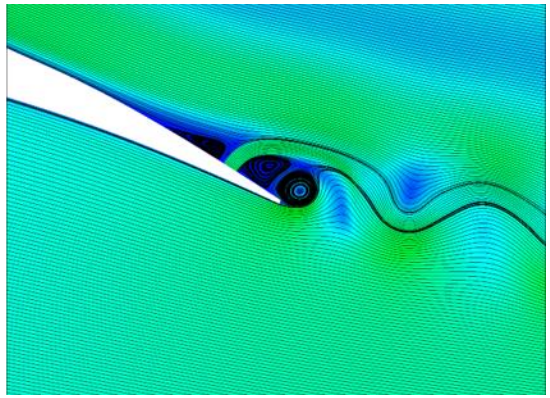
- Overview
- Computational setup on baseline multi-element airfoil NLR7301
  - Various grid sensitivities
- Investigation of flap microjet on NLR7301
  - Sensitivities of lift and drag to microjet settings
  - Microjet definition sensitivity
- Summary and Conclusions



Baseline (no jet)



Baseline + lower surface jet



Baseline + upper surface jet

What velocity profile is appropriate?

- We want to see the effects of developed flow profile on the overall flow field
- What is the Re#

Turbulent velocity profile: U = $U_{max}[1-\frac{r}{R}]^{1/n}$ $n = -1.7 + 1.8\log Re$

Laminar velocity profile: U = U_{max} [1-$(\frac{r}{R})^2$]

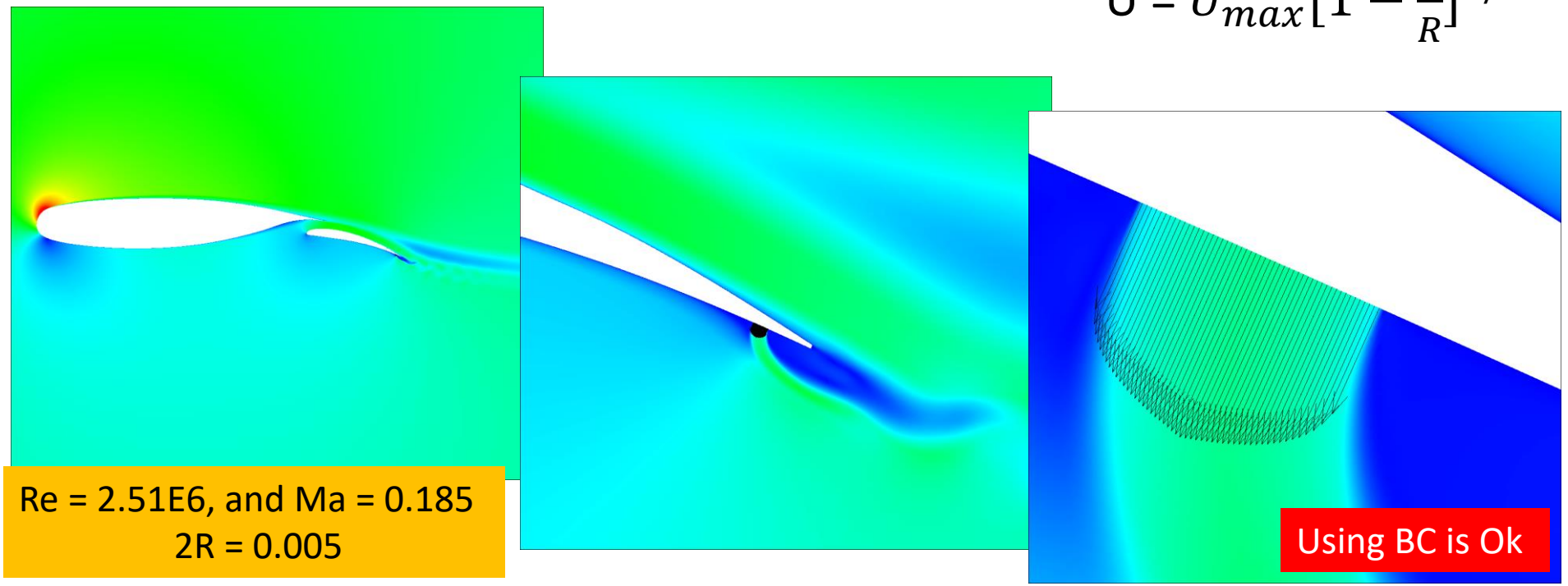
$$Re = \frac{ul}{\nu} = \frac{0.185*320.24*0.005}{1.81E-5} \approx 16{,}366$$ turbulent flow

n = 6

Effect of BC Velocity Profile: Turbulent n = 6

Flap 20˚	Cl	diff%	Cd	diff%
No jet	2.3946		0.0301	
Overflow BC (uniform), Cμ = 0.01	2.7586		0.0271	
Turbulent velocity profile, Umax = 1.18, Cμ = 0.0103	2.7557	**0.1%**	0.0276	**1.8%**

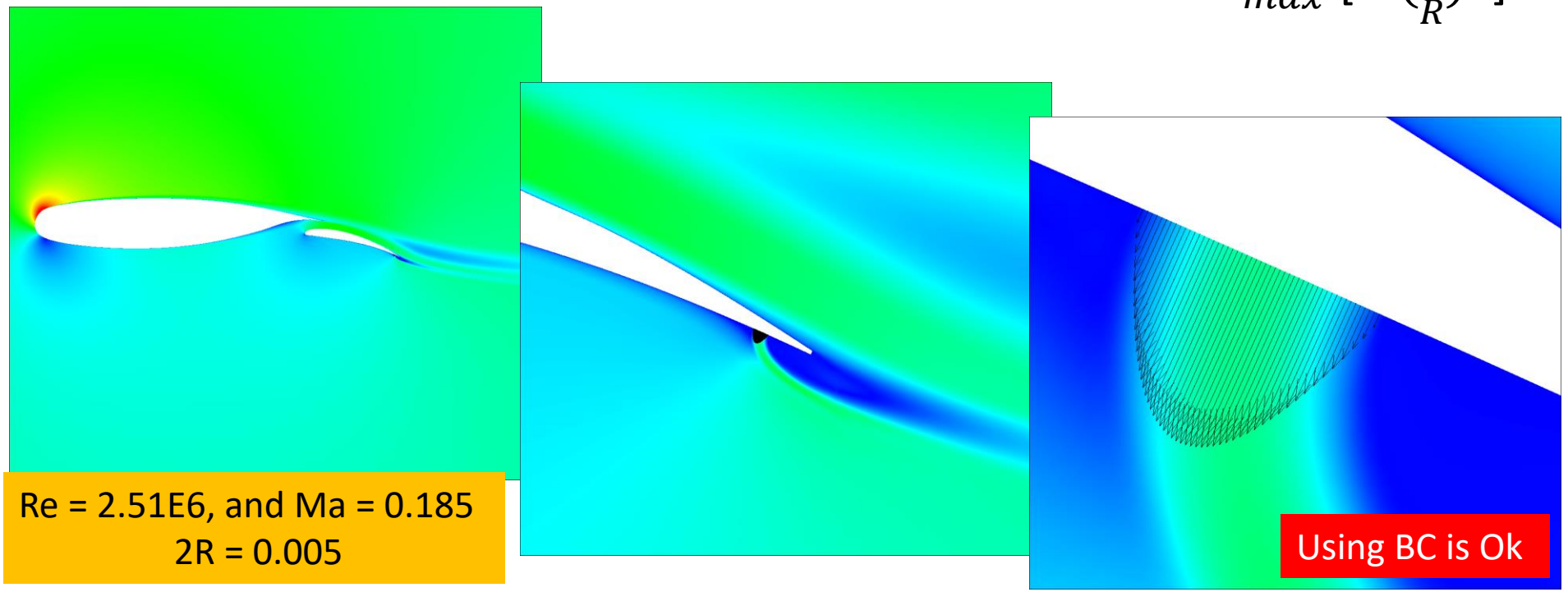
$$U = U_{max}\left[1 - \frac{r}{R}\right]^{1/n}$$



Effect of BC Velocity Profile: Laminar

Flap 20˚	Cl	diff%	Cd	diff%
No jet	2.3946		0.0301	
Overflow BC (uniform), Cμ = 0.01	2.7586		0.0271	
Laminar velocity profile, Umax = 1.36, Cμ = 0.00983	2.74278	**0.57%**	0.02733	**0.85%**

$$U = U_{max}\left[1-\left(\frac{r}{R}\right)^2\right]$$



Re = 2.51E6, and Ma = 0.185
2R = 0.005

Using BC is Ok

Outline

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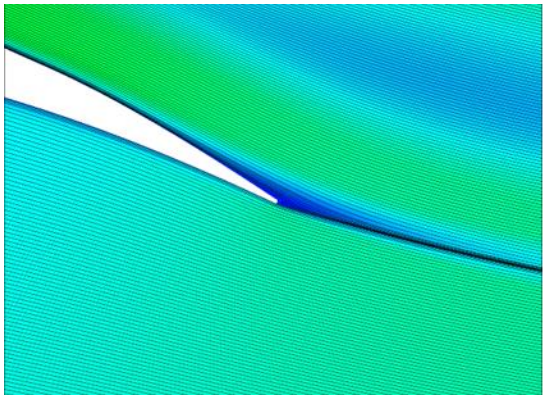
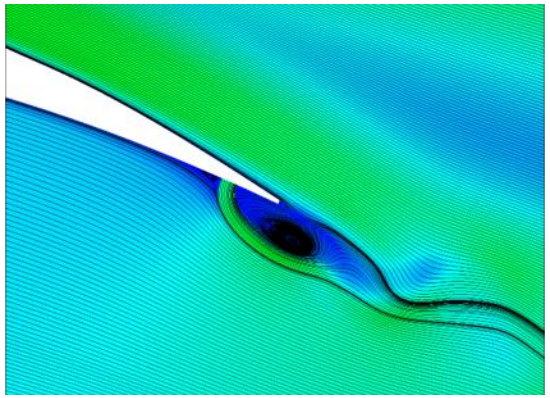
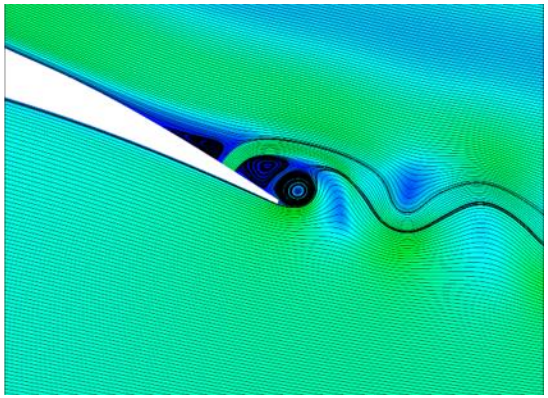

Summary and Next Steps

- CFD study to explore subsonic nominally-orthogonal jet as an active aerodynamic load control
  - Ability to enhance lift and reduce drag on geometries with and without trailing edge separation
    - lift in the linear region, maximum lift coefficient, and lift-to-drag ratio
  - Ability to mitigate separation on flaps with trailing edge separation
  - modeling microjet as a uniform boundary condition is sufficient. BC jet velocity profile is shown to have small effect on the overall microjet effect
- Future Work
  - 2D Jet characteristic sensitives (location, width, physical plenum vs. BC, and steady vs. pulsed)
  - 2+D studies to study the effects in the presence of cross flow
  - 3D, studies on a relative geometry (CRM)