Computational Investigation of Nominally-Orthogonal Pneumatic Active Flow Control for Aircraft High-Lift Systems

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January 9, 2018
Motivation

Active Flow Control for high-lift systems

- $C_{L_{\text{max}}}$
- L/D
- Lift in the linear region
Active Flow Control (AFC)

Separation Mitigation

Load Control

Kral 1998
Johnson et al. 2008
Vertical tabs (Gurney flaps) can increase L/D
- Geometric tabs increase loads (flap weight)
- Tabs require physical space
- Tabs are not necessarily continuous
- Quick movement of tab is desirable – AFC allows rapid activation

Storms and Ross, 1995
Johnson et al. 2010
AFC Load Control, Previous Work

• No mechanical tabs, instead small jets normal to the surface
• Steady-blowing microjets: TE flow control similar to microtabs
• Experimental studies on a single-element S819 airfoil suggest a significant lift enhancement for relatively low momentum coefficient values and relative velocities, $U_{jet}/U_\infty = 0.5 – 1.0$

Lift coefficient versus angle of attack for jets at $\text{Re} = 1.0E6$ with varying $C\mu$

Lift coefficient versus angle of attack for jets at $\text{Re} = 1.0E6$ with varying $C\mu$

$U_{jet}/U_\infty = 0.7$
Outline

• Computational setup prior to microjet activation
  – Various grid and solver sensitivities

• Investigation of flap microjet up to date
  – Microjet vs. Microtab
  – Sensitivities of lift and drag to microjet settings

• Future work and anticipated timeline
Airfoil Definition

- NLR7301: flap chord is 32%c_{ref}
  - Flap deflection 20°, overlap 0.053c, gap 0.026c
  - 2-dimentional $\alpha = 6^\circ$, $Re = 2.51E6$, and $M = 0.185$

Vandenberg and Oskam 1980
2-Dimensional Computational Setup

- Overset grid technology
  - O-grid topology growing 50c away
  - DCF mesh connectivity
- RANS OVERFLOW 2
  - 4\textsuperscript{th} order central difference and ARC3D diagonalized approximate factorization with matrix artificial dissipation
- SST turbulence model

<table>
<thead>
<tr>
<th>Clock Time [min] on 48 Haswell Processors</th>
<th>$C_l$</th>
<th>$\Delta C_l$% error</th>
<th>$C_d$</th>
<th>$\Delta C_d$% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.08</td>
<td>2.3946</td>
<td>1.05%</td>
<td>0.0301</td>
<td>31.4%</td>
</tr>
</tbody>
</table>
Microjet vs. Microtab Study

$\alpha = 6^\circ$, $Re = 2.51E6$, and $Ma = 0.185$, Steady State

- Literature suggested 1%c in height and 0.2%c thickness tabs at 95%c
- How to model the jet?
  - Modeled as a simple jet mass flow condition at the surface
    - Suggested by: the flow control workshop held in 2004, the Blaylock dissertation
- Boundary condition $U_j/U_\infty$ at flap TE was employed:

\[
C\mu = \frac{\dot{m}_j U_j}{\frac{1}{2} \rho_\infty U_\infty^2 S_{ref}} \quad \dot{m}_j = (\rho U A)_j \\
C\mu = \frac{\rho_j U_j^2 h_j b}{\frac{1}{2} \rho_\infty U_\infty^2 b c} \quad Incompressible \\
C\mu = 2 \frac{U_j^2}{U_\infty^2} h_j
\]
Microjet vs. Microtab Study

$\alpha = 6^\circ$, $Re = 2.51 \times 10^6$, and $Ma = 0.185$, Steady State

<table>
<thead>
<tr>
<th></th>
<th>$C_l$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (no AFC)</td>
<td>2.395</td>
<td></td>
</tr>
<tr>
<td>Microtab</td>
<td></td>
<td>2.626</td>
</tr>
<tr>
<td>Microjet</td>
<td></td>
<td>2.627</td>
</tr>
</tbody>
</table>

$C\mu = 0.004$

Mach Number: 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
Microjet vs. Microtab Study

$\alpha = 6^\circ$, $Re = 2.51E6$, and $Ma = 0.185$, Steady State

<table>
<thead>
<tr>
<th></th>
<th>$C_l$</th>
<th>$C_d$</th>
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</thead>
<tbody>
<tr>
<td>Baseline (no AFC)</td>
<td>2.395</td>
<td>0.0301</td>
</tr>
<tr>
<td>Microtab</td>
<td>2.626</td>
<td>0.0358</td>
</tr>
<tr>
<td>Microjet</td>
<td>2.627</td>
<td>0.0284</td>
</tr>
</tbody>
</table>

$C\mu = 0.004$

Mach Number: 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
Microjet Momentum Coefficient

\[ \alpha = 6^\circ, \text{ Re } = 2.51 \times 10^6, \text{ and } \text{ Ma } = 0.185 \]

- \( C_\mu \) range: 0.0004-0.04 for the jet exit \( h_j = 0.005 \)
  - \( C_\mu < 0.01 \) converged with steady state simulations
  - \( C_\mu \geq 0.01 \) required time-accurate simulations

Steps:
1. Steady state: converge the baseline airfoil (no microjet)
2. Steady state: turn on the microjet
3. If not converged, run time-accurate
Convergence Study

$\alpha = 6^\circ$, $Re = 2.51E6$, and $Ma = 0.185$, $C_\mu = 0.04$
Convergence Study

$\alpha=6^\circ$, $Re = 2.51E6$, and $Ma = 0.185$, $C_{\mu} = 0.04$
Flow Visualization

\( \alpha = 6^\circ, \text{Re} = 2.51 \times 10^6, \text{Ma} = 0.185, C_\mu = 0.04 \)

- **Baseline (no jet)**
  - Steady

- **\( C_\mu = 0.01 \)**
  - Unsteady, \( St = 0.072 \)

- **\( C_\mu = 0.04 \)**
  - Unsteady, \( St = 0.103 \)
Momentum Coefficient Sensitivity

\( \alpha = 6^\circ, \ Re = 2.51 \times 10^6, \text{ and } Ma = 0.185 \)

\[ \Delta C_l \approx 3.59 \sqrt{C_{\mu}} \]
Symmetric airfoil

\[ \Delta C_L = 3.9 \frac{C_\mu}{\sin \theta} \cdot \sin \theta \]

Malavard 1956.
Symmetric airfoil

Malavard 1956.
Spot Checks: Literature

Symmetric t/c = 18% airfoil

NACA 0018 airfoil

Leopold and Krothapalli 1983
Blaylock 2012
### Drag Validation

$\alpha = 0^\circ$, $Re = 2.51E6$, and $Ma = 0.185$, $C_{\mu} = 0.01$

<table>
<thead>
<tr>
<th>Case</th>
<th>Integration at</th>
<th>$C_l$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (no jet)</td>
<td>surface</td>
<td>1.624</td>
<td>0.01985</td>
</tr>
<tr>
<td>Baseline (no jet)</td>
<td>0.3c far-field</td>
<td>1.624</td>
<td>0.01979</td>
</tr>
<tr>
<td>Baseline (no jet)</td>
<td>0.5c far-field</td>
<td>1.624</td>
<td>0.01978</td>
</tr>
<tr>
<td>Baseline (no jet)</td>
<td>0.7c far-field</td>
<td>1.624</td>
<td>0.01977</td>
</tr>
<tr>
<td>Pressure side jet</td>
<td>surface</td>
<td>1.979</td>
<td>0.02285</td>
</tr>
<tr>
<td>Pressure side jet</td>
<td>0.3c far-field</td>
<td>1.980</td>
<td>0.02289</td>
</tr>
<tr>
<td>Pressure side jet</td>
<td>0.5c far-field</td>
<td>1.980</td>
<td>0.02304</td>
</tr>
<tr>
<td>Pressure side jet</td>
<td>0.7c far-field</td>
<td>1.982</td>
<td>0.02318</td>
</tr>
</tbody>
</table>
Effects on Lift and Drag

Re = 2.51E6, and Ma = 0.185, $C_\mu = 0.01$

$\alpha = 6^\circ$

$\Delta C_l = 0.36$

$\Delta C_l = -0.27$
Effect on Pressure Profiles

\[ \alpha = 6^\circ, \ Re = 2.51 \times 10^6, \text{ and } \Ma = 0.185, \ C_\mu = 0.01 \]
Drag Decomposition Study

Re = 2.51E6, and Ma = 0.185, $C_\mu = 0.01$

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

![Graph showing drag decomposition study with $\Delta C_d = -0.0113$ and $\Delta C_d = 0.0041$.](image)
Drag Decomposition Study

Re = 2.51E6, and Ma = 0.185, $C_μ = 0.01$

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

\[\Delta C_d = -0.0113\]
\[\Delta C_d = 0.0041\]
Effects on Lift and Drag

Re = 2.51E6, and Ma = 0.185, $C_\mu = 0.01$

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

<table>
<thead>
<tr>
<th>$C_l$ at $\alpha=6^\circ$</th>
<th>Baseline No jet</th>
<th>Pressure side jet</th>
<th>Suction side jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>2.39414</td>
<td>2.75046</td>
<td>2.13282</td>
</tr>
<tr>
<td>Viscous</td>
<td>0.00048</td>
<td>0.00076</td>
<td>0.00038</td>
</tr>
<tr>
<td>Momentum</td>
<td>0</td>
<td>0.00839</td>
<td>-0.00760</td>
</tr>
<tr>
<td>Total</td>
<td>2.39466</td>
<td>2.75961</td>
<td>2.12260</td>
</tr>
</tbody>
</table>

\[
F = \int (-P \delta_{ij} + \tau_{ij}) n_j dA + \int \rho u_i u_j n_j dA
\]

\[
L = -F_x \sin \alpha + F_z \cos \alpha
\]
Effects on Lift and Drag

Re = 2.51E6, and Ma = 0.185, $C_\mu = 0.01$

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

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<tr>
<th>$C_l$ at $\alpha=6^\circ$</th>
<th>Baseline No jet</th>
<th>Pressure side jet</th>
<th>Suction side jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>2.39414</td>
<td>+0.35632</td>
<td>-0.26132</td>
</tr>
<tr>
<td>Viscous</td>
<td>0.00048</td>
<td>+0.00028</td>
<td>-0.00010</td>
</tr>
<tr>
<td>Momentum</td>
<td>0</td>
<td>+0.00839</td>
<td>-0.00760</td>
</tr>
<tr>
<td>Total</td>
<td>2.39466</td>
<td>2.75961</td>
<td>2.12260</td>
</tr>
</tbody>
</table>

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

\[
L = -F_x \sin \alpha + F_z \cos \alpha
\]
Microjet vs. Microtab: Drag

$\alpha = 6^\circ$, $Re = 2.51E6$, and $Ma = 0.185$, Steady State

<table>
<thead>
<tr>
<th>$C_d$ at $\alpha = 6^\circ$</th>
<th>Baseline No jet</th>
<th>Pressure side tab</th>
<th>Pressure side jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>0.01995</td>
<td>0.02576</td>
<td>0.01622</td>
</tr>
<tr>
<td>Viscous</td>
<td>0.01014</td>
<td>0.01006</td>
<td>0.01007</td>
</tr>
<tr>
<td>Momentum</td>
<td>0</td>
<td>0</td>
<td>0.00211</td>
</tr>
<tr>
<td>Total</td>
<td>0.03008</td>
<td>0.03582</td>
<td>0.02839</td>
</tr>
</tbody>
</table>

$C_\mu = 0.004$
Conclusion

• The high lift system is a critical component of transport airplanes. E.g., for a large twin-engine civil transport jet on takeoff/landing (Boeing, 1993):
  – $\Delta(L/D) = +1\%$ results in an increase in airplane payload of 2,800 lb assuming second-segment climb limited performance
  – $\Delta C_{L_{max}} = +1.5\%$ results in an increase in airplane payload of 6,600 lb at fixed approach speed
  – $\Delta C_{L} = +0.10$ reduces required landing gear height results in a reduction in airplane empty weight of 1,400 lb

• This study focuses on the application of AFC for airplane high lift systems
  – Involves a nominally-orthogonal jet injecting momentum normal to the airfoil surface near the flap trailing edge, where it modifies the trailing edge flow and, thereby, the airfoil circulation.

• The initial 2-D CFD results for the two-element high lift airfoil demonstrate the feasibility of the microjet concept for high lift system performance enhancement and aerodynamic load control.
  - Ability to shift lift curve up (blowing on pressure side of flap) and down (blowing on suction side of flap) in linear regime of the curve
  - Modify the stall angle and maximum lift coefficient of the multi-element airfoil
  - Improve lift-to-drag ratio of the multi-element airfoil
The research reported in this paper was partially funded by Boeing Commercial Airplanes (BCA), The Boeing Company. The computing resources were provided by the NASA Ames Research Center (ARC). The authors acknowledge the help and inputs by Dr. Paul Vijgen, BCA, and Dr. William Chan and Dr. H. Dogus Akaydin, NASA ARC.
Immediate Next Steps

• Complete the microjet feasibility study on the two-element NLR7301 airfoil

• Validate CFD jet behavior:
  – Malavard et al (1956) experimental results

• 3-D Reynolds-averaged Navier-Stokes on NLR7301 flapped airfoil (or other multi-element airfoil configuration). Various microjet configurations
Thank You
BACKUP
Computational Setup/Validation

- Overset grid technology
  - O-grid topology growing 50c away
  - PEGASUS mesh connectivity
- RANS OVERFLOW 2
  - 4th order central difference and ARC3D diagonalized approximate factorization with matrix artificial dissipation
  - SA turbulence model
NLR7301 Experimental Data

- Reported accuracy
  - $C_l$ within ±0.4%
  - $C_d$ within ±2%
  - $C_p$ within ±0.5%
  - $\alpha$ within ±0.05°

Vandenberg and Oskam 1980
Vandenberg and Oskam 1980
Surface Grid Sensitivity

\( \alpha = 6^\circ, \text{ Re } = 2.51 \times 10^6, \text{ and } \text{Ma} = 0.185, \text{ Steady State} \)

Main TE thickness: 0.0009
Flap TE thickness: 0.00115

<table>
<thead>
<tr>
<th>Element</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>Extra-fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>600</td>
<td>800</td>
<td>1000</td>
<td>1200</td>
</tr>
<tr>
<td>Flap</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>600</td>
</tr>
</tbody>
</table>
Surface Grid Sensitivity

\( \alpha = 6^\circ, \text{ Re } = 2.51 \times 10^6, \text{ and } \text{Ma } = 0.185, \text{ Steady State} \)

\[ \Delta C_l \% = 0.3 < 0.4\% \text{ exp_accuracy} \]

\[ \Delta C_d \% = 5.2 > 2.0\% \text{ exp_accuracy} \]
Volume Grid Refinement
Volume Grid Sensitivity

\( \alpha = 6^\circ, \text{ Re } = 2.51 \text{E}6, \text{ and } \text{Ma } = 0.185, \text{ Steady State} \)

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

Wake grid addition to capture flap element TE wake

Lift improves:

\[ 0.14\% < 0.4\% \text{ exp\_accuracy} \]

Drag improves:

\[ 1.48\% < 2.0\% \text{ exp\_accuracy} \]

<table>
<thead>
<tr>
<th></th>
<th>( C_L )</th>
<th>( C_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>2.4321</td>
<td>0.0270</td>
</tr>
<tr>
<td>Grid refinement for shear layer</td>
<td>2.4371</td>
<td>0.0267</td>
</tr>
<tr>
<td>Wake layer grid addition</td>
<td>2.4325</td>
<td>0.0268</td>
</tr>
<tr>
<td>Both grid addition</td>
<td>2.4356</td>
<td>0.0266</td>
</tr>
<tr>
<td>Experimental</td>
<td>2.42</td>
<td>0.0229</td>
</tr>
</tbody>
</table>
Grid Connectivity Study

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

- PEGASUS: Outside of OVERFLOW

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

$\alpha = 6^\circ$, $Re = 2.51 \times 10^6$, and $Ma = 0.185$, Steady State

<table>
<thead>
<tr>
<th></th>
<th>$C_l$</th>
<th>$\Delta C_l$% error</th>
<th>$C_d$</th>
<th>$\Delta C_d$% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pegasus</td>
<td>2.436</td>
<td>0.65%</td>
<td>0.0266</td>
<td>16.2%</td>
</tr>
<tr>
<td>DCF</td>
<td>2.413</td>
<td>0.30%</td>
<td>0.0289</td>
<td>26.2%</td>
</tr>
</tbody>
</table>

DCF is the selected overset tool
Grid Modification

$\alpha = 6^\circ$, $Re = 2.51E6$, and $Ma = 0.185$, Steady State

$\Delta C_l$% error $\Delta C_d$% error

| Final Grid | 2.416 | 0.16% | 0.0284 | 24.0% |
### Solver Study

\( \alpha = 6^\circ, \ Re = 2.51 \times 10^6, \) and \( Ma = 0.185, \) Steady State

<table>
<thead>
<tr>
<th>LHS</th>
<th>RHS</th>
<th>Clock Time [min]</th>
<th>( C_l )</th>
<th>( \Delta C_l % ) error</th>
<th>( C_d )</th>
<th>( \Delta C_d % ) error</th>
</tr>
</thead>
<tbody>
<tr>
<td>00 ARC3D approx. factor.</td>
<td>Central diff.</td>
<td>27.30</td>
<td>2.4159</td>
<td>0.16%</td>
<td>0.0284</td>
<td>24.0%</td>
</tr>
<tr>
<td>20 ARC3D diag. approx. factor.</td>
<td>Central diff.</td>
<td>16.38</td>
<td>2.4159</td>
<td>0.16%</td>
<td>0.0284</td>
<td>24.0%</td>
</tr>
<tr>
<td>60 SSOR</td>
<td>Central diff.</td>
<td>39.11</td>
<td>2.4159</td>
<td>0.16%</td>
<td>0.0284</td>
<td>24.0%</td>
</tr>
<tr>
<td>26 ARC3D diag. approx. factor.</td>
<td>HLLE++ upwind</td>
<td>23.21</td>
<td>2.4276</td>
<td>0.31%</td>
<td>0.0286</td>
<td>24.9%</td>
</tr>
<tr>
<td>66 SSOR</td>
<td>HLLE++ upwind</td>
<td>42.14</td>
<td>2.4276</td>
<td>0.31%</td>
<td>0.0286</td>
<td>24.9%</td>
</tr>
</tbody>
</table>
\[
\frac{\partial \vec{q}}{\partial t} + \frac{\partial \vec{E}}{\partial \xi} + \frac{\partial \vec{F}}{\partial \eta} + \frac{\partial \vec{G}}{\partial \zeta} = 0
\]

\[
\begin{align*}
A & \approx LHS \\
& \left[ I + \frac{\Delta t}{1 + \theta} \frac{\partial \xi}{\partial \tau} \right] \left[ I + \frac{\Delta t}{1 + \theta} \frac{\partial \eta}{\partial \tau} \right] \left[ I + \frac{\Delta t}{1 + \theta} \frac{\partial \zeta}{\partial \tau} \right] \Delta q^{n+1,m+1} = \\
& - \left[ (q^{n+1,m} - q^n) - \frac{\theta}{1 + \theta} \Delta q^n + \frac{\Delta t}{1 + \theta} RHS^{n+1,m} \right] + \text{Error}
\end{align*}
\]

\[
\begin{align*}
\text{Error} &= \left( \frac{\Delta t}{1 + \theta} \right)^2 \left( \frac{\partial \xi}{\partial \eta} B + \frac{\partial \xi}{\partial \zeta} C + \frac{\partial \eta}{\partial \zeta} B \right) - \left( \frac{\Delta t}{1 + \theta} \right)^3 \left( \frac{\partial \xi}{\partial \eta} B \frac{\partial \zeta}{\partial \eta} C \right) \Delta q^{n+1,m+1}
\end{align*}
\]

\[
\begin{align*}
\xi &= \xi(x,y,z,t) \\
\eta &= \eta(x,y,z,t) \\
\zeta &= \zeta(x,y,z,t)
\end{align*}
\]

\[
q = \begin{bmatrix}
\rho \\
\rho u \\
\rho v \\
\rho w \\
\rho e_0
\end{bmatrix}
\]

\[
A \approx LHS \times b
\]

ARC3D approx. factor.
Solver Study

\( \alpha = 6^\circ, \text{Re} = 2.51 \times 10^6 \text{ and } \text{Ma} = 0.185, \text{Steady State} \)

\[
\begin{align*}
\frac{\partial \bar{q}}{\partial t} + \frac{\partial \bar{E}}{\partial \xi} + \frac{\partial \bar{F}}{\partial \eta} + \frac{\partial \bar{G}}{\partial \zeta} &= 0 \\
A &\approx \text{LHS} \\
\begin{bmatrix}
I + \frac{\Delta t}{(1 + \theta) \Delta \tau} + \frac{\Delta t}{1 + \theta} (\partial_\xi A + \partial_\eta B + \partial_\zeta C) \\
(q^{n+1,m} - q^n) - \frac{\theta}{1 + \theta} \Delta q^n + \frac{\Delta t}{1 + \theta} \text{RHS}^{n+1,m}
\end{bmatrix} &\Delta q^{n+1,m+1} = \\
\begin{bmatrix}
\xi = \xi(x,y,z,t) \\
\eta = \eta(x,y,z,t) \\
\zeta = \zeta(x,y,z,t)
\end{bmatrix} &q = [\begin{bmatrix}
\rho u \\
\rho v \\
\rho w \\
\rho e_0
\end{bmatrix}]
\end{align*}
\]

First order time diff: \( \theta = 0 \)
Second order time diff: \( \theta = 0.5 \)

Add pseudo time for time-accurate

\[
A = X_A \Lambda_A X_A^{-1} \\
B = X_B \Lambda_B X_B^{-1} \\
C = X_C \Lambda_C X_C^{-1}
\]

\[
X_A \left[ I + \frac{\Delta t}{1 + \theta} \partial_\xi \Lambda_A \right] X_A^{-1} X_B \left[ 1 + \frac{\Delta t}{1 + \theta} \partial_\eta \Lambda_B \right] X_B^{-1} X_C \left[ I + \frac{\Delta t}{1 + \theta} \partial_\zeta \Lambda_C \right] X_C^{-1} \Delta q^{n+1,m+1} = \\
\left[ (q^{n+1,m} - q^n) - \frac{\theta}{1 + \theta} \Delta q^n + \frac{\Delta t}{1 + \theta} \text{RHS}^{n+1,m} \right] + \text{Error}
\]
Solver Study

\[ \alpha = 6°, \quad \text{Re} = 2.51 \times 10^6 \quad \text{and} \quad \text{Ma} = 0.185, \quad \text{Steady State} \]

\[ \frac{\partial \vec{q}}{\partial t} + \left( \frac{\partial \vec{E}}{\partial \xi} + \frac{\partial \vec{F}}{\partial \eta} + \frac{\partial \vec{G}}{\partial \zeta} \right) = 0 \]

\[ \rho \]
\[ \rho u \]
\[ \rho v \]
\[ \rho w \]
\[ \rho e_0 \]

\[ A \approx LHS \]

\[ x \]

\[ Ax = b \]

Forward Sweep

\[ mk1 = mm + 1 \]
\[ mk2 = mm \]
\[ ml1 = mm + 1 \]
\[ ml2 = mm \]

Backward Sweep

\[ mk1 = mm \]
\[ mk2 = mm + 1 \]
\[ ml1 = mm \]
\[ ml2 = mm + 1 \]
Turbulence Model Study

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

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

<table>
<thead>
<tr>
<th>Turbulence Model</th>
<th>Clock Time [min]</th>
<th>$C_l$</th>
<th>Δ$C_l$% error</th>
<th>$C_d$</th>
<th>Δ$C_d$% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>16.38</td>
<td>2.4159</td>
<td>0.16%</td>
<td>0.0284</td>
<td>24.0%</td>
</tr>
<tr>
<td>SST</td>
<td>32.08</td>
<td>2.3946</td>
<td>1.05%</td>
<td>0.0301</td>
<td>31.4%</td>
</tr>
<tr>
<td>SST with Langtry-Menter transition</td>
<td>52.35</td>
<td>2.4609</td>
<td>1.69%</td>
<td>0.0260</td>
<td>13.5%</td>
</tr>
</tbody>
</table>

Future studies will implement SST with transition
Microjet vs. Microtab Study

$\alpha = 6^\circ$, Re = 2.51E6, and Ma = 0.185, Steady State
Microjet Momentum Coefficient

\( \alpha = 6°, \ \text{Re} = 2.51 \times 10^6, \ \text{and Ma} = 0.185 \)

- \( C_{\mu} \) range: 0.0004-0.04 for the jet exit \( h_j = 0.005 \)
  - \( C_{\mu} < 0.01 \) converged with steady state simulations
  - \( C_{\mu} \geq 0.01 \) required time-accurate simulations

Steps:
1. Steady state: converge the baseline airfoil (no microjet)
2. Steady state: turn on the microjet
3. If not converged, run time-accurate

\[
DT = \frac{\Delta T}{L \overline{U}} \quad \text{where} \quad \Delta T = \frac{1}{f} \rightarrow \text{need} \ f
\]

\[
S_t = \frac{f \cdot D}{U_\infty} \rightarrow \frac{1}{f} = \frac{D}{S_t U_\infty}
\]

\[
DT = \frac{D}{100LS_t}
\]

\( D = \) Height of equivalent micro-tab
\( St = .21 \) (White 2008)

\( L = 1 \)

\( DT = 0.000234 \)
Effect on Pressure Profiles

$\alpha = 11^\circ$, $Re = 2.51E6$ and $Ma = 0.185$, $C_\mu = 0.01$

dp/dx line plot is desired
Motivation

- High-lift systems have significant impact on sizing, economics and safety of transport airplanes
  - \( L/D \) and \( C_{l_{\text{max}}} \) 1.0% can increase passenger count by 14-22
  - \( V_s = \left( \frac{W}{S \rho C_{L_{\text{max}}}} \right)^{0.5} \)
  - \( V_{TO} = 1.2V_s = 1.2\left( \frac{W}{S \rho C_{L_{\text{max}}}} \right)^{0.5} \)
  - \( TOP = \left( \frac{W}{S} \right)_{TO} \frac{1}{C_{L_{\text{max}}}} \left( \frac{W}{S} \right)_{TO} \frac{1}{\sigma} \) \( \sigma = \frac{\rho_{TO}}{\rho_{SL}} \)

\[
STO = 20.9(TOP) + 87 \sqrt{TOP\left( \frac{T}{W} - \frac{1}{L/D} \right)} \quad \text{T/W: thrust-to-weight f(altitude)}
\]

- high-lift system accounts for somewhere between 6% and 11%
• The high lift system is a critical component of transport airplanes with small changes in its aerodynamic performance having a large impact on the overall performance of the airplane. E.g. for a large twin-engine civil transport jet (Boeing, 1993):
  – Takeoff/landing
    • $\Delta (L/D) = +1\%$ results in an increase in airplane payload of 2,800 lb assuming second-segment climb limited performance
    • $\Delta C_{L_{\text{max}}} = +1.5\%$ results in an increase in airplane payload of 6,600 lb at fixed approach speed
    • $\Delta C_{L} = +0.10$ reduces required landing gear height results in a reduction in airplane empty weight of 1,400 lb

• This study focuses on the application of active flow control (AFC) for airplane high lift systems.
• The AFC concept studied is the microjet to control the aerodynamic loads and performance of airplane high lift systems.
• The microjet involves a nominally-orthogonal jet injecting momentum normal to the airfoil surface near the flap trailing edge, where it modifies the trailing edge flow and, thereby, the airfoil circulation.
The study proposes the use of CFD to study achievable gains in the aerodynamic performance of the high lift system.

OVERFLOW is the CFD flow solver applied for this study. It uses structured overset grids to simulate fluid flow, and is being used on a wide range of aeronautical research projects in government labs, industry, and academia.

The CFD method was validated for a two-element high lift airfoil (NLR7301) for which benchmark experimental results are available in the open literature.

The initial 2-D CFD results for the two-element high lift airfoil demonstrate the feasibility of the microjet concept for high lift system performance enhancement and aerodynamic load control.

- Ability to shift lift curve up (blowing on pressure side of flap) and down (blowing on suction side of flap) in linear regime of the curve
- Modify the stall angle and maximum lift coefficient of the multi-element airfoil
- Improve lift-to-drag ratio of the multi-element airfoil
Next Steps II

• 3-D Reynolds-averaged Navier-Stokes on realistic airplane wing.
  • High lift version of the NASA Common Research Model (CRM). Extensively studied in a wide range of configurations by a large number of researchers.
  • Validate CFD results for the baseline high lift configuration
  • Apply findings of preceding 2-D and 3-D studies for microjet layout on CRM and study effects on airplane lift, drag, moment, and flap load, hinge moment.

• Overall system considerations for CRM configuration
  • Blowing power requirements
  • Mass flow requirements
  • Impact on overall airplane system
Future Studies

- Boeing Internship: Airplane Level Feasibility Study on a Boeing Geometry
- Microjet Airplane Level Studies AIAA 2019 Aviation Conference
- Microjet 3-D Sensitivities 2019 Sci-Tech Conference
- Microjet Validations Against Experimental Data
- Microjet Feasibility Study AIAA 2018 Sci-Tech Conference
- Microjet 2-D Sensitivities AIAA Flow Control Conference

Dates:
- Oct 2017
- Jan 2018
- Apr 2018
- Jul 2018
- Oct 2018
- Jan 2019
- Apr 2019
- Jul 2019
- Oct 2019
- Jan 2020