Computational Investigations of Surface-Normal Pneumatic Active Aerodynamic Load Control for Lift Enhancement and Separation Mitigation in High-Lift Systems

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Motivation

Active Flow Control for high-lift systems

For large twin-engine transport jet *

- $C_{L_{\text{max}}}$
  
  $+1\%C_{L_{\text{max}}} \propto 4400 \text{ lb (~22 passengers)}$

- L/D
  
  $+1\%L/D \propto 2800 \text{ lb (~14 passengers)}$

- $C_L$ modulation in the linear lift regime
  
  $+0.10 \Delta C_L \propto 14 \text{ in reduction in } h_{\text{landing gear}}$
  
  $\propto 1400 \text{ lb (~7 passenger)}$

Active Flow Control (AFC)

Flow Phenomenon

Active Flow Control

Devices and Actuators

Controls & Sensors

Separation Mitigation

Load Control*

Microtab and Microjet

Theoretical Developments

Assume: thin jet, inviscid, irrotational, and doesn’t mix with the flow external to the jet

\[ p_1 + \frac{1}{2} \rho_\infty u_1^2 = p_2 + \frac{1}{2} \rho_\infty u_2^2 \]

\[ p_1 + \frac{1}{2} \rho_j v_1^2 = p_2 + \frac{1}{2} \rho_j v_2^2 \]
Theoretical Developments

Irrotational flow assumption

\[ p_1 - p_2 = \frac{1}{2} \rho_\infty u_2^2 - \frac{1}{2} \rho_\infty u_1^2 \quad (1) \]

\[ \Gamma = \oint \mathbf{v} \cdot d\mathbf{l} = 0. \]

\[ v_1(R - \frac{1}{2} h_j) = v_2(R + \frac{1}{2} h_j) \quad (5) \]

\[ v_1 - v_2 = \frac{h_j}{2R}(v_1 + v_2) \quad (6) \]

Substitute (6) in (4)

\[ u_1 - u_2)(u_1 + u_2) = \frac{\rho_j}{\rho_\infty} (v_1 - v_2)(v_1 + v_2) \quad (4) \]

\[ (u_1 - u_2)(u_1 + u_2) = \frac{\rho_j}{\rho_\infty} (v_1 + v_2) \frac{h_j}{2R}(v_1 + v_2) \quad (7) \]

Assume small perturbations, and that u velocity is outside of boundary layer, entrainment region and recirculation region

\[ 2U_\infty(u_1 - u_2) = \frac{\rho_j}{\rho_\infty} \frac{h_j}{2R} 4U_j \]

\[ u_1 - u_2 = \frac{\rho_j U_j^2 h_j}{\rho_\infty U_\infty R} \]

\[ \gamma_j = u_1 - u_2 = \frac{\rho_j U_j^2 h_j}{\rho_\infty U_\infty R} \]

\[ p_1 - p_2 = -\rho_j U_j h_j / R \]

Violates the Kutta Condition!!
Theoretical Developments

Lift is augmented due to

i) Reaction due to the vertical component of the microjet momentum force

ii) Due to the vertical component of the pressure on the airfoil surface which is modified by the asymmetry microjet creates in the flow-field

\[
L = \rho_j U_j \Gamma_j + \rho_\infty U_\infty \Gamma_{\text{airfoils}}
\]

\[
\Gamma_j = \int_0^\infty \gamma_j ds = \int_0^\infty \frac{\rho_j U_j^2 h_j}{\rho_\infty U_\infty} ds
\]

\[
\Gamma_{\text{airfoil}} = \int_{0}^{\text{TE main element}} \gamma_{\text{main element}} dl + \int_{0}^{\text{TE flap element}} \gamma_{\text{flap element}} dl
\]
Theoretical Developments

Optimal Location for Circulation Control

The effect of airfoil camber is maximum at the TE and vanishes at the LE

\[ C_l = \frac{L'}{2\rho U_\infty^2 c} = 2\pi (A_0 + \frac{A_1}{2}) \]
\[ A_0 = \alpha - \frac{1}{\pi} \int_0^\pi \frac{d\eta_c}{dx} d\theta \]
\[ A_1 = \frac{2}{\pi} \int_0^\pi \frac{d\eta_c}{dx} \cos \theta d\theta \]

\[ C_l = 2\pi (\alpha + \frac{1}{\pi} \int_0^\pi (\cos \theta - 1) \frac{d\eta_c}{dx} d\theta) \]
\[ C_l = 2\pi \left( \alpha + \frac{2}{\pi} \int_0^1 \frac{d(\eta_c)}{d(\frac{x}{c})} \frac{\sqrt{\frac{x}{c} (1 - \frac{x}{c})}}{\frac{x}{c} - 1} d(\frac{x}{c}) \right) \]

\[ \frac{d(\eta_c)}{d(\frac{x}{c})} > 0 \] Largest lift reduction due to camber at the TE

\[ \frac{d(\eta_c)}{d(\frac{x}{c})} < 0 \] Largest lift increase due to camber at the TE
Project Scope

• **Selection of airfoil configuration**
• **CFD validation / computational sensitivities**
  • Surface and volume grid sensitivities
  • Grid connectivity
  • Solver sensitivities
• **2D microjet configuration studies**
  • Microjet and microtab comparison
  • Microjets effects over angle of attack range
  • Control volume analysis
  • Momentum coefficient sweeps
  • Microjet chordwise location and width
• **Extensive CFD studies of microjets**
  • 2.5-D: Microjet effects on infinite sheared wing
  • 3D: Application of microjets on CRM
• **Turbulence model**
• **Transition modeling**
• **Far field extent**
• **Initial power requirement analysis**
• **Microjet inlet velocity profile and effects of modeling as boundary condition vs. plenum**
• **Varying flap deflection and separation effects**
• **Pulsed vs. steady microjet**
• **Mach number and Reynolds number effects**

Publications:
• Journal of Aircraft in progress
• Journal of Aircraft paper in review
• Journal of Aircraft paper DOI: 10.2514/1.C035248
• AIAA paper 2019-3498 (Aviation 2019)
• AIAA paper 2019-0590 (SciTech 2019)
• AIAA paper 2018-0559 (SciTech 2018)
Computational Studies

- Summary of the computational setup on baseline multi-element airfoil NLR7301
- 2D investigations on the NLR7301 flaps 20° and 30°
- 2.5D (infinite sheared wing) the NLR7301 flap 30°
- CRM-HL in landing configuration
Computational Studies

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  - CRM-HL in landing configuration
Airfoil Definition*

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

Airfoil Definition

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

2-D CFD Setup Summary

- Extensive CFD sensitivity study (solver, grid, connectivity, turbulence model, transition) conducted in 2018
- Overset grid technology
  - O-grid topology growing 10,000c away
  - DCF mesh connectivity
- RANS OVERFLOW 2
  - 3\textsuperscript{rd} order accurate and ARC3D diagonalized approximate factorization with matrix artificial dissipation
  - SST turbulence model

\begin{table}[h]
\centering
\begin{tabular}{cccc}
\hline
Clock Time[\text{min}] & \(C_l\) & \(\Delta C_l\)\% w.r.t resp. & \(C_d\) & \(\Delta C_d\)\% w.r.t exp. \\
\hline
30.35 & 2.41 & 0.4\% & 0.0250 & 7.0\% \\
\hline
\end{tabular}
\end{table}

\(\Delta C_d\) discrepancy transition related
CFD – fully turbulent
Exp – free transition
Computational Studies

• Summary of the computational setup on baseline multi-element airfoil NLR7301
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Microtab and Microjet Modeling

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

Tab 1\%c in height and 0.2\%c thickness

\[
C \mu = \frac{\dot{m}_j U_j}{\frac{1}{2}\rho_\infty U_\infty^2 S_{ref}} \quad \dot{m}_j = (\rho U A)_j
\]

\[
C \mu = \frac{\rho_j U_j^2 h_j b}{\frac{1}{2}\rho_\infty U_\infty^2 b c}
\]

\[
C \mu = 2 \frac{U_j^2}{U_\infty^2} \frac{h_j}{c}
\]

**Incompressible**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( \frac{U_j}{U_\infty} )</th>
<th>( C_\mu )</th>
<th>( h_j )</th>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial microjet</td>
<td>1.0</td>
<td>0.010</td>
<td>0.005c_{ref}</td>
<td>95%C_{flap}</td>
</tr>
</tbody>
</table>

- All the simulations for microjet in the presentation are time-accurate. The results shared are time-averaged.
- The simulations for microtab are steady.
Microtab and Microjet Modeling

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

<table>
<thead>
<tr>
<th></th>
<th>( C_l )</th>
<th>( C_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (no AFC)</td>
<td>2.409</td>
<td>0.02499</td>
</tr>
<tr>
<td>Microtab</td>
<td>2.640</td>
<td>0.02965</td>
</tr>
<tr>
<td>Microjet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ C_\mu = 0.004 \]
Microtab and Microjet Modeling

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

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<tr>
<td>Microtab</td>
<td>2.640</td>
<td>0.02965</td>
</tr>
<tr>
<td>Microjet</td>
<td>2.640</td>
<td>0.02232</td>
</tr>
</tbody>
</table>

\( C\mu = 0.004 \)
Flap 20 Lift and Drag Investigation

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

- \( \Delta C_l \) effect on \( C_l \) corresponds well with experimental results for NACA 0018 with normal blowing at trailing edge by Malavard et al. (1956).
- \( \Delta C_d \) effect on \( C_d \) not accounted for and not well reported.

\( \Delta C_l \) vs. \( C\mu \) and \( \Delta C_d \) vs. \( C\mu \) graphs show:

- Curve Fitted \( \Delta C_l \approx 3.61 \sqrt{C\mu} \)

Graphs illustrate the influence of blowing on lift and drag coefficients for the given conditions.
Drag Validation

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

<table>
<thead>
<tr>
<th>Case</th>
<th>Integrated at</th>
<th>$C_l$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure-side microjet</td>
<td>Surface</td>
<td>2.011</td>
<td>0.01550</td>
</tr>
<tr>
<td>Pressure-side microjet</td>
<td>0.3c far-field</td>
<td>2.011</td>
<td>0.01551</td>
</tr>
<tr>
<td>Pressure-side microjet</td>
<td>0.5c far-field</td>
<td>2.011</td>
<td>0.01551</td>
</tr>
<tr>
<td>Pressure-side microjet</td>
<td>0.7c far-field</td>
<td>2.011</td>
<td>0.01551</td>
</tr>
</tbody>
</table>
Symmetric airfoil

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

Symmetric airfoil

Flap 20 Lift and Drag Investigation

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

Microjet at 95% flap chord with a fixed width of 0.005 reference chord

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

\[ L = -F_x \sin \alpha + F_z \cos \alpha \]
Flap 20 Lift and Drag Investigation

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

Microjet at 95% flap chord with a fixed width of 0.005 reference chord

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

$L = -F_x \sin \alpha + F_z \cos \alpha$
Flap 20 Lift and Drag Investigation

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

\[ D = F_x \cos \alpha + F_z \sin \alpha \]

\[ L = -F_x \sin \alpha + F_z \cos \alpha \]

\[ \alpha = 6^\circ, \text{Re} = 2.51E6, \text{and Ma} = 0.185 \]
Upper Surface Slot, x/c = 0.90

Baseline Pressure side microjet
Suction side microjet

Microjet at 95% flap chord with a fixed width of 0.005 reference chord

Flap 20 Lift and Drag Investigation

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

\[ \Delta C_l = +0.36 \]
\[ \Delta C_l = -0.27 \]

\[ \Delta C_d = -0.0110 \]
\[ \Delta C_d = +0.0043 \]
Computational Studies

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2D Investigations on the NLR7301 Flaps 20° and 30°

- Sensitivity of microjet aerodynamic effectiveness to configuration:
  - Microjet chordwise location
  - Microjet width
  - Preliminary air supply analysis
  - Microjet transpiration velocity profile
  - Microjet modeling: plenums
  - Preliminary analysis of power requirements
Flap 20 Microjet Chordwise Location

Jet Location: %80 of flap chord
Jet Location: %85 of flap chord
Jet Location: %90 of flap chord
Jet Location: %95 of flap chord
Jet Location: %97 of flap chord
Jet Location: %99 of flap chord

α=6°, Re = 2.51E6, Ma = 0.185, hj = 0.005c_{ref}, Cμ = 0.01
• Microjet lift enhancement increases as it gets closer to the trailing edge
• Microjet Drag reduction benefit decreases as it gets closer to the trailing edge
Flap 20 Microjet/Microtab Chordwise Location

\[\alpha = 6^\circ, \ Re = 2.51 \times 10^6, \ Ma = 0.185\]

\[H_{\text{microtab}} = 1\%c_{\text{ref}}, \ T_{\text{microtab}} = 0.2\%c_{\text{ref}}\]
2D Investigations on the NLR7301 Flaps 20° and 30°

- Sensitivity of microjet aerodynamic effectiveness to configuration:
  - Microjet chordwise location
  - Microjet width
  - Preliminary air supply analysis
  - Microjet transpiration velocity profile
  - Microjet modeling: plenums
  - Preliminary analysis of power requirements
Microjet Width Sensitivity Study

$\alpha=6^\circ$, $Re = 2.51E6$, $Ma = 0.185$, $C\mu = 0.01$

All the microjets are centered at 95% $c_{flap}$ and all the widths are in % $c_{ref}$
Microjet Width Sensitivity Study

$\alpha=6^\circ$, $Re = 2.51E6$, $Ma = 0.185$, $C\mu = 0.01$

$U_j/U_\infty$ Decreases for Constant $C\mu=0.01$

- Microjet slot ended at 95.7% flap chord
- Microjet slot centered at 95% flap chord
Flap 20 Microjet Width Sensitivity Study

Microjet is centered at 95% of the flap

Mass flow coefficient: \[ C_q = \frac{\dot{m}_j}{\rho_\infty U_\infty S_{ref}} \]

\[ C_q = \frac{C_\mu}{\frac{U_j}{2U_\infty}} \]

\[ \alpha = 6^\circ, \text{ Re } = 2.51 \times 10^6, \text{ Ma } = 0.185, C_\mu = 0.01 \]
2D Investigations on the NLR7301 Flaps 20° and 30°

- Sensitivity of microjet aerodynamic effectiveness to configuration:
  - Microjet chordwise location
  - Microjet width
  - Preliminary air supply analysis
  - Microjet transpiration velocity profile
  - Microjet modeling: plenums
  - Preliminary analysis of power requirements
Preliminary System Analysis: Air Supply

**Initial Microjet Configuration**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_j$</td>
<td>0.005</td>
</tr>
<tr>
<td>$U_j$</td>
<td>1.0</td>
</tr>
<tr>
<td>$C_\mu$</td>
<td>0.01</td>
</tr>
<tr>
<td>$\Delta C_l$</td>
<td>0.36</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>111 kg/s</td>
</tr>
</tbody>
</table>

- Reduce $C_\mu$
- Reduce $h_j$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_j$</td>
<td>0.005</td>
</tr>
<tr>
<td>$U_j$</td>
<td>0.01</td>
</tr>
<tr>
<td>$C_\mu$</td>
<td>0.004</td>
</tr>
<tr>
<td>$\Delta C_l$</td>
<td>0.23</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>74 kg/s</td>
</tr>
</tbody>
</table>

**Reference chord:** $c_{ref}$ 7 m

**Airspeed:** $U_\infty$ 133 knots

**Jet spanwise extent:** $w_j$ 38 m

Further reductions?
- Spanwise spacing
- Pulsed blowing

**Combine & optimize**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_j$</td>
<td>0.00125</td>
</tr>
<tr>
<td>$U_j$</td>
<td>2.2</td>
</tr>
<tr>
<td>$C_\mu$</td>
<td>0.012</td>
</tr>
<tr>
<td>$\Delta C_l$</td>
<td>0.36</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>61 kg/s</td>
</tr>
</tbody>
</table>

AFC coverage: $w_j$~ 38 m
2D Investigations on the NLR7301 Flaps 20° and 30°

- Sensitivity of microjet aerodynamic effectiveness to configuration:
  - Microjet chordwise location
  - Microjet width
  - Preliminary air supply analysis
  - Microjet transpiration velocity profile
  - Microjet modeling: plenums
  - Preliminary analysis of power requirements
## Microjet Transpiration Velocity Profile Sensitivity

### Parameters

- $\alpha = 6^\circ$
- $Re = 2.51 \times 10^6$
- $Ma = 0.185$
- $C\mu = 0.01$

### BC Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>$C_l$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (no AFC)</td>
<td>2.408</td>
<td>0.02499</td>
</tr>
<tr>
<td>Uniform BC, $C\mu = 0.01$</td>
<td>2.223</td>
<td>0.02571</td>
</tr>
<tr>
<td>BC based on turbulent velocity profile, $C\mu = 0.01$</td>
<td>2.640</td>
<td>0.02965</td>
</tr>
<tr>
<td>BC based on laminar velocity profile, $C\mu = 0.01$</td>
<td>2.720</td>
<td>0.03080</td>
</tr>
</tbody>
</table>

### Equations

- $U = U_{max} \left[ 1 - \frac{r}{R} \right]^{1/n}$
- $U = U_{max} \left[ 1 - \left( \frac{r}{R} \right)^2 \right]$
2D Investigations on the NLR7301 Flaps 20° and 30°

- Sensitivity of microjet aerodynamic effectiveness to configuration:
  - Microjet chordwise location
  - Microjet width
  - Preliminary air supply analysis
  - Microjet transpiration velocity profile
  - Microjet modeling: plenums
  - Preliminary analysis of power requirements
Flap 20 Microjet Modeling: Plenum

α = 6°, Re = 2.51E6, Ma = 0.185, Cμ = 0.01

Plenum A: \( h_j = 0.005c_{ref} \)

Plenum B: \( h_j = 0.005c_{ref} \)

Plenum C: \( h_j = 0.005c_{ref} \)

Plenum D: \( h_j = 0.00125c_{ref} \)
Flap 20 Microjet Modeling: Plenum

\[ \alpha = 6^\circ, \text{Re} = 2.51 \times 10^6, \text{Ma} = 0.185, C\mu = 0.01 \]

- **Plenum A:** \( h_j = 0.005 c_{ref} \)
- **Plenum B:** \( h_j = 0.005 c_{ref} \)
- **Plenum C:** \( h_j = 0 \)
- **Plenum D:** \( h_j = 0.00125 c_{ref} \)

\[
C_{\mu \text{effective}} = \frac{\int \rho u_j u_i n_j dA}{1/2 \rho_\infty U_\infty^2 A_{ref}}
\]

\( : h_j = 0.00125 c_{ref} \)
Equivalent Drag

Control volume analysis:

\[ D_{eq.} = D_{Press.} + D_{vis.} + D_{\Delta \text{mom.}} + D_{\text{power}} \]
\[ = D_{Press.} + D_{vis.} + \dot{m}U_\infty - D_{\text{mom}} + \frac{\text{Power}}{U_\infty} \]
\[ = D_{\text{comp}} + \dot{m}U_\infty + \frac{1}{2}\dot{m}U_j^2 \]

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

\[ D_{\text{comp}} = F_x \cos \alpha + F_z \sin \alpha \]

Non-dimensional:

\[ C_{d_{eq}} = C_{d_{comp}} + C_\mu \frac{U_j}{2U_\infty} + C_\mu \frac{U_\infty}{U_j} \]

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( \frac{U_j}{U_\infty} )</th>
<th>( C_\mu )</th>
<th>( C_1 )</th>
<th>( C_{d_{comp}} )</th>
<th>( C_{d_{eq}} )</th>
<th>( \frac{C_1}{C_{d_{comp}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (no jet)</td>
<td>-</td>
<td>-</td>
<td>2.41</td>
<td>0.0250</td>
<td>0.0250</td>
<td>96.4</td>
</tr>
<tr>
<td>Initial microjet</td>
<td>1.0</td>
<td>0.010</td>
<td>2.77</td>
<td>0.0206</td>
<td>0.0356</td>
<td>134.5</td>
</tr>
<tr>
<td>1% microtab</td>
<td>-</td>
<td>-</td>
<td>2.64</td>
<td>0.0297</td>
<td>0.0297</td>
<td>88.9</td>
</tr>
<tr>
<td>Matched microjet</td>
<td>0.6</td>
<td>0.004</td>
<td>2.64</td>
<td>0.0223</td>
<td>0.0302</td>
<td>118.4</td>
</tr>
</tbody>
</table>

\( \alpha = 6^\circ, \, \text{Re} = 2.51E6, \, \text{Ma} = 0.185 \)
Flap 30° is set up with the same overlap and gap as flap 20°

- No experimental data for 30° flap setting
Minor vs. Moderate TE Flow Separation

\[ \alpha = 6^\circ \]

\[ \Delta C_l = 0.37 \]

Flap 20

\[ \alpha = 6^\circ \]

\[ \Delta C_l = 0.36 \]

2% flap TE Separation

11% flap TE Separation

Baseline

Flap 30

\[ \alpha = 6^\circ \]

\[ \Delta C_l = 0.37 \]

11% flap TE Separation

Baseline

\[ Re = 2.51 \times 10^6, \ Ma = 0.185 \]
Minor vs. Moderate TE Flow Separation

$Re = 2.51E6, \ Ma = 0.185$

Flap 20

$\alpha = 6^\circ$

$\Delta C_l = 0.36$

Flap 30

$\alpha = 6^\circ$

$\Delta C_l = 0.37$

Re = 2.51E6, Ma = 0.185
Flap 30 Drag Decomposition

\[ \Delta C_d = -0.0160 \]

\[ \Delta C_d = +0.0008 \]

\[ \Delta C_d = -0.0228 \]

\[ \Delta C_d = +0.0060 \]

Re = 2.51E6, and Ma = 0.185, C\(\mu\) = 0.01
$\alpha = 6^\circ$, Re = 2.51E6, Ma = 0.185

Flap 20

$C_\mu = 0.01$

Flap 30

$C_\mu = 0.01$
Flap 30, Momentum Coefficient Sensitivity

$\alpha=6^\circ$, $Re = 2.51E6$, and $Ma = 0.185$, Microjet width: $h_j = 0.005c_{ref}$
Minor vs. Moderate TE Flow Separation

Re = 2.51E6, and Ma = 0.185

Note trailing edge separation mitigation for flap 30
Baseline: Re = 2.51E6, and Ma = 0.185
Re = 2.51E6, and Ma = 0.185, Cµ = 0.01, Microjet width: h_j = 0.005c_{ref}
Re = 2.51E6, and Ma = 0.185, Cμ sweep, Microjet width: h_j = 0.005c_{ref}
Flap 30°, Steady vs. Pulsed Blowing

\[ \alpha = 6°, \ Re = 2.51E6, \ and \ Ma = 0.185, \ Microjet \ width: \ h_j = 0.005c_{\text{ref}} \]

Constant Blowing \( U_{\text{max}} = 1, \ U_{\text{min}} = 1, \)

- \( F_+ = 0.02, \ U_{\text{max}} = 1, \ U_{\text{min}} = 0 \)
  - \( f = 37.3 \ [Hz] \)
- \( F_+ = 0.08, \ U_{\text{max}} = 1, \ U_{\text{min}} = 0 \)
  - \( f = 186.5 \ [Hz] \)
- \( F_+ = 0.2, \ U_{\text{max}} = 1, \ U_{\text{min}} = 0 \)
  - \( f = 373.0 \ [Hz] \)

Time is: 0-0.027[s]
Flap 30°, Steady vs. Pulsed Blowing

α=6°, Re = 2.51E6, and Ma = 0.185, Microjet width: h_j = 0.005c_{ref}

Pulsed blowing causes discontinuous flow pattern at TE, which has a negative impact on microjet effectiveness.
Flap 30° Mach and Re # Sensitivity

Results at higher Mach number (0.26) and Reynolds number (15.7 million) indicate microjet effectiveness in linear regime not affected by compressibility and Reynolds number effects.

<table>
<thead>
<tr>
<th>M</th>
<th>Re</th>
<th>ΔC_l  @ α=6°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.185</td>
<td>2.51E6</td>
<td>0.38</td>
</tr>
<tr>
<td>0.26</td>
<td>2.51E6</td>
<td>0.35</td>
</tr>
<tr>
<td>0.26</td>
<td>6.5E6</td>
<td>0.36</td>
</tr>
<tr>
<td>0.26</td>
<td>6.5E6</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Computational Studies

- Summary of the computational setup on baseline multi-element airfoil NLR7301
- 2D investigations on the NLR7301 flaps 20° and 30°
- 2.5D (infinite sheared wing) the NLR7301 flap 30°
- CRM-HL in landing configuration
• Infinite wing allows for study more detailed jet effects (compared to 2D airfoil)
• Infinite wing is constructed from the 2D grid
• URANS (OVERFLOW), same as the 2D study
  - 3rd order accurate and ARC3D diagonalized approximate factorization with matrix artificial dissipation
  - SST turbulence model

Straight infinite wing
  - Wall boundary condition sensitivity
  - Spanwise resolution

20° Sheared infinite wing
  - Wall boundary condition sensitivity
  - Spanwise resolution
  - Microjet effect
Flap 30° Sheared Wing Lift and Drag Investigation 2.5D

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

- \( C_\mu \) effect on \( C_l \) and \( C_d \) corresponds well with two-dimensional results

\[
\text{Curve Fitted } \Delta C_l \approx 3.75 \sqrt{C_\mu}
\]
Flap 30° Sheared Wing Lift and Drag Investigation

2.5D

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

Microjet at 95% flap chord with a fixed width of 0.005 reference chord
Flap 30° Sheared Wing Separation Mitigation  2.5D

a) $C_\mu = 0.0000$

b) $C_\mu = 0.0016$

c) $C_\mu = 0.0064$

d) $C_\mu = 0.0100$

e) $C_\mu = 0.0144$

f) $C_\mu = 0.0256$

g) $C_\mu = 0.0324$

h) $C_\mu = 0.0400$

Mach Number: 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
Computational Studies

- Summary of the computational setup on baseline multi-element airfoil NLR7301
- 2D investigations on the NLR7301 flaps 20° and 30°
- 2.5D (infinite sheared wing) the NLR7301 flap 30°
- CRM-HL in landing configuration
Geometry:
• CRM_HL is wing body configuration adapted from HiLiftPW-3. Slat and flaps are deployed at 30° and 37° respectively, without nacelle, pylon, tail or support brackets. The Full Chord Gap configuration is chosen for the microjet study.

Flow condition:
• Mach number = 0.2
• $\alpha = 8^\circ$
• Reynold number based on MAC = 3.26 million
• MAC = 275.8 inches full scale
• Domain Connectivity Function routines
• Roe upwind scheme for spatial discretization
• F3D Steger-Warming 2-factor
• SA-RC turbulent model
• RANS simulations on 432 Haswell processors
### CRM High-Lift: Grid Refinement

3D

α=8°, Re_{MAC} = 3.26E6, and M = 0.2

<table>
<thead>
<tr>
<th>Number of cells</th>
<th>Original medium grid by William Chan</th>
<th>65,423,213</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Refined grid for this study</td>
<td>68,538,927</td>
</tr>
</tbody>
</table>

- a) HiLiftPW-3 original medium grid
- b) refined grid for this study
CRM High-Lift: Original vs. Refined Grid Solutions

α=8°, Re_{MAC} = 3.26E6, and M = 0.2

Y = 277.5 in

Y = 638 in

Y = 947 in
CRM High-Lift: Original vs. Refined Grid Solutions

\( \alpha = 8^\circ, \text{Re}_{MAC} = 3.26E6, \text{and } M = 0.2 \)

<table>
<thead>
<tr>
<th>Simulation Type</th>
<th>( C_L )</th>
<th>( C_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original medium grid</td>
<td>1.752</td>
<td>0.1701</td>
</tr>
<tr>
<td>Refined medium grid</td>
<td>1.753</td>
<td>0.1700</td>
</tr>
</tbody>
</table>

a) Overflow simulation using the HiLiftPW-3 original medium grid

b) Overflow simulation using the refined medium grid for this study
CRM High-Lift: Preliminary Microjet Study

\[ \alpha = 8^\circ, \text{Re}_{MAC} = 3.26 \times 10^6, \text{and } M = 0.2 \]

Baseline

Inboard microjet at 95\% c_{flap} and U_j/U_\infty = 1.0
No microjet on outboard flap
CRM High-Lift: Preliminary Microjet Study

**3D**

\( \alpha=8^\circ, \text{Re}_{\text{MAC}} = 3.26E6, \) and \( M = 0.2 \)

---

Baseline

Outboard Microjet at 95% \( c_{\text{flap}} \) and \( U_j/U_\infty = 1.0 \). No microjet on inboard flap
CRM High-Lift: Preliminary Microjet Study

α = 8°, Re_{MAC} = 3.26E6, and M = 0.2

Baseline

Inboard and outboard Microjet at 95% c_{flap} and U_j/U_∞ = 1.0
CRM High-Lift: Preliminary Microjet Study

\( \alpha = 8^\circ, \text{Re}_{\text{MAC}} = 3.26 \times 10^6, \text{and } M = 0.2 \)

Baseline

Inboard and outboard Microjet at 95% \( c_{\text{flap}} \)
and \( U_j/U_\infty = 1.0 \)
The drag coefficient associated with the microjet is thought to be dominated by the induced drag due to lift enhancement and spanwise load distribution modification, \( \left( \frac{C_L^2}{\pi ARe} \right) \).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( C_L )</th>
<th>( \Delta C_L )</th>
<th>( C_D )</th>
<th>( \Delta C_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (no microjet)</td>
<td>1.752</td>
<td>-</td>
<td>0.1698</td>
<td>-</td>
</tr>
<tr>
<td>Pressure-side microjet on the inboard flap</td>
<td>1.832</td>
<td>0.080</td>
<td>0.1864</td>
<td>0.0166</td>
</tr>
<tr>
<td>Pressure-side microjet on the outboard flap</td>
<td>1.789</td>
<td>0.037</td>
<td>0.1743</td>
<td>0.0045</td>
</tr>
<tr>
<td>Pressure-side microjet on the inboard and outboard flaps</td>
<td>1.866</td>
<td>0.114</td>
<td>0.1903</td>
<td>0.0205</td>
</tr>
</tbody>
</table>

\( \alpha=8^\circ, \text{Re}_{MAC} = 3.26E6, M = 0.2, \frac{U_j}{U_\infty} = 1.0 \)
CRM High-Lift: Inboard Microjet

\( \alpha = 8^\circ, \text{Re}_{\text{MAC}} = 3.26 \times 10^6, M = 0.2, U_j/U_\infty = 1.0 \)

\( y = 277.5 \text{ in} \)

\( y = 638 \text{ in} \)

\( y = 947 \text{ in} \)
CRM High-Lift: Momentum Coefficient Sensitivity

\[ C_{\mu_{\text{effective}}} = \frac{\int \rho u_j u_i n_j dA}{\frac{1}{2} \rho_\infty U_\infty^2 A_{\text{ref}}} \]

\[ \alpha = 8^\circ, \text{Re}_{\text{MAC}} = 3.26 \times 10^6, \text{and } M = 0.2 \]

\[ \Delta C_L \approx 1.66 \sqrt{C_{\mu}} \]

\[ C_{D_{\text{pressure-total}}} = C_{D_i} + C_{D_{\text{pressure-profile}}} \]
CRM High-Lift: Lift and Drag, Inboard Microjet

\[ \text{Re}_{\text{MAC}} = 3.26 \times 10^6, \text{ and } M = 0.2 \]

Conclusions and Contributions

- Proposed microjet as an AFC concept for lift enhancement and separation mitigation for high-lift systems
- Extensive study conducted on the various microjet characteristics in a building block approach (2D to 3D) addressing microjet effects on both lift and drag
- Confirmed that the investigated trailing edge microjets can provide significant control and produce improvements in high-lift characteristics of an airfoil, including
  - Lift enhancement and reduction (modulation in lift curve)
  - Lift enhancement in terms of $\Delta C_l \propto K \sqrt{C_\mu}$
  - Separation mitigation
  - Possible pressure drag reduction
Conclusions and Contributions

• Proposed microjet as an AFC concept for lift enhancement and separation mitigation for high-lift systems.

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• Confirmed that the investigated trailing edge microjets can provide significant improvements in high-lift characteristics:
  • Lift enhancement and reduction (modulation in lift curve)
  • Lift enhancement in terms of $\Delta C_l \propto K \sqrt{C_\mu}$
  • Separation mitigation
  • Possible pressure drag reduction

Conclusions and Contributions
Follow-on Efforts - I

• CFD
  • 3D CRM-HL
    • Investigate the pressure drag behavior
    • Microjet configuration studies
    • Solidity ratio sensitives combined with momentum coefficient sensitivity and pulsed blowing
    • Upper surface blowing
    • Takeoff configuration for reduced flap flow separation
  • Modeling of flap internal flow paths and microjets
    • Predict pressure losses, determine minimum loss configurations
    • Study ram-air options
    • Study hybrid flow (ram-air + pressurized air) options
Follow-on Efforts – II and III

• Wind Tunnel
  • Test at TAMU
  • Use NLR 7301 2-element airfoil model
  • Study focused on jet characteristics and impact on airfoil aerodynamic characteristics
    • Determine characteristics of jet flow, including jet angle, exit pressure and velocity profile, mass flow rate and associated power requirement

• System analysis
  • How best to apply this technology?
  • Synergism - focus has been on high lift but how effective can this system then be in cruise?
  • Aerodynamic load control - tab versus blowing (or both?)
  • Industry involvement

* https://www.nasa.gov/directorates/heo/scan/engineering/technology-txt_accordion1.html
Acknowledgment

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Thank you for listening