LES of high-Reynolds-number Coanda flow separating from a rounded trailing edge of a circulation control airfoil

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Introduction: Circulation Control (CC) airfoil

~ For the next generation of passenger aircraft ~

Circulation control by “Coanda jet”

Jet flow attaches on a rounded trailing edge of an airfoil
→ Circulation is increased
→ Lift is enhanced

CC for Aircraft applications
- Lift enhancement (by single jet-blowing)
- Maneuver support (by dual jet-blowing)

Coanda effect:
The tendency of a fluid jet to stay attached to an adjacent curved wall, named after Henri Coanda

Hydrogen bubble flow visualization of a CC airfoil (NASA LaRC, 2002)

Concept image of hybrid-wing-body aircraft employing CC devices
Introduction: Separation of turbulent Coanda flow

~ A major difficulty in current RANS Simulations ~

Coanda jet over a cylinder
(Exp. by Wygnanski et al.)

- No external flow
- Transitional (K-H vs. Görtler)
- Wall jet
- Coanda surface
- Flow separation

Jet flow characteristics are sensitive to the transition process

Coanda jet over a rounded trailing Edge of a CC airfoil

- Turbulent boundary layer
- Immediate transition to turbulence
- Jet slot
- Coanda surface
- Flow separation

Jet flow develops to fully turbulent at the jet exit
Objectives of the study

1. To investigate detailed physics (flow structures and statistics) of the fully turbulent Coanda jet applied to a CC airfoil, by using LES

2. To compare LES and RANS results to figure out how to improve the performance of existing RANS models for this type of flow
- 20%-thick, non-cambered, elliptic-leading-edge CC airfoil
  (designed by Dr. Englar’s research group at GTRI – currently tested at NASA Langley)

- Two independent jet plenums for the upper and lower sides
  (lower jet slot is closed in this study – may be used for “dual blowing” in future studies)

- Chord Reynolds number: 0.49 million

- Wavy transition strip attached near the leading edge
Numerical methods (LES)

**Incompressible Navier-Stokes solver “CDP”**
(developed at the Center for Turbulence Research, Stanford University)

- Unstructured, finite-volume solver
- Energy-conservative, 2nd-order central difference scheme
- Fully-implicit, 2nd-order time integration scheme
- Dynamic Smagorinsky model for the subgrid-scale (SGS) stresses
- Running on massively parallel supercomputers (256 CPU’s used)
Computational domain & Boundary conditions

Wind tunnel geometry: NASA Langley Basic Aerodynamics Research Tunnel (BART)

Spanwise (periodic) domain size: 14 mm = 0.0641c = 27.8h
- The domain wide enough to study turbulent structures in the Coanda jet
- 3D RANS study has shown little sidewall effects at low jet-blowing case
## Jet blowing conditions (at the jet exit)

<table>
<thead>
<tr>
<th>Jet-blowing rate</th>
<th>$U_j$ [m/s]</th>
<th>$U_{j,\text{max}}$ [m/s]</th>
<th>$Re_j$</th>
<th>$C_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>105.3</td>
<td>$\approx 135$</td>
<td>$\approx 4500$</td>
<td>0.044</td>
</tr>
<tr>
<td>High</td>
<td>173.4</td>
<td>$\approx 216$</td>
<td>$\approx 7200$</td>
<td>0.120</td>
</tr>
</tbody>
</table>

$U_j$ : Bulk jet velocity (mean of the time-averaged velocity profile)

$U_{j,\text{max}}$ : Maximum jet velocity (maximum of the time-averaged velocity profile)

$Re_j$ : Jet Reynolds number ($= U_{j,\text{max}} h / \nu$)

$C_\mu$ : Jet momentum coefficient ($= 2U_j^2 h / U_\infty^2 c$)
Mean flow profiles (at the jet exit)

Streamwise velocity

Reynolds stresses

Jet oscillating due to alternating (von Kármán type) vortex shedding behind the thin jet blade
Computational grids

Multi-block structured grids for the whole domain

3 levels of grids for the Coanda region

(Nθ x Nr x Nz)

Coarse
400 x 160 x 128

Medium
800 x 160 x 128

Fine
800 x 160 x 256

Wavy transition strip

Total number of grid points: 116 million (Fine grid)
Wavy transition strip

Wavy strip directly meshed using multi-block structured grids

- Strip height: 0.56 mm
- Strip width: 3.0 mm
- Wavelength: 7.0 mm
- Amplitude: 2.0 mm
## Grid resolution (Fine grid)

<table>
<thead>
<tr>
<th>Coanda surface</th>
<th>Resolution [mm]</th>
<th>Resolution in wall units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( (\theta = 10^\circ \sim 170^\circ) )</td>
<td>( (\theta = 15^\circ) )</td>
</tr>
<tr>
<td>Chordwise</td>
<td>0.0902</td>
<td>( \approx 95 )</td>
</tr>
<tr>
<td>Wall-normal</td>
<td>0.00127</td>
<td>( \approx 1.4 )</td>
</tr>
<tr>
<td>Spanwise</td>
<td>0.0547</td>
<td>( \approx 55 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Airfoil surface</th>
<th>Resolution [mm]</th>
<th>Resolution in wall units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( (x/c = 0.5) )</td>
<td>( \text{upper, } x/c = 0.5 )</td>
</tr>
<tr>
<td>Chordwise</td>
<td>0.4906</td>
<td>( \approx 70 )</td>
</tr>
<tr>
<td>Wall-normal</td>
<td>0.00254</td>
<td>( \approx 0.4 )</td>
</tr>
<tr>
<td>Spanwise</td>
<td>0.0547</td>
<td>( \approx 7.5 )</td>
</tr>
</tbody>
</table>

SGS eddy viscosity: Up to about 5 times larger than the molecular viscosity \( \mu \) (just downstream of the jet exit, where RANS eddy viscosity is about 40 to 50 \( \mu \))
LES results: Flow around the airfoil

- **Instantaneous streamwise velocity**

- **Time-averaged pressure coefficient**
LES results: Flow around the airfoil

Instantaneous spanwise vorticity

$\Omega_z \frac{h}{U_\infty}$

$y/c$

$x/c$
LES results: Flow around the airfoil

Skin friction coefficient

Coanda surface

Leading edge

Jet-slot exit

Trailing edge

Wavy transition strip

Upper surface

Lower surface

0 0.1 0.9 1

x/c

x/c
**LES results: Self-sustained transition**

Turbulence was sustained with no “inlet disturbances” given in the present LES (disturbances were given to the whole domain only at the initial stage).

**Upper side**
- Spanwise modulation
- Transition to turbulence sustained around $x/c = 0.1$

**Lower side**
- 3D separation behind the strip
- Transition to turbulence sustained around $x/c = 0.4$
LES results: Flow around the jet exit
LES results: Coanda jet profiles

Top: Streamwise velocity
Bottom: Reynolds shear stress
LES results: Vortical flow structures in the Coanda jet

Isosurfaces of $Q$
(2nd Invariant of velocity gradient tensor)
colored based on velocity magnitude
LES results: Backward-tilted hairpin vortices

- Backward-tilted (i.e., head of each hairpin is located upstream of its legs)
- Located above the high-momentum jet flow
- Creating a strong upwash between the legs

→ Lifting the high-momentum flow upward → Turbulent mixing enhanced
Les results: Plots of velocity fluctuations

\( \theta = 30 \) degrees

\[ n/c = 0.0035 \]
LES results: Plots of velocity fluctuations

\[ \theta = 30 \text{ degrees} \]

\[ \frac{n/c}{0.0055} \]

\[ \left( \frac{U_{\theta}}{10U_\infty}, \frac{u_{\theta,\text{rms}}}{U_\theta}, \frac{u_{r,\text{rms}}}{U_\theta} \right) \]

\[ n/c = 0.0055 \]
Comparisons between LES and RANS

Mean pressure distributions

![Diagram showing mean pressure distributions for RANS (S-A), RANS (SST), LES, and Experiments.](image)
Comparisons between LES and RANS

RANS (S-A)                     RANS (SST)                     LES

Jet separation: 75.0 deg.    69.0 deg.    69.5 deg.
Bubble size: 0.058c          0.080c       0.060c
Lift coefficient: 1.85       1.60         1.36
Comparisons between LES and RANS

Streamwise velocity

Reynolds shear stress
Conclusions

High-resolution LES of a turbulent Coanda jet (applied to a circulation control airfoil) was performed and was compared with RANS results

**LES results:**

1. Pressure distributions agreed well with the preliminary experiments
2. Many “backward-tilted” hairpin vortices were observed in the outer shear layer of the jet; the hairpins lift high-momentum flow upward

**Comparisons between LES and RANS:**

3. S-A and SST models predicted a larger circulation and a higher lift, even though SST model predicted a correct jet separation location
4. Both models predicted a smaller jet spreading rate than the LES as the eddy viscosity was too small in the outer shear layer of the jet
Similar but opposite to “forward-tilted” hairpins in boundary-layer flows

Boundary-layer flows: $\partial U/\partial y > 0$
Wall-jet flows: $\partial U/\partial y < 0$