International Conference on Flow Physics and its Simulation
In memory of Prof. Jaw-Yen Yang

CFD Simulation of Serpentine S-Duct
With Flow Control

December 03-05, 2016
National Taiwan University

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Huntington Beach, CA
Outline

- Experimental & CFD Models
  - ONERA test model
  - Overset Grids for Half Model
  - OVERFLOW RANS/URANS

- Validation
  - Surface Pressures
  - Pressure contours at PAI

- Passive Flow Control
  - Effects of VG number, height, and orientation angle
  - Recovery and Distortion

- Active Flow Control
  - Blowing jets model

- Time Accurate Run (URANS)

- Conclusions
S-duct Test Case (serpentine diffuser)
Nomenclature

- Flow in +X direction
- Aerodynamic Interface Plane (AIP)
- Polar angle in circumferential direction ($\Phi$)

Diagram:
- Flow in +X direction
- Aerodynamic Interface Plane (AIP) at X=730.68 mm
- Polar angles: $\Phi=0^\circ$, $\Phi=90^\circ$, $\Phi=180^\circ$
Overset Grid System

- Half model (180 deg)
- 15 grids ~ 27M pts
- Pegasus for interpolation

area ratio=1.52
Overset Grid System

- 4 VGs for half model
- ~1.2 M pts for each VG
- ~11 M pts for VG box

- 18 degree relative to free stream
- 6 mm height
- 24 mm length
- 0.6 mm thickness

- each VG consists 2 grids
Flow Solver/Boundary Conditions

**OVERFLOW (RANS):**
- NASA developed/overset technique
- 3 level multi-grid
- central diff, matrix dissipation
- SST turbulence model

**Boundary Conditions:**
- free stream/characteristic condition
- no-slip adiabatic wall
- symmetry plane
- specify mass flow

Specify mass flow:
- 2.427 kg/s (standard case)
- 1.356 kg/s (optional case)

$M_\infty = 0.01$
Validation – Surface Pressures

Pressure Distribution along the S-duct at $\phi = 0^\circ$, $90^\circ$, and $180^\circ$  
Overset Grid (OVERFLOW)  
The Boeing Company - RANS - SST Turbulence

No VGs

With VGs
Validation – Pressure Contours at AIP

Exp. No VGs

Exp. With VGs

CFD

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Passive Flow Control - VGs
Passive Flow Control - VG Number Effect

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- no VG
- 1 VG
- 2 VGs
- 3 VGs
- 4 VGs
- 5 VGs
- Baseline
# Passive Flow Control - VG Number Effect

<table>
<thead>
<tr>
<th>No VGs</th>
<th>3 VGs</th>
<th>1 VGs</th>
<th>2 VGs</th>
<th>3 VGs</th>
</tr>
</thead>
</table>

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Passive Flow Control - VG Number Effect

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4 VGs (baseline)

5 VGs
Mach contours at different X cut
No VGs vs With VGs (mass flow = 2.427 kg/s)
Passive Flow Control - VG Height Effect

Baseline

VG height 3mm

VG height 4mm

VG height 6mm

VG height 9mm
# Passive Flow Control - VG height Effect

## Engineering, Operations & Technology

<table>
<thead>
<tr>
<th>Height</th>
<th>Image</th>
<th>Image</th>
<th>Image</th>
<th>Image</th>
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<tbody>
<tr>
<td>3mm</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<td>4mm</td>
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<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
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<tr>
<td>6mm baseline</td>
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<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
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<tr>
<td>9mm</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
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</table>

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Passive Flow Control – VG Angle Effect

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VG Angle 8 degree

VG Angle 13 degree

VG Angle 18 degree

VG Angle 28 degree

Baseline
Passive Flow Control - VG Angle Effect

<table>
<thead>
<tr>
<th>VG@ 8 deg</th>
<th>VG@ 13 deg</th>
<th>VG@ 18 deg baseline</th>
<th>VG@ 28 deg</th>
</tr>
</thead>
</table>

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Passive Flow Control - VGs

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- **5X5**
  - S-duct at M4=0.4
  - Orange Grid
  - The Boeing Company/CSULB - RANS - SST Turbulence

- **13X5**
  - Pressure ratio at M4=0.4
  - Blue Grid
  - CSULB - RANS - SST Turbulence

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**Average Recovery**

- **Total number of VGs**
  - At 0, 1, 2, 3, 4, 5

- **Average Recovery**
  - At 0.965, 0.970, 0.975, 0.980, 0.985, 0.990

- **DPCPAVE**
  - At 0.015, 0.020, 0.025, 0.030, 0.035, 0.040

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**Average Recovery vs VG height (mm)**

- **No VGs**
  - VG height: 0, 1, 2, 3, 4, 5

- **No VGs**
  - VG height: 0, 1, 2, 3, 4, 5

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**Average Recovery vs VG angle (deg)**

- **No VGs**
  - VG angle: 0, 15, 30

- **No VGs**
  - VG angle: 0, 15, 30
**Active Flow Control – Surface Blowing Jets**

- Blowing jets applied at surface with pre-defined velocity and direction.
- Jet velocity is controlled by $P/P_\infty$.
- Mass flow rate of the jets is decided by the jet velocity and area it applies.
- Three AFC configurations (areas) each with three different mass flow rate are simulated.
### Active Flow Control – Surface Blowing Jets

<table>
<thead>
<tr>
<th>Surface Blowing Jets</th>
<th>Mach Number</th>
<th>PolHs</th>
</tr>
</thead>
<tbody>
<tr>
<td>60mm² Pt22.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60mm² Pt29.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60mm² Pt36.5</td>
<td></td>
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</tr>
</tbody>
</table>

![Diagram of Active Flow Control](image_url)
Active Flow Control – Surface Blowing Jets
Active Flow Control – Surface Blowing Jets

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240mm² Pt14.6

240mm² Pt22.4

240mm² Pt29.2
Active Flow Control – Surface Blowing Jets

![Graph showing average recovery and DCPA V E against AFC Jet mdot with points for different P/P∞ values and VG recovery and distortion markers.](chart.png)
Active Flow Control – Surface Blowing Jets
Time Accurate Run (URANS)
Time Accurate Results – ONERA S-Duct

AIP Face Recovery

0.9707

SAE DPCPAV for all rings

0.0374

Mach Number

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7

Pt/Pto

0.86 0.88 0.90 0.92 0.94 0.96 0.98 1.00

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**Time Accurate Results – ONERA S-Duct**

**Steady State Results**

- **AIP Face Recovery**: 0.9707
- **SAE DPCPAV**: 0.0347
for all rings

**Time Accurate Averaged**

- **AIP Face Recovery**: 0.9691
- **SAE DPCPAV**: 0.0231
for all rings
Conclusions

- CFD simulation using Overset grid approach is conducted for serpentine S-duct with and without VGs
- CFD results are validated with experimental data
- VG configurations include VG number, height, and orientation angle are simulated and studied
- Recovery and circumferential distortion are computed to measure flow quality
- CFD based AFC technique is employed to improve the flow quality
- AFC offers better improvement relative to passive control
Back Up Charts
**Validation – Turbulence Model**

*Pressure Distribution along the S-duct at $\phi = 0^\circ$, 90$^\circ$, and 180$^\circ$*

*Overset Grid (OVERFLOW)*

*The Boeing Company - Turbulence Model Study*
Results – Symmetric Plane Mach and Pi/Pio Contours

No VGs vs With VGs (mass flow = 2.427 kg/s)
Results – AIP Mach and Pi/Pio Contours
No VGs vs With VGs (mass flow = 2.427 kg/s)
Results – Mach contours at different X cut
No VGs vs With VGs (mass flow = 2.427 kg/s)
Results – Mach contours at different X cut
No VGs vs With VGs (mass flow = 2.427 kg/s)
Results – Mach contours at different X cut
No VGs vs With VGs (mass flow = 2.427 kg/s)
Results – Pi/Pio Contours at different X cut

No VGs vs With VGs (mass flow = 2.427 kg/s)

No VGs

With VGs
Results – Pi/Pio Contours at different X cut

No VGs vs With VGs (mass flow = 2.427 kg/s)
Results – Pi/Pio Contours at different X cut
No VGs vs With VGs (mass flow = 2.427 kg/s)

No VGs

With VGs
Results – Mach & Pi/Pio Contours

No VGs (mass flow = 2.427 kg/s)
Results – Mach & Pi/Pio Contours
With VGs (mass flow = 2.427 kg/s)
Results – BL Profiles (x=-76.58 mm)
VGs vs No VGs (mass flow = 2.427 kg/s)

Φ = 0°
Φ = 90°
Φ = 180°
Results – BL Profiles (x=-76.58 mm)

No VGs (mass flow = 2.427 kg/s)
Results – AIP Mach Contours

No VGs vs With VGs (mass flow = 2.427 kg/s)

No VGs

With VGs
Results – AIP Pi/Pio Contours

No VGs vs With VGs (mass flow = 2.427 kg/s)
Passive Flow Control - VGs

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3 VGs, 6mm height, 18 deg

4 VGs, 4mm height, 18 deg

4 VGs, 6mm height, 13 deg
Passive Flow Control - VGs

No VGs,

4 VGs, 9mm height, 18 deg

4 VGs, 6mm height, 28 deg
Results – Mach & Pi/Pio Contours

Standard Case (mass flow = 2.427 kg/s)

- S-duct at M\(\lambda\) = 0.4
  - Overset Grid
  - The Boeing Company/CSULB - RANS - SST Turbulence

\[ P_{ave} = 0.97091 \]

\[ 5\times 5 = 25 \text{ data points} \]

\[ P_{ave} = 0.97327 \]  
\[ (\sim 0.24\%) \]

\[ 13\times 5 = 65 \text{ data points} \]

\[ P_{ave} = 0.97278 \]  
\[ (\sim 0.19\%) \]
Active Flow Control – Surface Blowing Jets

Jet Surface Area ~ 240 mm²

Jet Surface Area ~ 120 mm²

Jet Surface Area ~ 60 mm²
Active Flow Control – Surface Blowing Jets

The graph illustrates the relationship between average recovery and AFC jet mdot (mass flow rate) for different values of $P/P_o$. The graph shows lines with markers for $P/P_o = 2.5$, $P/P_o = 2.0$, and $P/P_o = 1.5$. The graph also highlights that 1.5% of the total mdot is a significant parameter in this context.
Passive vs Active Flow Control
Passive vs Active Flow Control

3 VGs
Recovery = 0.9777
DPCP_ave=0.0216

60 mm², P/P₀=1.5
Recovery = 0.9779
DPCP_ave=0.0296

120 mm², P/P₀=2.0,
Recovery = 0.9822
DPCP_ave=0.0207