Use of Vortex Generators to Reduce Distortion for Mach 1.6 Streamline-Traced Supersonic Inlets

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Objectives

**Main Objective:** Reduce the total pressure distortion at the engine-fan face due to low-momentum flow caused by the interaction of an external terminal shock at the turbulent boundary layer along a streamline-traced external-compression (STEX) inlet for Mach 1.6.

**Approach:** Incorporate passive devices (vortex generators) to generate vortices to mix the higher-momentum core flow with the low-momentum flow of the boundary layer.

**Key Questions to Answer:**
- What type of vortex generators work well for STEX inlets?
- What geometric properties of the vortex generators work well?
- How much can distortion reduced with vortex generators?
STEX Inlet Design

- Freestream of Mach 1.664 corresponds to NASA Glenn 8x6-foot wind tunnel condition.
- Engine-fan face of diameter $D_2 = 0.9793$ feet with a spinner and Mach number of $M_2 = 0.4776$ based on scaled GE F404 engine.
- Supersonic diffuser created by streamline-tracing of a circular cross-section through an axisymmetric, inward-turning, Otto-ICFA-Busemann flowfield with an outflow of Mach 0.90.
- Subsonic cowl lip cut-out allows subsonic spillage for terminal shock stability.
- Axisymmetric subsonic diffuser.
- SUPIN was used to design the inlet and create the geometry.
Baseline STEX Inlet Performance

- At Mach 1.664, MIL-E-5008B estimates total pressure recovery at $p_{t2}/p_{t0} = 0.9521$.
- SUPIN: $p_{t2}/p_{t0} = 0.9336$, $W_2/W_0 = 1.0000$, $C_{Dwave} = 0.0162$.
- Wind-US: $p_{t2}/p_{t0} = 0.9339$, $W_2/W_0 = 0.9717$, $C_{Dwave} = 0.03627$, IDC = 0.0851, IDR = 0.1036
Vortex Generators: Vane-Type

- Explore vane-type VGs.
- Design parameters:
  - $L_{vg}$, Length (ft)
  - $h_{vg}$, Height (ft)
    - Traditional VGs
    - Micro-VGs
  - $AR_{vg}$, Aspect ratio ($h/L$)
  - $\phi_{vg}$, Angle of incidence (deg)
  - $s_{vg}$, Spacing (ft)
  - $x_{vg}$, Axial placement of vane center (ft)
Vortex Generators: Ramp-Type

- Explore ramp-type VGs.
- Design parameters:
  - $b_{vg}$, Width of the base (ft)
  - $L_{vg}$, Length (ft)
  - $h_{vg}$, Height (ft)
  - $d_{vg}$, Width of trailing edge (ft)
  - $AR_{vg}$, Aspect ratio ($h/L$)
  - $\phi_{vg}$, Angle of incidence (deg)
  - $s_{vg}$, Spacing (ft)
  - $x_{vg}$, Axial placement of ramp center (ft)
CFD Analysis

- Wind-US, steady-state RANS solver.
- SST turbulence model
- Multi-block, structured grid
- 2-15 million grid points.
- $\Delta y^+ \approx 1$.

Outflow is modeled with an outflow converging-diverging nozzle or a Mach number boundary condition to back-pressure the inlets.
Preliminary VG Study: 2D Inlet

Simplification of STEX inlet to 2D inlet for a preliminary study:

- Rectangular Duct
- Inviscid Sidewalls
- No corner flows

**Objective:**
- Study vane-type and ramp-type flow controls within the 2D inlet for the improvement of the total pressure recovery and reduction of total pressure distortion.

**Observation:**
- Implementation of vanes on the 2D inlet show overall more improvement in the AIP boundary layer compared to ramps.

**Comparison study:**
- Best performing vane of the inlet was compared to a BAY model.
Flow control study on 2D inlet

<table>
<thead>
<tr>
<th>Case</th>
<th>c/h</th>
<th>s/h</th>
<th>DIST</th>
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<tbody>
<tr>
<td>Baseline</td>
<td>-</td>
<td>-</td>
<td>0.1916</td>
</tr>
<tr>
<td>Anderson</td>
<td>7.2</td>
<td>7.5</td>
<td>-</td>
</tr>
<tr>
<td>DV1</td>
<td>4.2</td>
<td>6.0</td>
<td>0.1834</td>
</tr>
<tr>
<td>DV2</td>
<td>3.7</td>
<td>8.3</td>
<td>0.1885</td>
</tr>
<tr>
<td>DR1</td>
<td>5.5</td>
<td>13.4</td>
<td>0.1863</td>
</tr>
<tr>
<td>DR2</td>
<td>6.6</td>
<td>10.8</td>
<td>0.1910</td>
</tr>
<tr>
<td>UV1</td>
<td>2.1</td>
<td>12.5</td>
<td>0.1862</td>
</tr>
<tr>
<td>UV2</td>
<td>2.0</td>
<td>12.5</td>
<td>0.1866</td>
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<tr>
<td>UR1</td>
<td>5.5</td>
<td>31.3</td>
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</tr>
<tr>
<td>UR2</td>
<td>4.3</td>
<td>25.3</td>
<td>0.1905</td>
</tr>
</tbody>
</table>

Upwash:

Downwash:
Flow control study on 2D inlet

- Total Pressure Recovery vs Inlet Flow Ratio
- DPR/P² vs DPC/P²
- Baseline Inlet
- VG Cases: Critical
- VG Cases: Supercritical
US Vane Study on 2D inlet

\[ \Delta x/h \]

0
7
13
20
27
33
40
47
53
60
67
73
80

NSBLI

M
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1

wx [1/s]
1000
750
500
250
0
-250
-500
-750
-1000
DS Vane Study on 2D inlet

Grid Resolution Study

- Grid I: Coarest spacing. Equivalent to Baseline.
- Grid II: One-half spacing of Grid I.
- Grid III: One-third spacing of Grid II.
- Grid IV: Finest spacing. Equivalent to Gridded Vanes.

Peak Vorticity Profiles of Case Dr

- Gridded Model
- Bay Model - Grid 1
- BAY Model - Grid 2
- BAY Model - Grid 3
- BAY Model - Grid 4

Δx/h

0 15 30 45 60 75 91 106 121

BAY Model
Gridded Vanes

u/\text{u}_{\text{inf}}: 0.05 0.1 0.15 0.2 0.25 0.3 0.35
Study of VGs in the STEX Inlet

- Study vane-type flow control within the STEX inlet for the improvement of the total pressure recovery and reduction of total pressure distortion.

- Objectives include:
  - Discern significant differences between upstream and downstream vanes (ahead or downstream of the terminal shock).
  - Discern significant differences between counter-rotating vanes and co-rotating vanes.
  - Quantify significant relationships between vane geometry factors (height, length, spacing, angle, position).

- Responses: 1) Total pressure recovery at AIP (cane curve), 2) IDC and IDR.
Preliminary Study of VGs on the External Supersonic Diffuser

28 vanes
Height comparable to the sonic height
\( \frac{h}{L} \approx 0.275 \)
\( \frac{h}{\delta} \approx 0.359 \)

\[
\begin{align*}
\frac{w_2}{w_0} &= 0.9710 \\
\frac{p_{t2}}{p_{t0}} &= 0.9343 \\
IDC &= 0.0857 \\
IDR &= 0.0976
\end{align*}
\]

\[
\begin{align*}
\frac{w_2}{w_0} &= 0.9615 \\
\frac{p_{t2}}{p_{t0}} &= 0.9235 \\
IDC &= 0.0891 \\
IDR &= 0.1054
\end{align*}
\]

\[
\begin{align*}
\frac{w_2}{w_0} &= 0.9648 \\
\frac{p_{t2}}{p_{t0}} &= 0.9280 \\
IDC &= 0.1166 \\
IDR &= 0.0800
\end{align*}
\]
Preliminary Study of VGs in the Subsonic Diffuser

- Started exploring vanes in subsonic diffuser using BAY model of Wind-US.
- Vanes of local boundary layer height (0.381 inches). Aspect ratio is 2.0.
- Solution U1.N852.
Two-Level Fractional Factorial Design

o Vane-type VGs
o Distribute VGs about upper 70% of the inner circumference of inlet.
o Height of the vanes will vary along the circumference of the diffuser to keep proportional to local boundary layer.

o Use outflow nozzle setting of Baseline U1 inlet at the critical point (U1N851).

o Use BAY model of Wind-US.

o Four groupings:

i. Downstream. Con-Div Pairs.
iii. Upstream. Con-Div Pairs.

Factors (i. Downstream. Con-Div Pairs.)

1) $x_{VG}$ (ft): 0.4264, 0.8038
2) $(h/\delta)_{VG}$ : 0.5, 1.0
3) $\alpha_{VG}$ (deg): 8 deg, 16 deg
4) $(L/h)_{VG}$ : 2, 3
5) $(s/h)_{VG}$ : 3, 5

Responses

1) Flow Ratio
2) Total Pressure Recovery
3) Distortion (IDC, IDR)

$2^{5-2}$ Design uses 8 runs to establish main effects
Quarter-Fractional Factorial Design $2^{k-2}_{III}, k = 5$

- Fractional Factorial Design consists of 8 Runs & 5 Factors to establish main effects:

<table>
<thead>
<tr>
<th>Runs</th>
<th>Zone</th>
<th>h/δ</th>
<th>L/h</th>
<th>s/h</th>
<th>Counter-Rotating $\alpha$ (°)</th>
<th>Co-Rotating $\alpha$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>US</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>-/+ 16</td>
<td>- 16</td>
</tr>
<tr>
<td>#2</td>
<td>DS</td>
<td>0.5</td>
<td>2</td>
<td>3</td>
<td>-/+ 8</td>
<td>- 8</td>
</tr>
<tr>
<td>#3</td>
<td>DS</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>-/+ 8</td>
<td>- 8</td>
</tr>
<tr>
<td>#4</td>
<td>US</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>-/+ 8</td>
<td>- 8</td>
</tr>
<tr>
<td>#5</td>
<td>US</td>
<td>0.5</td>
<td>3</td>
<td>5</td>
<td>-/+ 8</td>
<td>- 8</td>
</tr>
<tr>
<td>#6</td>
<td>US</td>
<td>0.5</td>
<td>3</td>
<td>3</td>
<td>-/+ 16</td>
<td>- 16</td>
</tr>
<tr>
<td>#7</td>
<td>DS</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>-/+ 16</td>
<td>- 16</td>
</tr>
<tr>
<td>#8</td>
<td>DS</td>
<td>0.5</td>
<td>2</td>
<td>5</td>
<td>-/+ 16</td>
<td>- 16</td>
</tr>
</tbody>
</table>

- Two-Level Operators:

  "Low" operator:
  "High" operator:

<table>
<thead>
<tr>
<th>Zone</th>
<th>h/δ</th>
<th>$\alpha$ (°)</th>
<th>L/h</th>
<th>s/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>0.5</td>
<td>8</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>DS</td>
<td>1</td>
<td>16</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

- Responses:
  o Response I: Total Pressure Recovery
  o Response II: Circumferential distortion descriptor
  o Response III: Radial tip distortion descriptor

**Abbreviations**

US: Upstream
DS: Downstream
Fractional Factorial Design for Vane-Type VGs

**Grid Interpolation to Bay Model:**

- Reference Data
- Interpolation onto Grid
- Interpolation in Streamwise Direction
  - Interpolation in Angular Direction
  - Interpolation in Radial Direction
- Numerical Estimation
- Polar/Cartesian to Vector Conversion
- Interpolation (with Reference Data)

**Abbreviations**
- US: Upstream
- DS: Downstream

**Notes:**
- VG heights vary along the circumference of the diffuser to keep proportional to local boundary layer.

**VGs distributed about upper 70% of inner circumference**

30% station

U1.N852
(No VGs)
Fractional Factorial Design Study @ AIP

<table>
<thead>
<tr>
<th>Run #</th>
<th>h/δ</th>
<th>s/h</th>
<th>c/h</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run #1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>-16</td>
</tr>
<tr>
<td>Run #2</td>
<td>0.5</td>
<td>3</td>
<td>2</td>
<td>-8</td>
</tr>
<tr>
<td>Run #3</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>-8</td>
</tr>
<tr>
<td>Run #4</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>-8</td>
</tr>
<tr>
<td>Run #5</td>
<td>0.5</td>
<td>3</td>
<td>3</td>
<td>-16</td>
</tr>
<tr>
<td>Run #6</td>
<td>0.5</td>
<td>3</td>
<td>3</td>
<td>-16</td>
</tr>
<tr>
<td>Run #7</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>-16</td>
</tr>
<tr>
<td>Run #8</td>
<td>0.5</td>
<td>5</td>
<td>2</td>
<td>-16</td>
</tr>
</tbody>
</table>

Co-Rotating Vanes

Counter-Rotating Vanes
Height seems to have greatest effect. The points group according to height. “Outliers” have 8° angle in common.

Height seems to have greatest effect. The points group according to height. “Outliers” have 8° angle in common.
Circumferential Distortion, *IDC*

Radial Tip Distortion, *IDR*

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F404-GE-400 Limit

- U1. No VGs. No Bleed.
- U1. DOEa. *h_vg* = 50%.
- U1. DOEa. *h_vg* = 75%.
- U1. DOEa. *h_vg* = 100%.
- U1.DOEa.10

Height seems to have greatest effect, but 100% height aggravated circumferential distortion and 50% height had little effect on radial distortion.
Conclusions and Future Plans

• Explore the use of flow control devices within the inlet.
• Continue to work on the DOE of vane-type VGs in a converging-diverging pattern that will explore height, aspect ratio, and spacing for one nozzle setting. Response variables will be flow ratio, total pressure recovery, IDC and IDR.
• Explore interactions between different factors.
• Explore unsteady (DES) simulation of inlet flow with and without VGs.