Design Optimization for Boundary-Layer Ingesting Inlet on Overset Grid System

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Outline

• Background & Motivation
  – Physics of Boundary-Layer-Ingesting Inlet
  – Previous Design Works for Offset Inlets
• Definition of Problem & Grid System
• Design Applications
  – Prevention of Boundary Layer Growth
  – Design Exploration of Vortex Generators*
• Concluding Remarks

*Optimization process using meta-model-assisted MOGA and data-mining process are carried out with the help of Dr. T. Kumano
Background and Motivation

• Physics of Boundary-Layer-Ingestion Offset Inlet
  – The N+2B configuration
    • Flush-mounted propulsion system
  – Features
    • Reduction of
      - Ram drag
      - Structural weight
      - Wetted area
      - Noise
  – Drawbacks
    • Boundary Layer Ingestion
    • Separation and Swirling Flow

30% Boundary Layer Ingestion

Lip Separation

AIP Station

Non-Uniform Flow

N+2B Concept Configuration
Background and Motivation

• Recent Design Works for Offset Inlets
  – Conventional S-shaped Inlets
  – BLI Offset Inlets

Passive Flow Control using VGs
Flow Control with VGs for Offset inlet
Effect of VGs for BLI inlet
• **Goals**
  – Flow control for high performance BLI inlet via optimal design approaches on overset mesh system
  – Prevention of abrupt boundary layer growth by surface design
    • High DOF design
    • Gradient based optimization using adjoint method
  – Design exploration of VG configuration
    • Single or Multi-objective GA based on Surrogate model
    • *Data-mining for guidance and physical insight* in VG design to define size, orientation and position of individual VGs
Flow Analysis

• Geometry of Baseline Model

\[ H_{bl} = 0.35D_c \]
\[ D_c = 1.942 \]
\[ H_i = 1.703 \]
\[ a = 0.477 \]
\[ L = 7.697 \]

\[ C_r = A_c / A_2 = 0.9346 \]
\[ A_2 / A_i = 1.070 \]
\[ A_c = 5.760 (\text{in}^2) \]

• Geometric Information of VGs

<table>
<thead>
<tr>
<th>Specification of Baseline VGs (Optimized by Allan et al.)</th>
<th>Bottom VGs</th>
<th>Side VGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h ) (in.)</td>
<td>0.181</td>
<td>0.163</td>
</tr>
<tr>
<td>( c ) (in.)</td>
<td>0.367</td>
<td>0.367</td>
</tr>
<tr>
<td>( \alpha ) (°)</td>
<td>12.94</td>
<td>11.54</td>
</tr>
<tr>
<td>( d ) (in.)</td>
<td>0.216</td>
<td>0.30</td>
</tr>
<tr>
<td>( y_1, y_2 ) (in.)</td>
<td>0.246</td>
<td>0.721</td>
</tr>
<tr>
<td>( x_{le} ) (in.)</td>
<td>1.224</td>
<td>1.224</td>
</tr>
</tbody>
</table>
• The Overset Mesh System
  • Components (14 million pts.)
    – 5 body fitted blocks (6.3 million pts.)
      • Duct Surface, Entrance Collar, Lip Collar, Cover, VG box
    – 6 Background blocks (1.7 million pts.)
    – 12 VG Blocks (0.5 million pts. per each VG)

• Time cost for a flow analysis
  – 340 cores on NAS Pleiades-Westmere
  – 5 hrs. for preprocessing
  → Needs the parallel algorithm for speed-up
  – 16 hrs. for flow analysis
Grid Modification I

- **Grid Modification Strategy for Surface Shaping**
  - 468 control points for flexible geometric change
  - Modification of overset grids are carried out by using mapping from physical domain to spline domain.

Surface modification using control points

Modification of surface and volume grids of overset blocks
## Grid Modification II

- Schematics for Displacement of VG blocks

<table>
<thead>
<tr>
<th>Pre-made VG Block</th>
<th>Displacement</th>
<th>Rotation and Projection</th>
<th>Displaced VG Block</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Pre-made VG Block" /></td>
<td><img src="image2" alt="Displacement" /></td>
<td><img src="image3" alt="Rotation and Projection" /></td>
<td><img src="image4" alt="Displaced VG Block" /></td>
</tr>
</tbody>
</table>

Duct Surface

Example for distributed VGs
Hole-searching and Domain connectivity

• Hole-cutting
  – Hole-searching around zero-thickness VGs by distance measuring

• Domain Connectivity
  – Sub-cell TFI for surface orphan cells
  – No overlap optimization (but considering CDP)
  → Trimmed approach for inlet geometries except the region around VG blocks

Hole cutting at Vane Box grid
Flow Analysis

• Numerical Schemes
  - Governing Eqns.: 3-Dimensional RANS
  - Turbulence Model: $k-\omega$ SST
  - Spatial Discretization: MUSCL with TVD limiter for high order spatial accuracy
  - Time Integration: LU-SGS
  - Parallel Computation: MPI

• Boundary Conditions
  - Inflow Condition
    - Boundary layer profiles are evaluated by CFD solution of turbulent flat plate flow. (35% BLI with respect to the height of inlet highlight)
    - $M=0.85$, $Re#=3.8\text{mil.}$
    - Extension of computational domain: $-20 \leq x/D_2 \leq 20$
  - Outflow condition (Outlet of Inlet)
    - Specify the static pressure to match desired MFR
    - Use Chung and Cole (1995) formula to give initial estimate of static pressure
Performance Metrics

• Inlet Flow Distortion
  – Spatial variation in the total pressure contour at AIP (Aerodynamic Interface Plane).
    • Increase high cycle fatigue on fan blades.
    • Reduced compressor stability margin.
    • Causes engine surge (stall)

• SAE average circumferential distortion

\[
DPCP_{avg} = \frac{1}{N_{rings}} \sum_{i=1,5} (P_{t,avg,i} - P_{t,low,avg,i}) / P_{t,avg,i}
\]

\[
N_{rings} = 5 \quad : \text{Number of Rings}
\]

\[
P_{t,avg,i} \quad : \text{Average of Total Pressure for } i^{th} \text{ ring}
\]

\[
P_{t,low,avg,i} \quad : \text{Average of } P_{t,n,i} (\leq P_{t,avg,i}) \text{ at } i^{th} \text{ ring}
\]

SAE Standard 40-Probe Rakes (Area Weighted)
Optimization Case I
Prevention of Boundary Layer Growth

- Sensitivity Analysis
- Definition of Design Problem
- Results & Discussion
Sensitivity Analysis

- Discrete Adjoint Formulation for Overset Mesh System
  - Computational time cost is independent of number of design variables

- Objective Function

\[ f(Q_i, Q^F_i, X_i, X^F_i, D; i = 1, 2, \cdots) \quad F: \text{Fringe Cell} \]

- Residuals

\[ R_i \left( Q_i, Q^F_i, X_i, D \right) = 0 \quad R^F_i \left( Q^F_i, (1 - \delta_{i,j})Q_j, X^F_i, D \right) = 0 \]

- Sensitivity

\[
\frac{df}{dD} = \sum_i \left[ \frac{\partial f}{\partial Q_i} \frac{dQ_i}{dD} + \frac{\partial f}{\partial Q^F_i} \frac{dQ^F_i}{dD} + \frac{\partial f}{\partial X_i} \frac{dX_i}{dD} + \frac{\partial f}{\partial X^F_i} \frac{dX^F_i}{dD} + \frac{\partial f}{\partial D} \right]
\]
Sensitivity Analysis

- Discrete Adjoint Formulation for Overset Mesh System
  - Sensitivity Equations combined with Residual Constraints

\[
\frac{df}{d\mathbf{D}} = \sum_i \left\{ \left[ \frac{\partial f}{\partial \mathbf{Q}_i} + \Lambda_i \frac{\partial \mathbf{R}_i}{\partial \mathbf{Q}_i} + (1 - \delta_{i,j}) \Lambda_j^F \frac{\partial \mathbf{R}_j^F}{\partial \mathbf{Q}_i} \right] \frac{d\mathbf{Q}_i}{d\mathbf{D}} + \left[ \frac{\partial f}{\partial \mathbf{Q}_i^F} + \Lambda_i \frac{\partial \mathbf{R}_i}{\partial \mathbf{Q}_i^F} + \Lambda_i^F \frac{\partial \mathbf{R}_i^F}{\partial \mathbf{Q}_i^F} \right] \frac{d\mathbf{Q}_i^F}{d\mathbf{D}} \right\}
\]

- Formulations of Adjoint Equations

\[\Lambda_1 \frac{\partial \mathbf{R}_1}{\partial \mathbf{Q}_1} + \Lambda_2 \frac{\partial \mathbf{R}_2^F}{\partial \mathbf{Q}_1} = - \frac{\partial f}{\partial \mathbf{Q}_1}\]

\[\Lambda_1 \frac{\partial \mathbf{R}_1}{\partial \mathbf{Q}_1^F} + \Lambda_2^F \frac{\partial \mathbf{R}_2}{\partial \mathbf{Q}_1^F} = - \frac{\partial f}{\partial \mathbf{Q}_1^F}\]

\[\Lambda_1^F \frac{\partial \mathbf{R}_1^F}{\partial \mathbf{Q}_2} + \Lambda_2 \frac{\partial \mathbf{R}_2}{\partial \mathbf{Q}_2} = - \frac{\partial f}{\partial \mathbf{Q}_2}\]

\[\Lambda_1^F \frac{\partial \mathbf{R}_1^F}{\partial \mathbf{Q}_2^F} + \Lambda_2^F \frac{\partial \mathbf{R}_2^F}{\partial \mathbf{Q}_2^F} = - \frac{\partial f}{\partial \mathbf{Q}_2^F}\]
Design Optimization - Case I

– Design Formulation
  Minimize : \( DPCP_{avg} \)
  Subject to : \( |\Delta z_i| \leq z_L \)
  \( z_i \) : \( z \) coordinate of \( i^{th} \) control point
  \( z_L \) : limit of design variable (10% of \( D_c \))

– Design Condition
  • \( M=0.85, \ Re# = 3.8 \text{mil.}, A_0/A_c = 0.533 \)
  • BLI thickness : 35% of Inlet Height

– Design Variables
  • Control Points of B-Spline Patch

– Design Tools
  • Gradient Based Optimization
  • Optimizer : BFGS (Broyden-Fletcher-Goldfarb-Shanno)
  • Sensitivity Analysis : Discrete Adjoint Method

Flow Chart of GBOM
Design Optimization - Case I

- **Design History**
  - Simultaneous improvements of total pressure recovery and distortion.
  - Fundamental change of core region of low total pressure region.

![Graph showing Total Pressure Recovery and DPCP changes over Design Iterations]

- Total Pressure Recovery increases by 3.25%
- DPCP decreases by 51.52%
Design Optimization - Case I

- Comparison of Flow Patterns
  - Uniform flow at bottom surface (reduction of secondary flow)
  - Decrease of the size of lip separation

Baseline Model

Optimized Model

Total Pressure Contour and Streamlines
Design Optimization - Case I

- Flow Patterns Corresponding to Geometric Change

Magnified view of streamlines near inlet throat on plane $y/D_2=0.5$, Revealing a valley following a mild peak and preceding a major one.
Design Optimization - Case I

- Flow Pattern Change

Comparison of boundary layer thicknesses and shape factor on symmetry plane.
Optimization Case II
Design Exploration of VG Configuration

\[ a = 0.477 \]
\[ L = 7.697 \]
\[ H_i = 1.703 \]
\[ 0.6L \]
Design Objectives
- Maximize total pressure recovery
- Minimize distortion (DPCP)

Design Condition
- $M=0.85$, $Re#=3.8\text{mil.}$, $A_0/A_c=0.509$
- BLI thickness: 35% of Inlet Height

Design Variables
- Position of VGs (24 DVs)
- Inclination angle of VGs (12 DVs)
- Height and length of VGs (4 DVs)

Design Tools
- Kriging model-assisted MOGA
  - Initial Sample Points: Latin hyper cube approach
  + Additional sample points for maximum Expected Improvement.
Design Optimization - Case II

- Self Organizing Maps from initial sample points

<table>
<thead>
<tr>
<th>PR</th>
<th>DPCP</th>
<th>Length - Bottom VGs</th>
<th>Height - Bottom VGs</th>
<th>Length - Side VGs</th>
<th>Height - Side VGs</th>
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<tr>
<td>$L_B$</td>
<td>?</td>
<td>0<del>0.2 (0.18</del>0.252)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_B$</td>
<td>?</td>
<td>0.2<del>0.4 (0.144</del>0.198)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_S$</td>
<td>?</td>
<td>0.7<del>1.0 (0.432</del>0.54)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_S$</td>
<td>?</td>
<td>0<del>0.2 (0.08</del>0.128)</td>
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Guideline for VG sizing

$L_B$ : Length of Bottom VGs
$H_B$ : Height of Bottom VGs
$L_S$ : Length of Side VGs
$H_S$ : Height of Side VGs
Design Optimization - Case II

- Distribution of initial samples and predicted Pareto front
Design Optimization - Case II

• Investigation of optimal designs
  (i) Optimal Point 1: $PR = 0.9711$, $DPCP = 0.01598$
  Bottom VGs: $h = 0.2148$ (in.), $c = 0.1904$ (in.)
  Side VGs: $h = 0.1442$ (in.), $c = 0.4166$ (in.)
Design Optimization - Case II

- Investigation of optimal designs
  (i) Optimal Point 1: $PR = 0.9711$, $DPCP = 0.01598$
  Bottom VGs: $h = 0.2148$ (in.), $c = 0.1904$ (in.)
  Side VGs: $h = 0.1442$ (in.), $c = 0.4166$ (in.)
Investigation of optimal designs

(ii) Optimal point 2: PR = 0.9694, DPCP = 0.01501
Bottom VGs: \( h = 0.2157 \text{ (in.)}, \ c = 0.2393 \text{ (in.)} \)
Side VGs: \( h = 0.0945 \text{ (in.)}, \ c = 0.4281 \text{ (in.)} \)
Design Optimization - Case II

• Investigation of optimal designs
  (ii) Optimal point 2: \( PR = 0.9694,\ DPCP = 0.01501 \)
  Bottom VGs: \( h = 0.2157 \) (in.), \( c = 0.2393 \) (in.)
  Side VGs: \( h = 0.0945 \) (in.), \( c = 0.4281 \) (in.)
Conclusion

- VG design for BLI inlet with a high-fidelity flow analysis on overset mesh system.
  - Through design applications for BLI inlet, the capability of overset mesh system for positioning of parts is successfully demonstrated.

- Prevention of abrupt growth of boundary layer
  - Gradient-based optimization approach using discrete adjoint method for extended design space to find out a new geometry with less information about the flow field for the surface design.
  - Simultaneous improvement in distortion and total pressure recovery.

- Design exploration of VG configuration
  - The positioning of individual VG showed a potential for further improvement in performance.
  - The guideline of VGs design is obtained through data-mining.
## Conclusion

- Guidelines for VG design.

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<th>DPCP</th>
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<td>0~0.2</td>
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<td>$H_B$</td>
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<td>(0.08~0.128)</td>
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**Guideline for VG sizing**

- **$L_B$**: Length of Bottom VGs
- **$H_B$**: Height of Bottom VGs
- **$L_S$**: Length of Side VGs
- **$H_S$**: Height of Side VGs

1. Long chord length and short height of side VGs
2. Short chord length and medium height of bottom VGs

Mixing at the top

Flow mixing from the juncture flow

Mixing at the bottom

Thin low total pressure layer

**Bottom Wall**

**Side Wall**

![Diagram](image-url)
Future Plan

- Design of hybrid wing/body configuration and embedded BLI-inlet
Thank you for your attention