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

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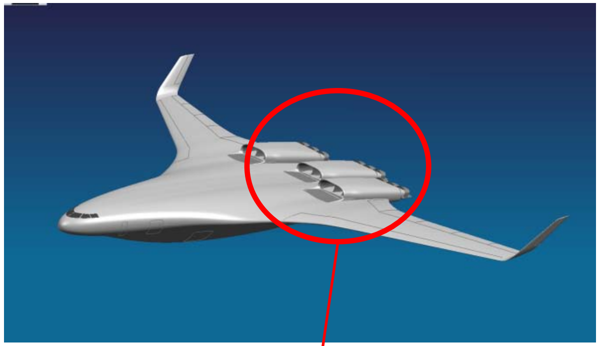
Outline

- 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

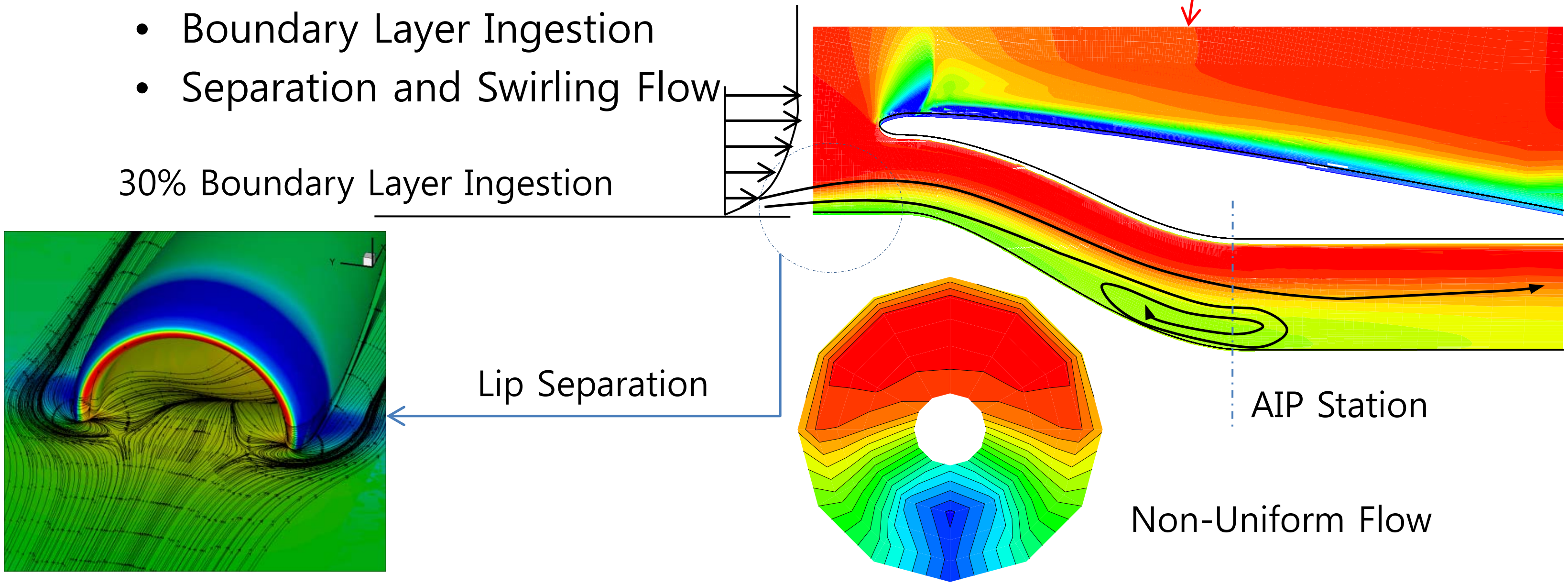
*Optimization process using meta-model-assisted MOGA and data-mining process are carried out with the help of Dr. T. Kumano

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

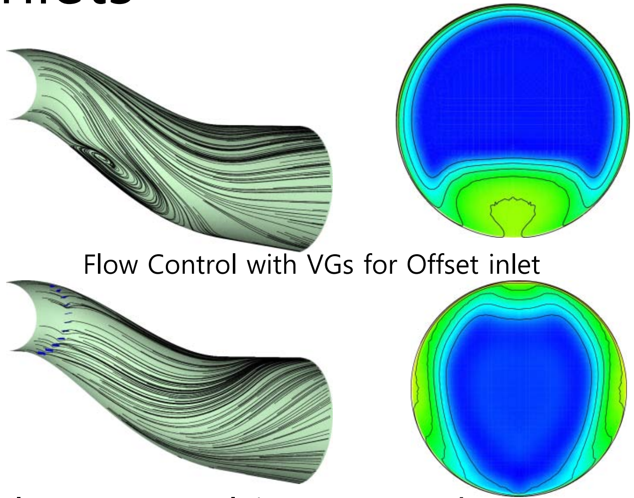


N+2B Concept Configuration



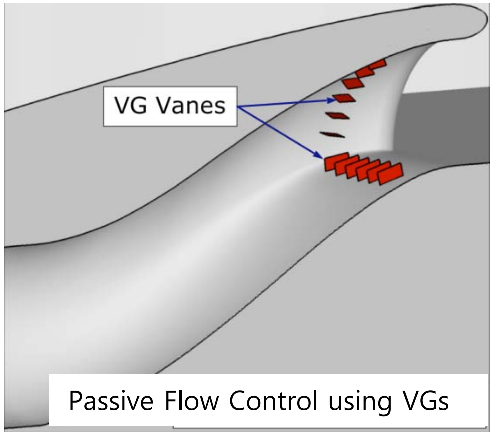
Background and Motivation

- Recent Design Works for Offset Inlets
  - Conventional S-shaped Inlets
    - A. Jirasek, "Development and Application of Design Strategy for Design of Vortex Generator Flow Control in Inlets", AIAA 2006-1050

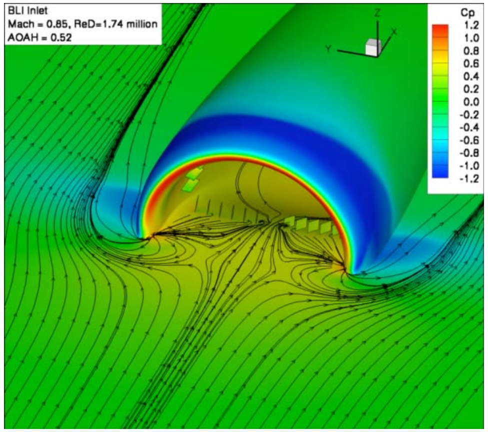


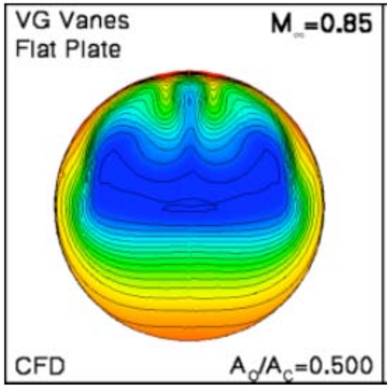
Flow Control with VGs for Offset inlet

  - BLI Offset Inlets
    - B.G.Allan *et al.*, "Numerical Modeling of Flow Control in a Boundary-Layer-Ingesting Offset Inlet Diffuser at Transonic Mach Numbers", AIAA 2006-845



Passive Flow Control using VGs





Effect of VGs for BLI inlet

Background and Motivation

- Goals
  - Flow control for high performance BLI inlet via optimal design approaches on overset mesh system

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  - 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

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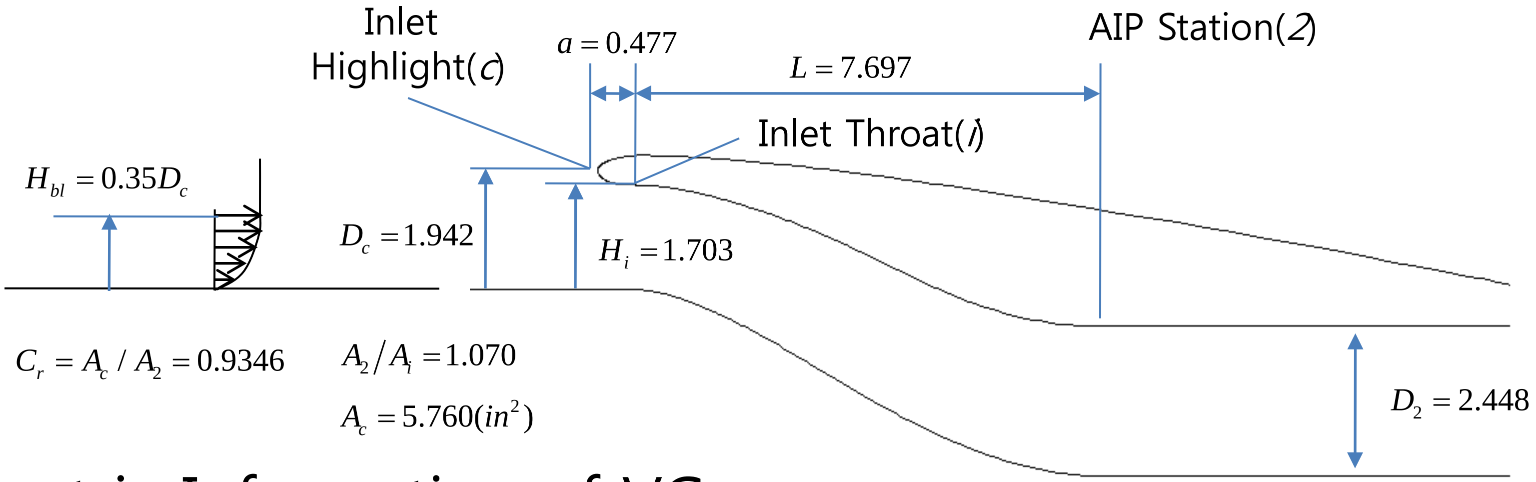
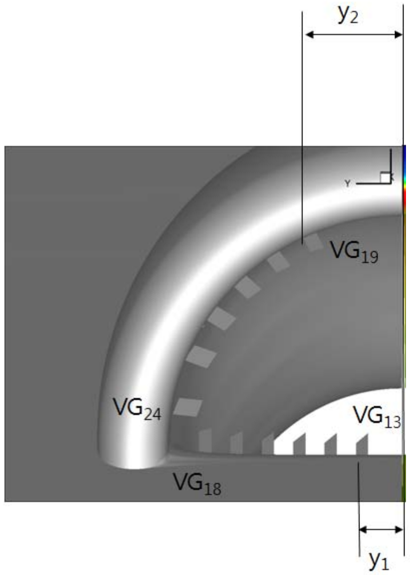
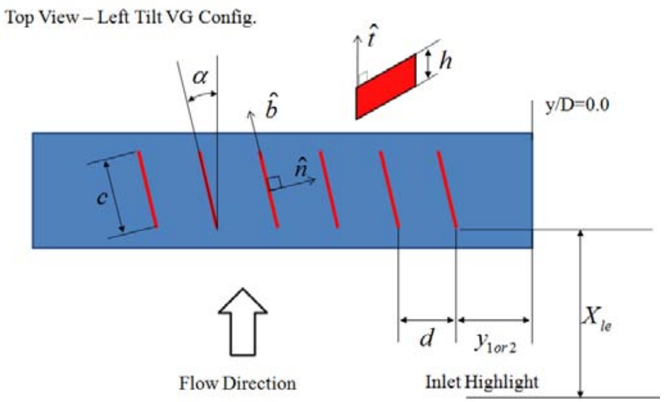
Flow Analysis

- Geometry of Baseline Model



- Geometric Information of VGs





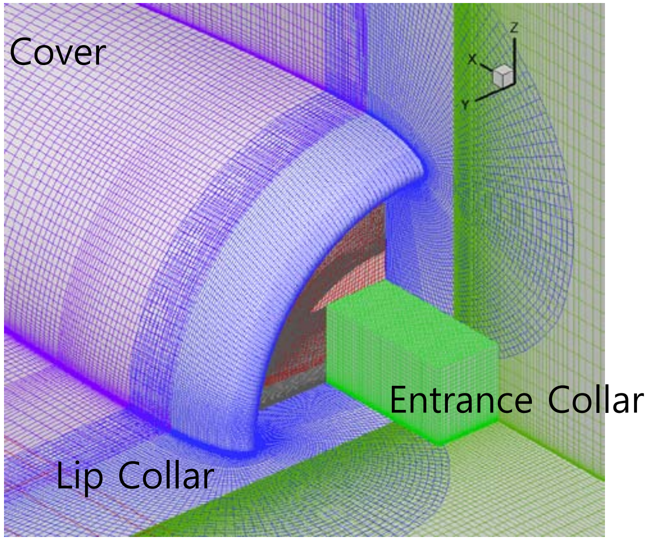
	Bottom VGs	Side VGs
h (*in.*)	0.181	0.163
c (*in.*)	0.367	0.367
α (˚)	12.94	11.54
d (*in.*)	0.216	0.30
y_1, y_2 (*in.*)	0.246	0.721
x_{le} (*in.*)	1.224	1.224

Specification of Baseline VGs
(Optimized by Allan et al.)

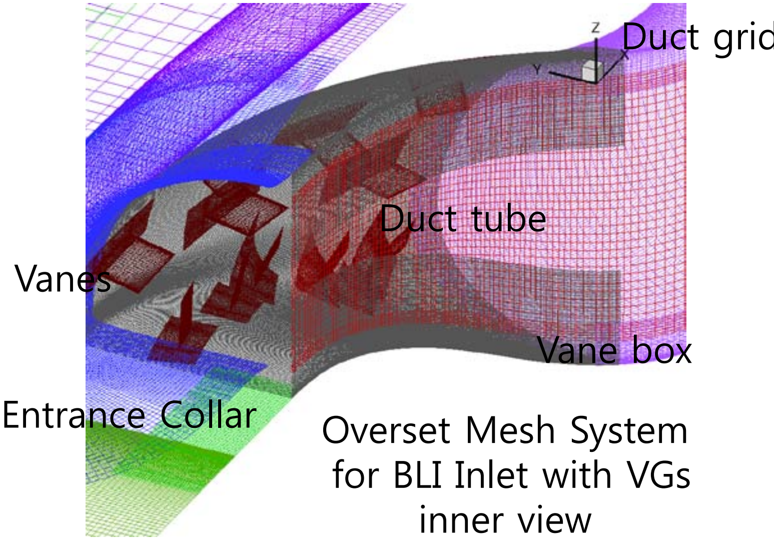
Grid System

- 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



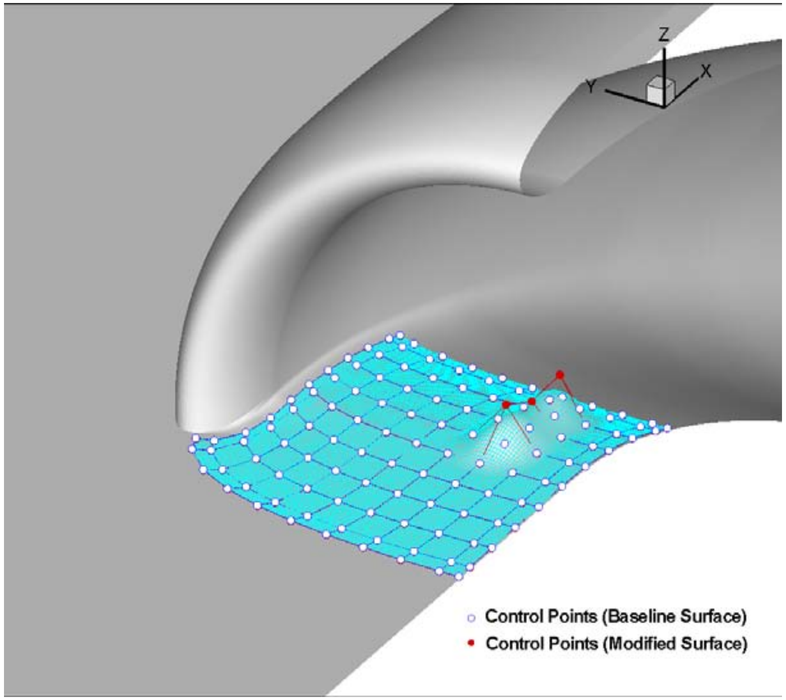
Overset Mesh System for BLI Inlet outer view



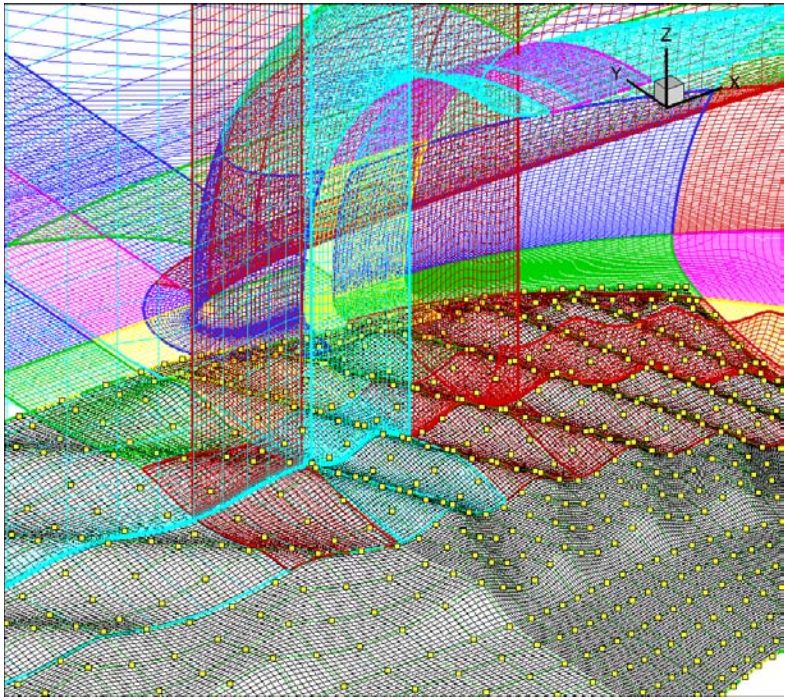
Overset Mesh System for BLI Inlet with VGs inner view

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.



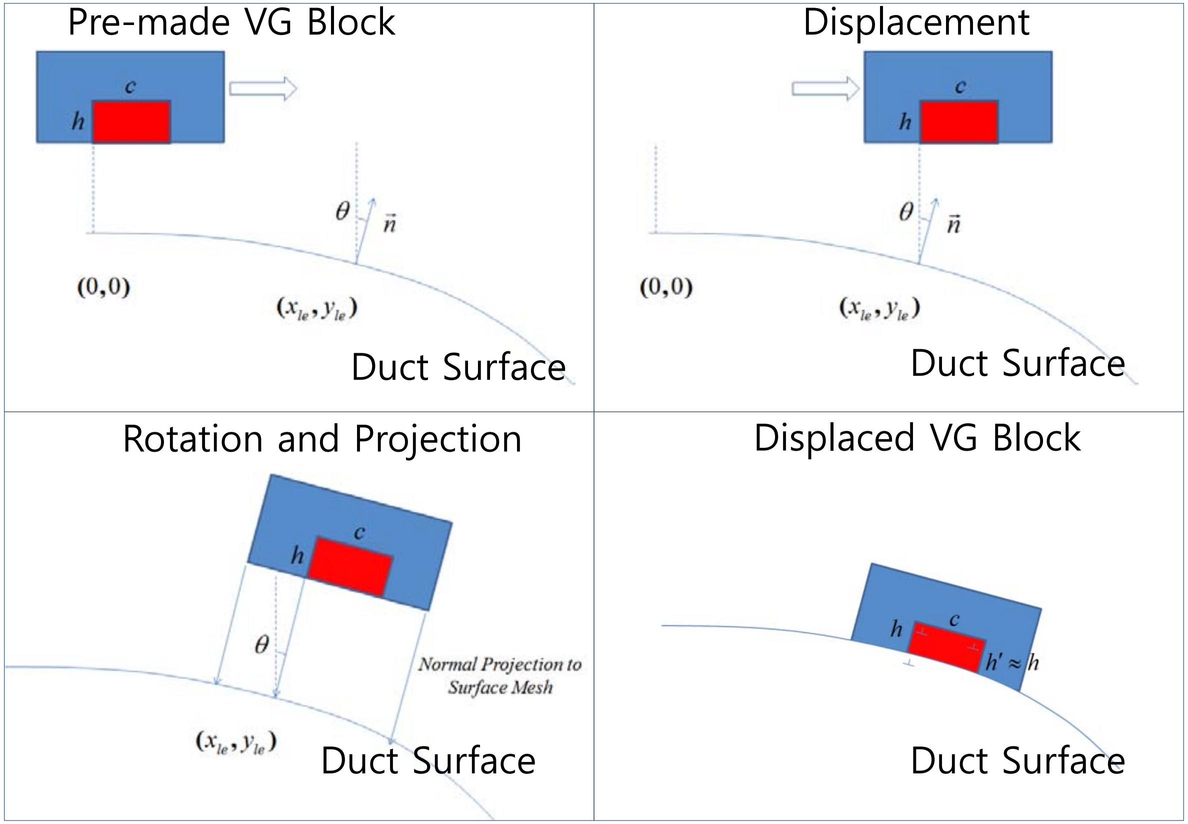
Surface modification using control points

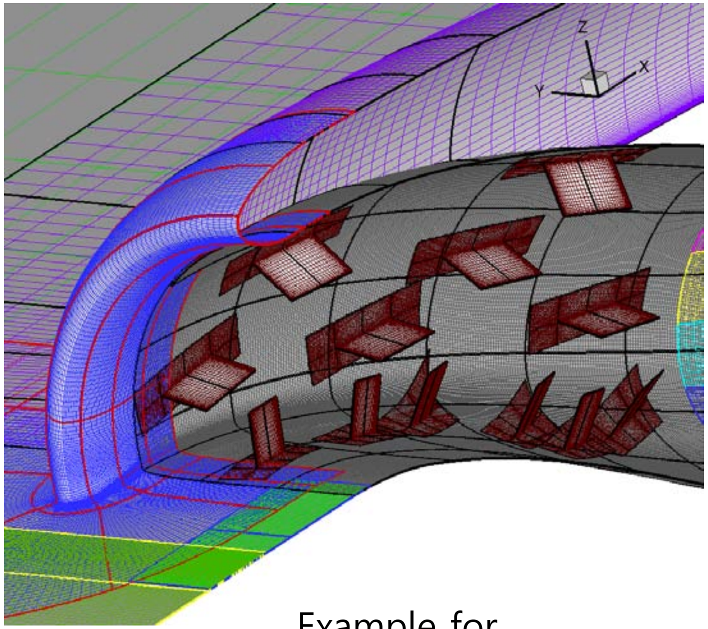


Modification of surface and volume grids of overset blocks

Grid Modification II

- Schematics for Displacement of VG blocks

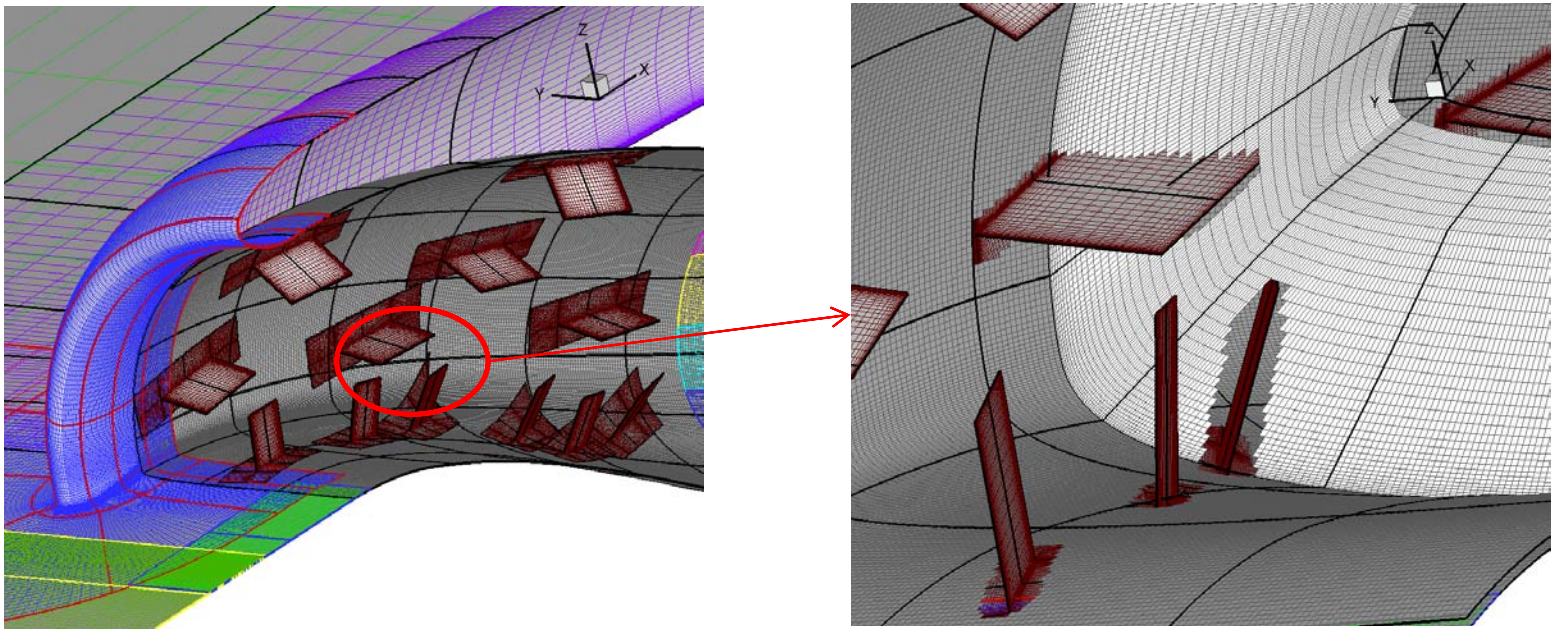




Example for
distributed VGs

Hole-searching and Domain connectivity

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



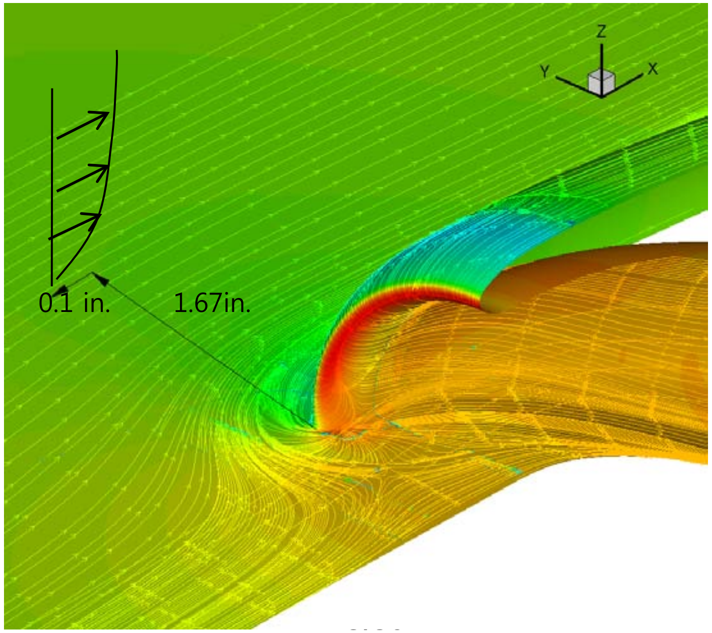
Hole cutting at Vane Box grid

- 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

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 Layer Profile for Inflow Condition

- 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#=3.8mil.
    - Extension of computational domain: $-20 \le x/D_2 \le 20$
  - 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)

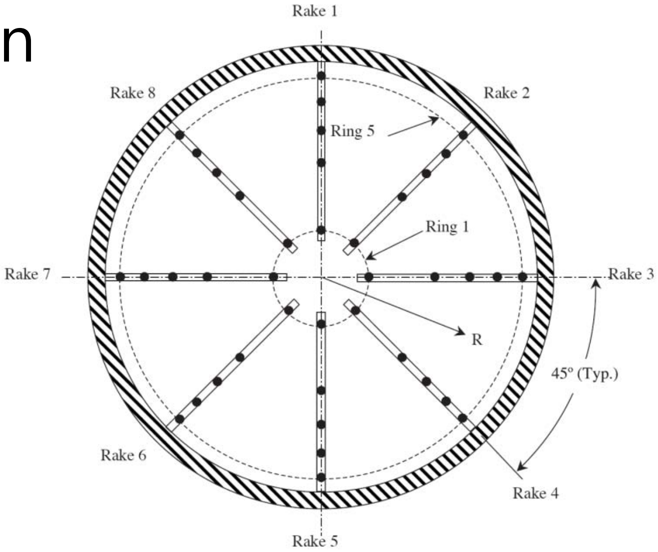
- SAE average circumferential distortion

$$DPCP_{avg} = 1/N_{rings} \sum_{i=1,5} (P_{t_{avg,i}} - P_{t,low_{avg,i}}) / P_{t_{avg,i}}$$

$N_{rings} = 5$: Number of Rings

$P_{t_{avg,i}}$: Average of Total Pressure for i^{th} ring

$P_{t,low_{avg,i}}$: Average of $P_{t_{n,i}} (\leq P_{t,avg_i})$ at i^{th} 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

$$f(\mathbf{Q}_i, \mathbf{Q}_i^F, \mathbf{X}_i, \mathbf{X}_i^F, \mathbf{D}; i = 1, 2, \cdots) \qquad F: \text{ Fringe Cell}$$

  - Residuals

$$\mathbf{R}_i\left(\mathbf{Q}_i, \mathbf{Q}_i^F, \mathbf{X}_i, \mathbf{D}\right) = 0 \qquad \mathbf{R}_i^F\left(\mathbf{Q}_i^F, (1-\delta_{i,j})\mathbf{Q}_j, \mathbf{X}_i^F, \mathbf{D}\right) = 0$$

  - Sensitivity

$$\frac{df}{d\mathbf{D}} = \sum_i \left[\frac{\partial f}{\partial \mathbf{Q}_i}\frac{d\mathbf{Q}_i}{d\mathbf{D}} + \frac{\partial f}{\partial \mathbf{Q}_i^F}\frac{d\mathbf{Q}_i^F}{d\mathbf{D}} + \frac{\partial f}{\partial \mathbf{X}_i}\frac{d\mathbf{X}_i}{d\mathbf{D}} + \frac{\partial f}{\partial \mathbf{X}_i^F}\frac{d\mathbf{X}_i^F}{d\mathbf{D}} + \frac{\partial f}{\partial \mathbf{D}} \right]$$

Sensitivity Analysis

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

$$\frac{df}{d\mathbf{D}} = \sum_i \left\{ \begin{aligned} &\left[\frac{\partial f}{\partial \mathbf{Q}_i} + \boldsymbol{\Lambda}_i \frac{\partial \mathbf{R}_i}{\partial \mathbf{Q}_i} + (1-\delta_{i,j}) \boldsymbol{\Lambda}_j^F \frac{\partial \mathbf{R}_j^F}{\partial \mathbf{Q}_i} \right] \frac{d\mathbf{Q}_i}{d\mathbf{D}} + \left[\frac{\partial f}{\partial \mathbf{Q}_i^F} + \boldsymbol{\Lambda}_i \frac{\partial \mathbf{R}_i}{\partial \mathbf{Q}_i^F} + \boldsymbol{\Lambda}_i^F \frac{\partial \mathbf{R}_i^F}{\partial \mathbf{Q}_i^F} \right] \frac{d\mathbf{Q}_i^F}{d\mathbf{D}} \\ &+ \left[\frac{\partial f}{\partial \mathbf{X}_i} + \boldsymbol{\Lambda}_i \frac{\partial \mathbf{R}_i}{\partial \mathbf{X}_i} \right] \frac{d\mathbf{X}_i}{d\mathbf{D}} + \left[\frac{\partial f}{\partial \mathbf{X}_i^F} + \boldsymbol{\Lambda}_i^F \frac{\partial \mathbf{R}_i^F}{\partial \mathbf{X}_i^F} \right] \frac{d\mathbf{X}_i^F}{d\mathbf{D}} + \frac{\partial f}{\partial \mathbf{D}} + \boldsymbol{\Lambda}_i \frac{\partial \mathbf{R}_i}{\partial \mathbf{D}} \end{aligned} \right\}$$

  - Formulations of Adjoint Equations

$$\boldsymbol{\Lambda}_1 \frac{\partial \mathbf{R}_1}{\partial \mathbf{Q}_1} + \boldsymbol{\Lambda}_2^F \frac{\partial \mathbf{R}_2^F}{\partial \mathbf{Q}_1} = -\frac{\partial f}{\partial \mathbf{Q}_1} \qquad \boldsymbol{\Lambda}_2 \frac{\partial \mathbf{R}_2}{\partial \mathbf{Q}_2} + \boldsymbol{\Lambda}_1^F \frac{\partial \mathbf{R}_1^F}{\partial \mathbf{Q}_2} = -\frac{\partial f}{\partial \mathbf{Q}_2}$$

$$\boldsymbol{\Lambda}_1 \frac{\partial \mathbf{R}_1}{\partial \mathbf{Q}_1^F} + \boldsymbol{\Lambda}_1^F \frac{\partial \mathbf{R}_1^F}{\partial \mathbf{Q}_1^F} = -\frac{\partial f}{\partial \mathbf{Q}_1^F} \qquad \boldsymbol{\Lambda}_2 \frac{\partial \mathbf{R}_2}{\partial \mathbf{Q}_2^F} + \boldsymbol{\Lambda}_2^F \frac{\partial \mathbf{R}_2^F}{\partial \mathbf{Q}_2^F} = -\frac{\partial f}{\partial \mathbf{Q}_2^F}$$

Design Optimization - Case I

- Design Formulation

  Minimize : $DPCP_{avg}$

  Subject to : $|\Delta z_i| \le z_L$

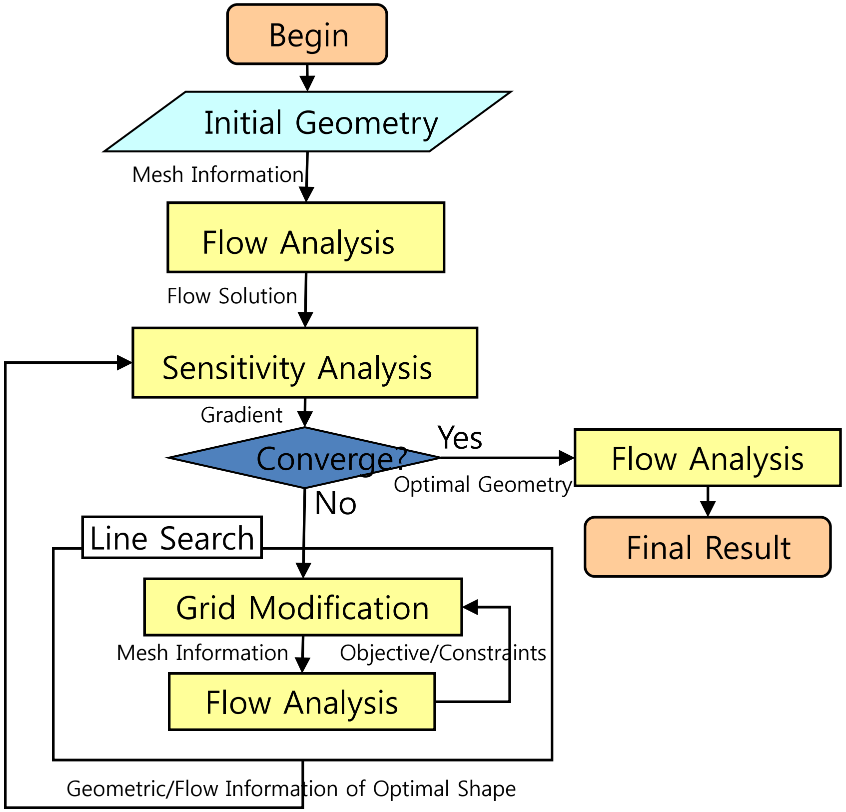
  z_i : z coordinate of i^{th} control point

  z_L : limit of design variable (10% of D_c)

- Design Condition
  - M=0.85, Re#=3.8mil., A_0/A_c=0.533
  - BLI thickness : 35% of Inlet Height

- Design Variables
  - Control Points of B-Spline Patch

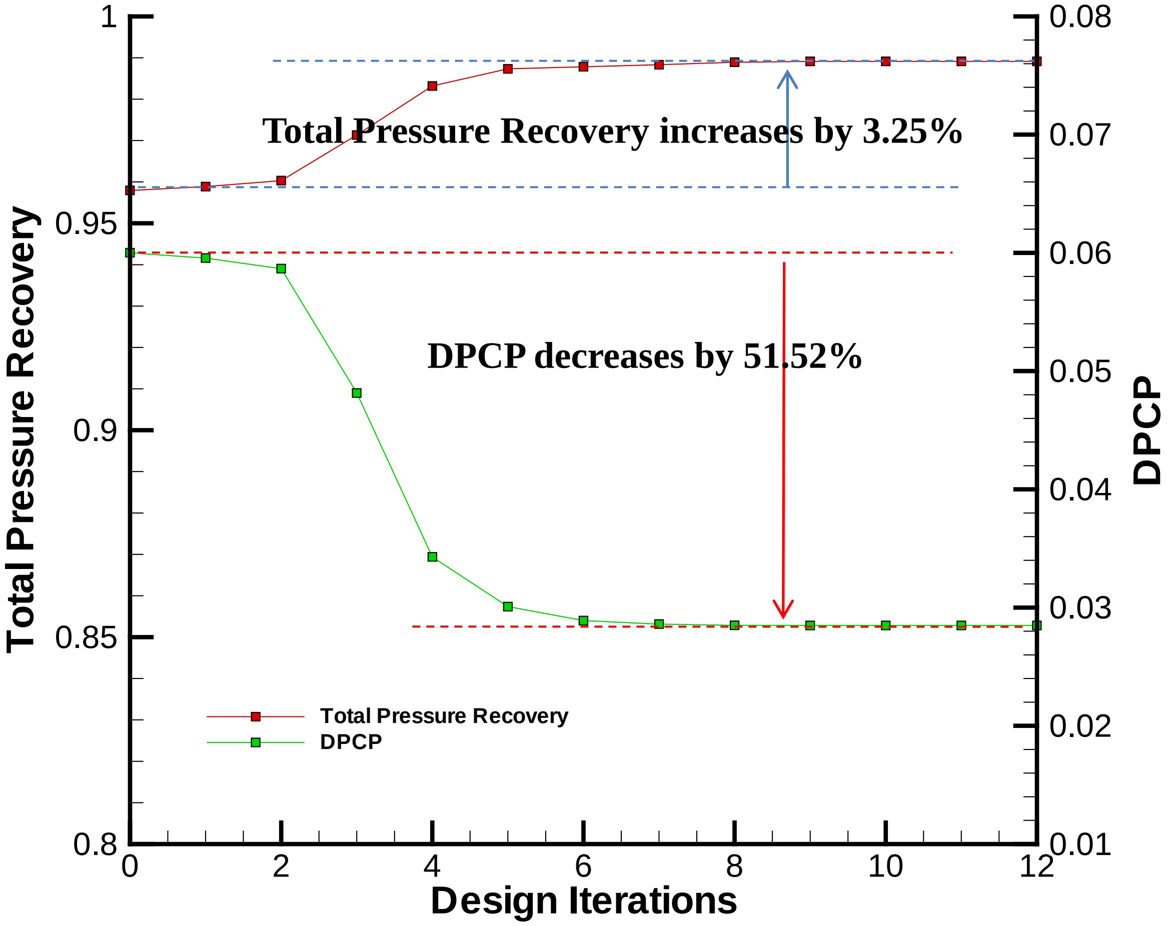
- Design Tools
  - Gradient Based Optimization
  - Optimizer : BFGS (Broyden-Fletcher–Goldfarb–Shanno)
  - Sensitivity Analysis : Discrete Adjoint Method

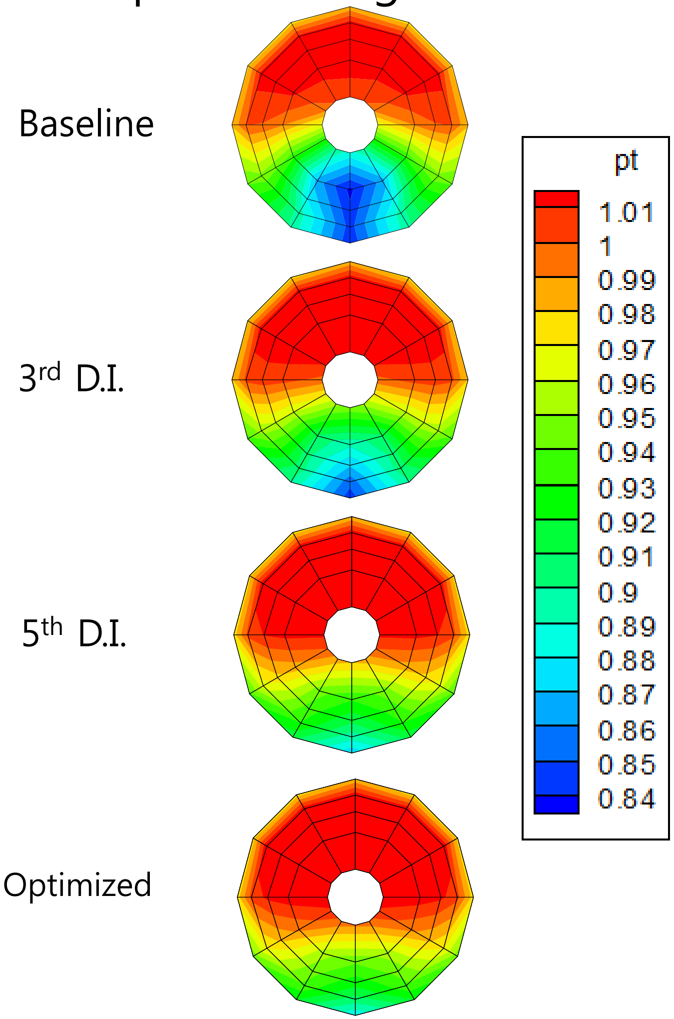


Flow Chart of GBOM

Design Optimization - Case I

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

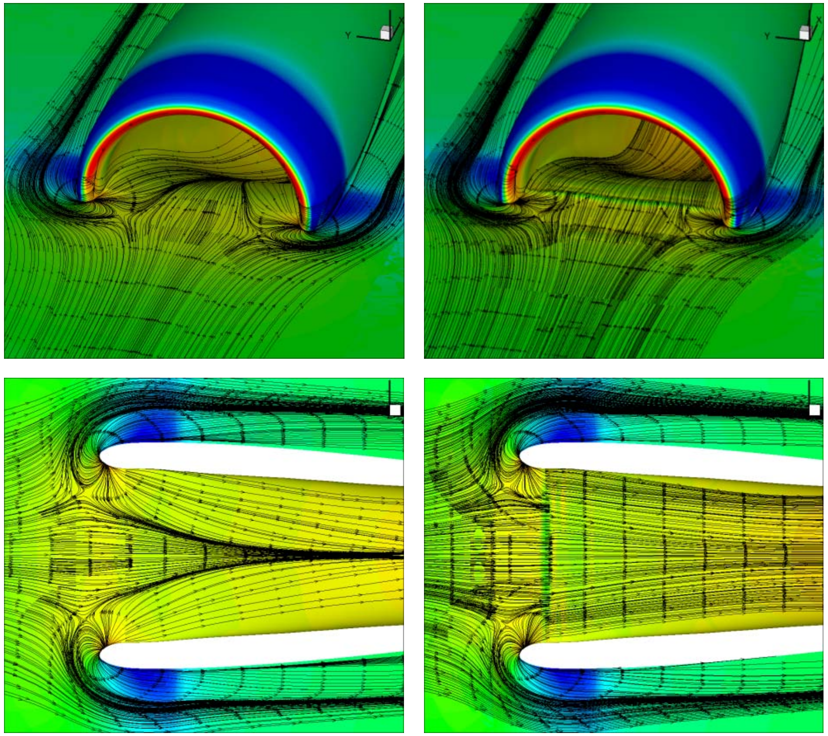




Design Optimization - Case I

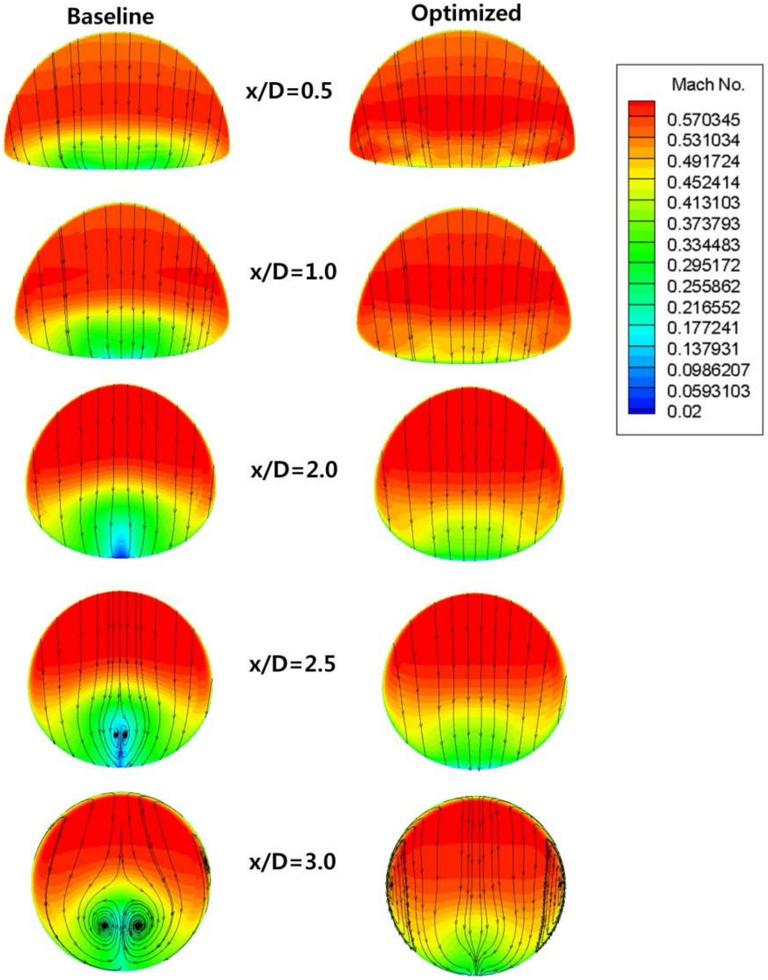
- Comparison of Flow Patterns
  - Uniform flow at bottom surface (reduction of secondary flow)
  - Decrease of the size of lip separation

Oil Flow Patterns



Baseline Model

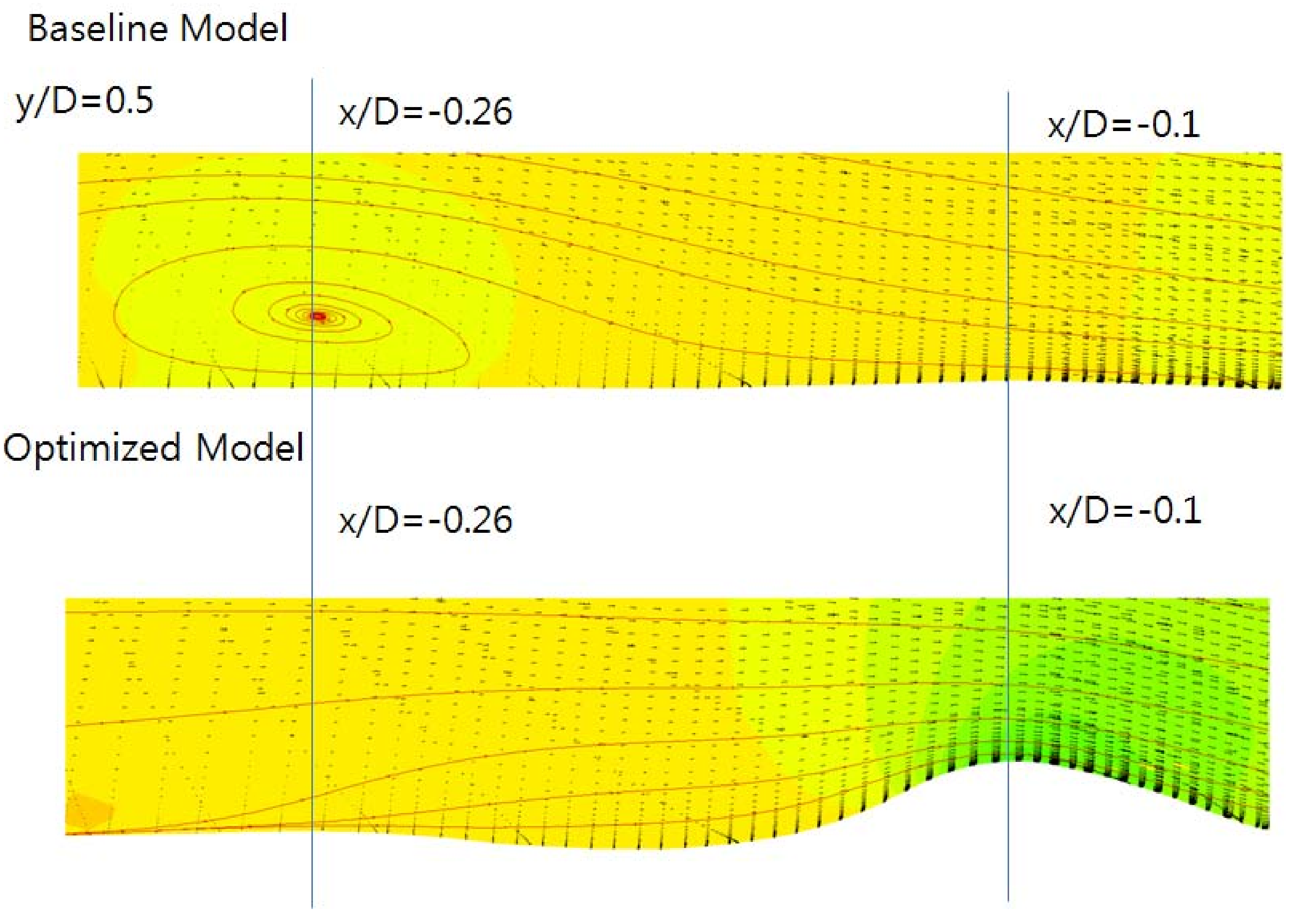
Optimized Model



Total Pressure Contour and Streamlines

Design Optimization - Case I

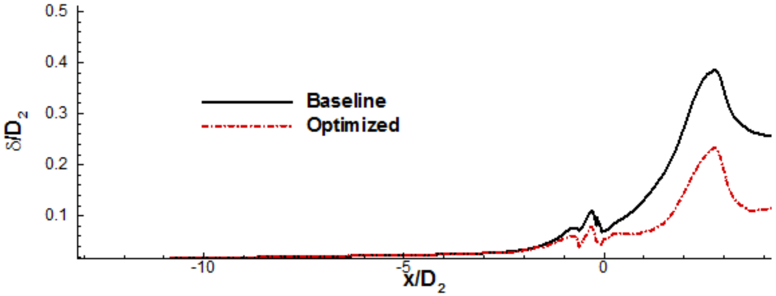
- Flow Patterns Corresponding to Geometric Change



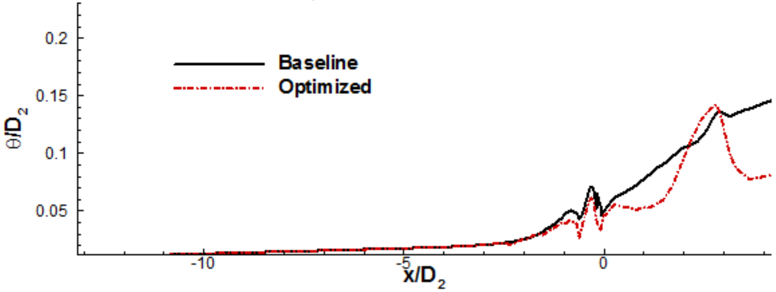
Magnified view of streamlines near inlet throat on plane $y/D_2=0.5$,
Revealing a valley following a mild peak and preceding a major one.

Design Optimization - Case I

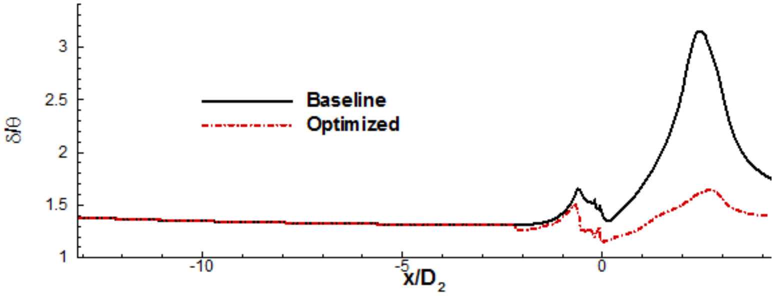
- Flow Pattern Change



(a) Displacement Thickness



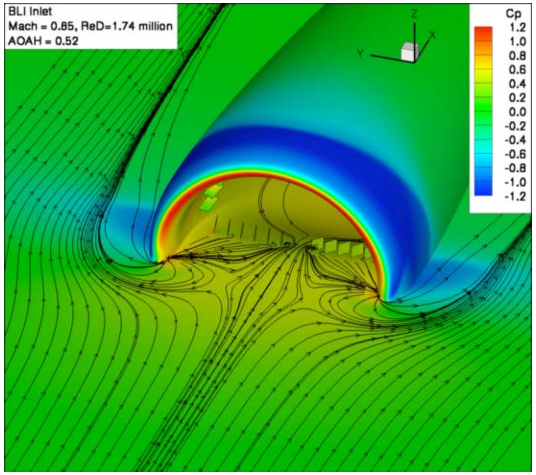
(b) Momentum Thickness

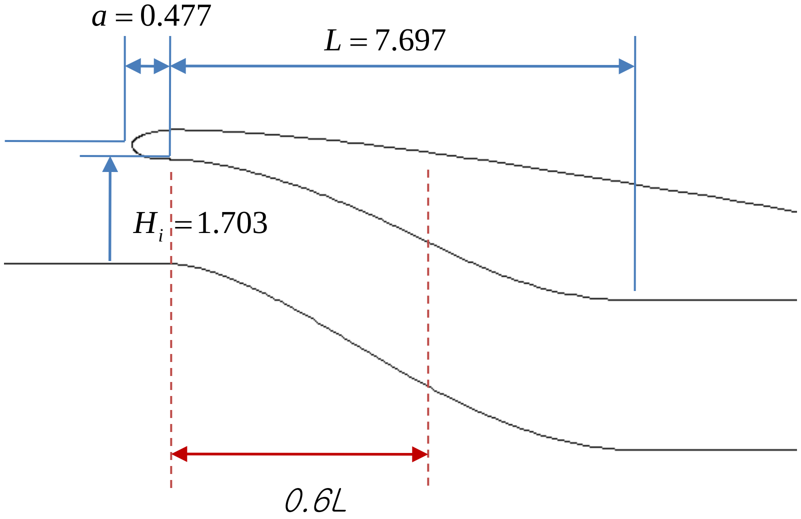


(c) Shape Factor

Comparison of boundary layer thicknesses and shape factor on symmetry plane.

Optimization Case II
Design Exploration of VG Configuration





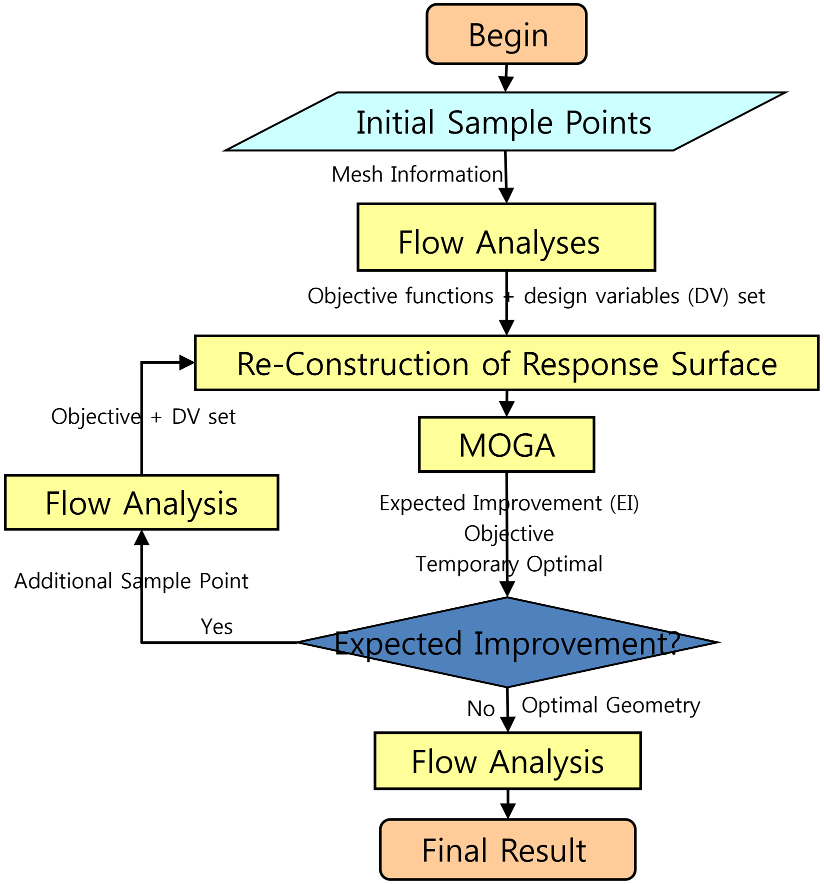
Design Optimization - Case II

- Design Objectives
  - Maximize total pressure recovery
  - Minimize distortion (DPCP)

- Design Condition
  - M=0.85, Re#=3.8mil., 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.



Flow Chart of DOE

Design Optimization - Case II

- Self Organizing Maps from initial sample points

	PR	DPCP
L_B	?	0~0.2 (0.18~0.252)
H_B	?	0.2~0.4 (0.144~0.198)
L_S	?	0.7~1.0 (0.432~0.54)
H_S	?	0~0.2 (0.08~0.128)

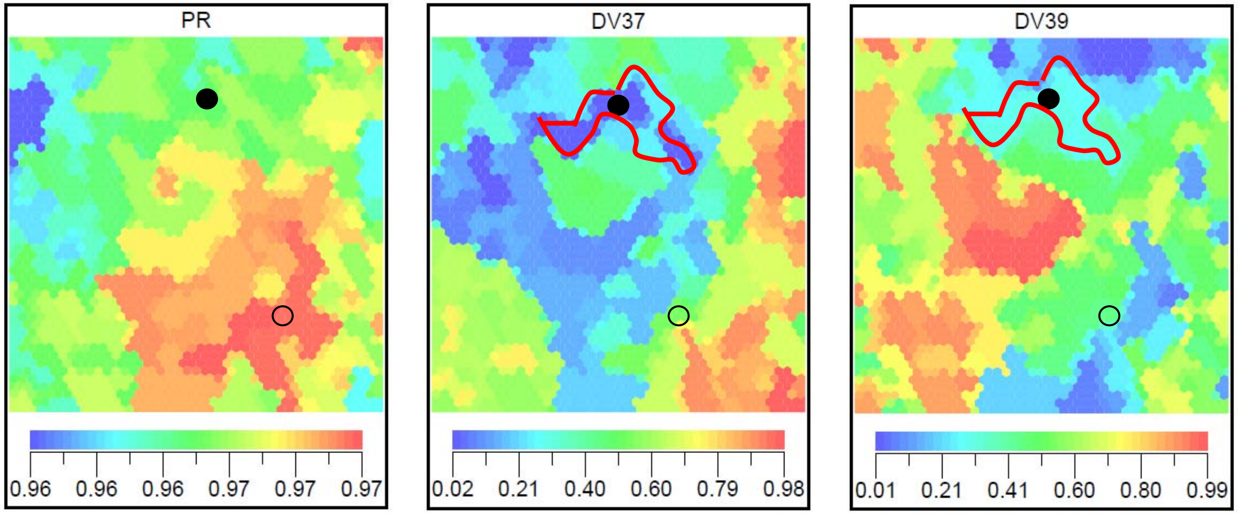
Guideline for VG sizing

L_B :Length of Bottom VGs

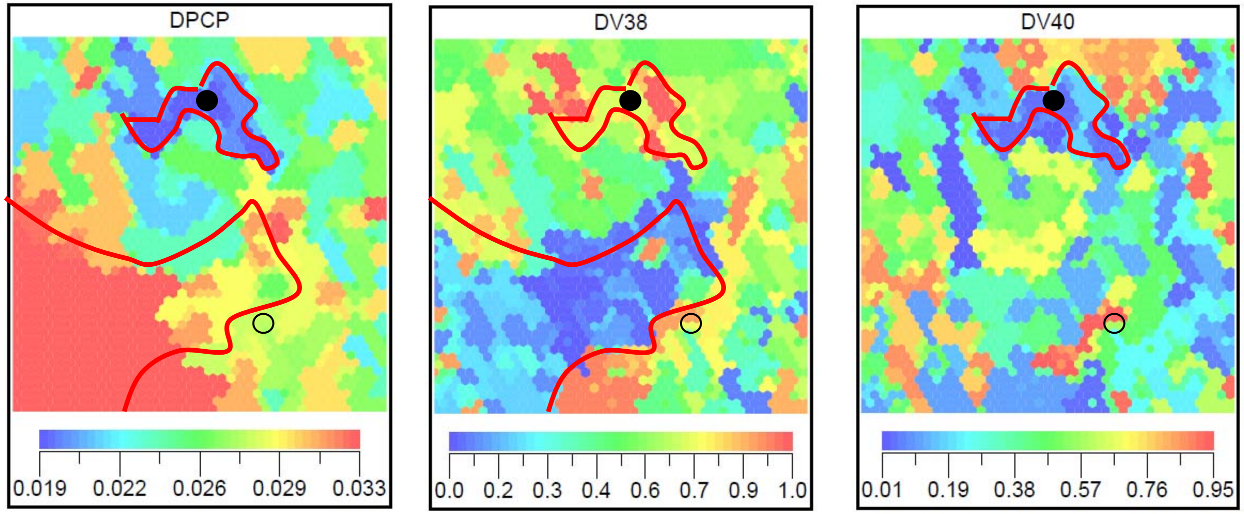
H_B :Height of Bottom VGs

L_S :Length of Side VGs

H_S :Height of Side VGs



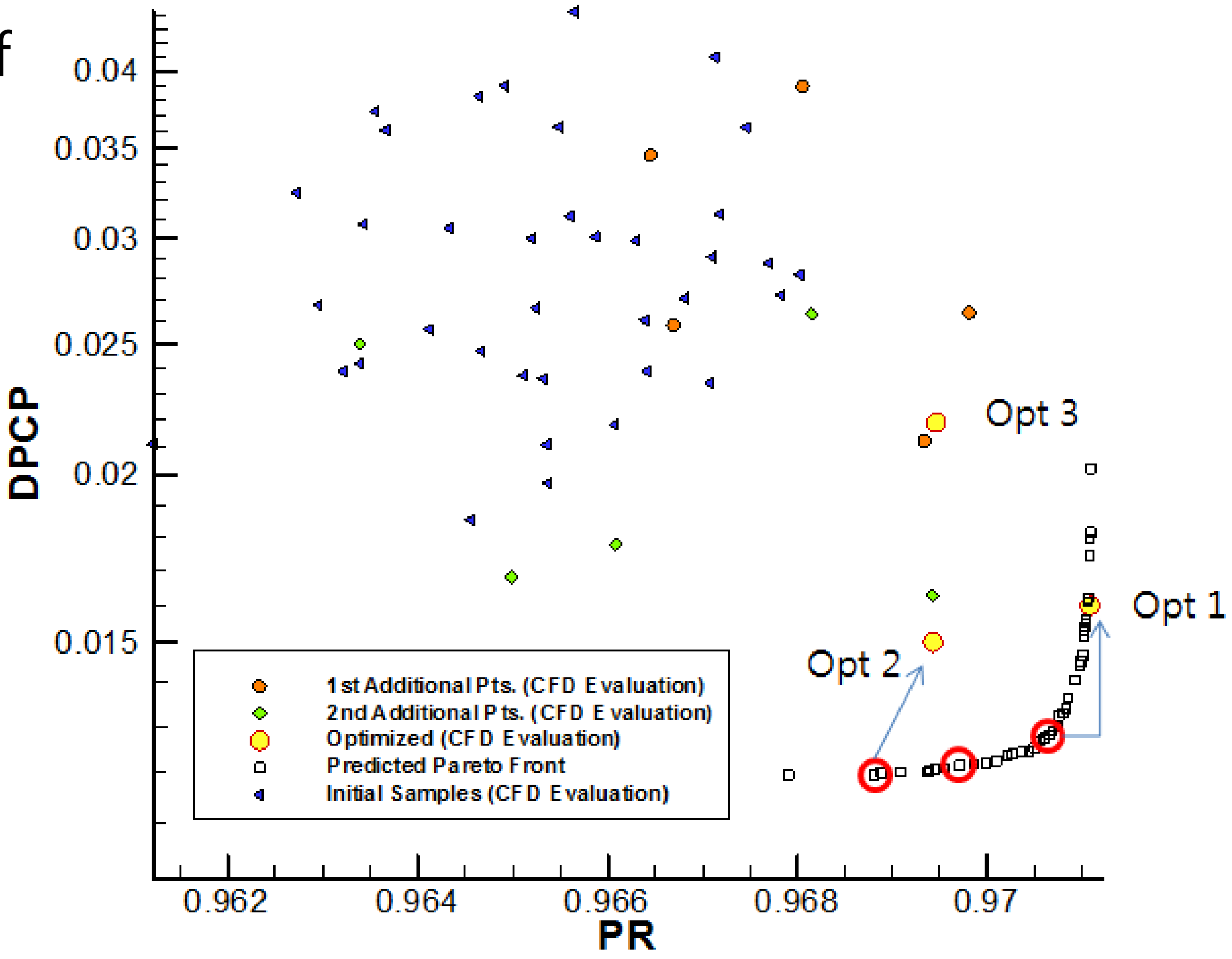
PR Length – Bottom VGs Height – Bottom VGs



DPCP Length – Side VGs Height – Side VGs

Design Optimization - Case II

- Distribution of initial samples and predicted Pareto front



○ : selected optimal points on the Pareto front for the CFD evaluation

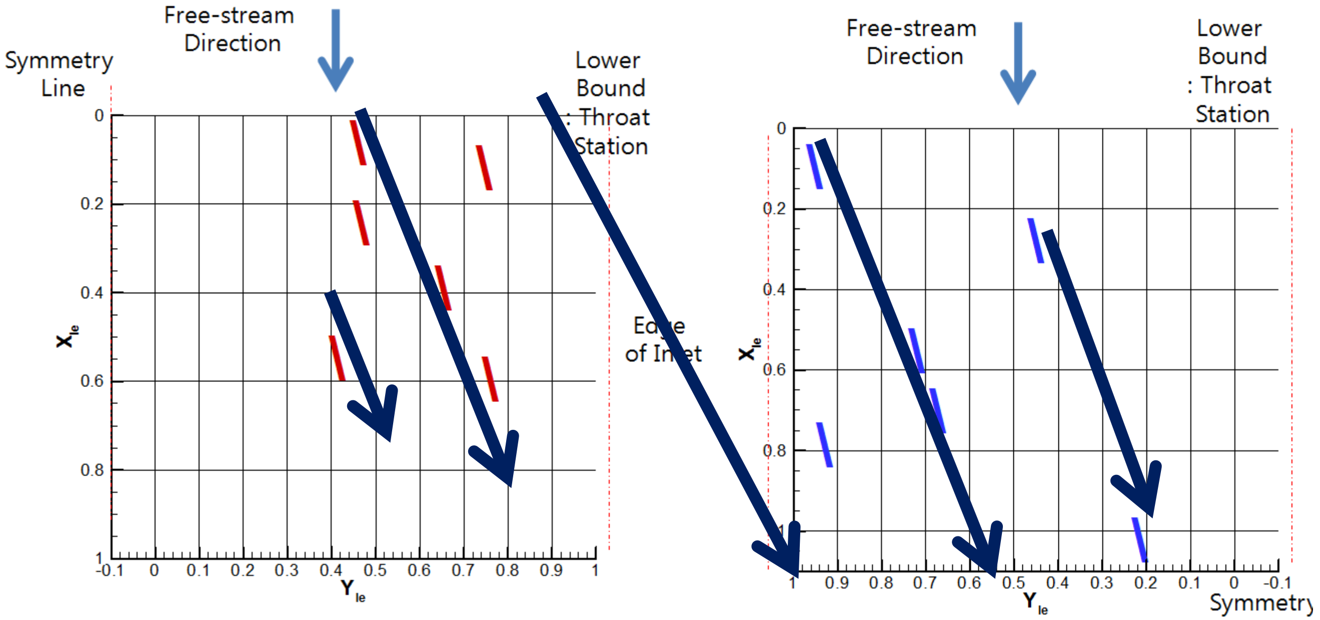
Design Optimization - Case II

- Investigation of optimal designs

(i) Optimal Point 1 : PR= 0.9711 , DPCP = 0.01598

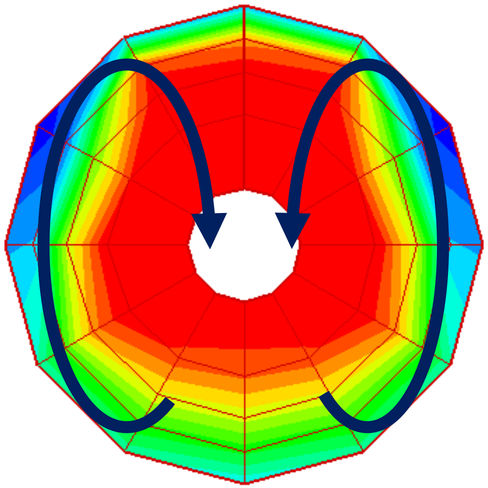
Bottom VGs : *h=0.2148* (*in.*), *c=0.1904* (*in.*)

Side VGs : *h=0.1442* (*in.*), *c=0.4166* (*in.*)



Bottom VGs

Side VGs



AIP Contour

Design Optimization - Case II

- Investigation of optimal designs

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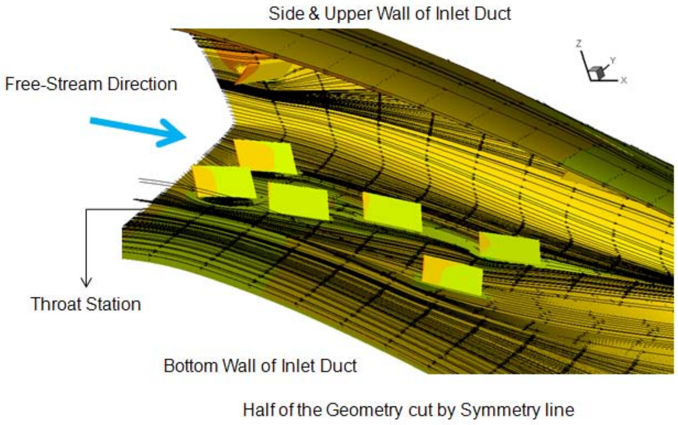
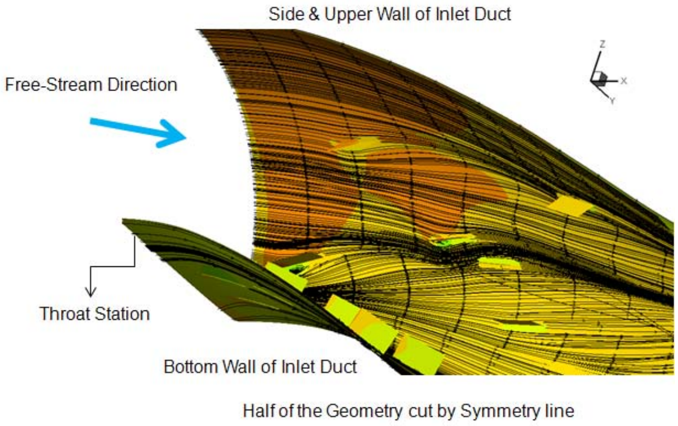
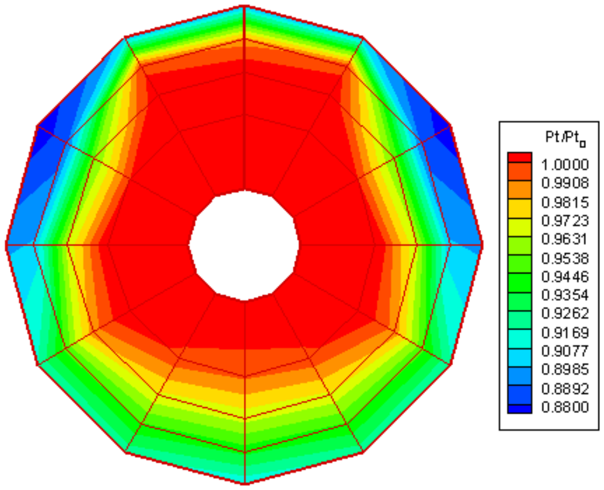


Bottom VGs



Side VGs



AIP Contour

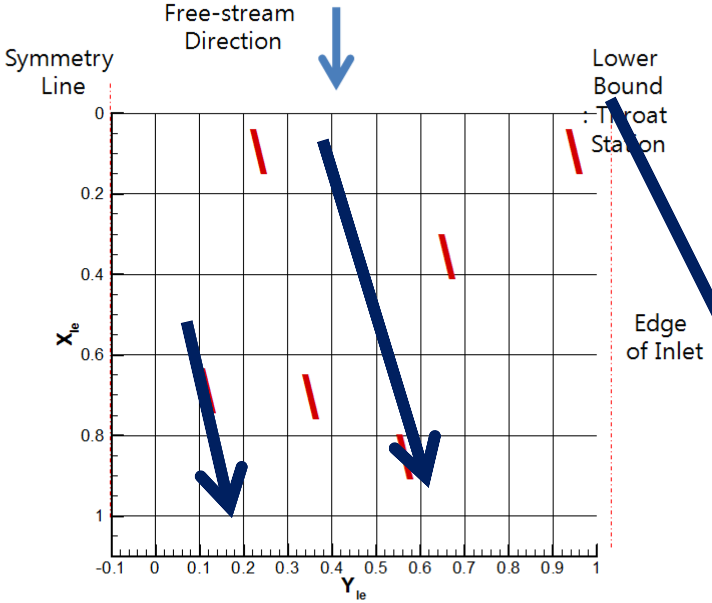
Design Optimization - Case II

- Investigation of optimal designs

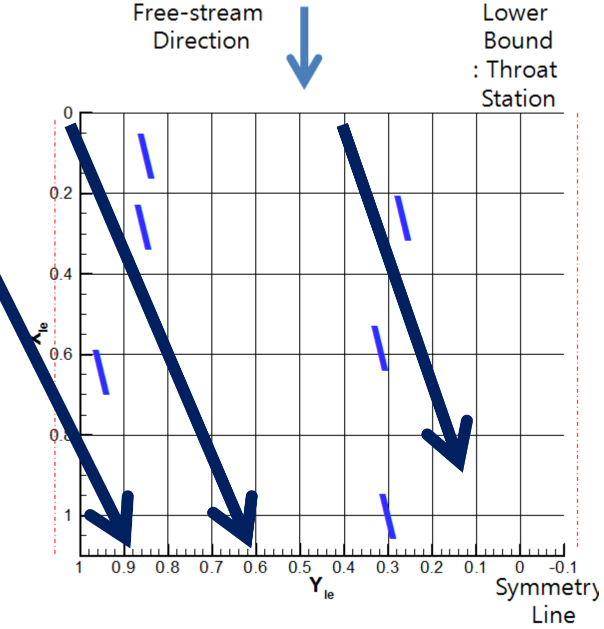
  (ii) Optimal point 2 : PR= 0.9694, DPCP= 0.01501

  Bottom VGs : *h=0.2157* (*in.*), *c=0.2393* (*in.*)

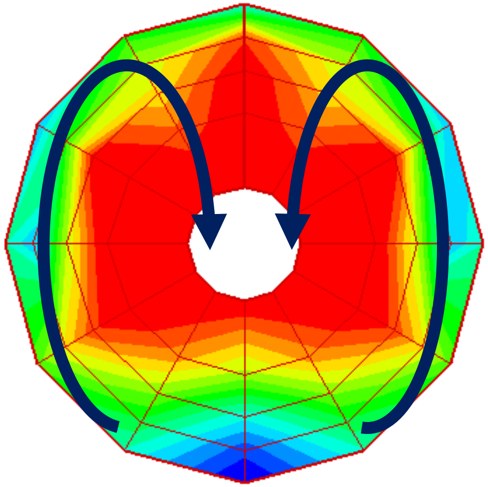
  Side VGs : *h=0.0945* (*in.*), *c=0.4281* (*in.*)



Bottom VGs



Side VGs



AIP Contour

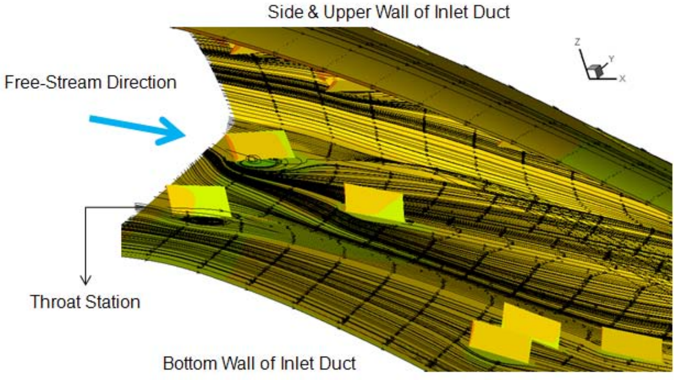
Design Optimization - Case II

- Investigation of optimal designs

  (ii) Optimal point 2 : PR= 0.9694, DPCP= 0.01501

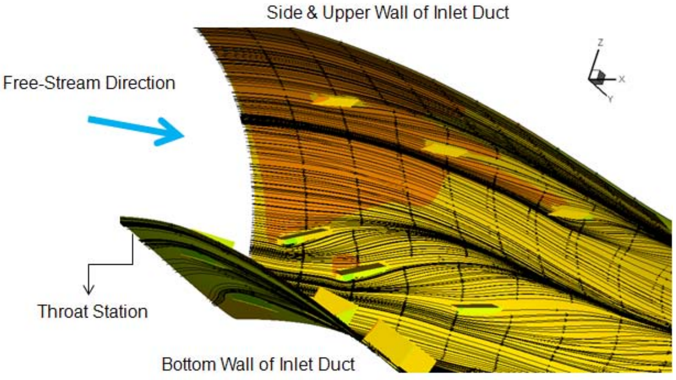
  Bottom VGs : $h=0.2157$ (*in.*), $c=0.2393$ (*in.*)

  Side VGs : $h=0.0945$ (*in.*), $c=0.4281$ (*in.*)



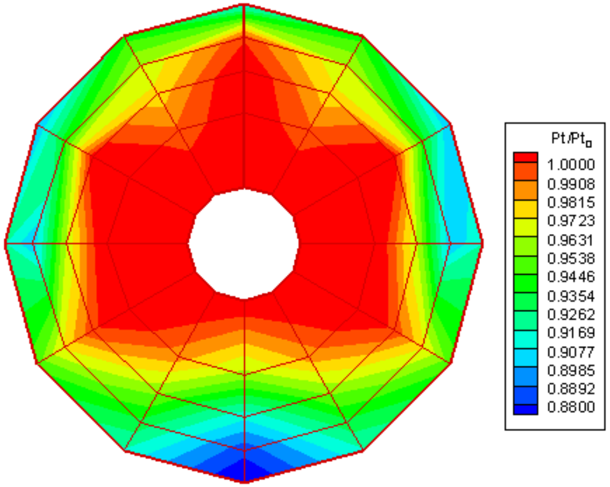
Half of the Geometry cut by Symmetry line

Bottom VGs



Half of the Geometry cut by Symmetry line

Side VGs



AIP Contour

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.

	PR	DPCP
L_B	?	0~0.2 (0.18~0.252)
H_B	?	0.2~0.4 (0.144~0.198)
L_S	?	0.7~1.0 (0.432~0.54)
H_S	?	0~0.2 (0.08~0.128)

Guideline for VG sizing

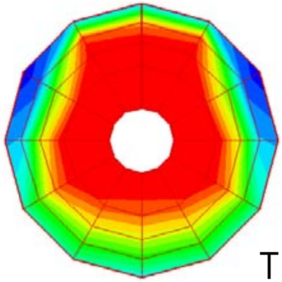
L_B :Length of Bottom VGs

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



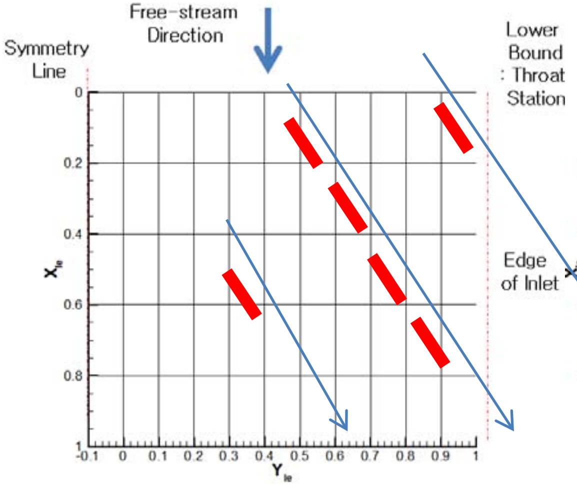
Mixing at the top

Mixing at the bottom

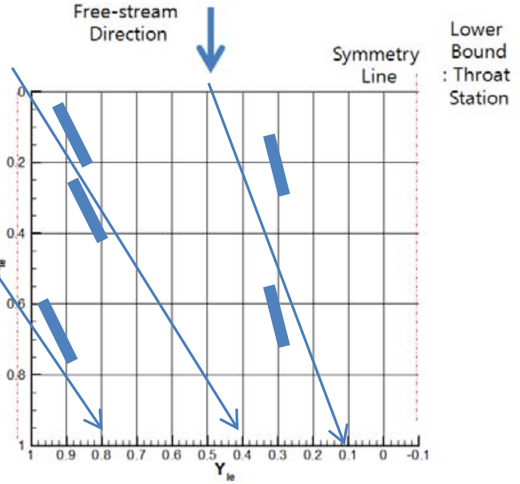
Flow mixing from the juncture flow

Thin low total pressure layer

Bottom Wall

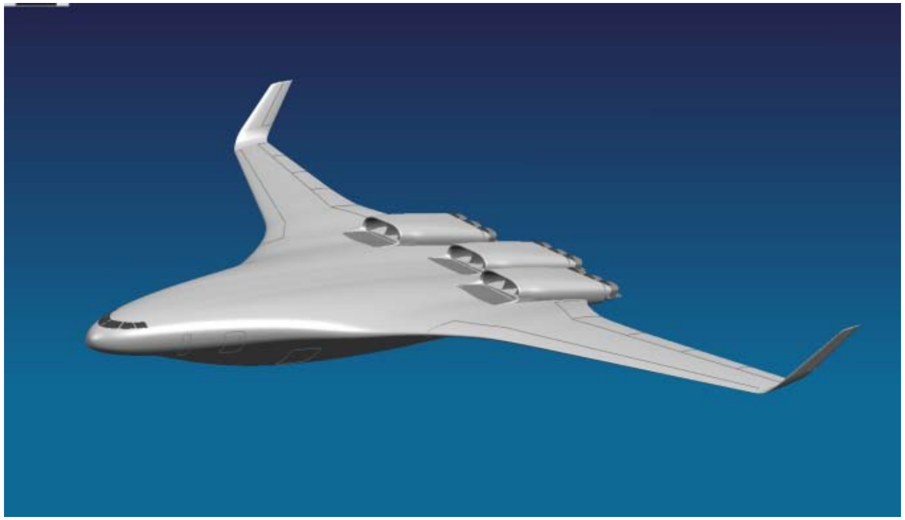


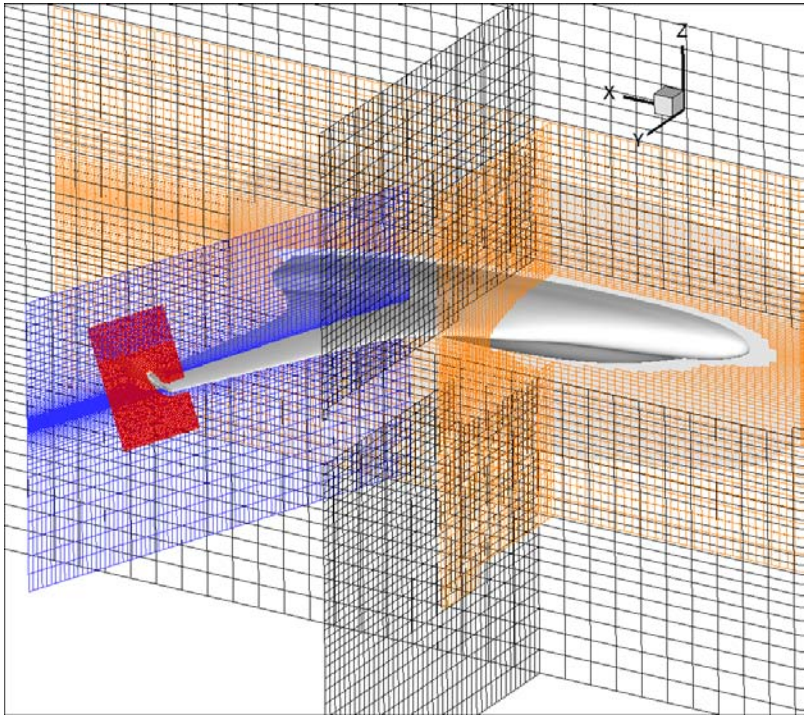
Side Wall



Future Plan

- Design of hybrid wing/body configuration and embedded BLI-inlet





Thank you for your attention