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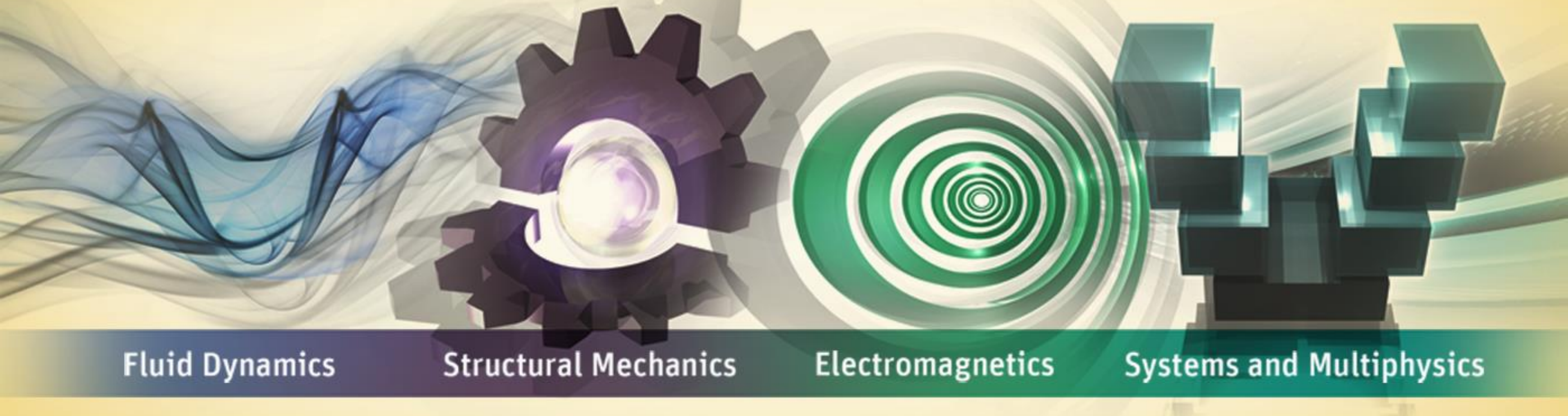
A Methodology for Topology Optimization in Fluid Dynamics



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Contents & Abstract

A CFD case study is presented to demonstrate a methodology of topology optimization. A flow cell with non-uniform thickness profile is prepared in ANSYS DesignModeler using parametric surfacing techniques. Flow characteristics and uniformity are evaluated using ANSYS CFX. Geometric design variations are explored then refined to satisfy performance criteria using Design of Experiments and optimization routines in ANSYS DesignXplorer.

Introduction

Demonstrate a methodology to optimize fluid behavior by introducing a variable thickness shape profile to a flow channel.

The focus of this discussion is on:

- Preparing a model to solve quickly and accurately without failure for a large set of parameters.
- Detailing a typical optimization procedure

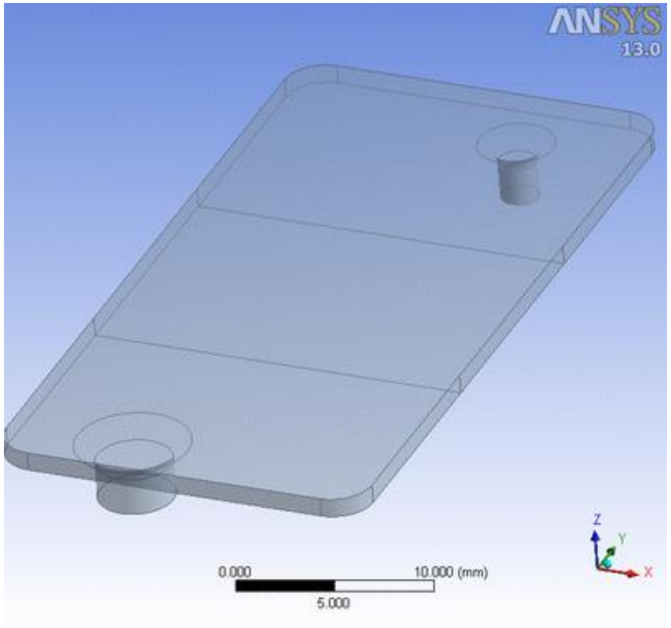
This methodology is relevant for many industrial applications and can be adapted to different types of simulation. It has been demonstrated to significantly enhance performance for biomedical equipment and fuel cells.

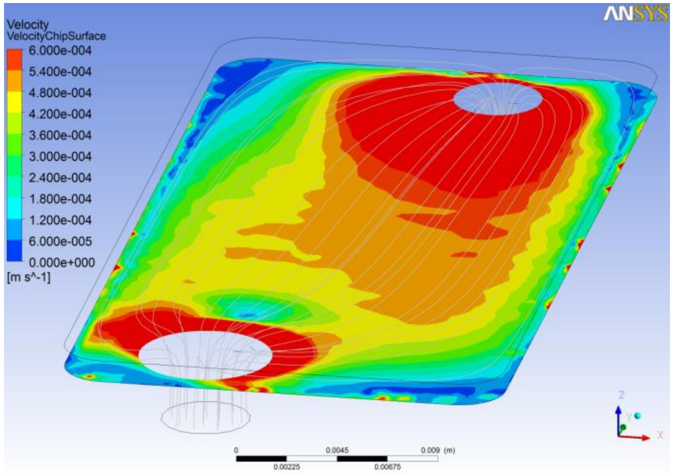
Description of Problem

Fluid passes through a flow cell. Properties of the fluid are measured on the sensor surface. To obtain accurate measurements, the fluid should have a uniform velocity.

The baseline design features a constant thickness channel with circular inlet & outlet.

Optimize the geometry by applying a non-uniform thickness profile along the top surface of the flow cell. The objective is to improve sensor performance by increasing flow uniformity.





  April 21, 2021

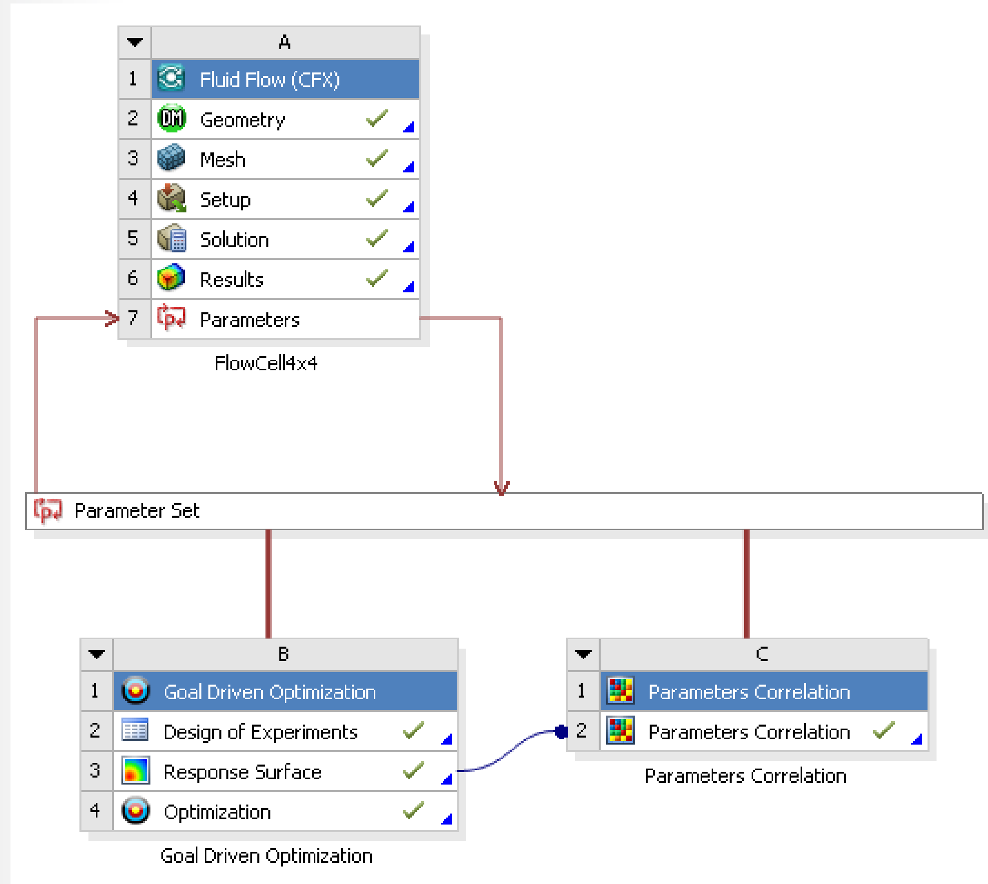
Workbench Solution Approach

Parametric geometry is created using DesignModeler.

A mesh with inflation boundary is created using Workbench Meshing

The fluid model is setup, solved, and post-processed using CFX.

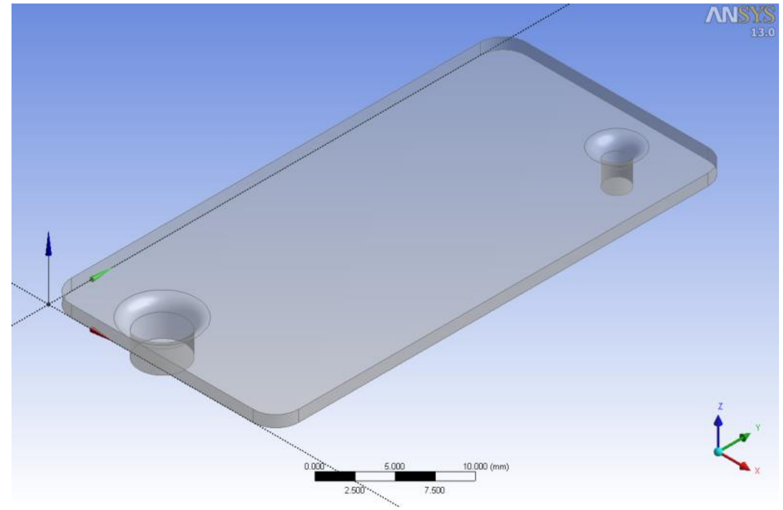
The design space is explored using DesignXplorer and parameters are refined to improve performance.



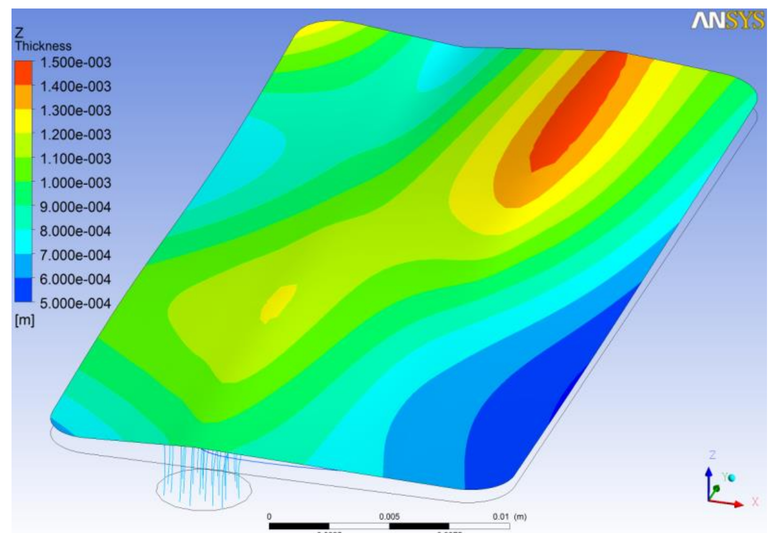
Geometry - Overview

Parametric geometry creation relies on a few simple operations:

- **Offset Sketching Planes**
- **Skin/Loft**
- **Merge Surface**
- **Boolean Unite**
- **Blend**
- **Named Selections**

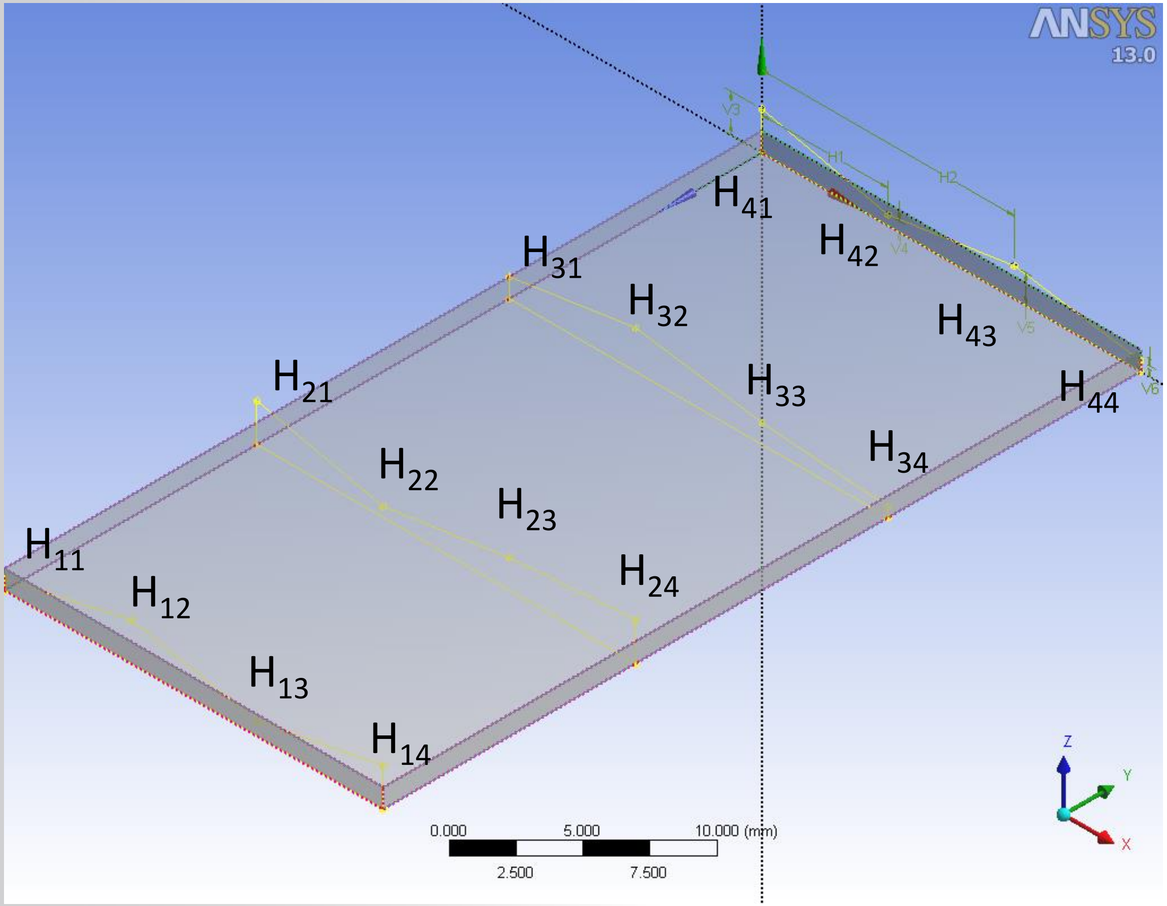


Baseline template model



Contour plot showing channel thickness

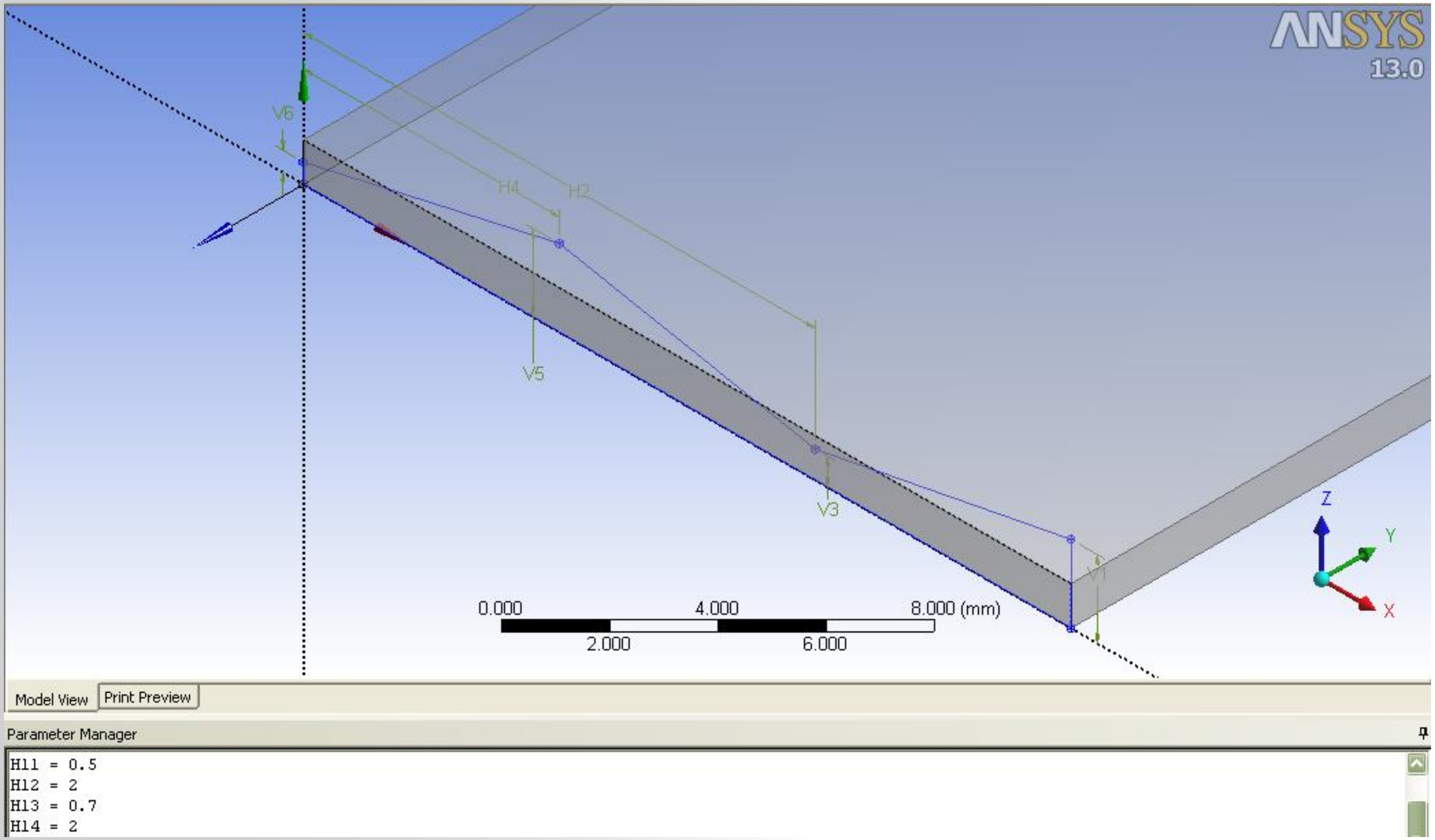
Geometry - Approach



The variable thickness fluid domain is created using a 4x4 array of evenly-spaced control points which are sketched over the template geometry.

16 parameter names are assigned to thickness control points (named Hij where 1≤i≤4 and 1≤j≤4).

Geometry - Sketching Planes

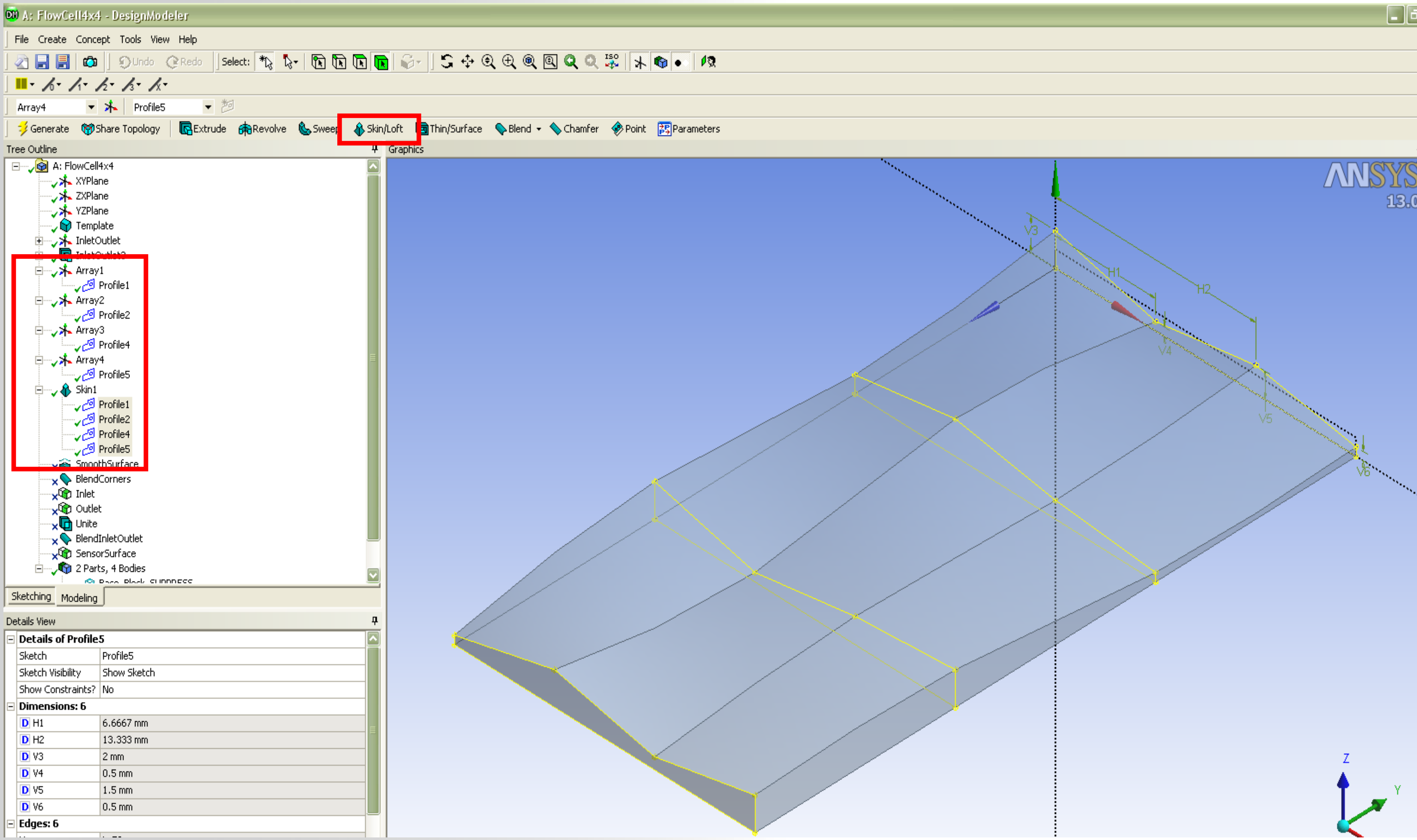


Face-boundary outline plane features fixed lines (black-dashed) from the scoped geometry.

Non-parametric features are spaced constrained to existing solid edge outlines.

Thickness control points are dimensioned from the sensor surface (bottom) and parameterized.

Geometry - Skin/Loft



Loft through a series of profiles on different planes.

This enables a robust part with parameterized thicknesses.

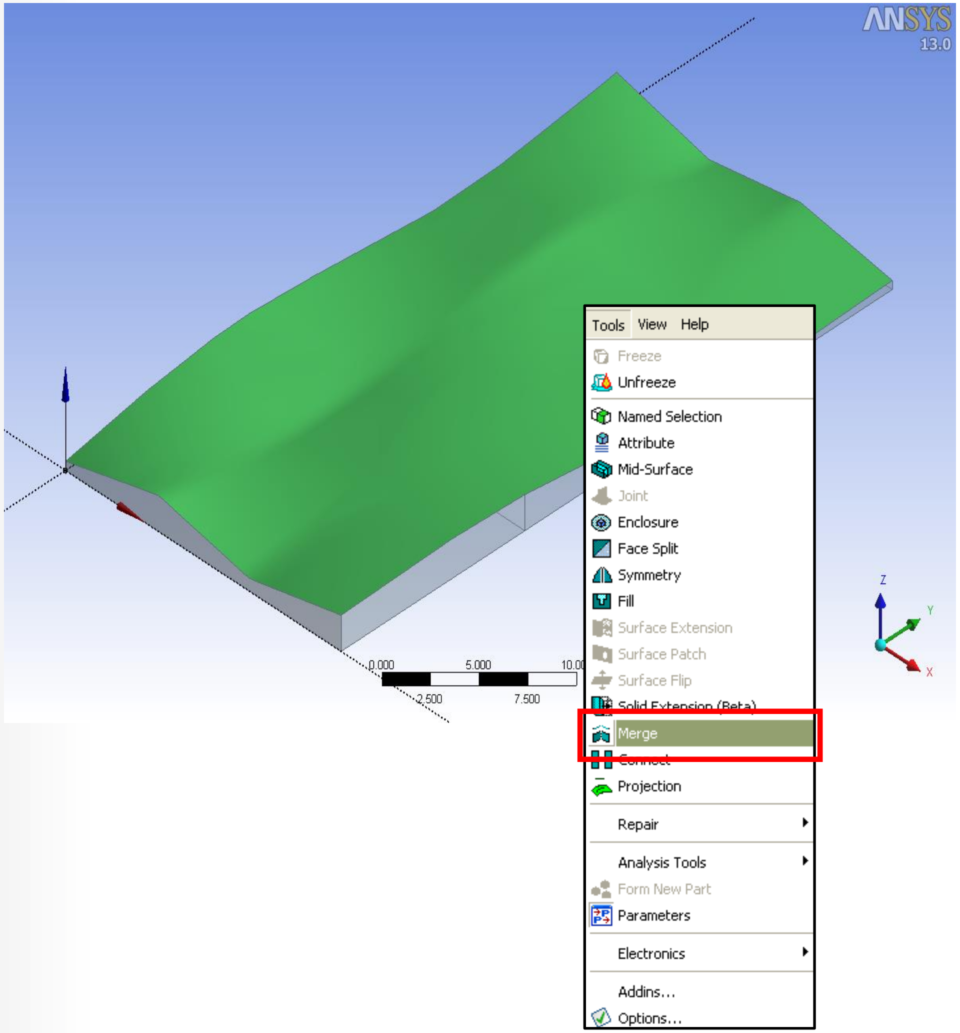
Geometry – Surface Merge

The multi-faceted surface is smoothed by merging faces.

Typically, the merge operation is used to remove sharp edges and simplify geometry for meshing (virtual topology).

Alternate methods lead to a high rate of DOE failure.

- Penetration at thin cross-sections.
- Spline orientation



Geometry – Finalized

Boolean Unite:

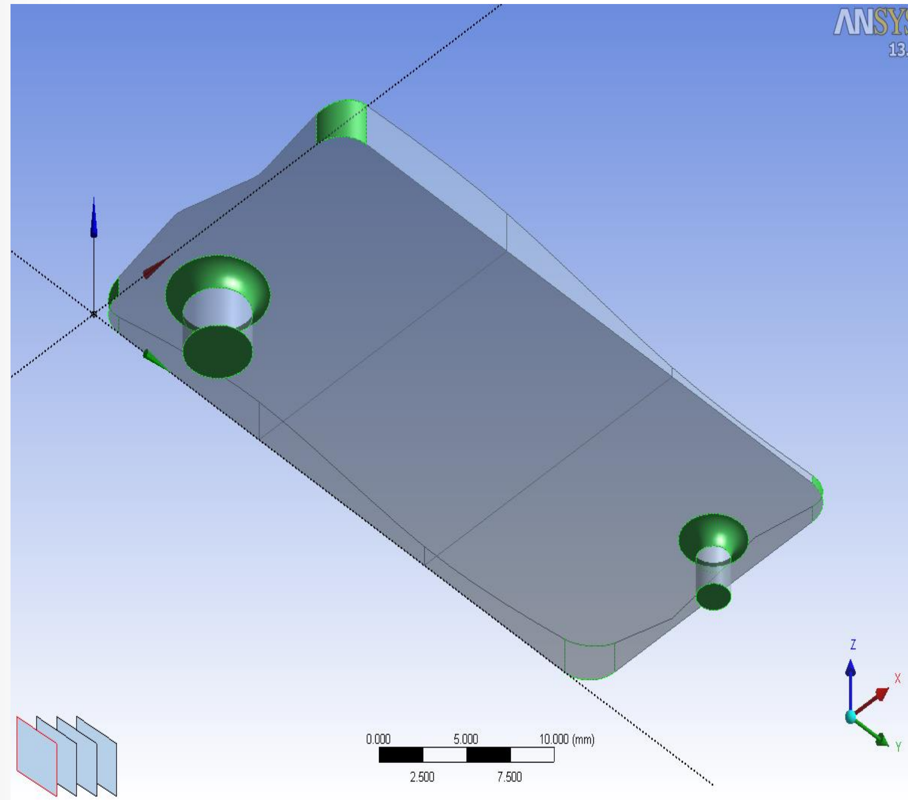
- Merges the inlet/outlet tubes with the channel
- Single part, continuous mesh, no domain interfaces required

Blend Edges:

- Creates smooth transitions.
- Should follow the skin/loft operation.

Named Selections:

- Simplify setup operations
- Automatic mesh inflation
- CFX-Pre boundary conditions
- CFX-Post results evaluation
- Specified Inlet, Outlet, and SensorSurface

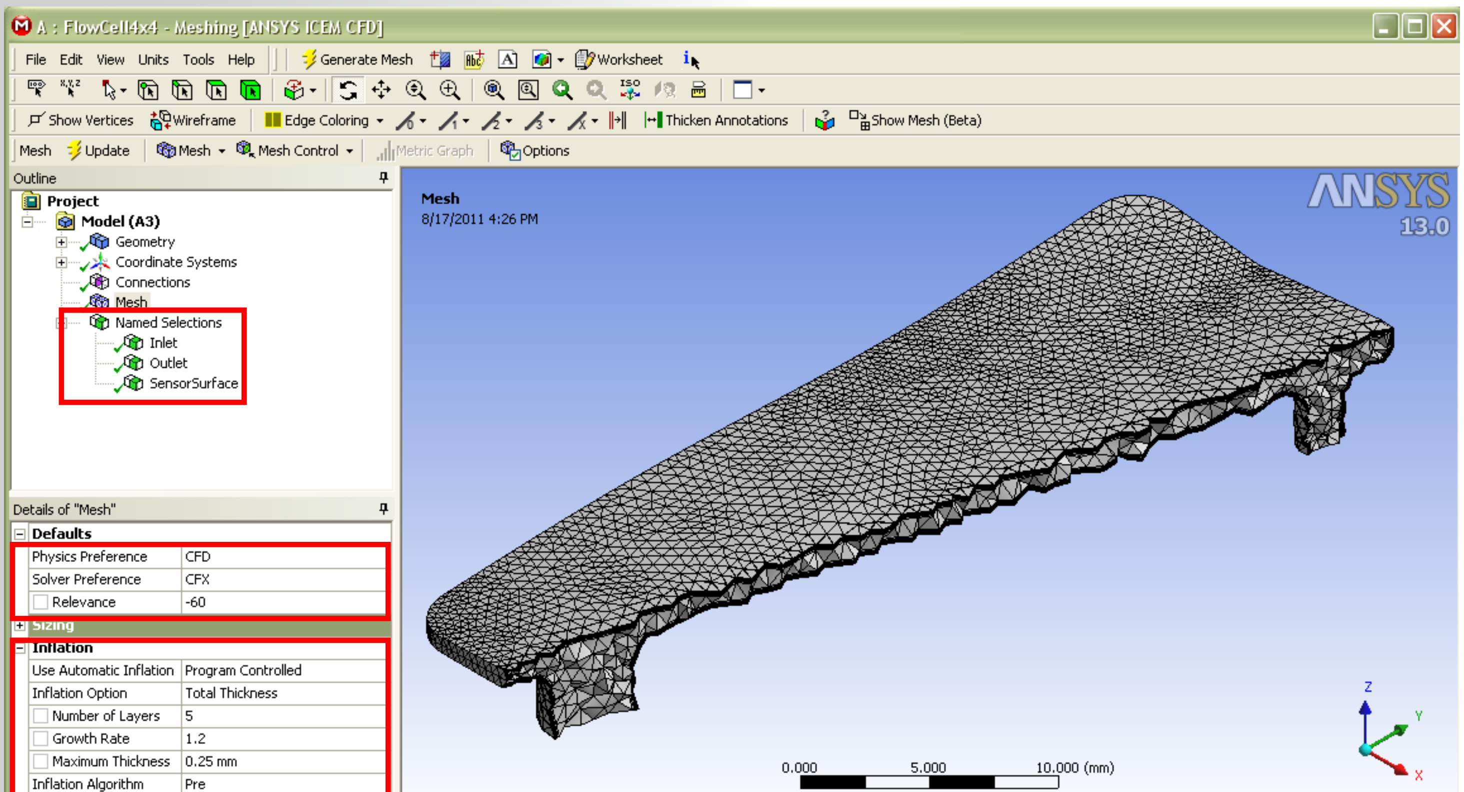


Meshing

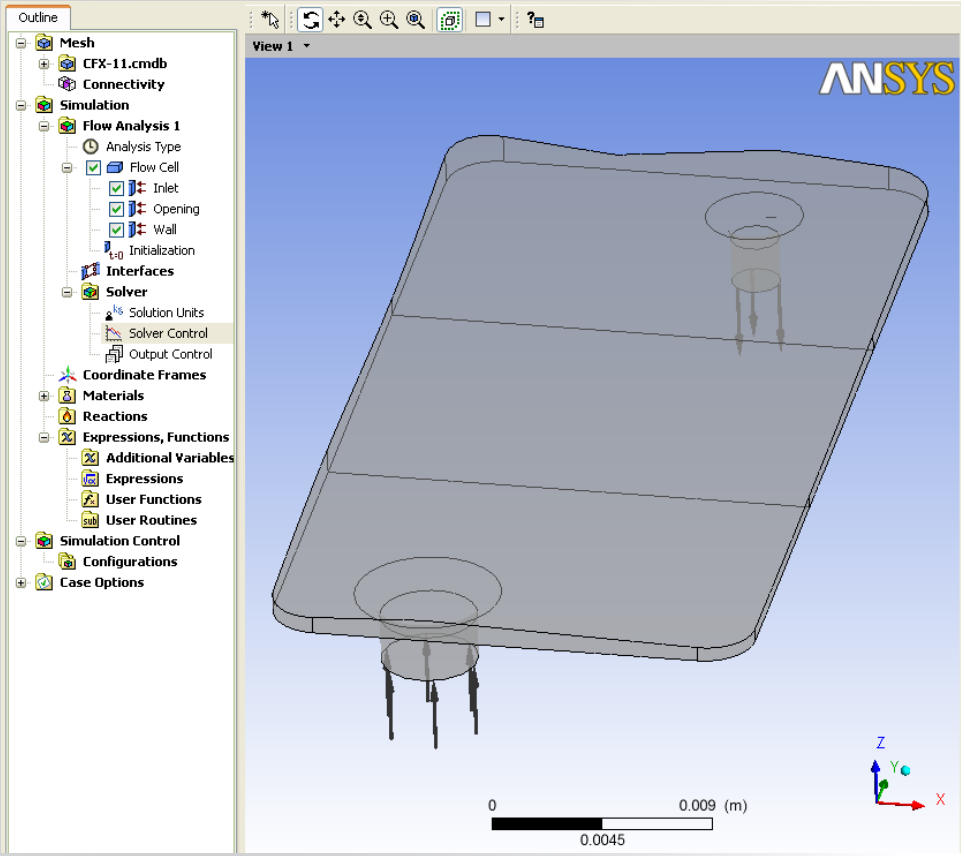
Default settings for the CFD physics preference, with automatic inflation enabled.

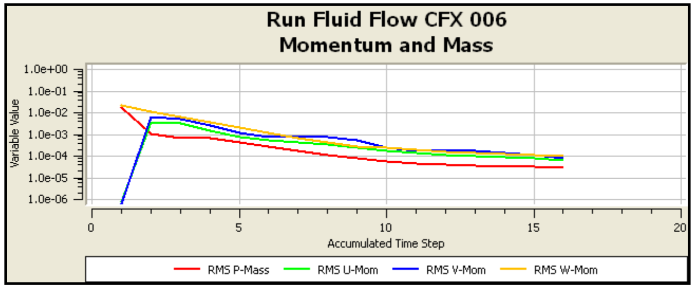
Named selection settings are modified for program controlled inflation. “SensorSurface” is included and “Inlet/Outlet” are excluded as boundaries.

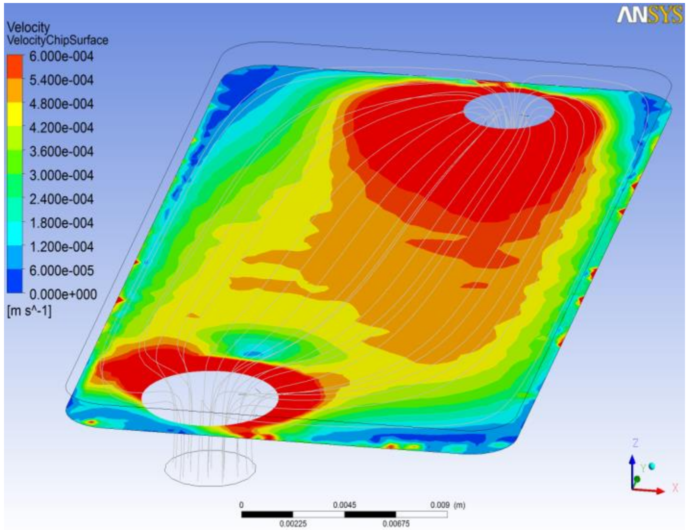
Balance conflicting objectives of obtaining reasonable solution accuracy vs. very short solution times by running a mesh convergence study.



CFD – Setup, Solution, Results







A simple steady-state fluid analysis is setup in CFX-Pre.

The analysis solves in less than 1 minute in CFX-Solver on a mid-range workstation.

The objective of this optimization is to obtain a uniform fluid velocity along the sensor surface. The metric used to quantify uniformity is standard deviation of fluid velocity.

CFD – Standard Deviation

Standard deviation provides a measurement of result variation from the mean. Uniform flow corresponds to minimized standard deviation of velocity.

Standard deviation is not a standard function within CFD-Post.

Evaluate using expressions:

1. Calculate the number of nodes in the region.

```
StDev Count = count()@SensorSurface
```

2. Calculate the mean value of the desired variable.

```
StDev Mean = sum(Velocity)@SensorSurface / StDev Count
```

3. Define variance as the squared difference between the variable and the mean value.

```
StDev Variance = sum((Velocity - StDev Mean )^2 )@SensorSurface / (StDev Count - 1)
```

4. Define standard deviation as the square root of variance.

```
StDev Sensor Velocity = sqrt(StDev Variance)
```

Additional information on these expressions is available on the ANSYS Customer Portal.

Optimization - Summary

Optimization is implemented using ANSYS DesignXplorer, which supports any analysis type or CAD available to Workbench.

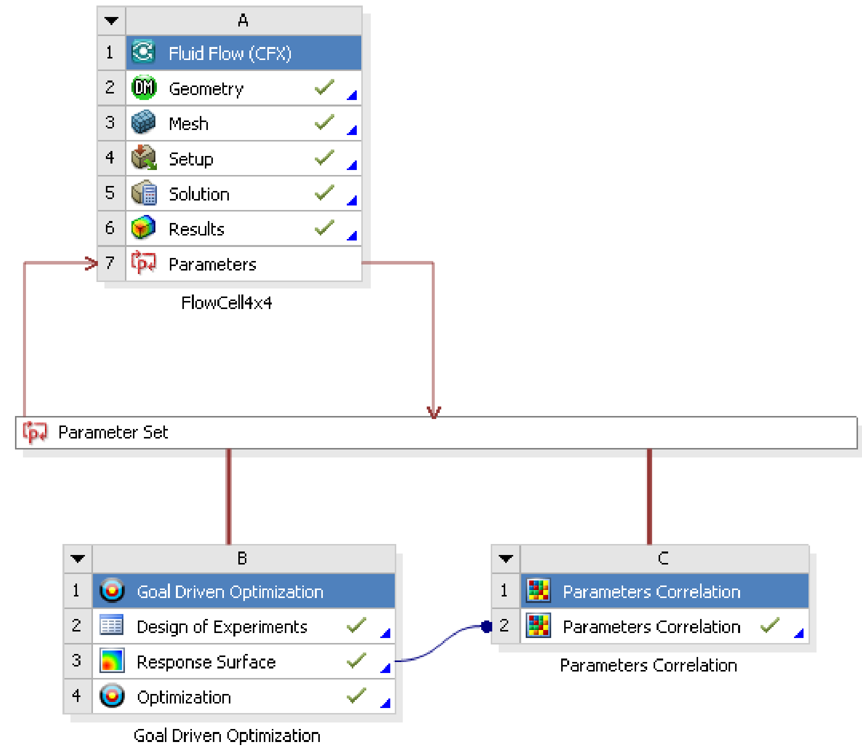
Optimization falls under the broad approach of design exploration – the process of understanding the relationship between design inputs and response outputs. Common tasks include:

- What-if studies
- Design of experiments
- Response surface modeling
- Min-max search
- Parameter correlation
- Goal driven optimization
- Six Sigma

Optimization expands on results obtained through design exploration by predicting and verifying designs to satisfy goals using response surface methodology.

Optimization – Typical Workflow

1. Generate and solve DOE
2. Generate response surface(s) and review Goodness of Fit
3. Review Parameters Correlation
4. Screen to select preliminary candidates
5. Optimize to refine candidates
6. Solve design points to validate leading candidates



Design of Experiments

Design of Experiments (DOE) refers to the structured generation of a set of data used to gain understanding on the relationship between design variables.

A minimum number of DOE solutions are required by DesignXplorer to build a response surface:

2 variables → 9 samples

8 variables → 81 samples

16 variables → 289 samples

Design of Experiments

Specify ranges for all input parameters:

0.3mm ≤ Thickness ≤ 1.5mm

Select the DOE methodology:

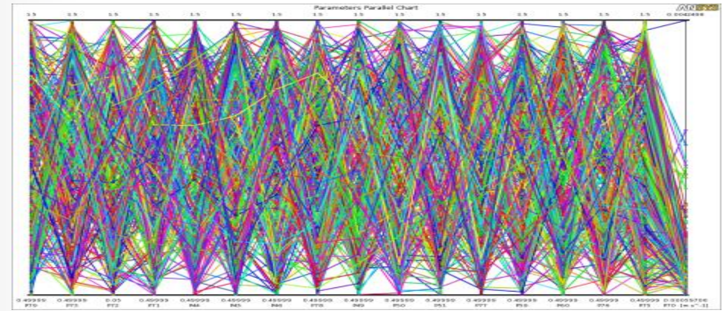
Optimal Space-Filling

Central Composite Design

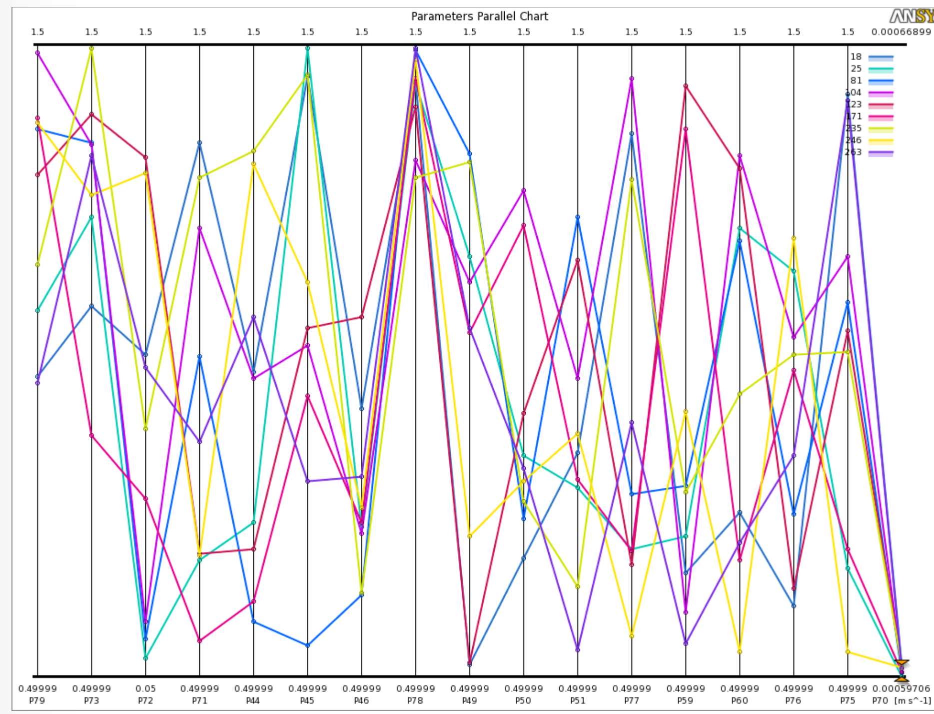
Custom

Samples are distributed throughout the design space.

Review DOE results using Parameters Parallel Charts



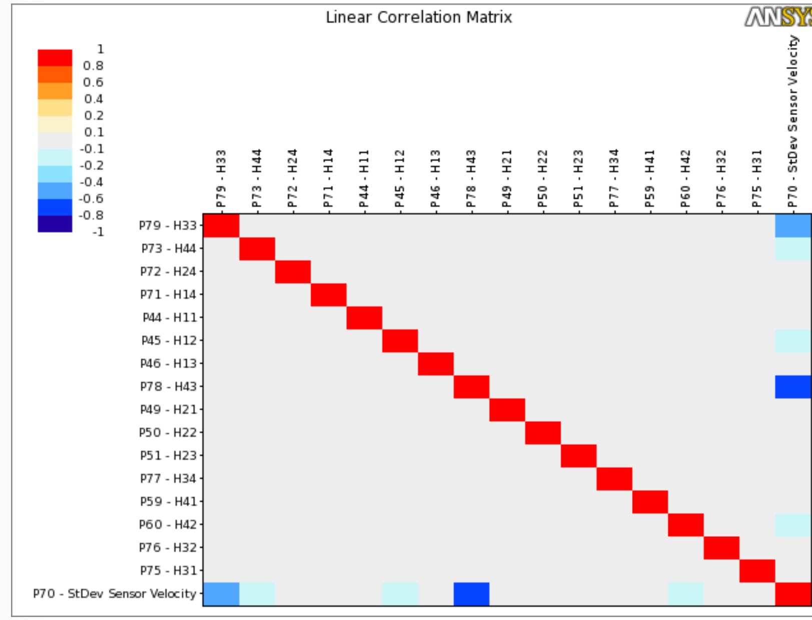
Full Chart



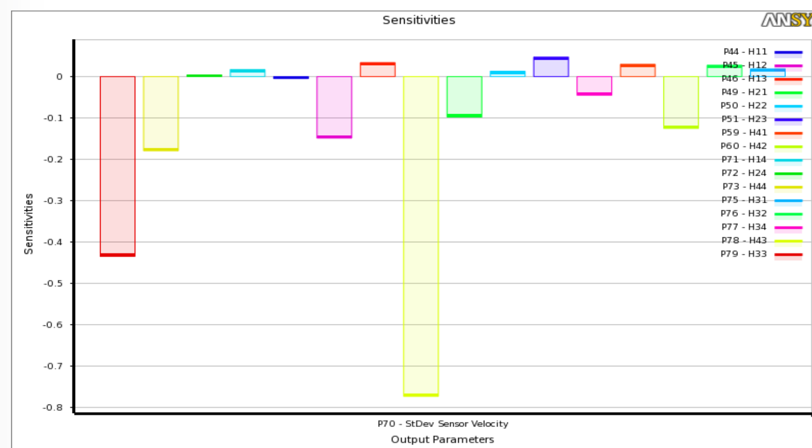
Filtered to best results

Parameter Correlation

- **Visualize importance and nature of variable relationships**
- **Mathematical sampling methods are used to identify parameter relationships for inputs and outputs.**
- **Remove less-important input parameters from design exploration**
  - **Reduce the size of the DOE**
  - **Increase speed and accuracy of surface response generation**
- **Use existing DOE results or auto-generate new samples**



Correlation matrix



Output sensitivities

Response Surface

The meta model approximates the relationship between inputs and outputs by curve-fitting DOE sampling data.

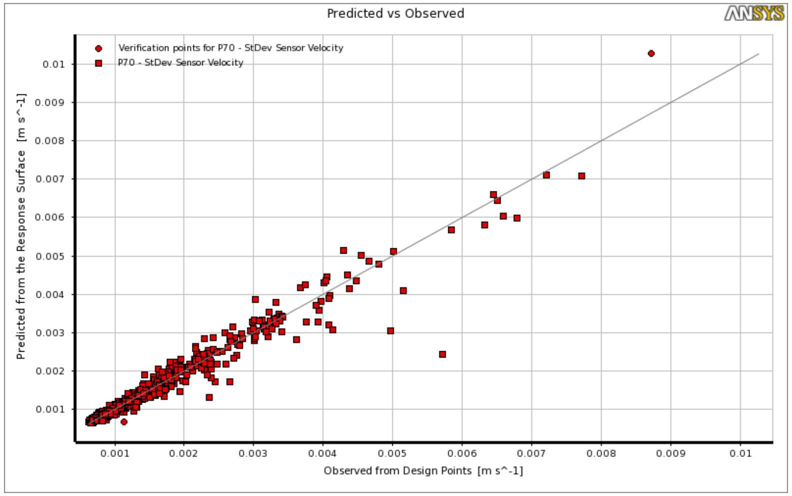
Benefit: Rapidly predict results for theoretical designs without solving hard points.

Response surface training methodology:

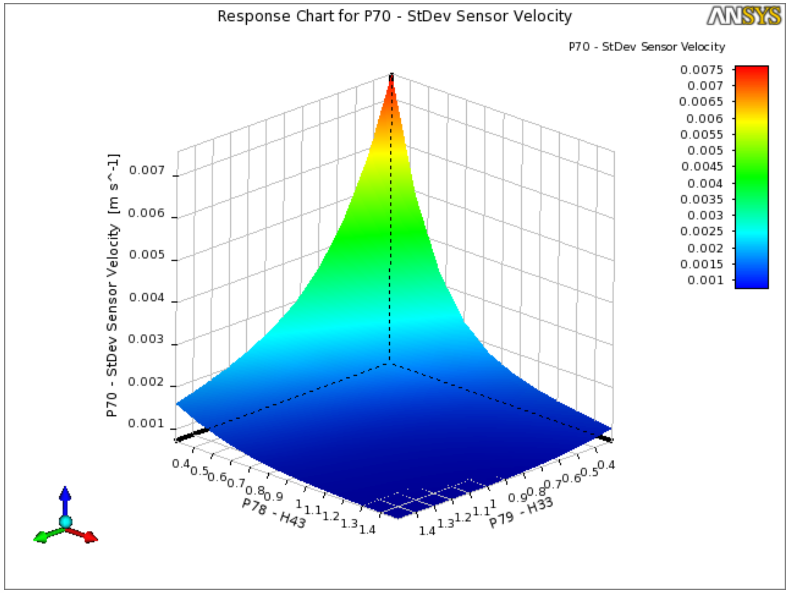
Second-Order Polynomial

Kringing, Non-Parametric Regression, Neural Network

Review & refine Goodness-of-Fit



Second-order polynomial (Goodness-of-Fit 0.95)



3D chart for parameters: H33, H43, StDev Velocity

Goal Driven Optimization

A technique to obtain the best designs from a sample set by evaluating theoretical inputs using response surface methodology. Weighted parameter guidance sets optimization goals and rules.

Specify objectives for output and input parameters:

- **Minimize, Maximize, Relative to target**
- **Prioritize objectives**
- **Specify initial values**

Screening:

- **Overview of design space using random number generation**
- **Multiple design optimization candidates**

NLPQL:

- **Single-objective gradient-based optimizer**
- **Prone to local minima**
- **Single optimization design candidate**

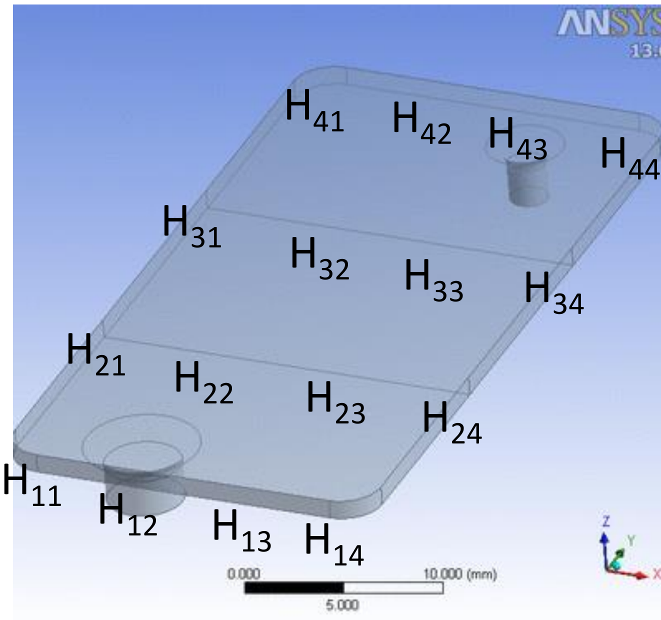


Table of Schematic I4: Optimization

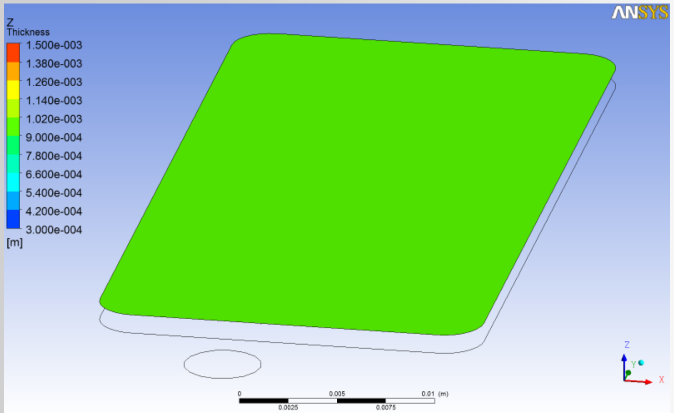
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1		P79 - H33	P73 - H44	P72 - H24	P71 - H14	P44 - H11	P45 - H12	P46 - H13	P78 - H43	P49 - H21	P50 - H22	P51 - H23	P77 - H34	P59 - H41	P60 - H42	P76 - H32	P75 - H31	P70 - StDev Sensor Velocity (m s^-1)
2	Optimization Study																	
3	Initial Value	1.498	1.4982	0.3	0.3	1.1	1.4982	0.5	1.4948	1.45	0.5	0.5	1.3	0.4	1.498	0.4	0.4	
4	Objective	No Ob...	No O...	No O...	No O...	No O...	No O...	No O...	No Ob...	No O...	No Ob...	No O...	No Objective	No O...	No O...	No O...	No O...	Minimize
5	Target Value																	
6	Importance	Default	Default	Default	Default	Default	Default	Default	Default	Default	Default	Default	Default	Default	Default	Default	Default	Higher
7	Candidate Points																	
8	Candidate A	1.4983	1.4...	0.2...	0.3	1.1	1.4...	0.5	1.4948	1.1...	1.4983	0.3	0.3	0.3	1.4...	0.3	1.4983	0.00019672
9	Verification A																	0.00057896

Final Results

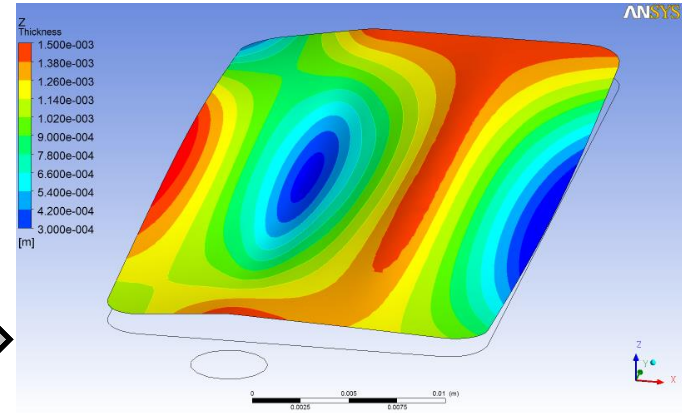
Baseline Design / Optimized Design

Flow Cell Thickness Contour

Baseline Design:

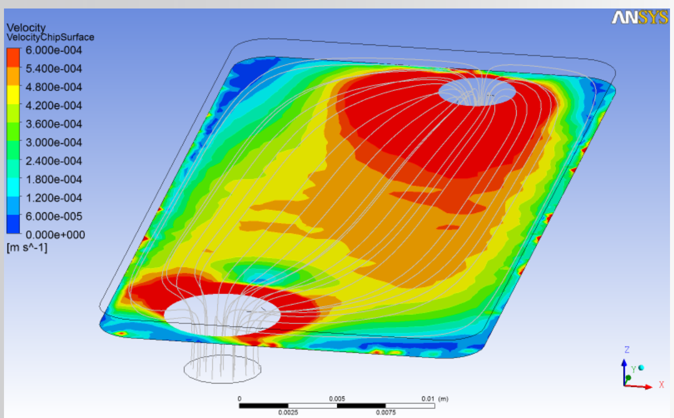


Optimized Design:

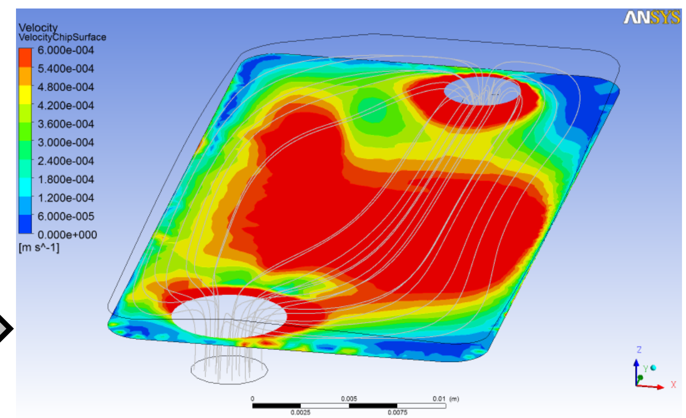


Sensor Velocity Contour

Baseline Design:



Optimized Design:



The contoured thickness profile of the optimized design leads to 40% improvement in flow uniformity at the sensor surface (StDev 0.57 mm/s compared to 0.91 mm/s).

Additional refinement iterations and more extensive parameter ranges can be incorporated to improve results further.

Summary

This presentation has demonstrated how ANSYS products & technology can be used to create robust parametric models and solve shape optimization for a fluid domain.

These results show that parametric modeling and optimization techniques can be employed to rapidly and accurately refine a product design to include amorphous features which improve flow characteristics.

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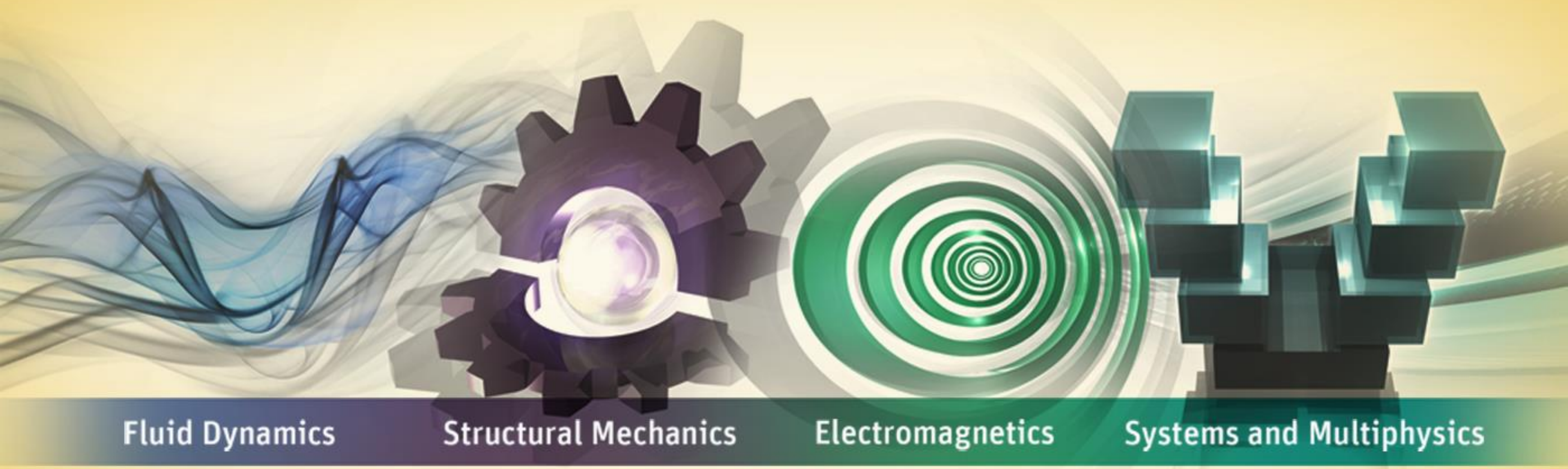
QUESTIONS ?

Thank you for your attention



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