

Pathways Internship Final Presentation

Satvik Kumar

May 19, 2022



5...4...3...2...1...

SPACE LAUNCH SYSTEM

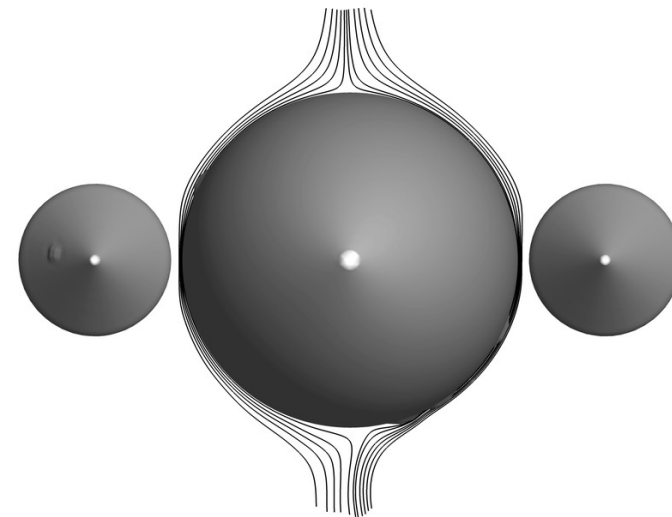
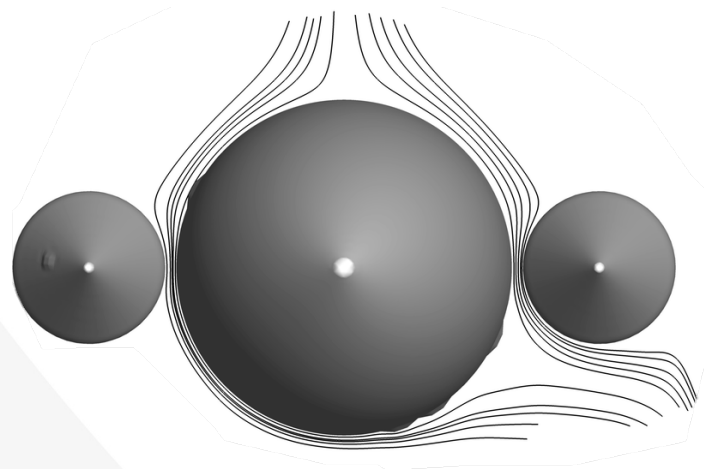
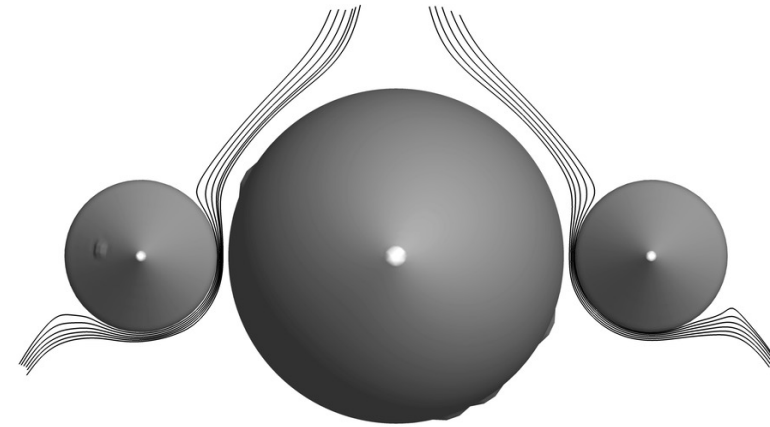
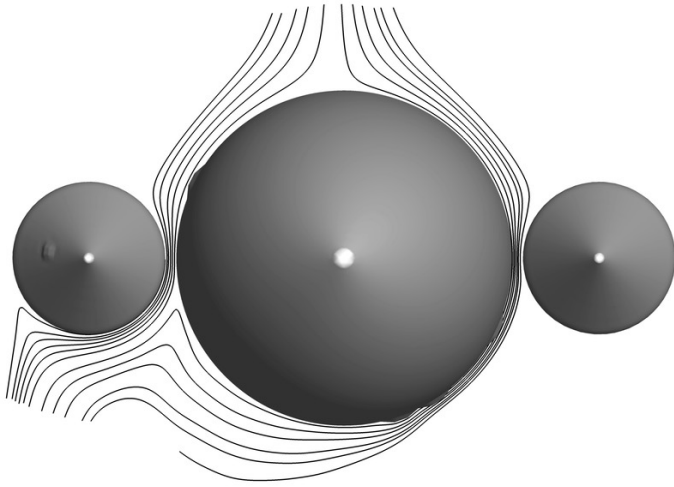
Exploring Coanda Effect with 3 Cylinder Geometry

Satvik Kumar

Mentors: Brent Pomeroy and Karen Deere

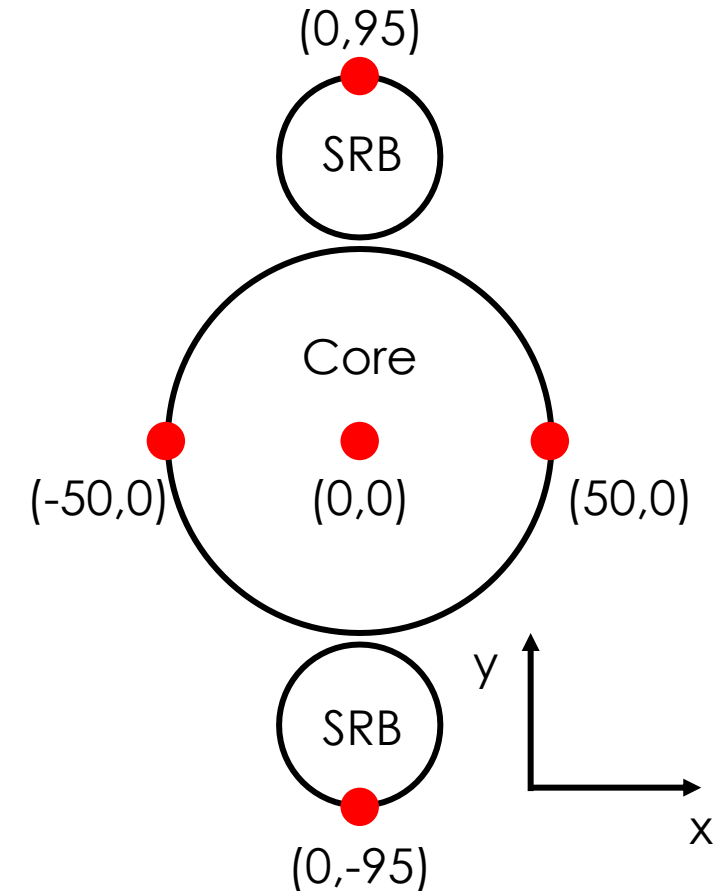
INTRODUCTION/ COANDA EFFECT

- High-alpha feature (tendency of flow to remain attached to concave surface)
- Noticed on SLS Rocket



PROBLEM DEFINITION/GOAL

- Study the Coanda Effect using a simplified geometry
- Geometry
 - 3 Cylinder configuration to mimic 3 Body and SLS
 - Model in 2D: depth 500 inches
 - $D_{\text{core}} = 100$ in.
 - $D_{\text{srb}} = 42$ in.
 - Spacing between Core and SRBs = 3 in.



APPROACH AND TOOLS

- **Geometry Creation**
 - MATLAB
- **Patching**
 - GridTool
- **Grid Exploration/Mesh Creation**
 - HeldenMesh
- **Solution**
 - Kestrel
- **Post-Processing/Analysis**
 - TecPlot

GRID EXPLORATION – FINAL PARAMETERS SELECTED

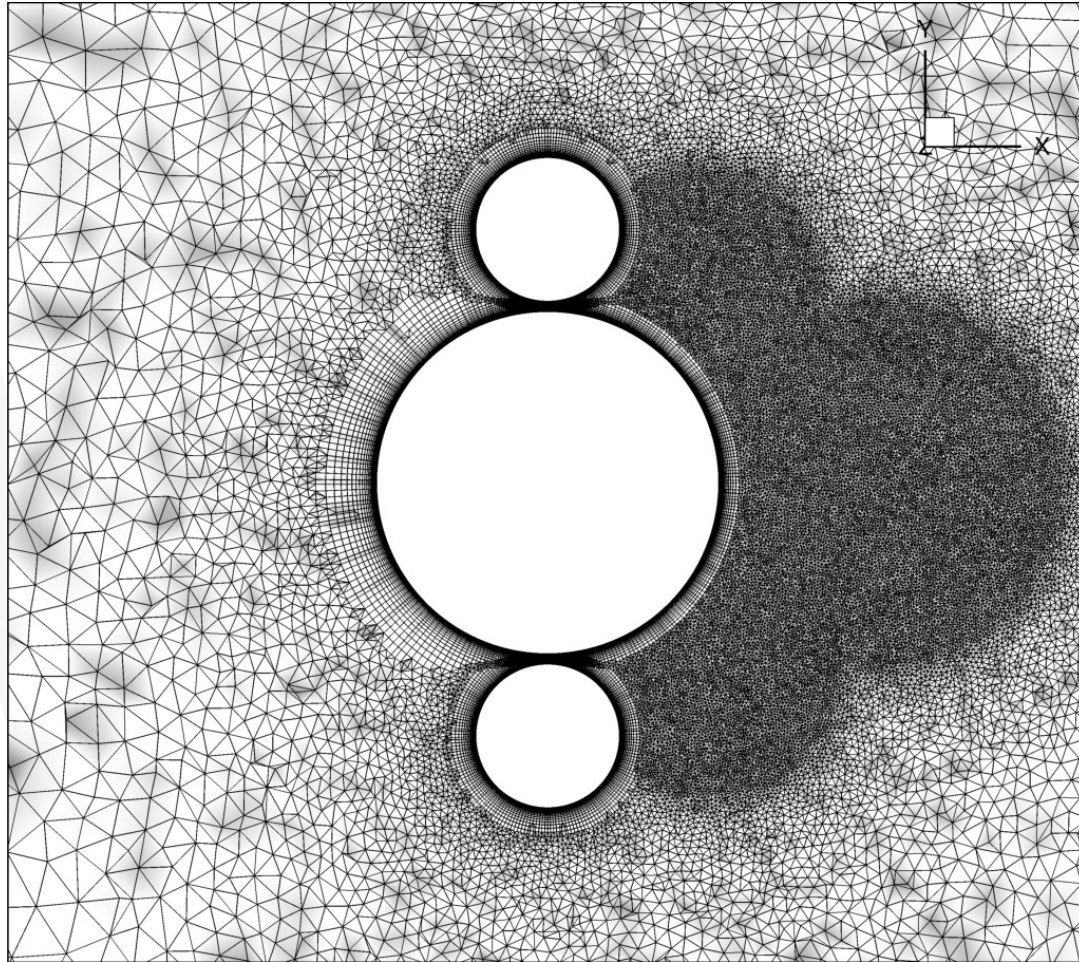
- **Core Surface Cell Size:** 1.5 in
- **SRB Surface Cell Size:** 0.75 in

Cylindrical Sources	y+	N	Surface Tris	Prisms	Pyramids	Tetrahedrals	Total Cells
9	0.75	32	2,600,486	82,702,318	307,092	88,538,278	~173M

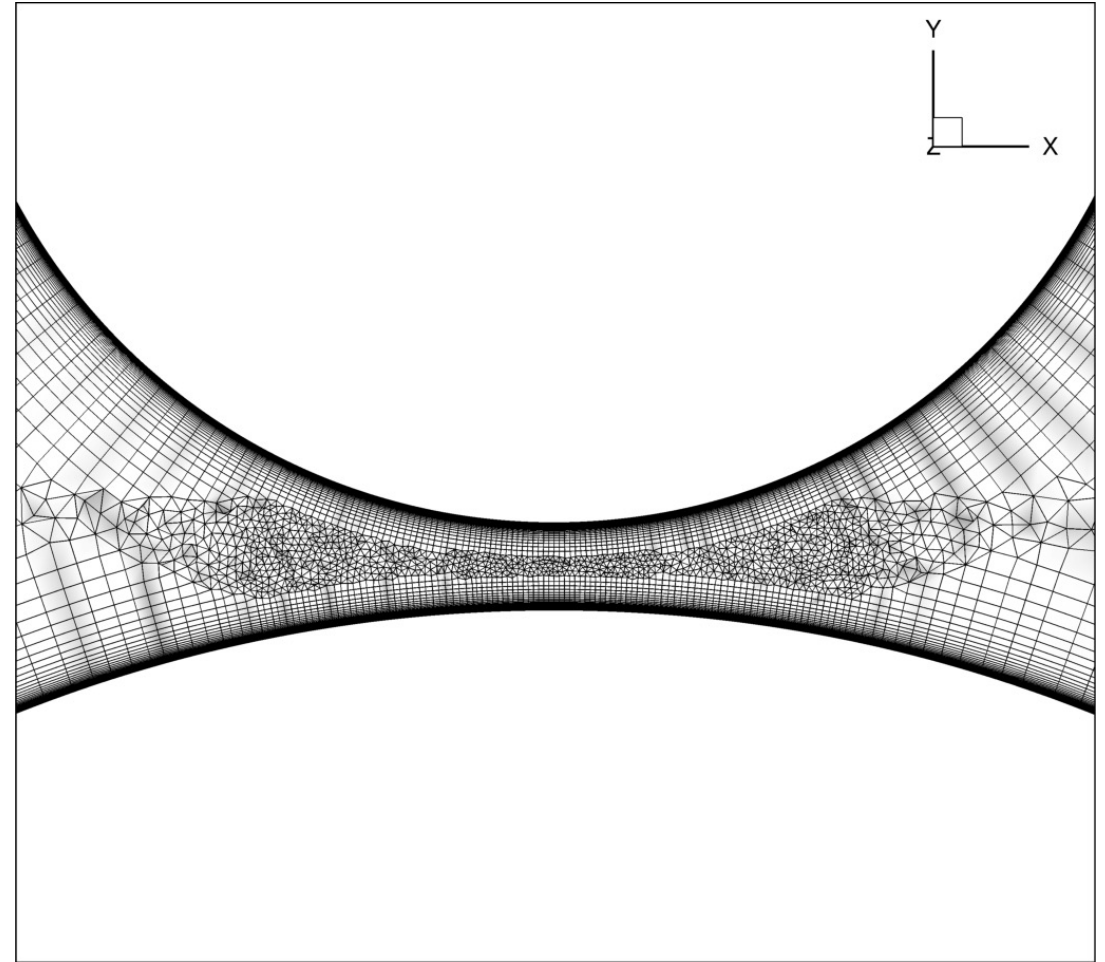
Source Type	Purpose	x	y	z	s	Radius
cylindrical	Channel	0	± 51.5	± 250	0.2	3
cylindrical	Channel	± 15	± 51.5	± 250	0.25	4
cylindrical	Wake	96	0	± 250	1	52
cylindrical	Wake	53	± 55	± 250	1	35

GENERATED GRID (SINGLE UNSTRUCTURED MESH)

Wake Region



Channel

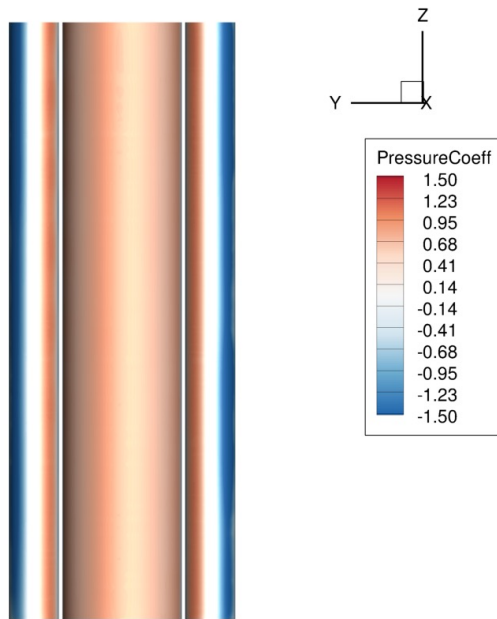


KESTREL RUN SETTINGS

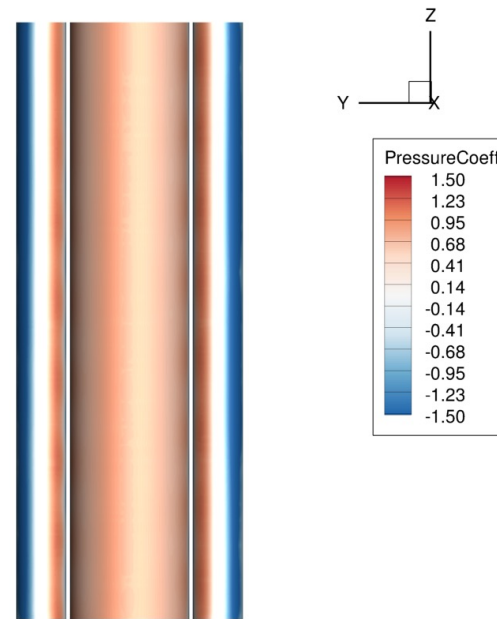
- **Default Kestrel Settings Utilized as Utilized for SLS**
- **Improved Delayed Detached-Eddy Simulation (IDDES)**
- **SA Turbulence Model**
- **Symmetry Boundary Conditions at $z_{\min}$ and $z_{\max}$**
- **No Slip Walls**
- **Time Step**
 - Nondimensional Time Step: 0.00369
 - Dimensional Time Step: 0.00015
- **Starting Flow Conditions**
 - Reynolds Number: 20,000
 - Mach Number: 0.183
 - Temperature: 522° R

FRONT SURFACE C_p DISTRIBUTION

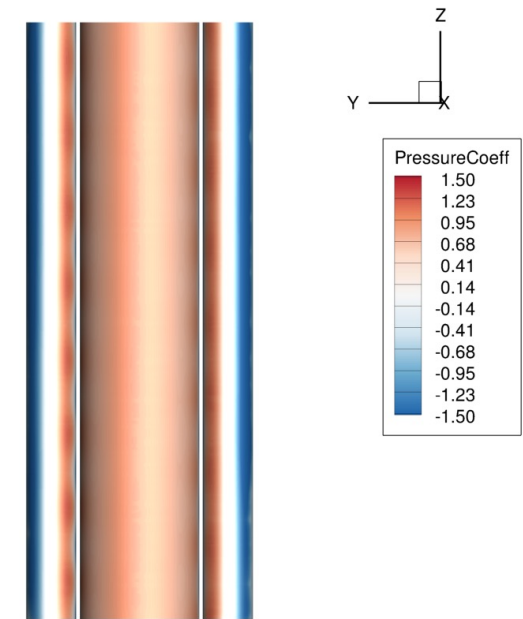
8,000 iterations, 1.2 seconds



12,000 iterations, 1.8 seconds



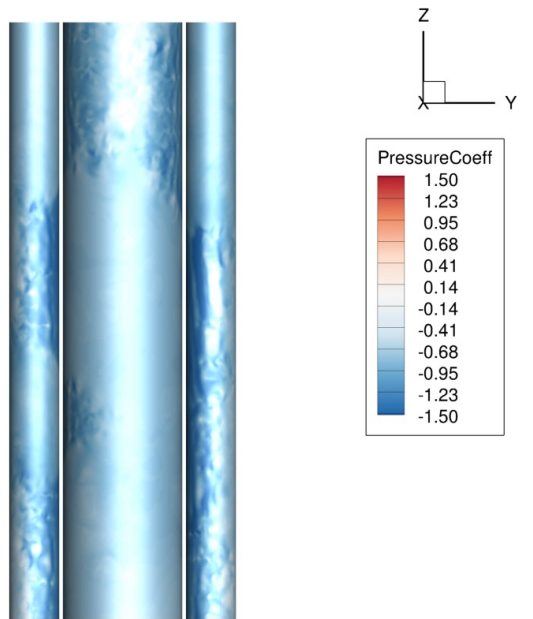
16,000 iterations, 2.4 seconds



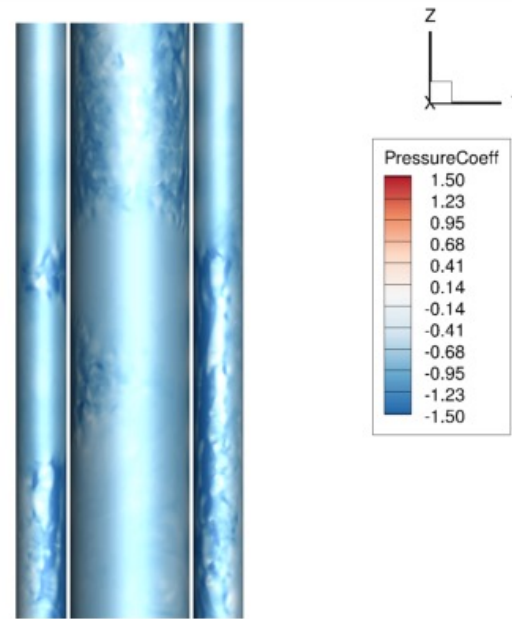
- Front pressure distribution is as expected with slow velocities and stagnation points

BACK SURFACE C_p DISTRIBUTION

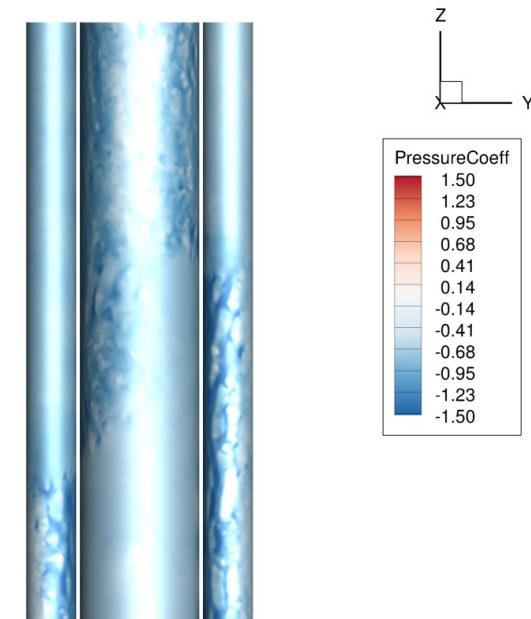
8,000 iterations, 1.2 seconds



12,000 iterations, 1.8 seconds



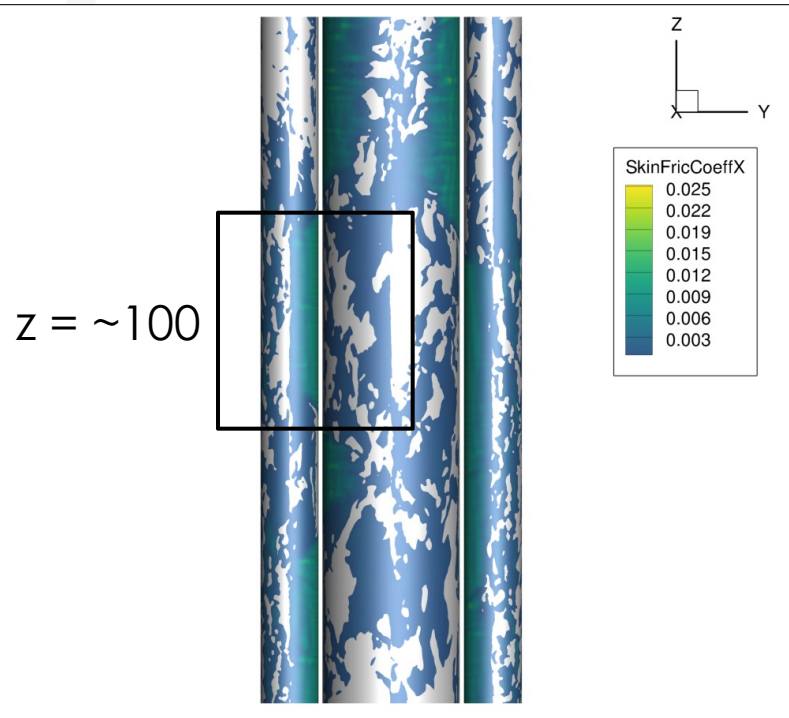
16,000 iterations, 2.4 seconds



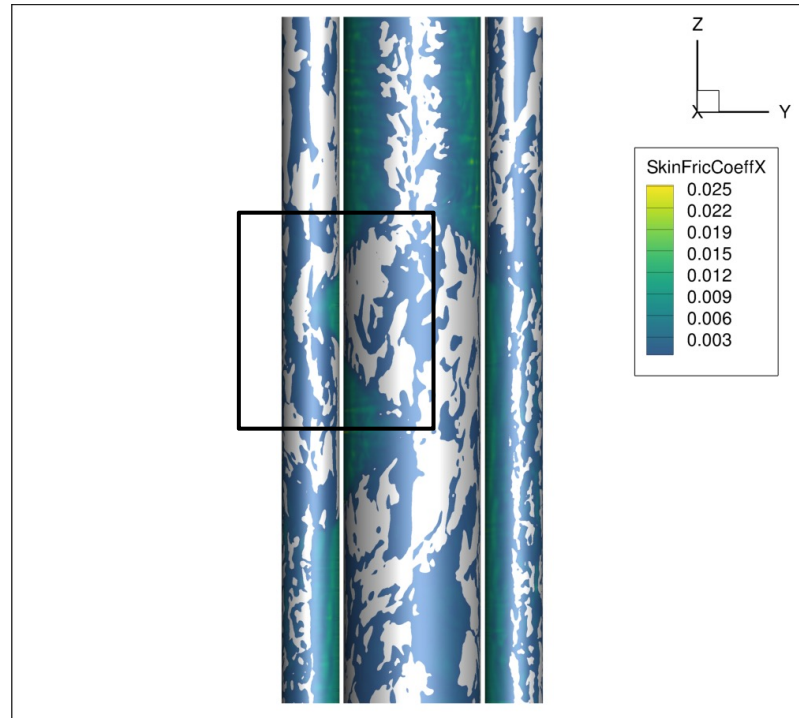
- Back surface has higher velocities as expected
- Start seeing positions with higher velocities on the surface that varies based on the z value

BACK SURFACE C_F DISTRIBUTION

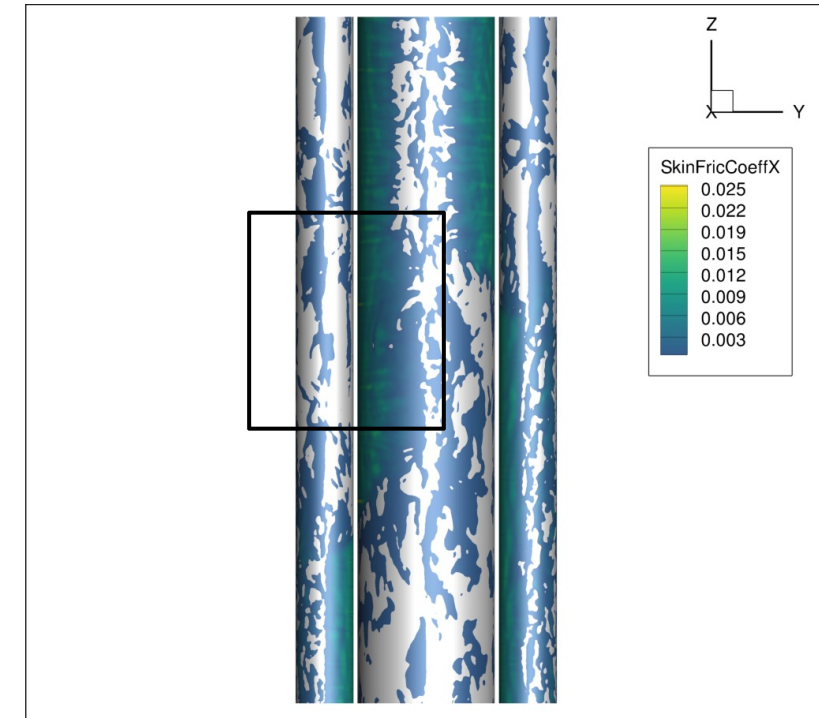
8,000 iterations, 1.2 seconds



12,000 iterations, 1.8 seconds



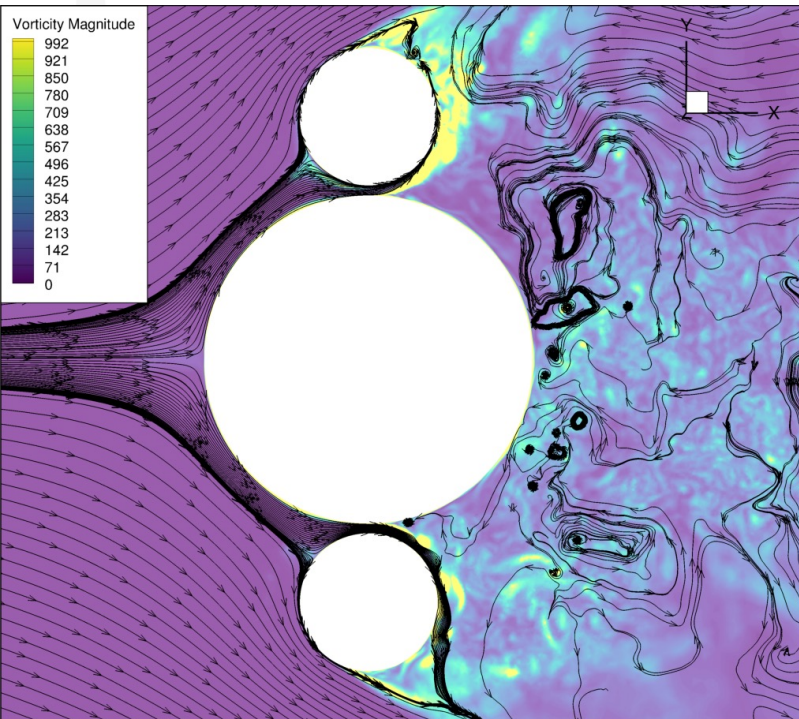
16,000 iterations, 2.4 seconds



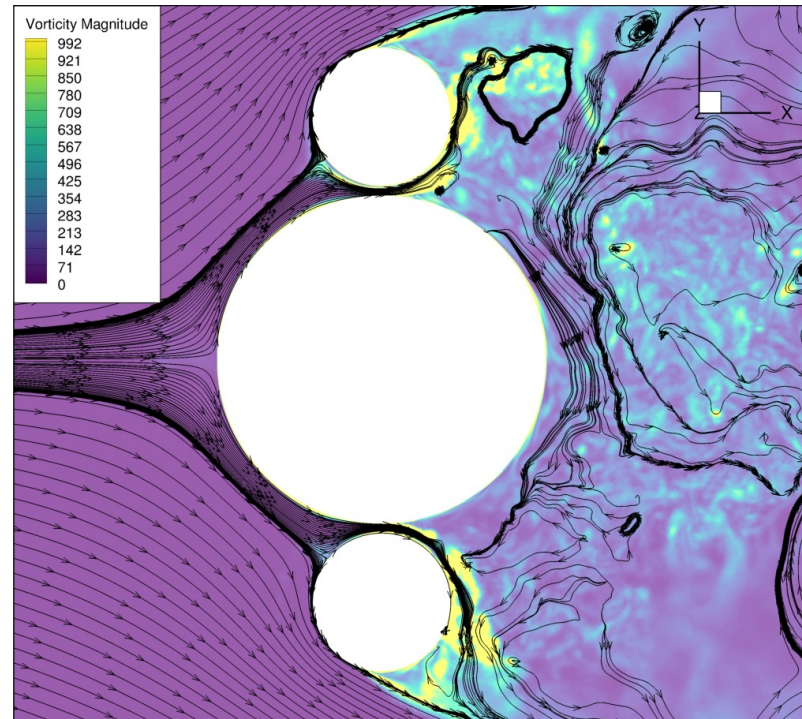
- Flow is attaching to either the center body or SRB in many locations
- The body to which the flow attaches varies based on the z location
- At $z \sim 100$ flow changes direction in time

STREAMLINES AND VORTICITY MAGNITUDE, Z=-200

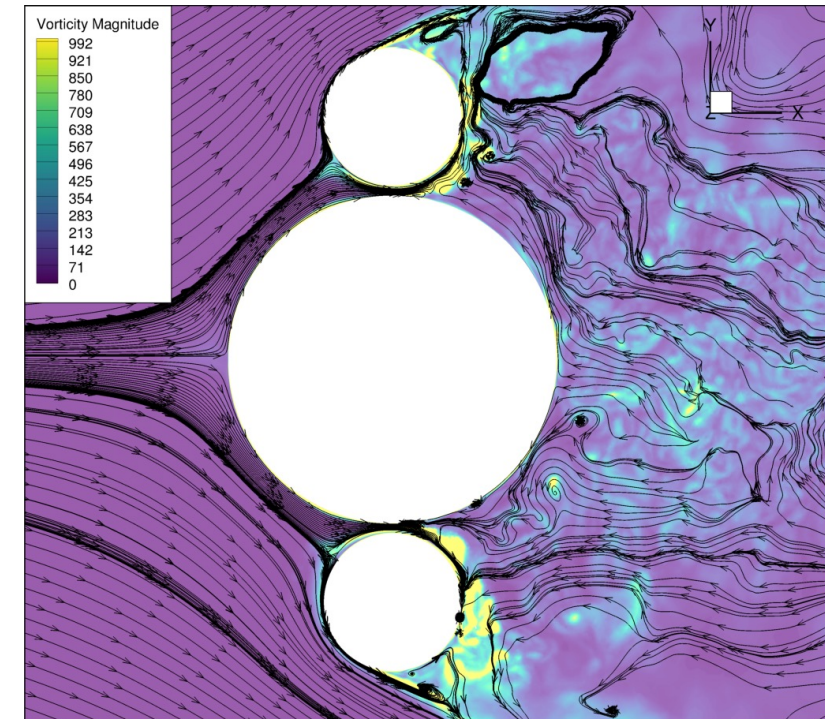
8,000 iterations, 1.2 seconds



12,000 iterations, 1.8 seconds



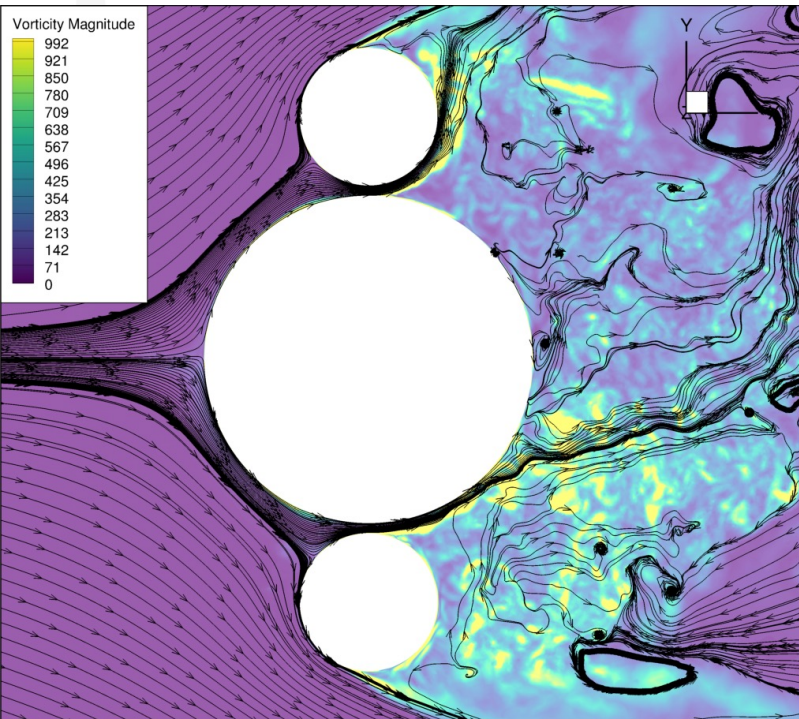
16,000 iterations, 2.4 seconds



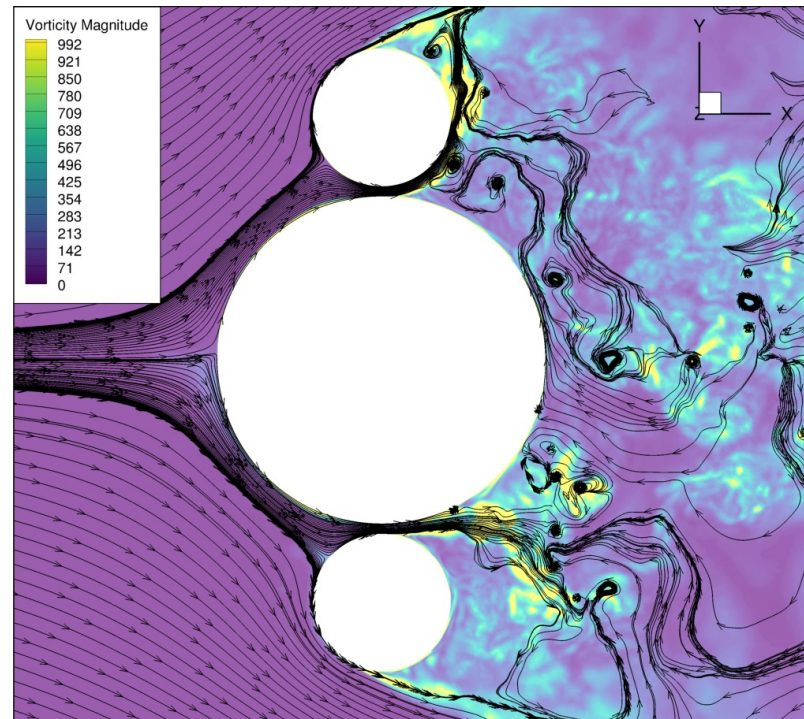
- Flow tends to remain attached to the SRBs
- High vorticity in the wake and around the cylinders where flow is attached
- Very minimal change through time

STREAMLINES AND VORTICITY MAGNITUDE, Z=-100

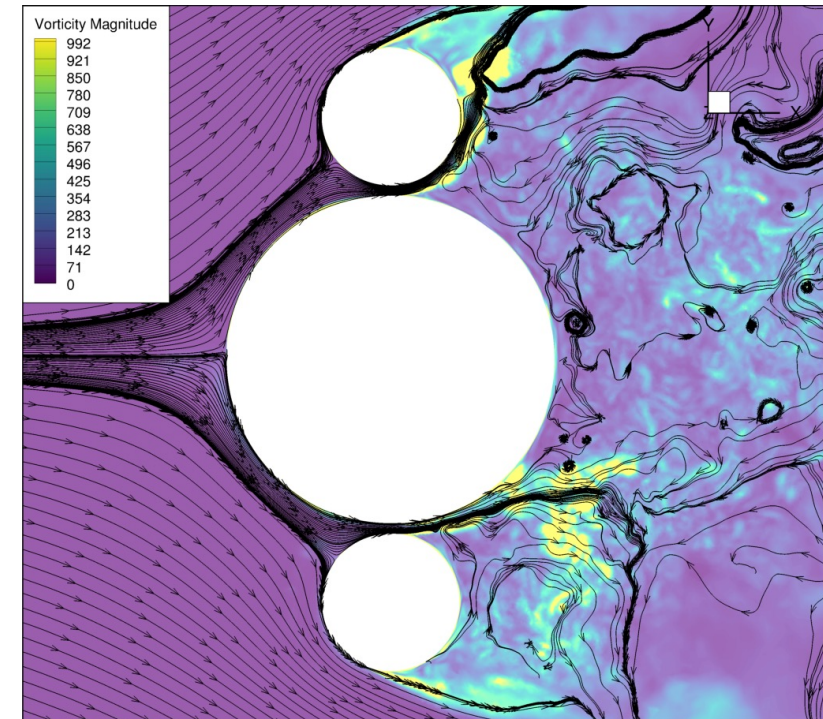
8,000 iterations, 1.2 seconds



12,000 iterations, 1.8 seconds



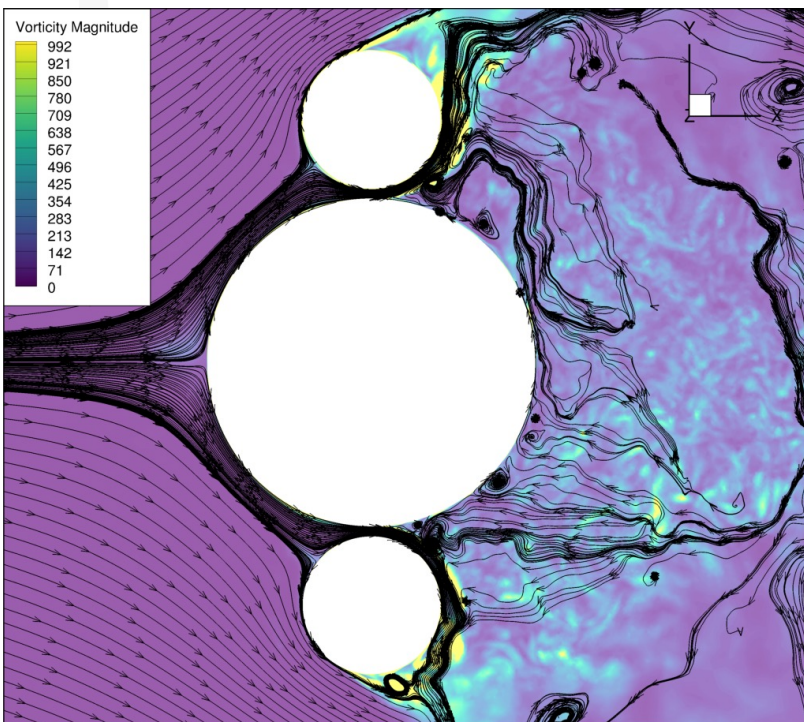
16,000 iterations, 2.4 seconds



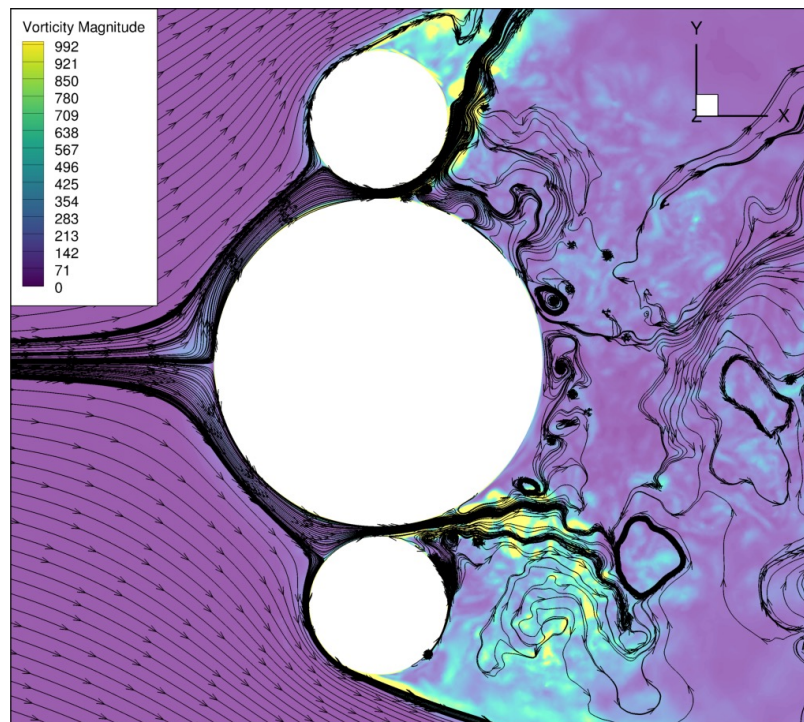
- Flow tends to remain attached to the SRBs or center body
- High vorticity in the wake and around the cylinders where flow is attached
- Very minimal change through time

STREAMLINES AND VORTICITY MAGNITUDE, Z=0

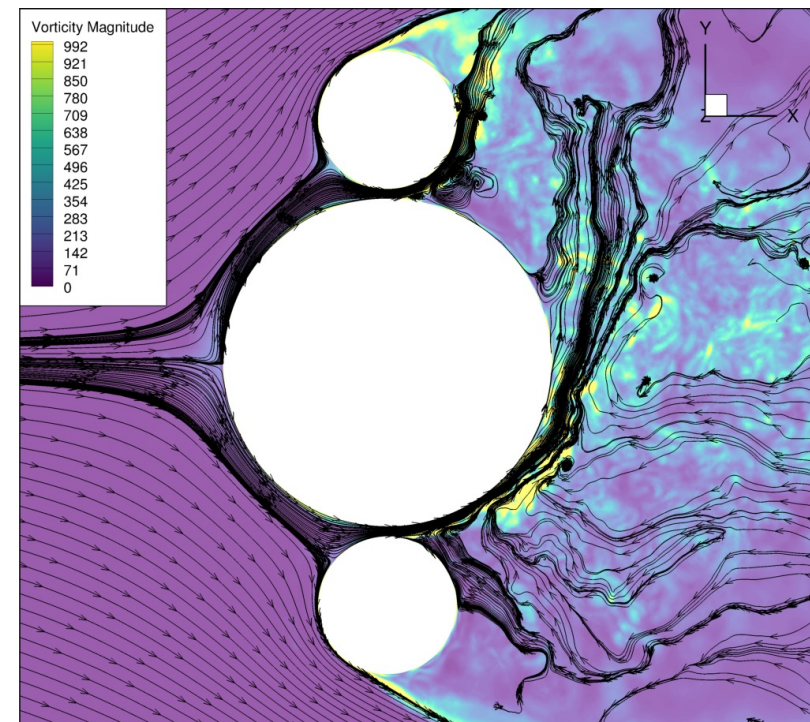
8,000 iterations, 1.2 seconds



12,000 iterations, 1.8 seconds



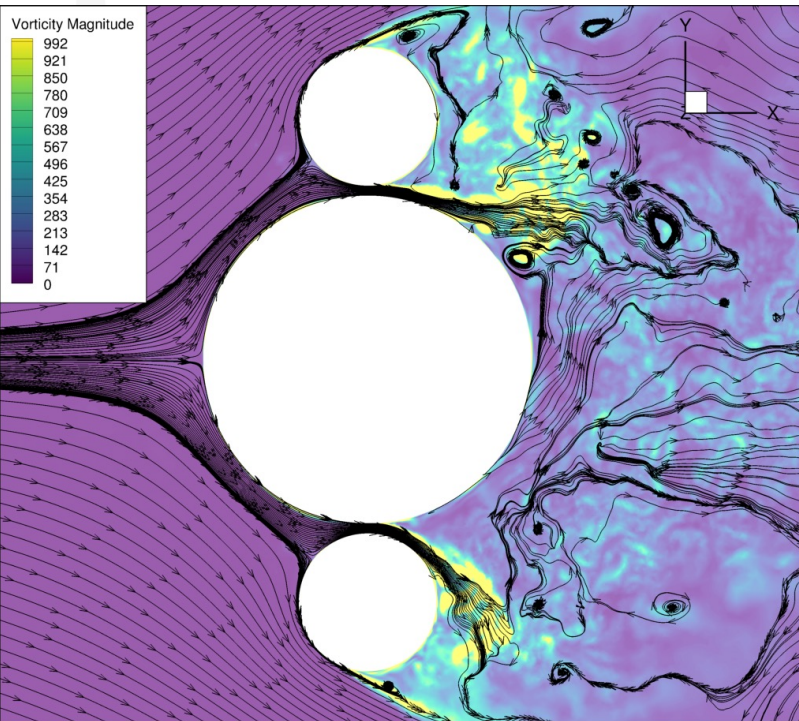
16,000 iterations, 2.4 seconds



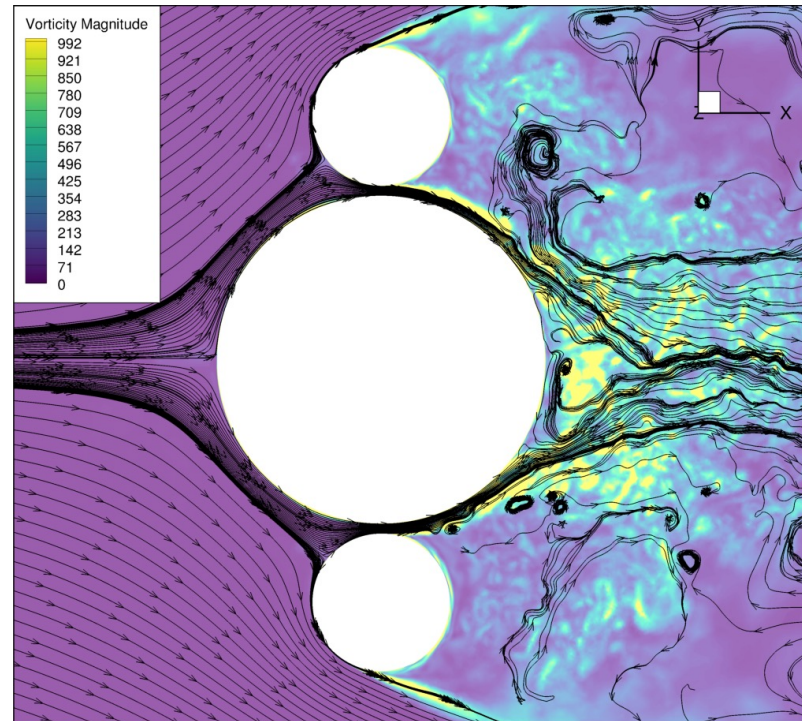
- Flow tends to remain attached to the SRBs or center body
- High vorticity in the wake and around the cylinders where flow is attached
- Start seeing some change through time

STREAMLINES AND VORTICITY MAGNITUDE, Z=100

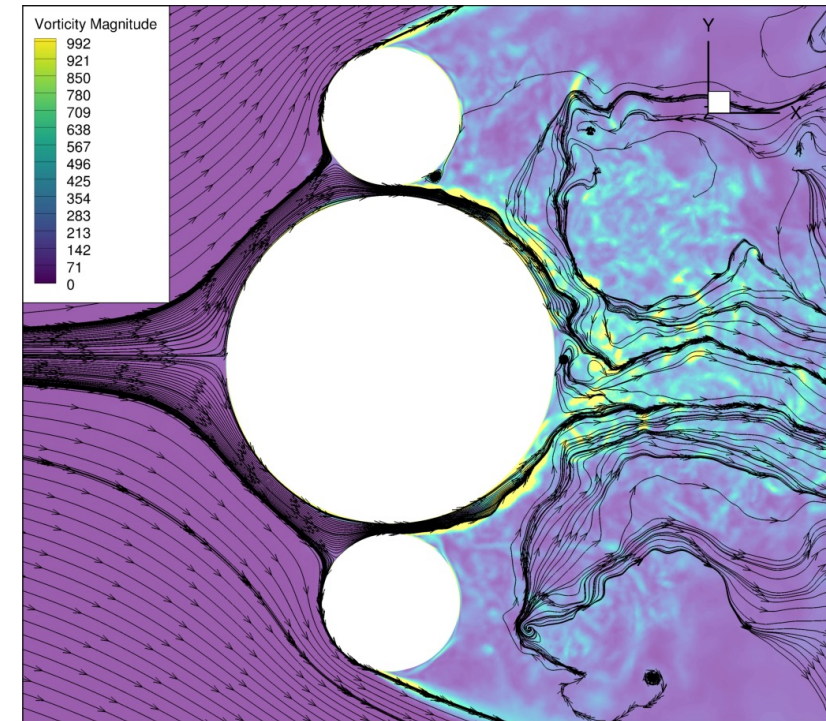
8,000 iterations, 1.2 seconds



12,000 iterations, 1.8 seconds



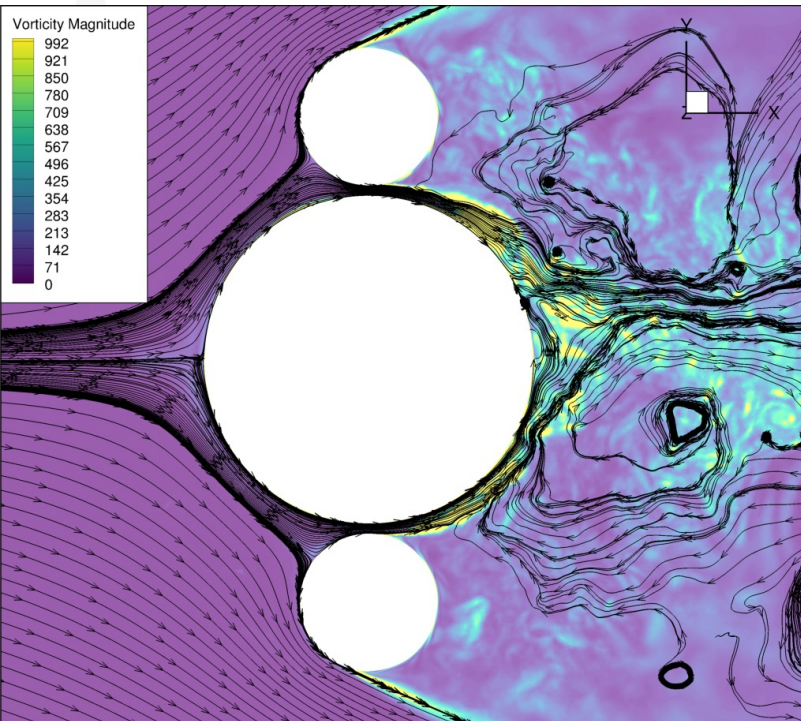
16,000 iterations, 2.4 seconds



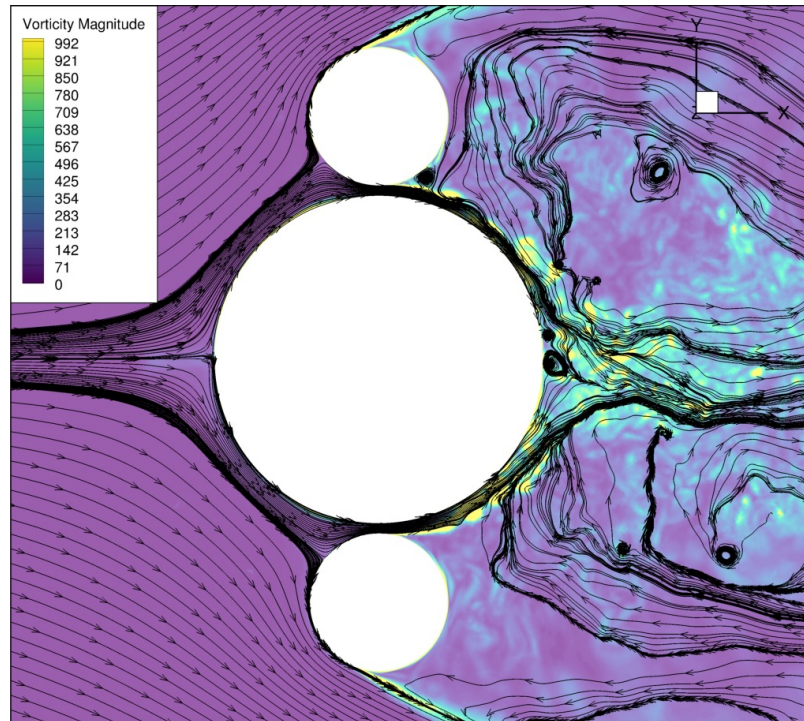
- Flow tends to remain attached to the SRBs or center body
- High vorticity in the wake and around the cylinders where flow is attached
- Flow completely changes direction on the port SRB through time

STREAMLINES AND VORTICITY MAGNITUDE, Z=200

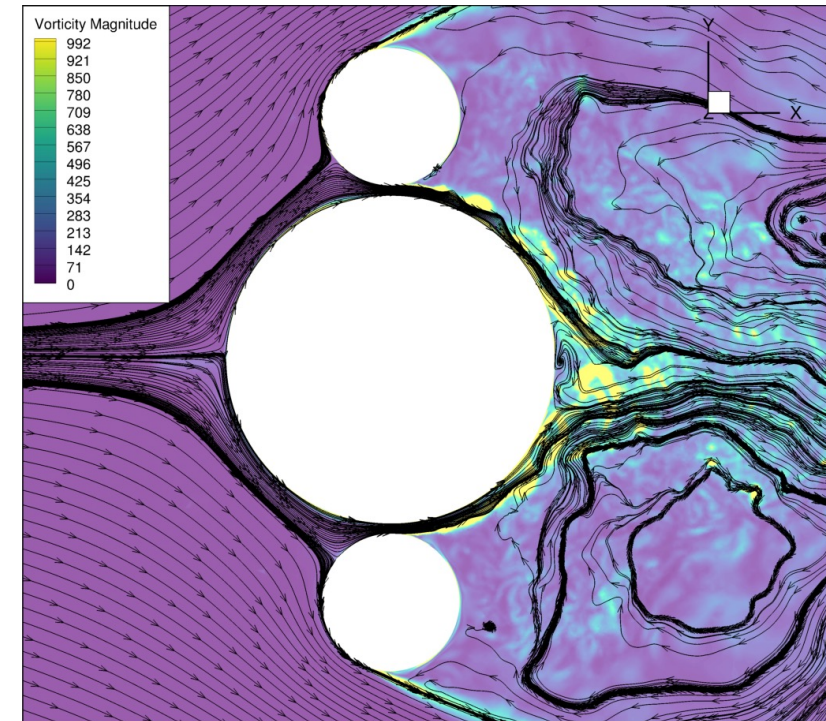
8,000 iterations, 1.2 seconds



12,000 iterations, 1.8 seconds



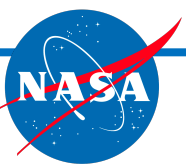
16,000 iterations, 2.4 seconds



- Flow tends to remain attached to the center body
- High vorticity in the wake and around the cylinders where flow is attached
- Very minimal change through time

TAKEAWAYS/CONCLUSION

- **Flow tended to attach to the centerbody or the SRB**
- **Differences in attachment based on the z location of flow**
- **Some observations of flow switching directions over time**
- **Next Steps**
 - Run more than 17,000 iterations for more time data
 - Periodic boundary conditions
 - Dual mesh adaption



Design Exploration of Airfoil Thickness for Conventional and Slotted Airfoil Concepts



Mentors: Brett Hiller, Dick Campbell, Michelle Lynde
Configuration Aerodynamics Branch
NASA Langley Research Center

Spring 2022

Cruise Slotted Airfoil

Concept

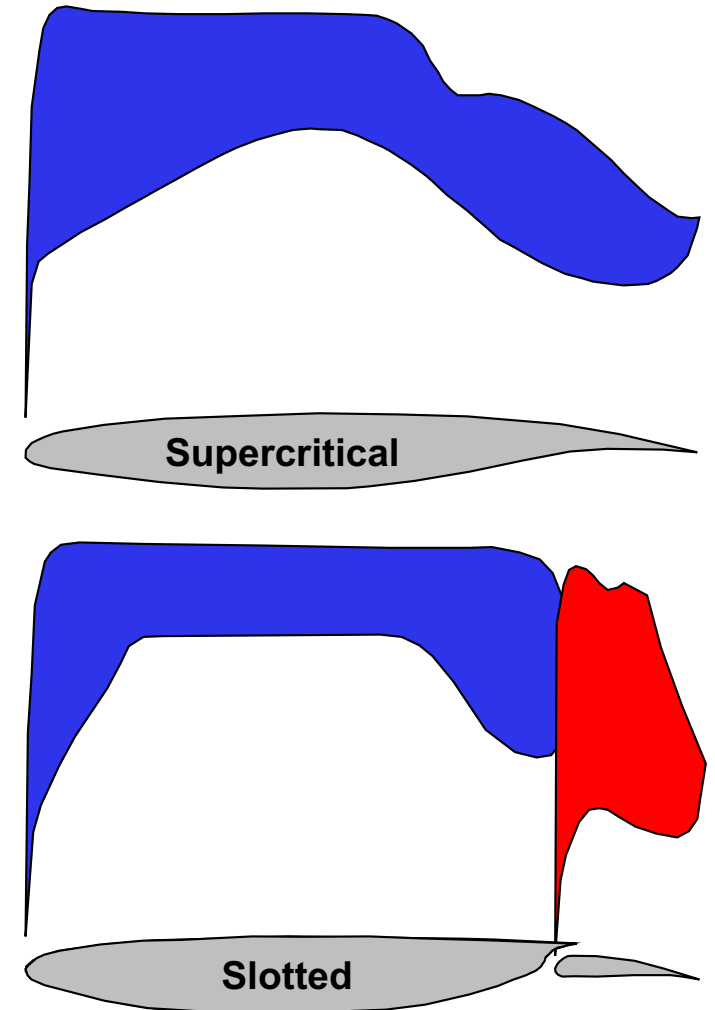
Flow-through slot permits stronger pressure recovery without separation – enables greater aft loading

Potential Benefits

- Reduced drag → Greater fuel efficiency
- Hold drag constant with:
 - Increased thickness → Lighter structure, more storage
 - Reduced sweep → Lighter structure, laminar flow easier
 - Increased speed → More city-pair options

Current Research Objective

Quantify impact of airfoil thickness on aerodynamic performance for conventional and slotted airfoils



Research Questions

1. Conventional – Turbulent Design

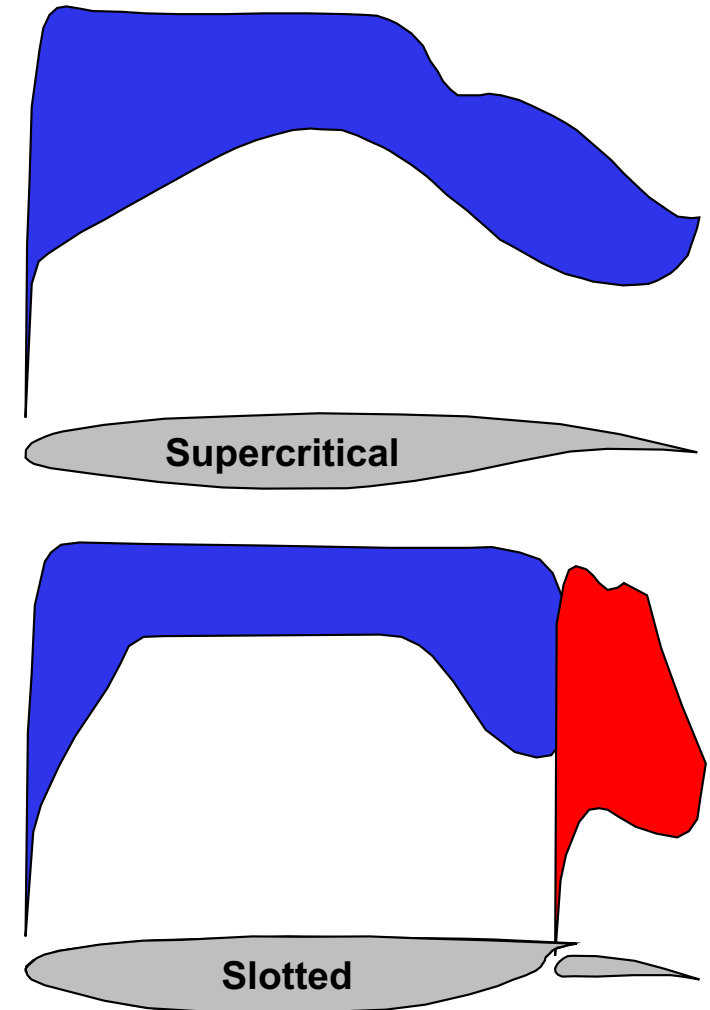
- How does thickness impact aerodynamic performance at a fixed cruise lift coefficient?

2. Slotted – Turbulent Design

- How does relative performance to the conventional airfoil change with differences in design thickness?
- What flap loading yields the most optimal aerodynamic performance at a fixed cruise lift coefficient and thickness?

3. Slotted – Laminar Flap Design

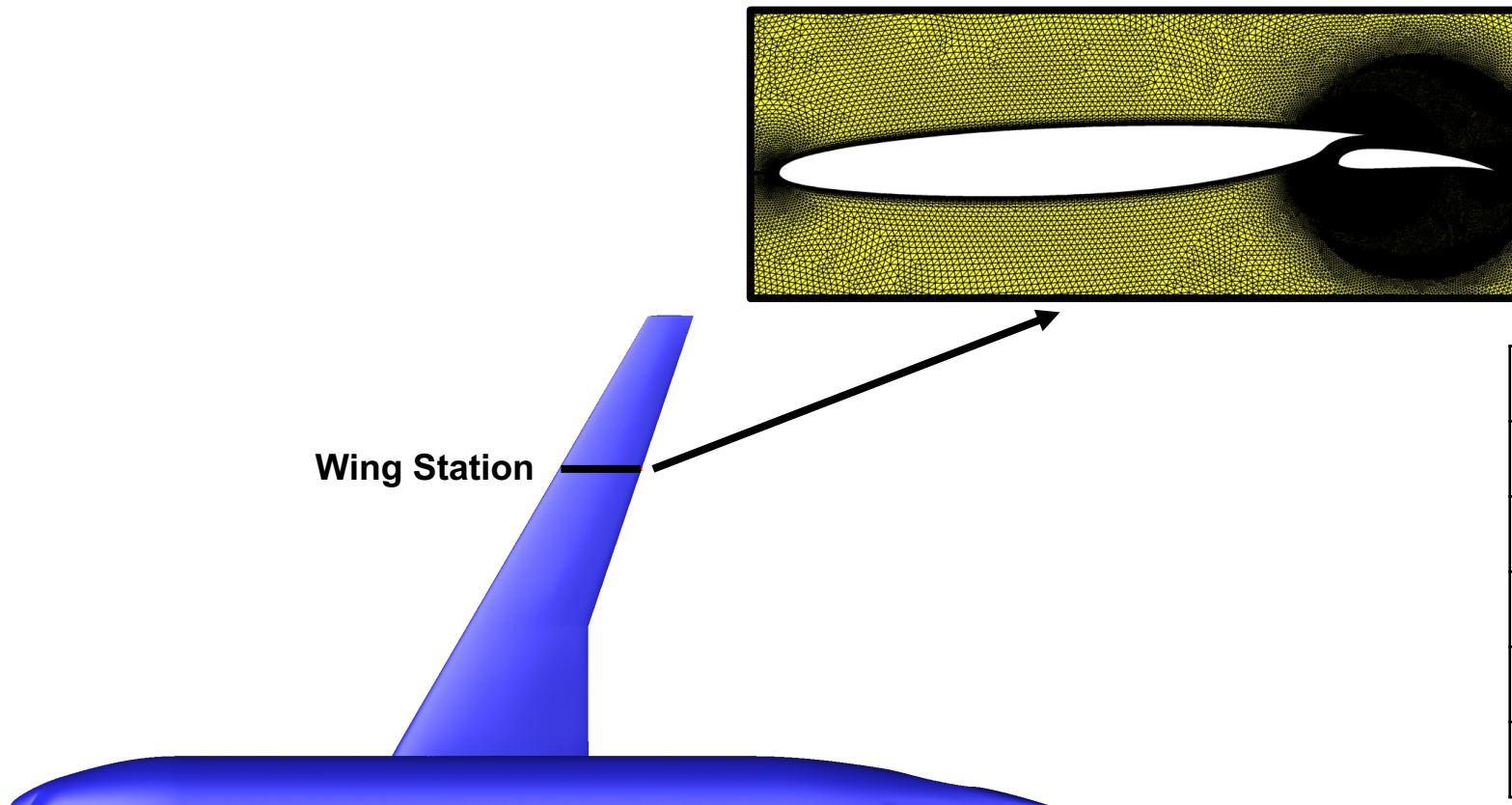
- How does slotted airfoil performance change when designing for laminar flow on the flap element?



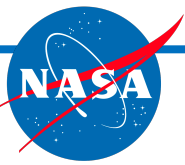
2D Geometry and Conditions

Configuration

- Common Research Model scaled down to be representative of single-aisle transport class
- Geometry and flight conditions scaled using simple sweep theory



Parameter	3D	2D
$\Lambda_{c/2}$	22.6°	0°
Re	14.9×10^6	12.7×10^6
M_∞	0.800	0.739
c_l	0.645	0.756
$(t/c)_{\max}$	0.096	0.104



Computational Tools

USM3D-ME

Flow Solver

NEWUG

Modify Grid

**Flow/Geometry
Extraction**

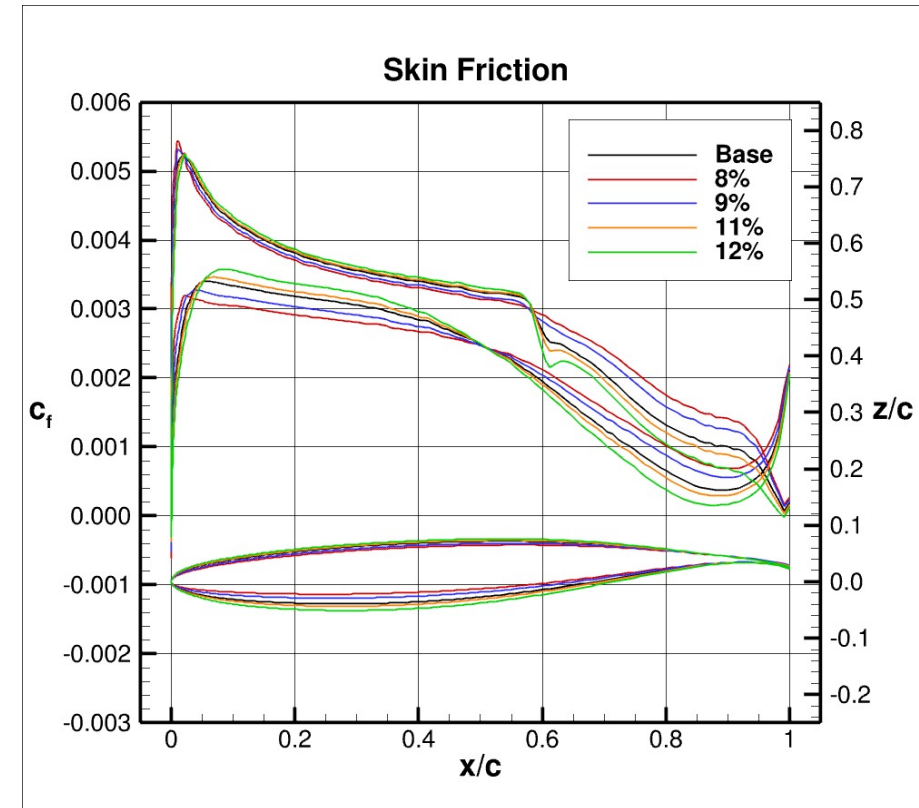
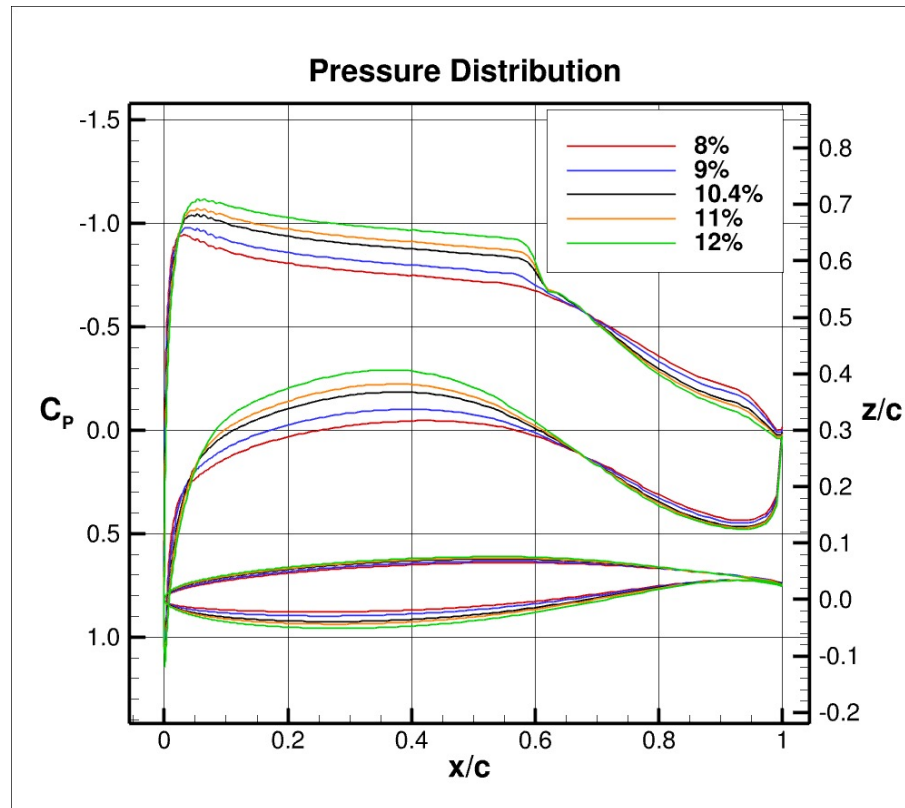
CUTSURF

Design

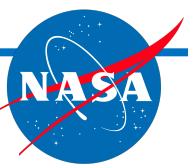
CDISC

RQ1: Impact of Thickness on Conventional Airfoil Performance

α : 2.703°, M_∞ : 0.739, Re_c : 12.7x10⁶

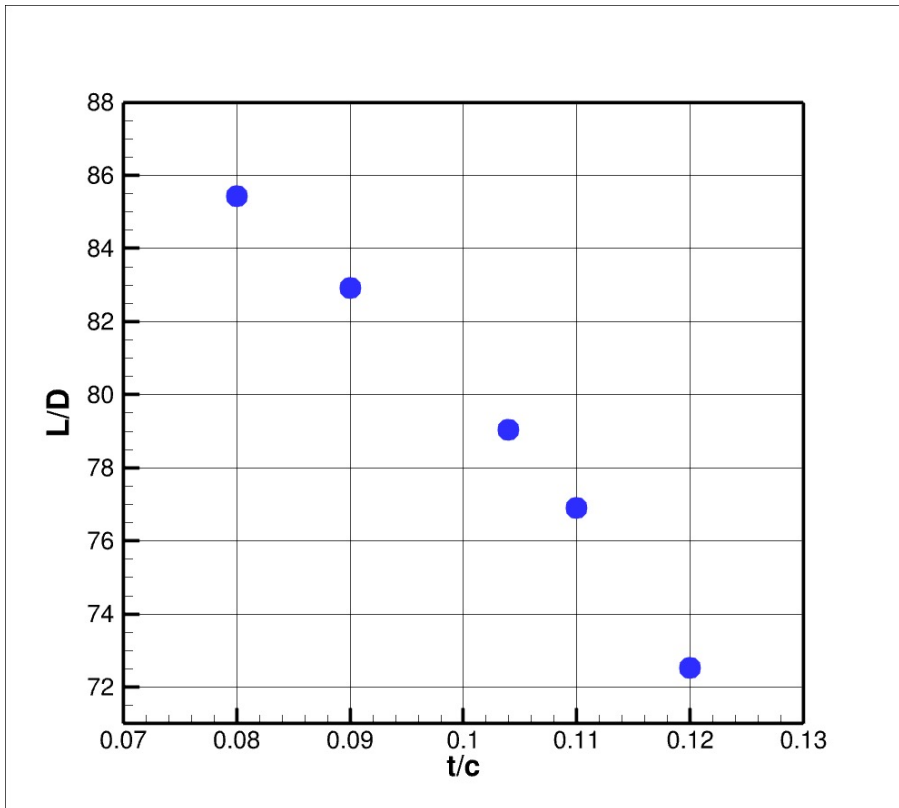


- Increased thickness leads to increased upper and lower surface velocities near the leading edge and decreased velocities near the trailing edge
 - Stronger shocks (relatively same location)
- Skin-friction distribution follows general velocity trends



RQ1: Impact of Thickness on Conventional Airfoil Performance

Alpha: 2.703, **Mach:** 0.739, **Re:** 12.7×10^6



t/c	L/D	C _l (total)	C _d (total)	C _{d,p}	C _{d,f}	C _m
0.080	85.4	0.755	0.0088	0.0037	0.0051	-0.148
0.090	82.9	0.754	0.0091	0.0040	0.0051	-0.147
0.104	79.0	0.758	0.0096	0.0046	0.0050	-0.146
0.110	76.9	0.758	0.0099	0.0049	0.0050	-0.145
0.120	72.5	0.757	0.0104	0.0055	0.0049	-0.143

Drag increases as thickness is increased which causes L/D to decrease. Total drag increase mainly due to pressure drag increase

Research Questions

1. Conventional – Turbulent Design

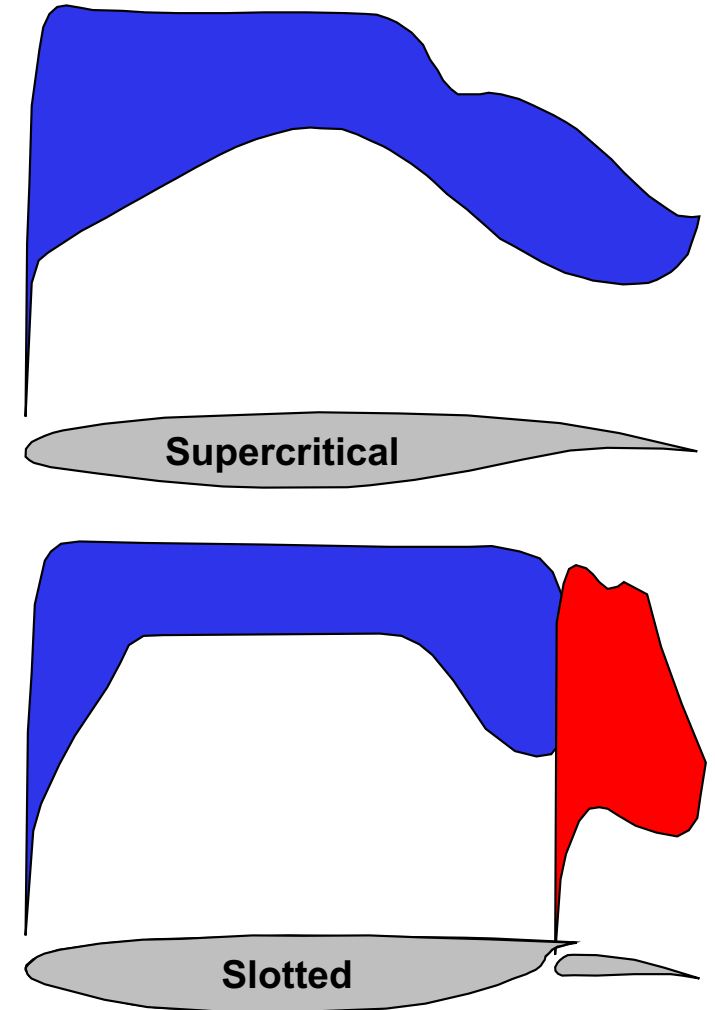
- How does thickness impact aerodynamic performance at a fixed cruise lift coefficient?

2. Slotted – Turbulent Design

- How does relative performance to the conventional airfoil change with differences in design thickness?
- What flap loading yields the most optimal aerodynamic performance at a fixed cruise lift coefficient and thickness?

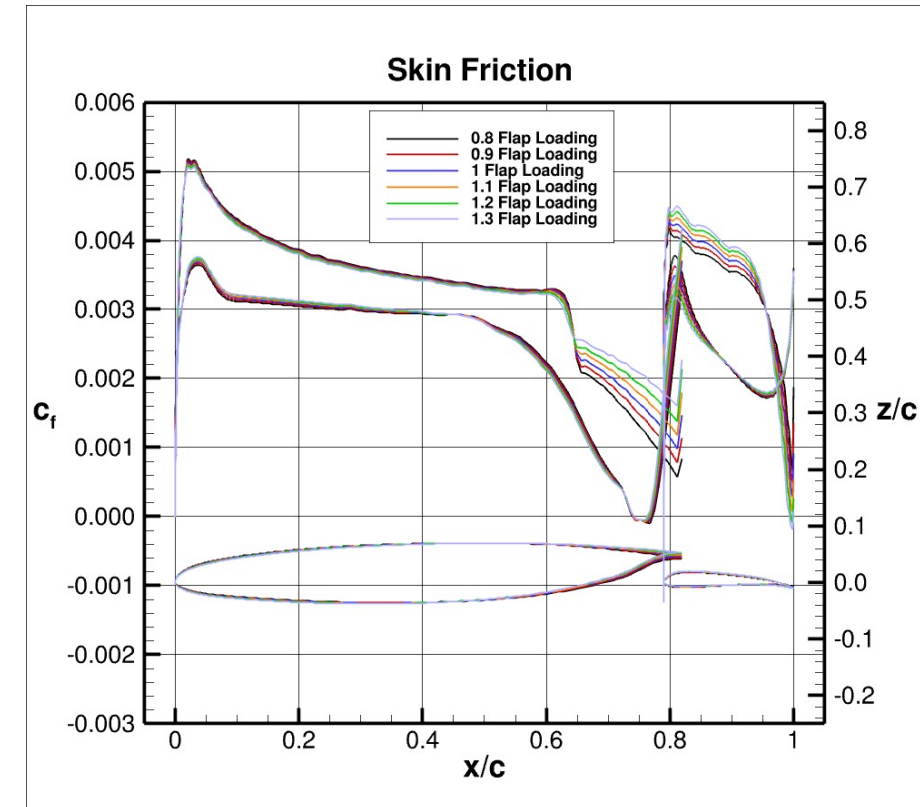
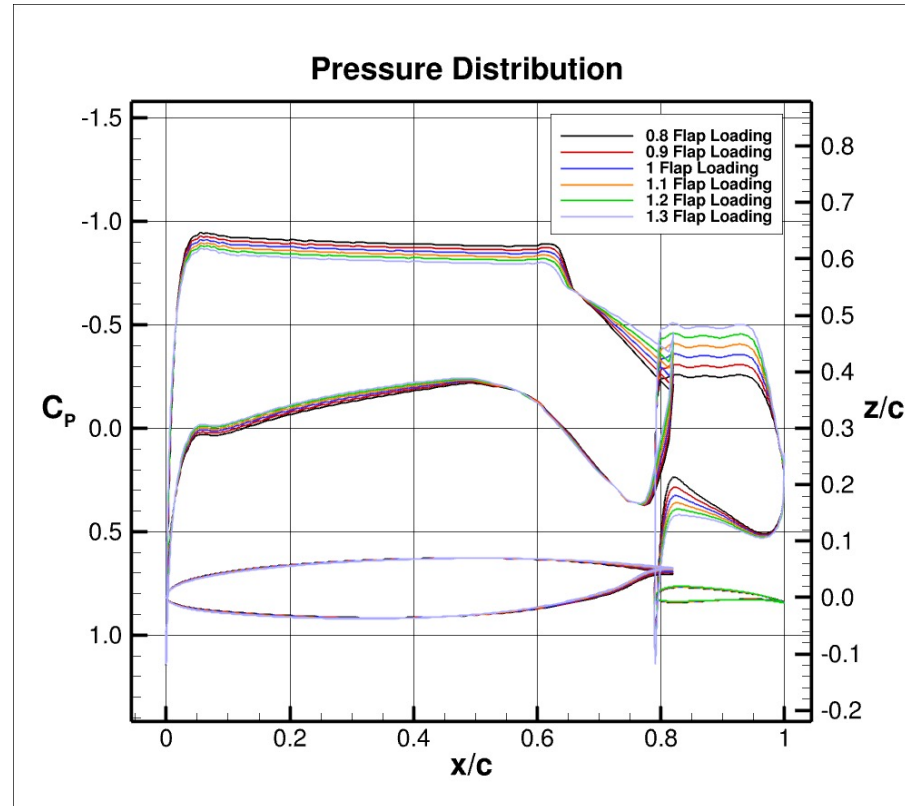
3. Slotted – Laminar Flap Design

- How does slotted airfoil performance change when designing for laminar flow on the flap element?

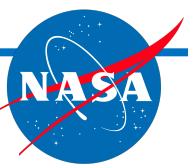


RQ2: Impact of Flap Loading on Slotted Airfoil Performance

t/c : 0.104, c_f : 0.757, Re : 12.7×10^6

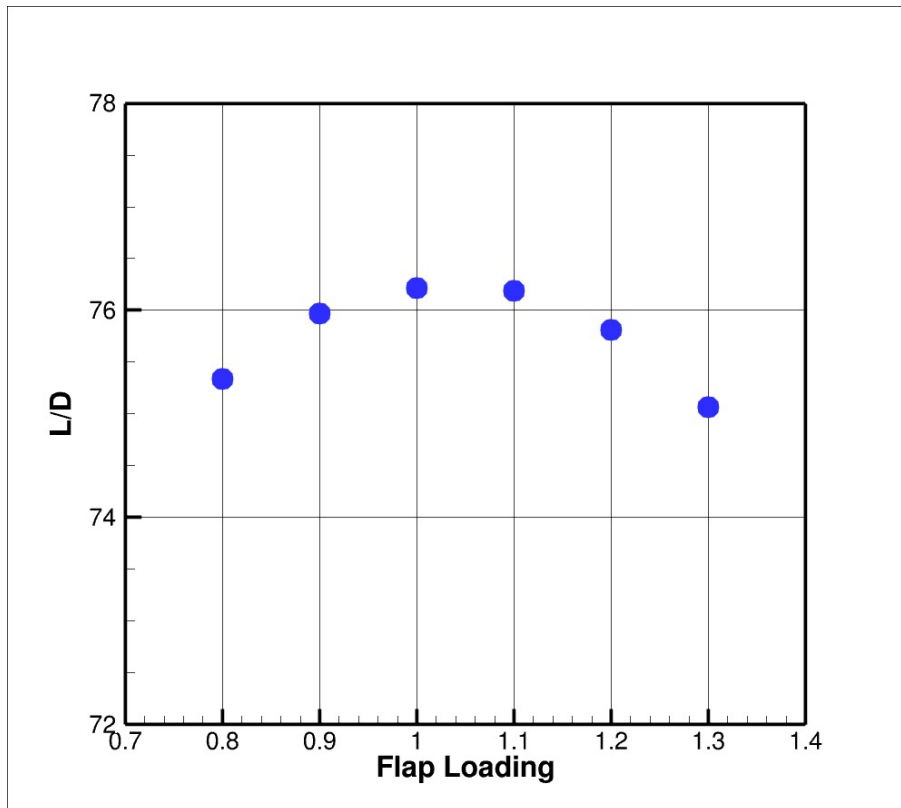


- Increased flap loading leads to expected pressure distribution to match loading across elements
- Skin friction continues to follow velocity trends



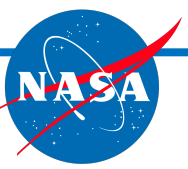
RQ2: Impact of Flap Loading on Slotted Airfoil Performance

t/c : 0.104, c_i : 0.757, Re : 12.7×10^6

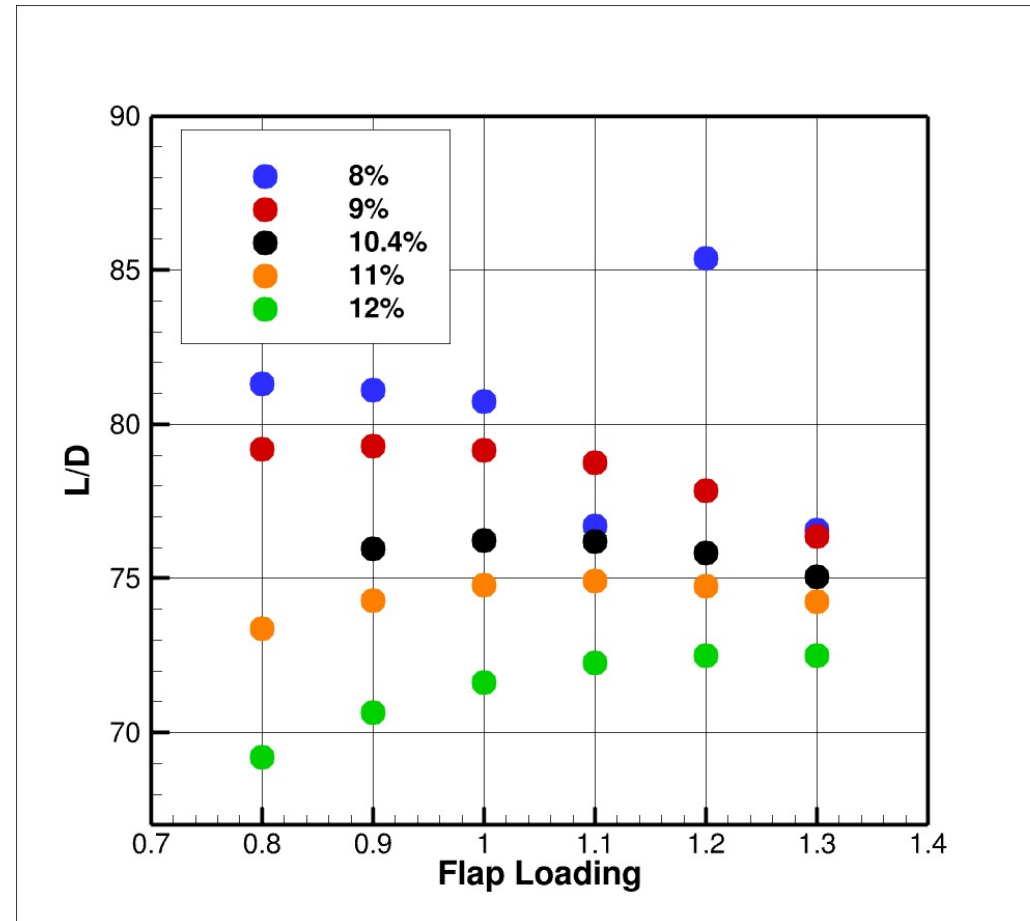


Flap Loading	L/D	C _d (total)	C _{d,p}	C _{d,f}	C _m
0.8	75.3	0.0101	0.0040	0.0060	-0.172
0.9	76.0	0.0100	0.0039	0.0061	-0.180
1.0	76.2	0.0099	0.0038	0.0061	-0.188
1.1	76.2	0.0100	0.0038	0.0061	-0.195
1.2	75.8	0.0100	0.0038	0.0062	-0.202
1.3	75.1	0.0101	0.0039	0.0062	-0.209

There is an optimal flap loading at which L/D is maximized



RQ2: Impact of Flap Loading on Slotted Airfoil Performance



- L/D trend largely attributed to thickness rather than flap loading
- Optimal flap loading value increases as thickness is increased

Research Questions

1. Conventional – Turbulent Design

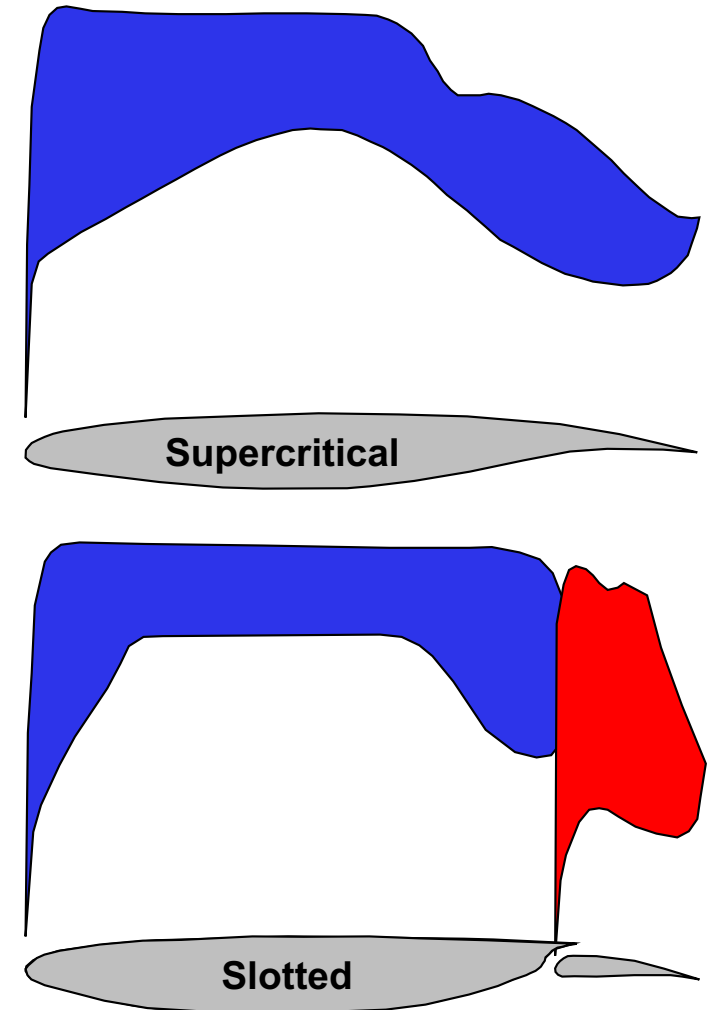
- How does thickness impact aerodynamic performance at a fixed cruise lift coefficient?

2. Slotted – Turbulent Design

- How does relative performance to the conventional airfoil change with differences in design thickness?
- What flap loading yields the most optimal aerodynamic performance at a fixed cruise lift coefficient and thickness?

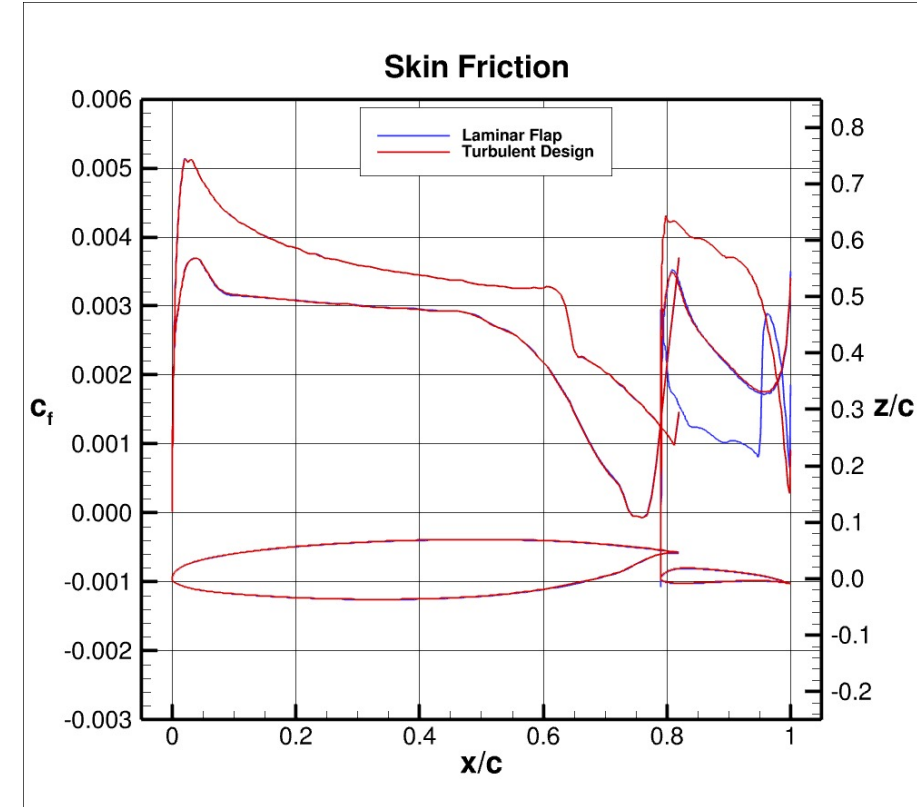
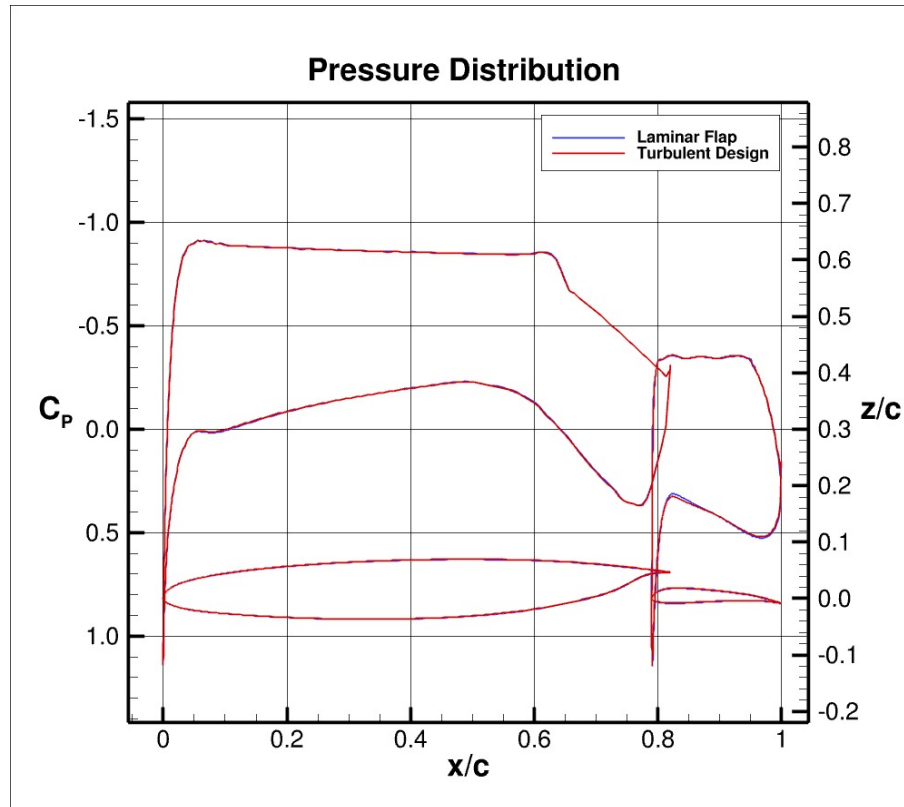
3. Slotted – Laminar Flap Design

- How does slotted airfoil performance change when designing for laminar flow on the flap element?

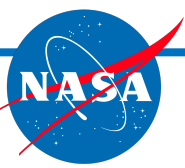


RQ3: Impact of Laminar Flow on Flap Element on Slotted Airfoil Performance

t/c : 0.104, c_f : 0.757, Re : 12.7×10^6

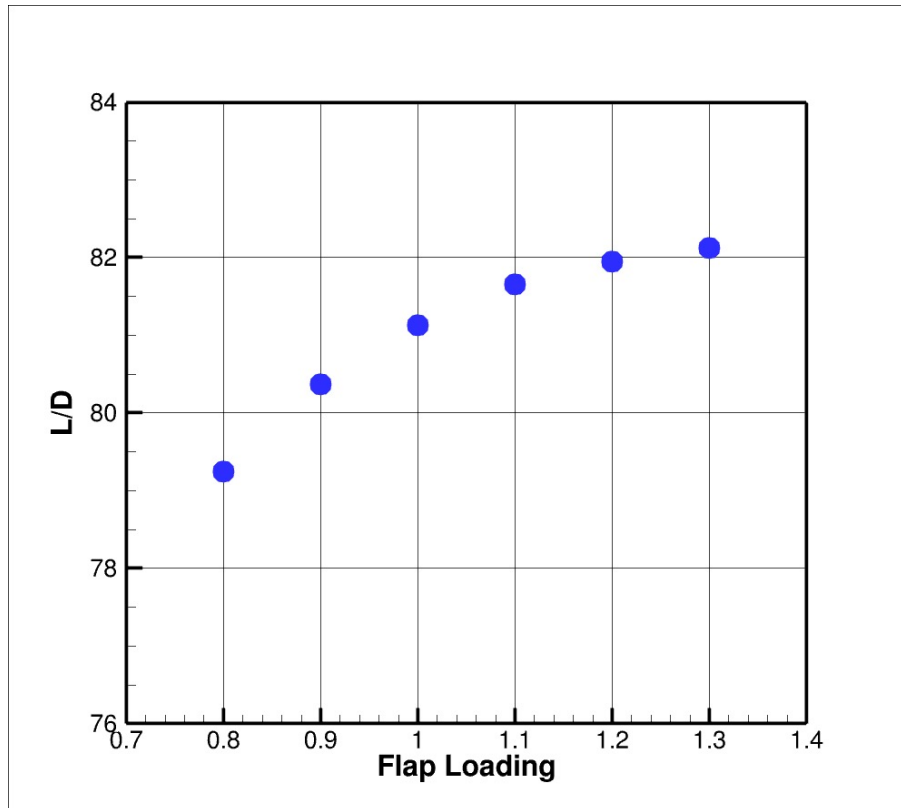


- Laminar flow over the flap element leads to lower skin friction levels as expected
- Not much change in pressure distribution over airfoil



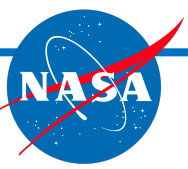
RQ3: Impact of Laminar Flow on Flap Element on Slotted Airfoil Performance

t/c : 0.104, c_i : 0.757, Re : 12.7×10^6

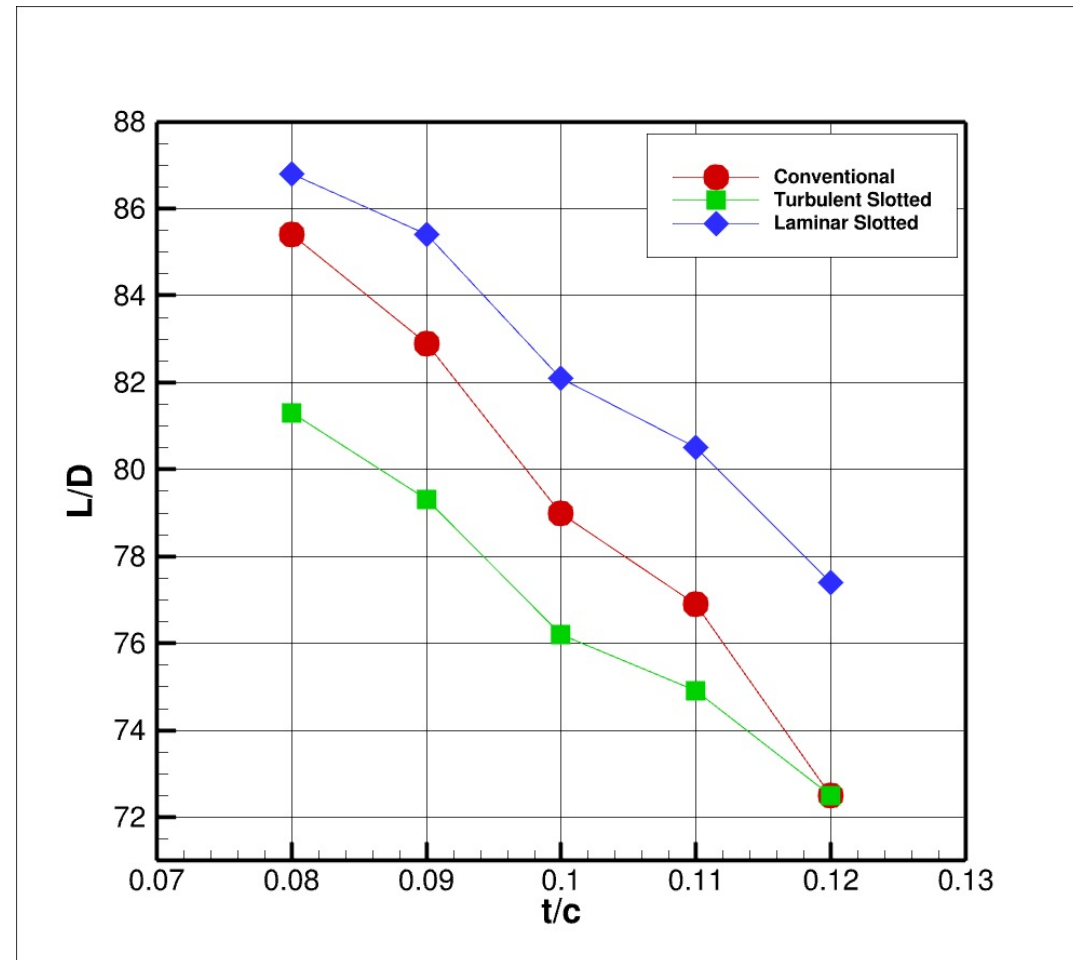


Flap Loading	L/D	C _d (total)	C _{d,p}	C _{d,f}	C _m
0.8	79.2	0.0096	0.0039	0.0056	-0.171
0.9	80.4	0.0094	0.0038	0.0057	-0.179
1.0	81.1	0.0094	0.0037	0.0057	-0.187
1.1	81.7	0.0093	0.0036	0.0057	-0.195
1.2	81.9	0.0093	0.0036	0.0057	-0.202
1.3	82.1	0.0092	0.0035	0.0057	-0.209

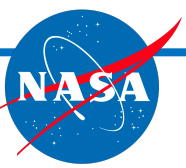
Laminar flow on flap element leads to higher L/D and a greater flap loading at which L/D is maximized



Comparison of All Cases

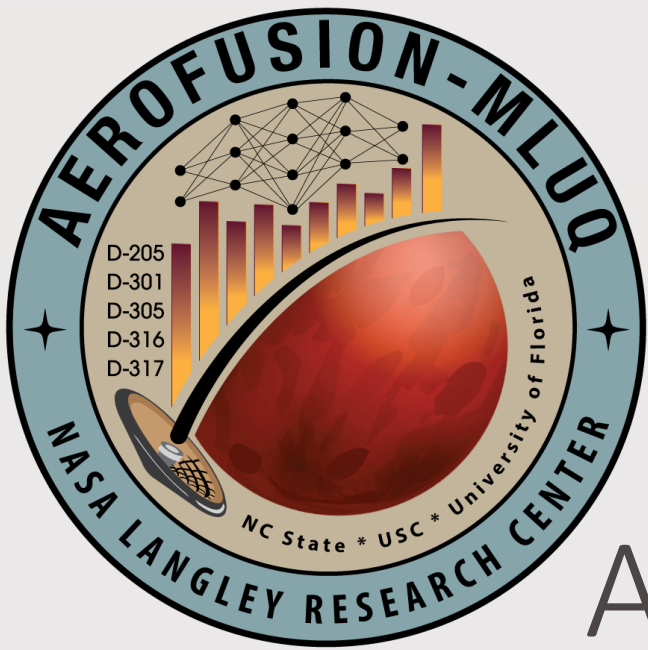


Laminar slotted airfoil offers the greatest L/D values



Conclusion

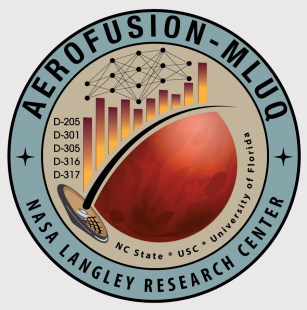
- **As thickness is increased, L/D ratio decreases**
- **For a given thickness, laminar slotted airfoil achieved the highest L/D values**
 - Possibilities to design a turbulent slotted airfoil with a flap loading that can achieve greater performance than a conventional airfoil
- **For a laminar slotted airfoil, there is an optimal flap loading which is dependent on the thickness**
- **Next Steps**
 - Run more cases to quantify the relationship between thickness and flap loading



Aerofusion Presentation

Satvik Kumar



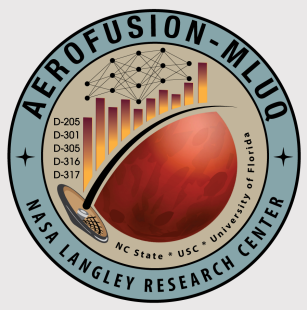


Data Overview

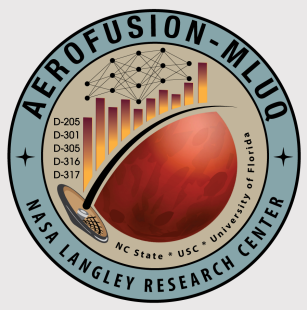


Data Overview

- Orion 133-CA Data
- 7475 Total Points, 17 Notable Features
- Geometry/Configuration Overview:
 - 30: 700D Abort
 - 40: 700D Abort Fenced
 - **50: IDAT – 3273 Data Points**
 - 52: 700D Abort Tripped
 - 55: IDAT Tripped



Goodness of Fit and Percent Captured



Motivation

- Key Performance Parameter
 - Reduction of magnitude of “coverage factors” for model uncertainties
- Provides Insight into effectiveness of uncertainty capturing data
- Demonstration of difference between prediction of nominal value and spread



Methodology

- Training Fractions between 20% and 80% in intervals of 4%
- 10 Trials at Each Training Fraction
 - Data split with different random seed so distinct train and test sets
- Configuration: 50 (IDAT)
- Inputs: Alpha and FMV (Mach number)
- RegressorUQ – Kernel Ridge Regression (KRR) and Interval Predictor Model (IPM)
- Results:
 - R^2 – Regression Models
 - Percent Captured – Interval Models

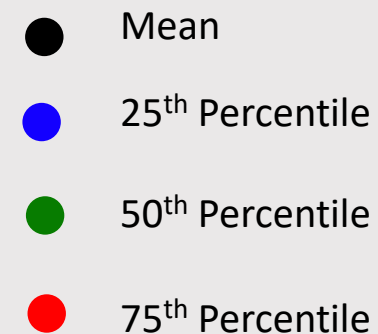
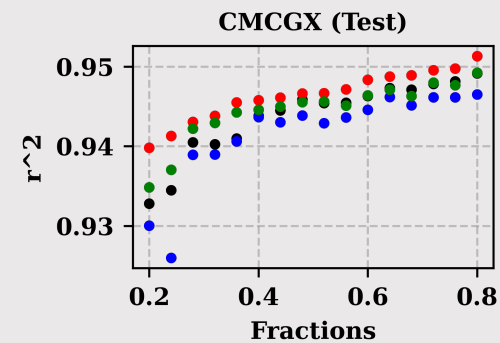
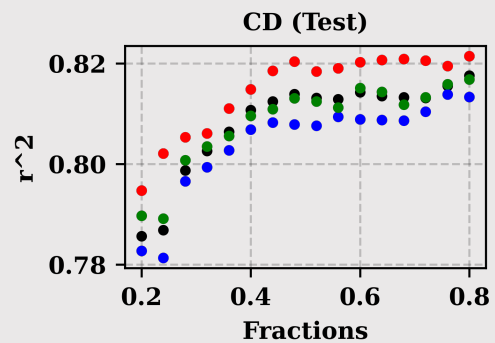
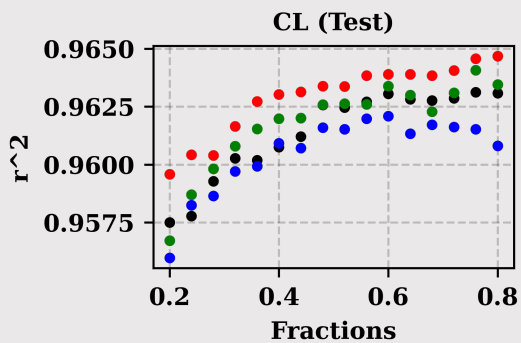
$$\text{Percent Captured} = \frac{\text{Number of Points Within Interval (eg. 5\% - 95\%)}}{\text{Total Number of Points}}$$



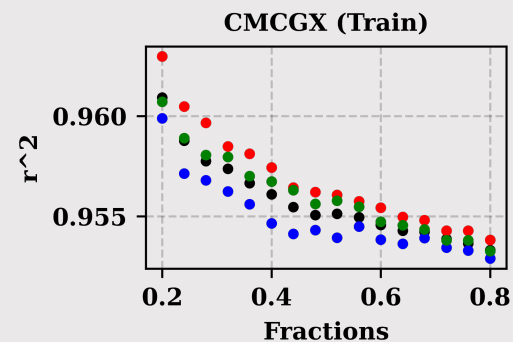
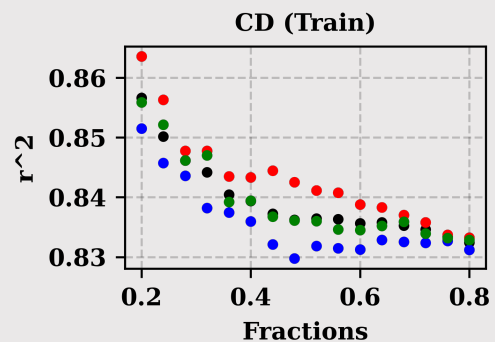
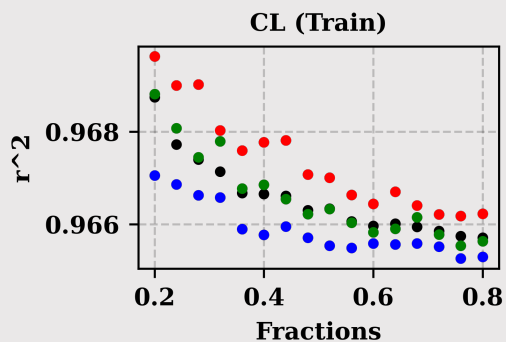
R² From KRR Regression

Model: RegressorUQ, Geometry: 50

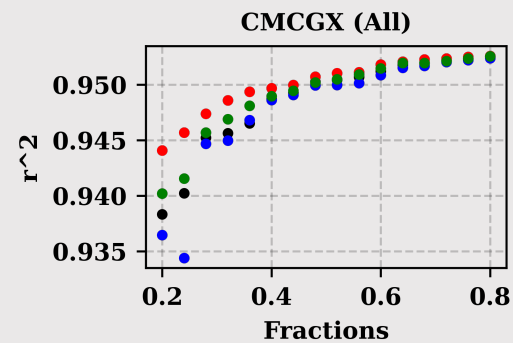
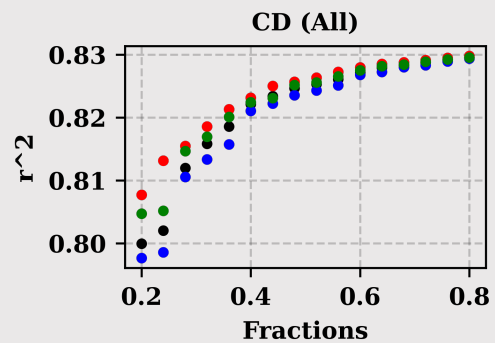
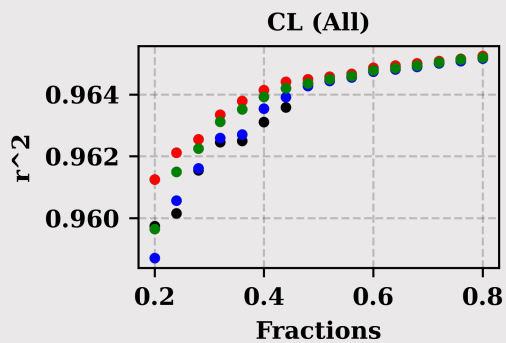
Test



Train



All



R² increases as fraction of training data increases for test set

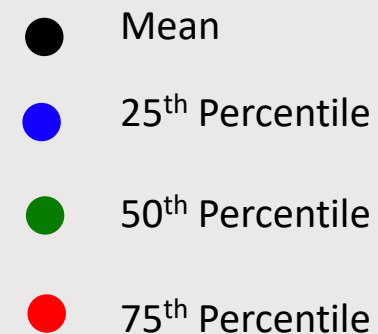
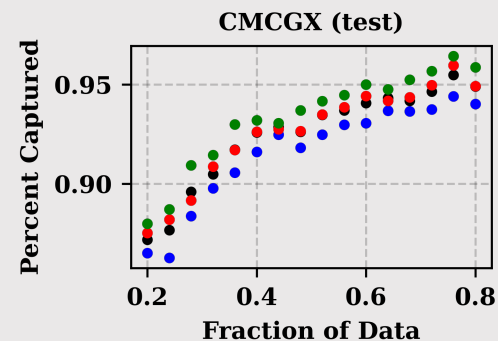
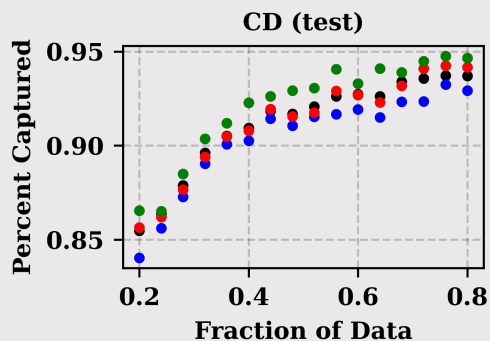
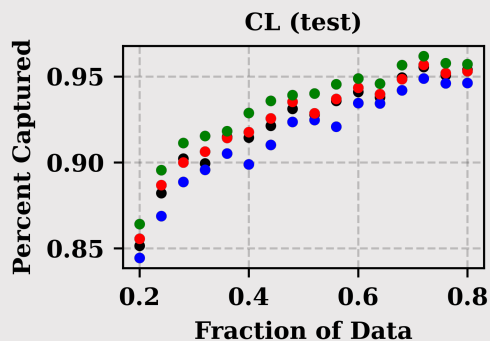




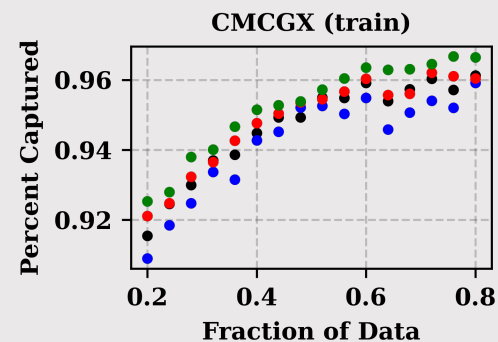
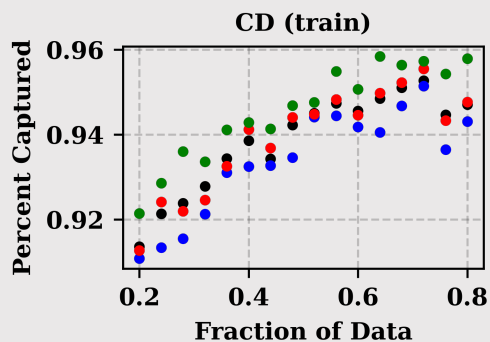
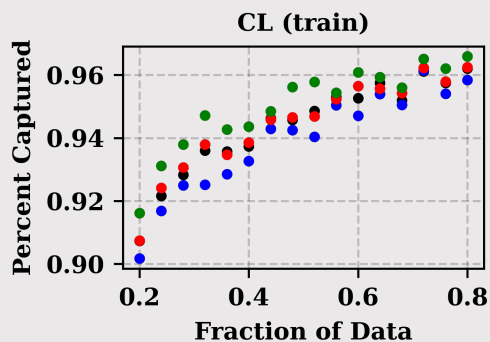
Percent Captured IPM (RegressorUQ)

Model: RegressorUQ, Geometry: 50

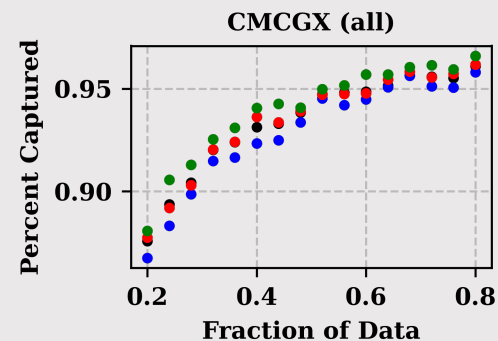
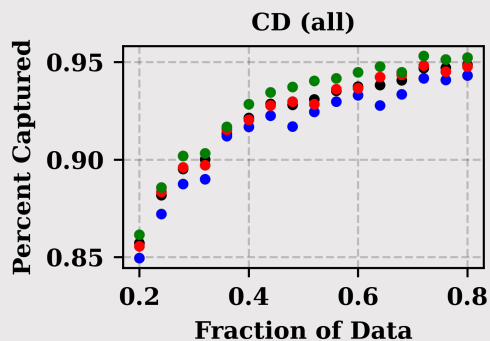
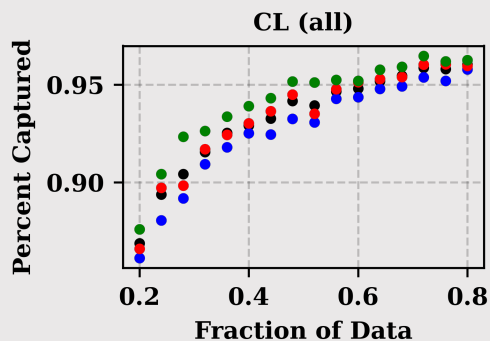
Test



Train

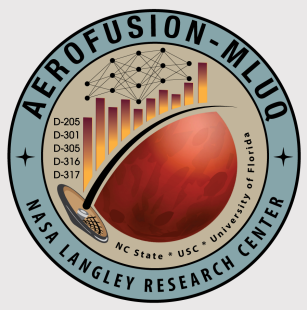


All



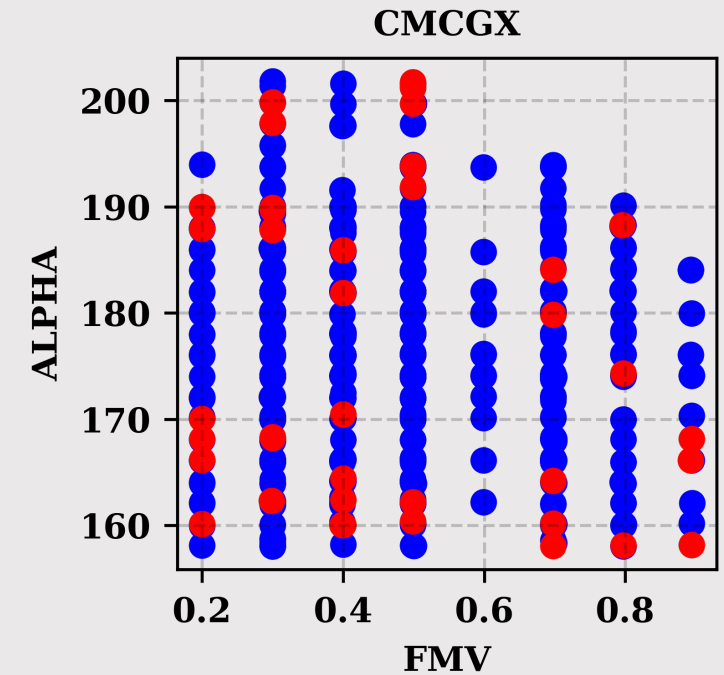
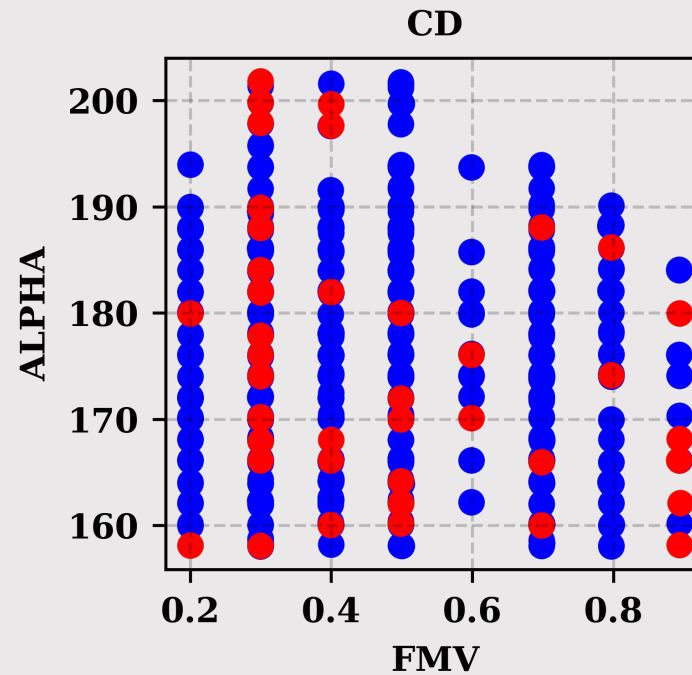
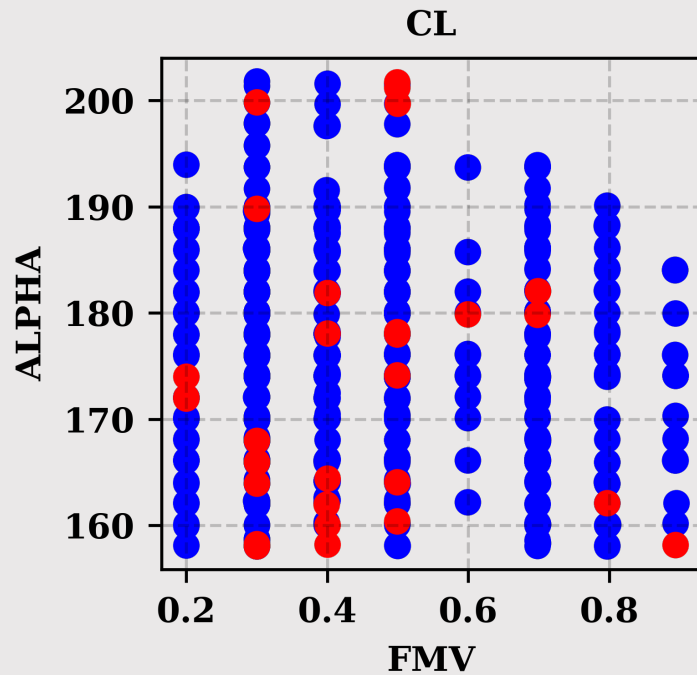
Percent captured increases as fraction of training data increases





Scatter Plot of Missed Points at Geometry 50

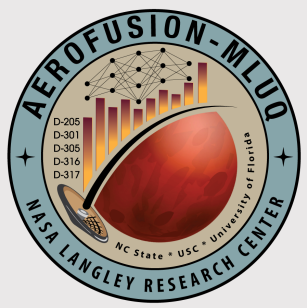
Model: RegressorUQ, Geometry: 50



80% of Training Data

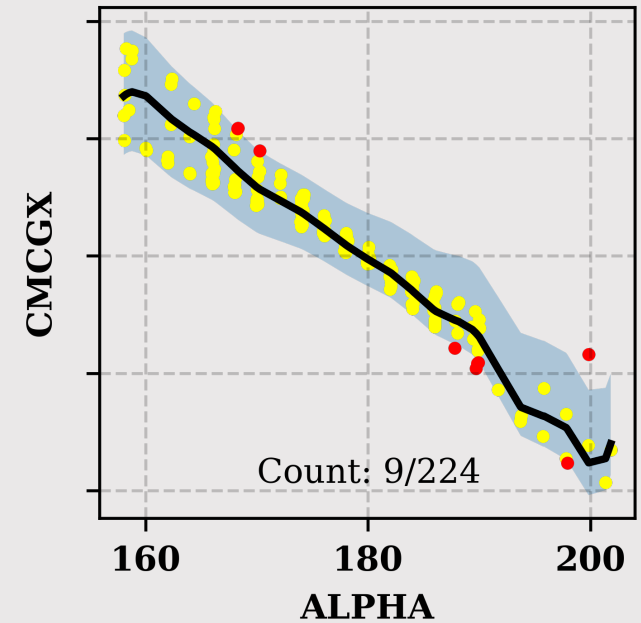
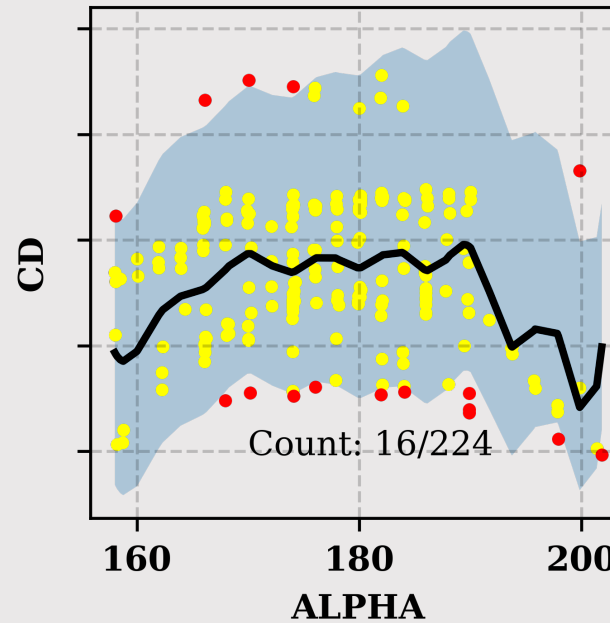
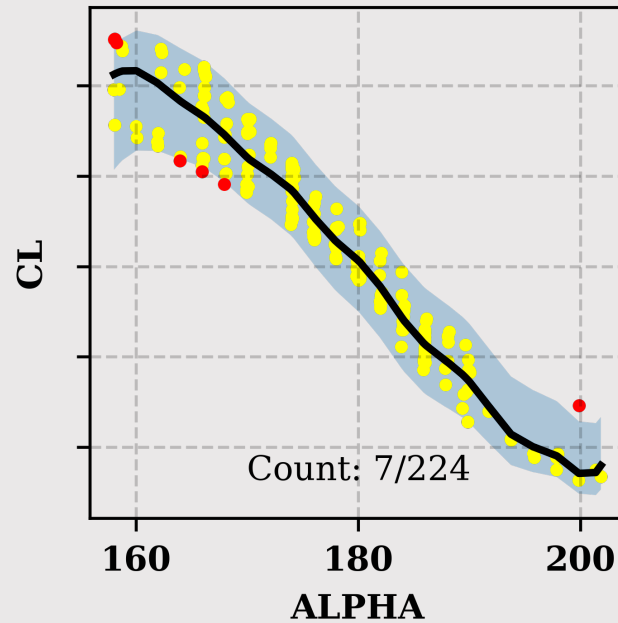
No clear trend for points that are missed





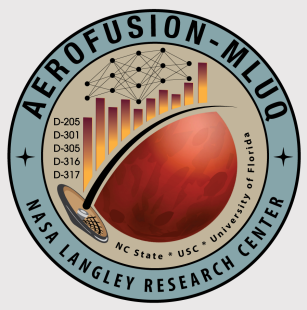
Interval Plot at FMV=0.3 and Configuration 50

Model: RegressorUQ, Geometry: 50, FMV: 0.3



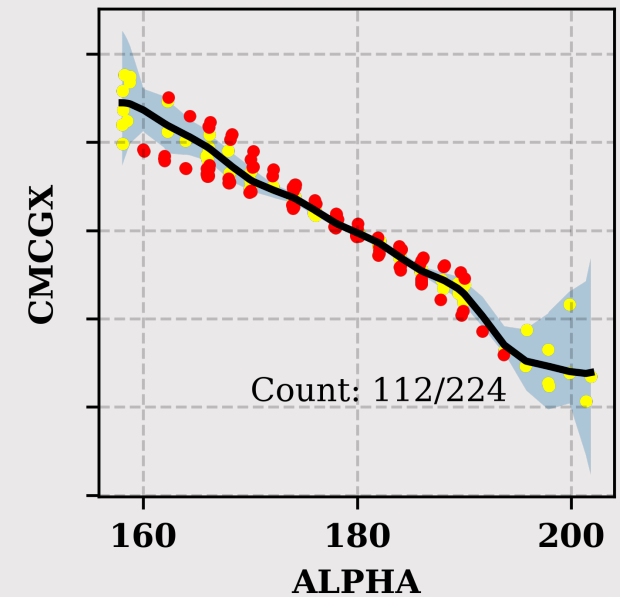
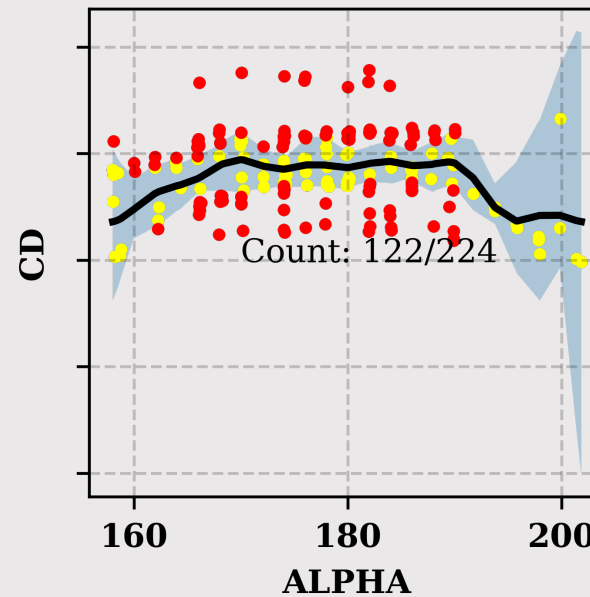
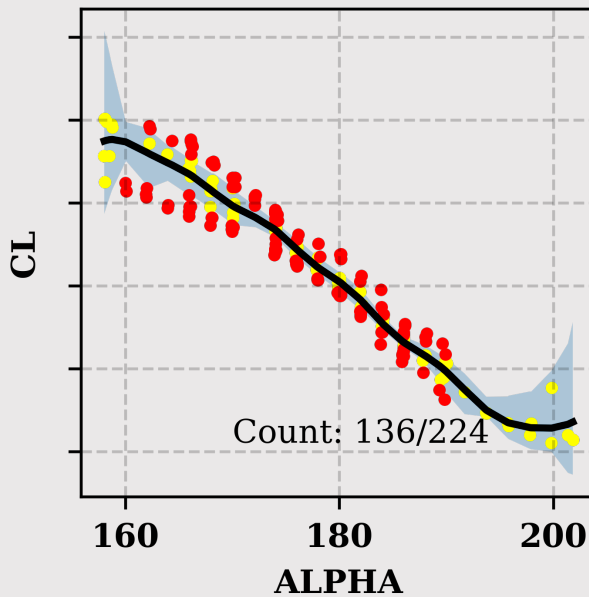
Points that are Missed Tend to be on the Boundary





Prediction of Spread vs. Nominal Value

Model: BootstrapUQ, Geometry: 50, FMV: 0.3



BootstrapUQ does extremely well capturing the nominal value but struggles with spread

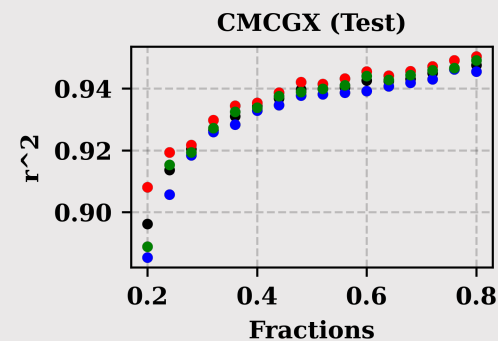
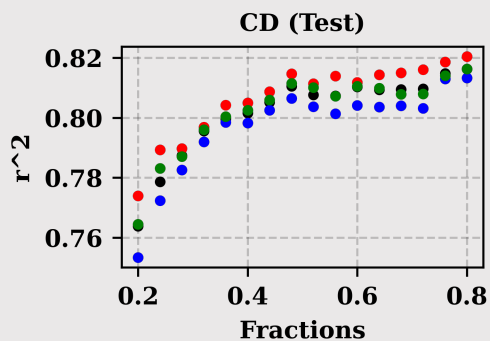
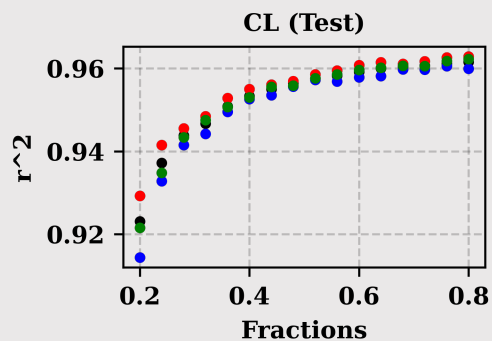




Prediction of Spread vs. Nominal Value

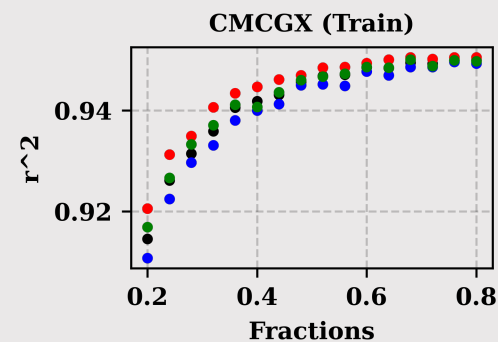
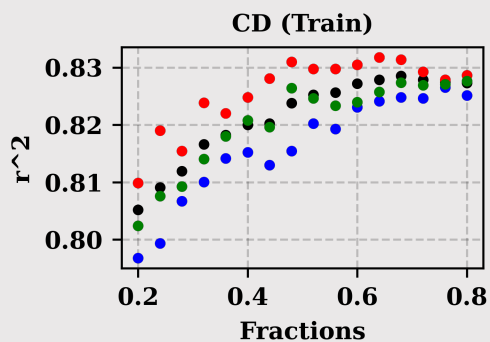
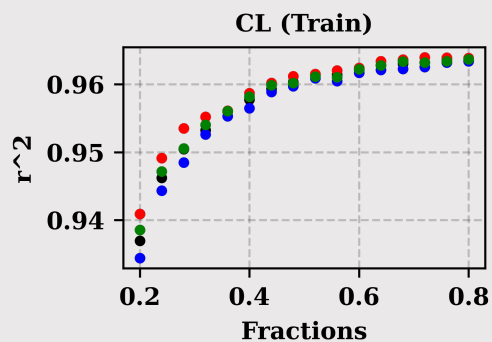
Model: BootstrapUQ, Geometry: 50

Test

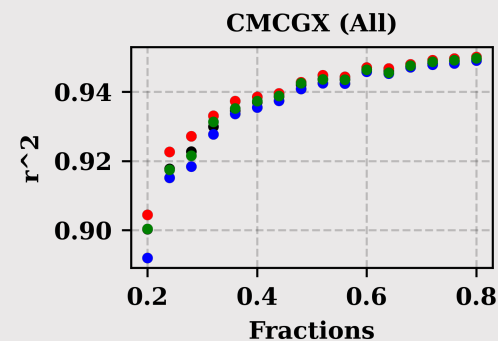
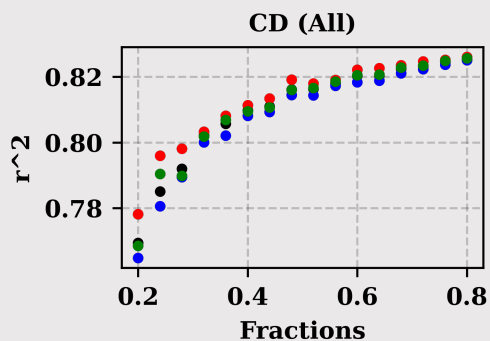
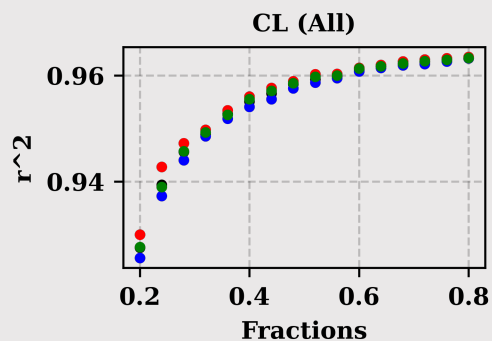


- Mean
- 25th Percentile
- 50th Percentile
- 75th Percentile

Train

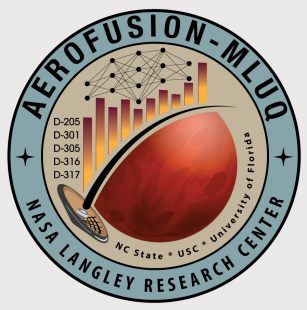


All



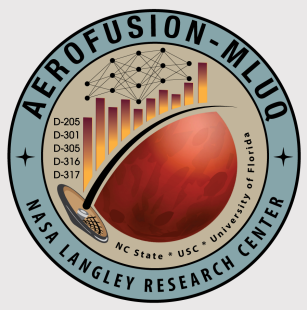
High R^2 shows BootstrapUQ does well capturing nominal





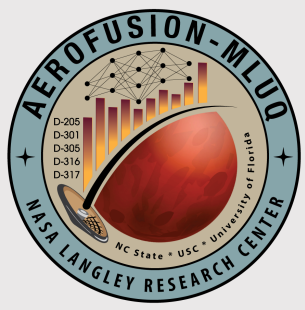
Reynolds Number Study





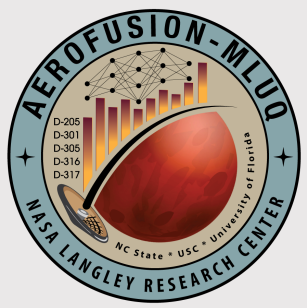
Motivation

- Dependence of Reynolds Number on Accuracy of models
- Provides avenue to test models with similar data



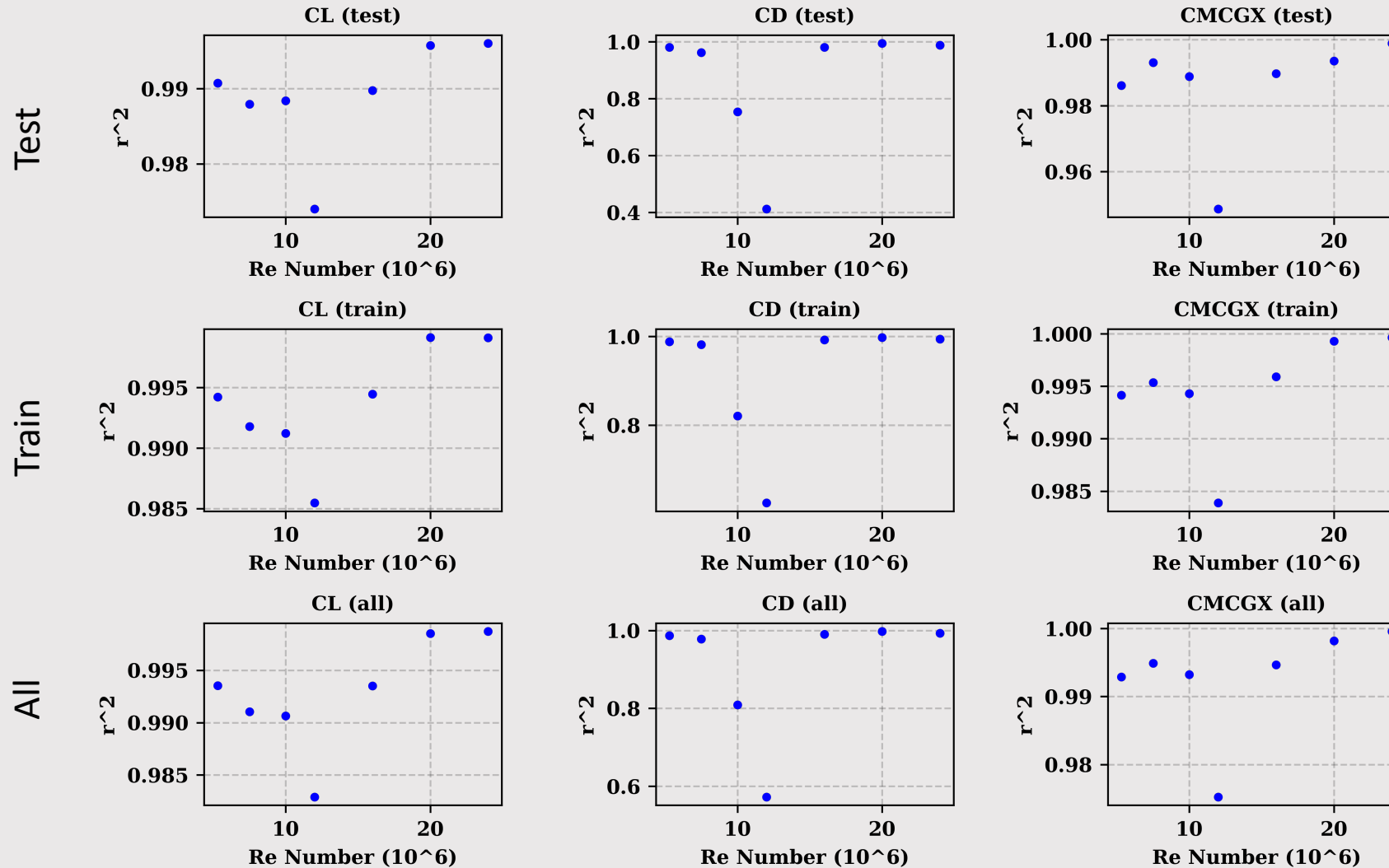
Methodology

- Found Common Reynolds Numbers Throughout Data
- Split Data by Reynolds Number and Configuration
 - Discard sets with <100 data points
- For each Reynolds Number and Configuration Combination Split into Training and Testing sets (80% Train, 20% Test)
- Inputs: Alpha and FMV (Mach number)
- Metrics:
 - R^2
 - Percent Captured (5%-95% Interval)



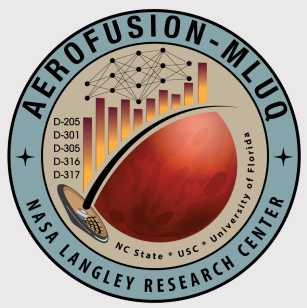
R² Plots

Model: RegressorUQ, Geometry: 50



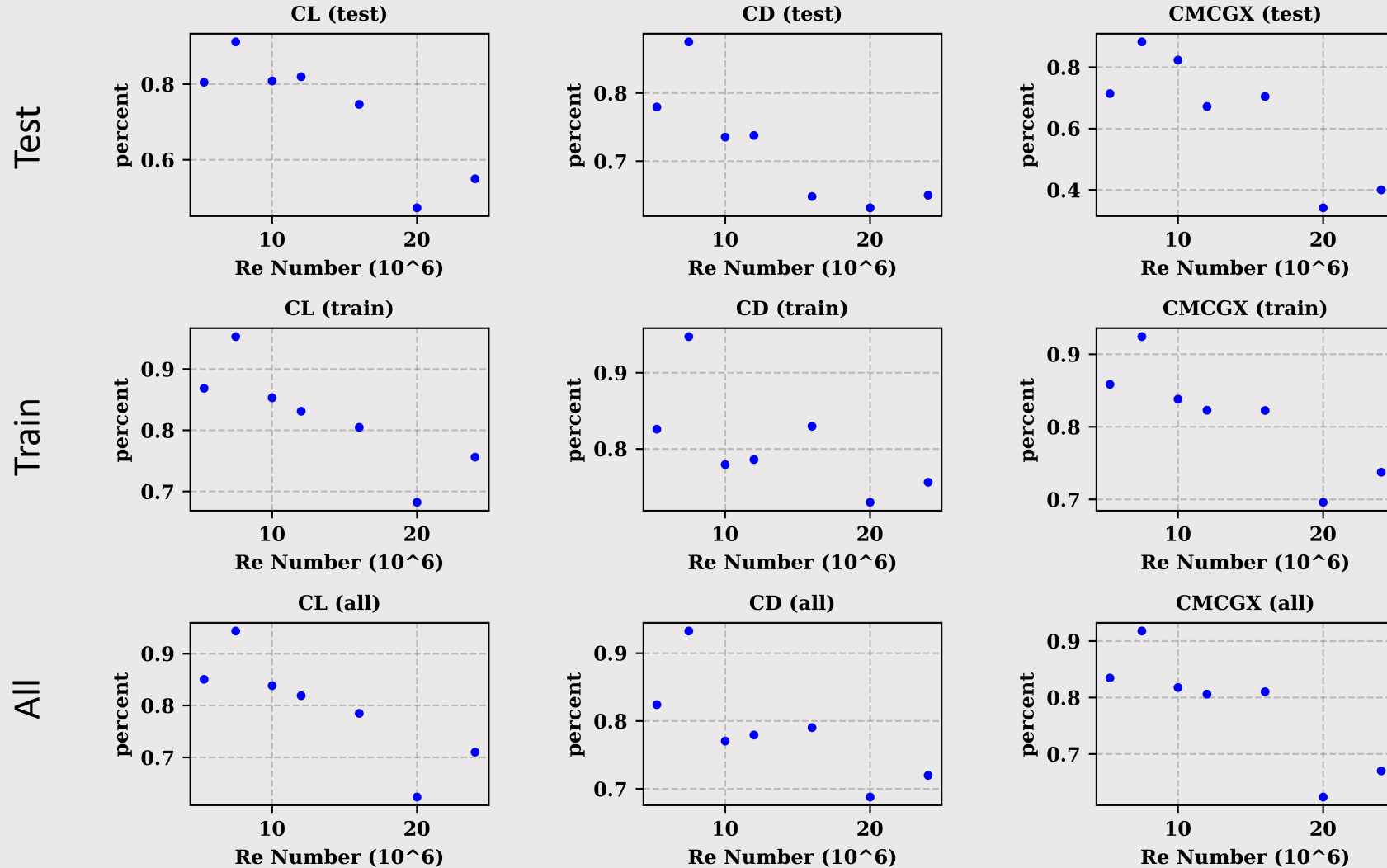
High r^2 at higher Reynolds Number. Dip likely explained by shift to fully turbulent flow





Percent Captured Configuration 50

Model: RegressorUQ, Geometry: 50



Percent captured decreases as Reynolds Number Increases

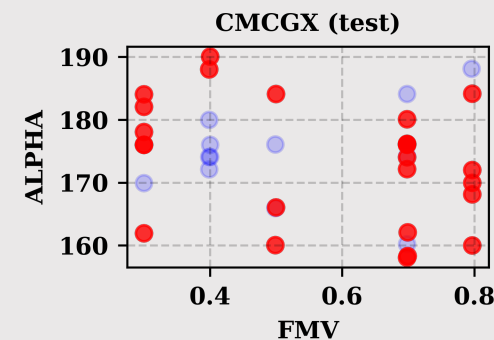
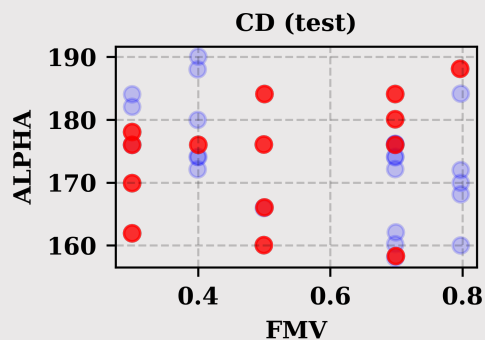
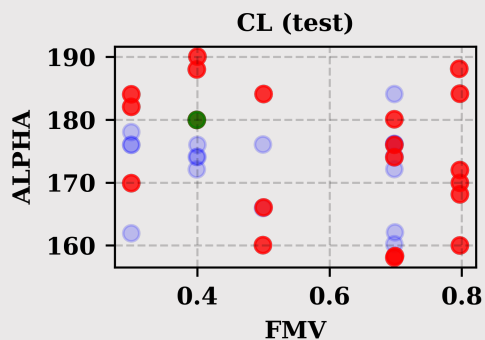




Scatter Plot Configuration 50 (Re: 19.7×10^6)

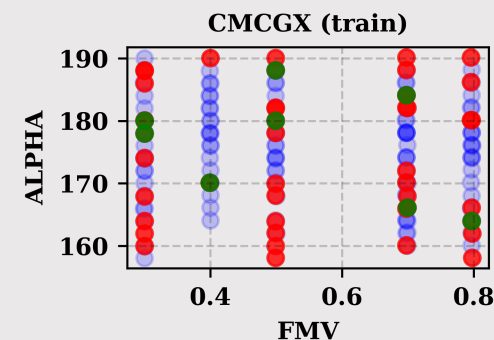
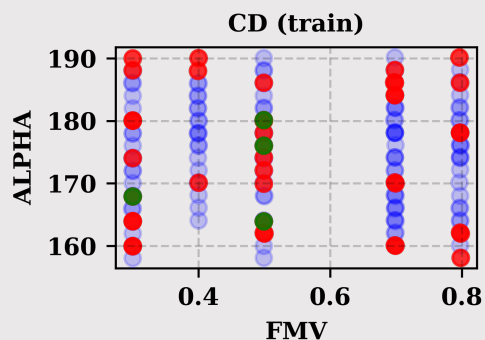
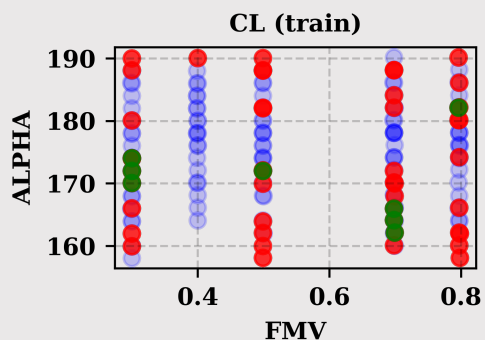
Model: RegressorUQ, Geometry: 50, Re Number: 19.7×10^6

Test

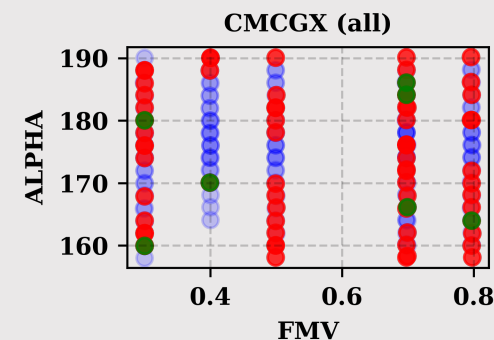
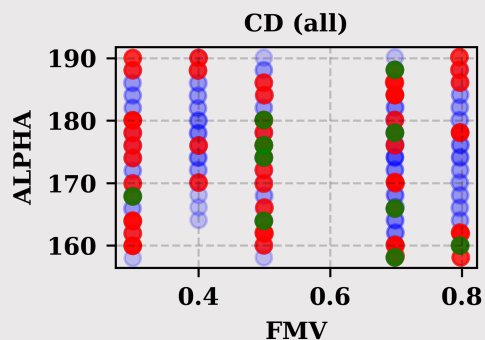
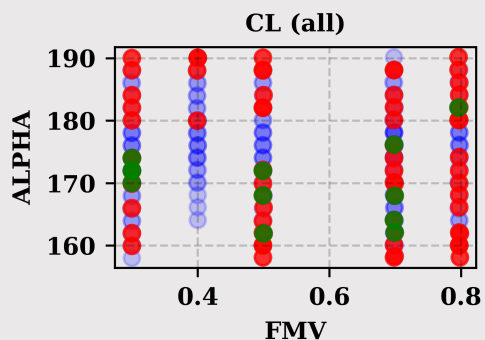


- Inside 5-95% Interval
- Inside 0.3-99.7% Intervals
- Outside Both Intervals

Train



All



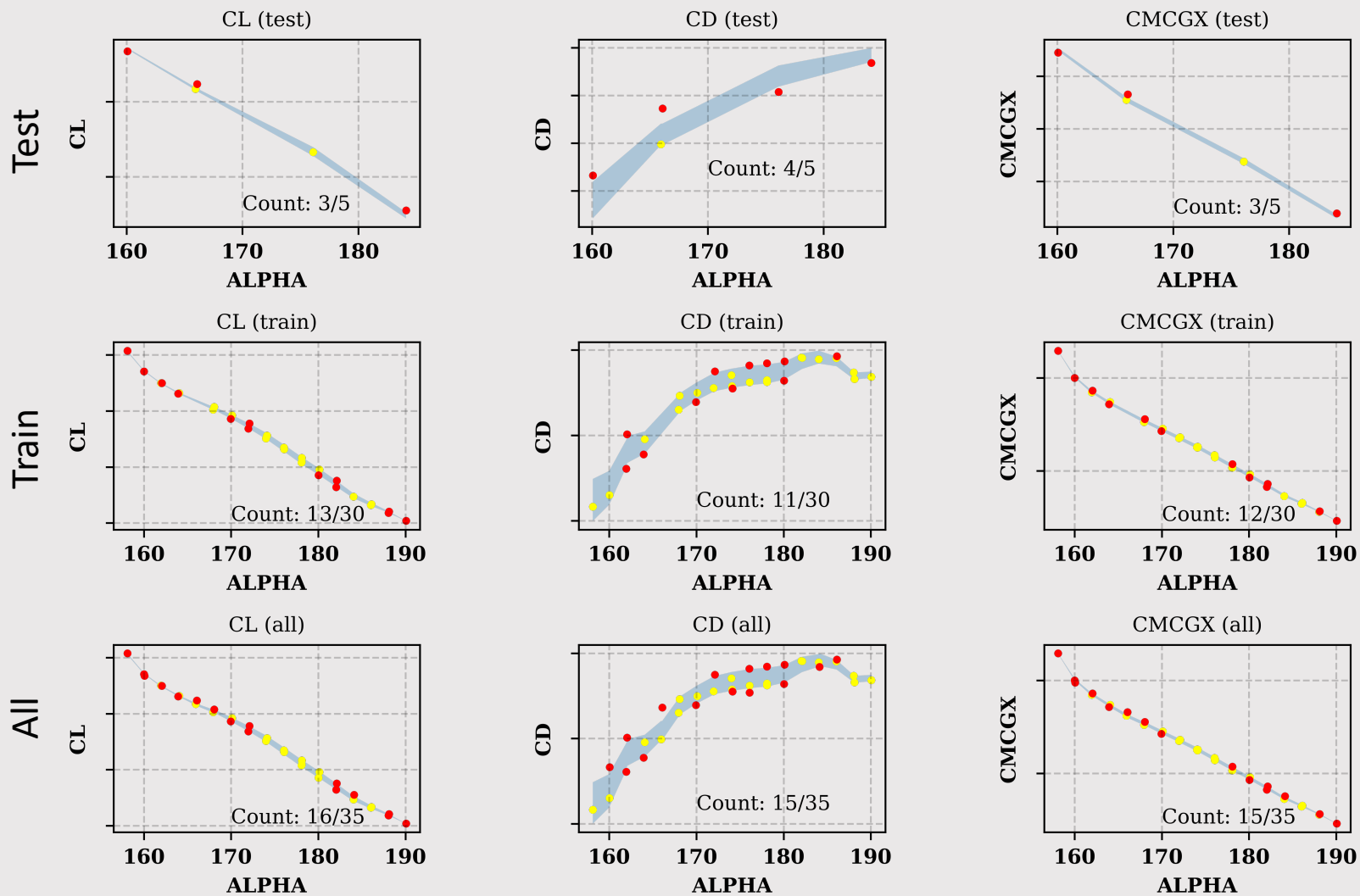
No clear trend examined

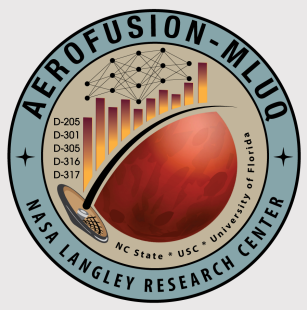




Reynolds Number: 19.7×10^6 (FMV: 0.5)

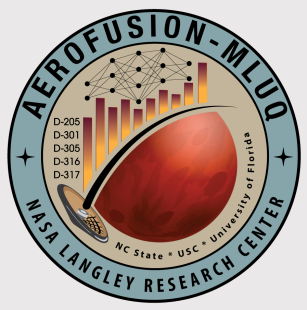
Model: RegressorUQ, Geometry: 50, Re Number: 19.7×10^6 , FMV: 0.5



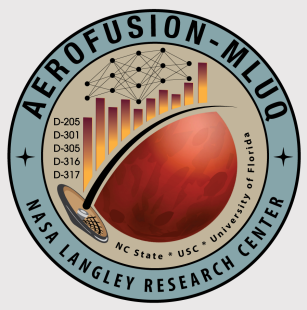


Interesting Trends

- As Reynolds Number Increased R^2 increased
- As Reynolds Number increased, percent captured decreased
- As Reynolds Number increased interval got thinner
 - Potential reason for why percent captured decreased

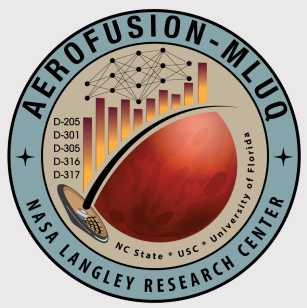


Multifidelity Modeling

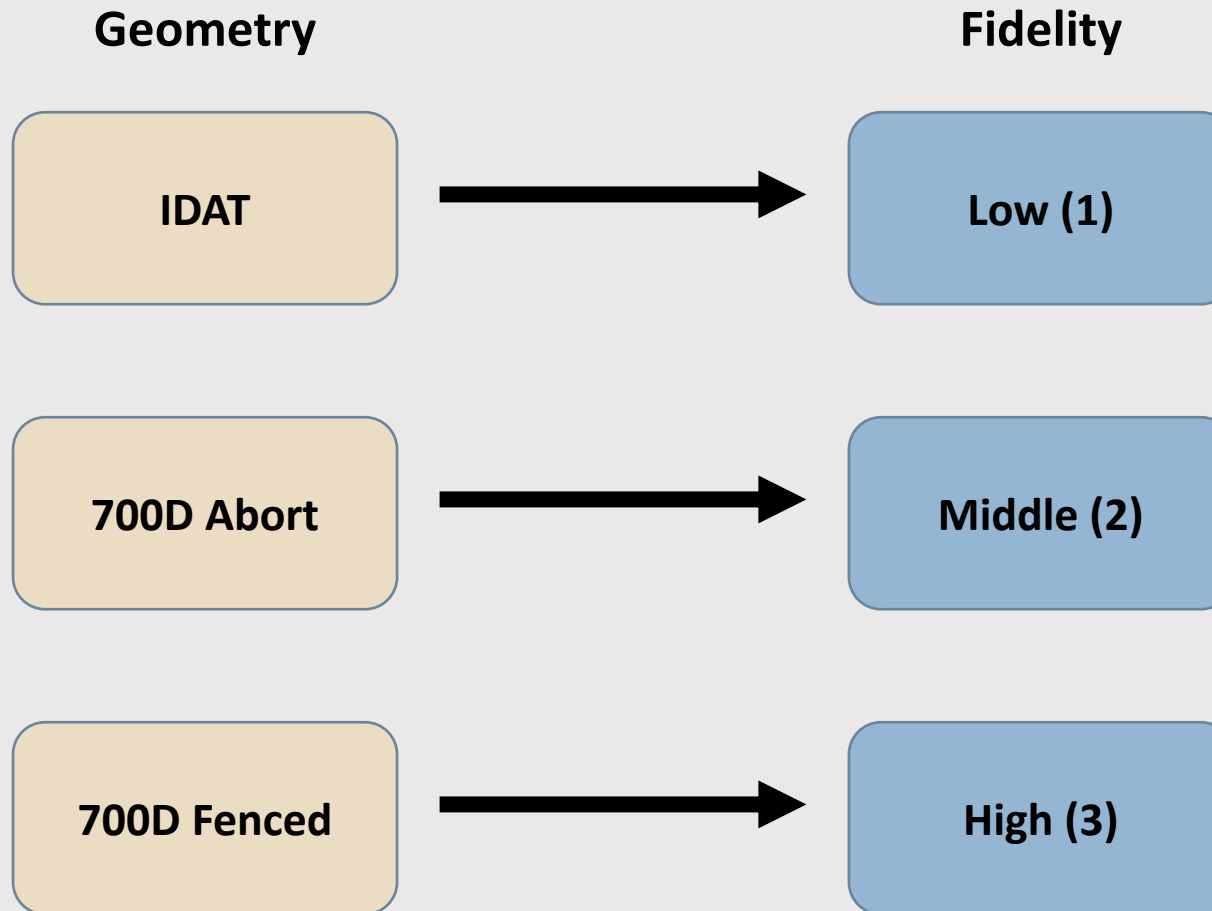


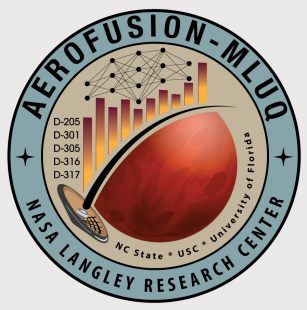
Motivation

- Key Performance Parameter
 - Reduction of reliance on high fidelity data to generate comparable fidelity full aerodynamic model
- Avenues to incorporate abundant data
 - Fidelity levels of data variable



Fidelity Mapping





Fidelity Methodology

- Marked Fidelity Levels on Data
- Split into Training and Testing sets (80% Train, 20% Test)
- Inputs: Alpha, FMV, Beta
- Other Variations: Reynolds Number
- Metrics:
 - R^2
 - Percent Captured (5%-95% Interval)
 - Performed on high fidelity data



Fidelity Models

Single Fidelity Gaussian Process Regressor (SFGPR)

- Fits only to the highest fidelity data set
- Single Fidelity Baseline

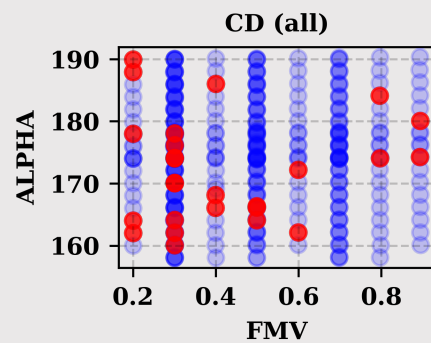
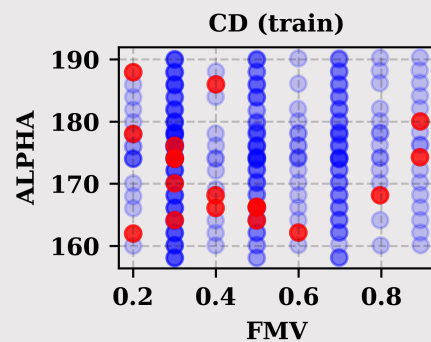
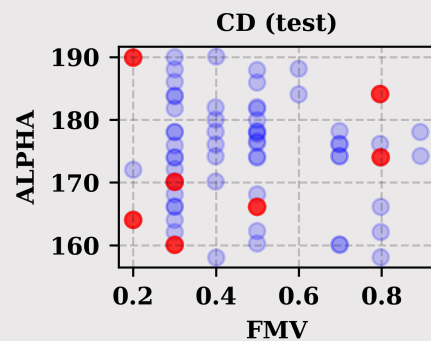
Nonlinear Autoregressive Gaussian Process (NARGP)

- Learns nonlinear correlations between fidelity levels
- Multifidelity

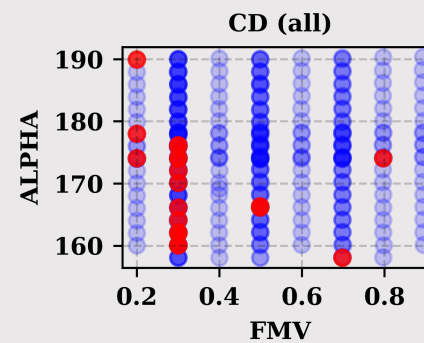
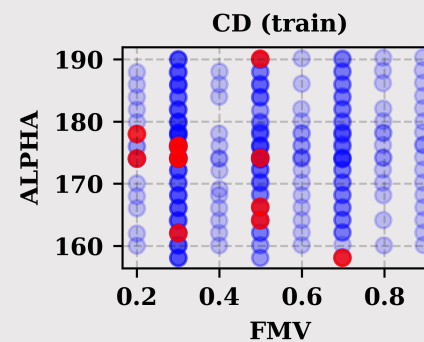
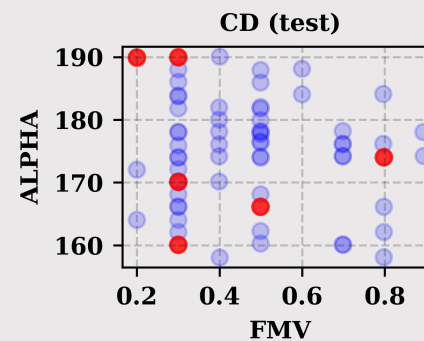


Scatterplots

Model: SFGPR

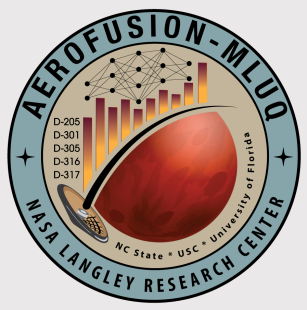


Model: NARGP



Accounting for fidelity misses less points





Conclusion

- These methods perform relatively well to capture mean and spread in a variety of data
- Incorporating fidelity is possible and sometimes leads to better fit of high fidelity data
- Tradeoff between capturing mean and spread