Aeroelastic Prediction Workshop

Lessons learned in the selection and development of test cases for the Aeroelastic Prediction Workshop:

Rectangular Supercritical Wing

Jennifer Heeg, Pawel Chwalowski, Carol Wieseman,
Jennifer Florance, and David Schuster

What did we learn from RSW?

- Wall presence effects
- FRF main contributors
- Relationships between steady-state and oscillatory solutions
- Flow physics of supercritical airfoils

- Too many things were varied

Aeroelastic Computational Benchmarking

- **Technical Challenge: Assess state-of-the-art methods & tools for the prediction and assessment of aeroelastic phenomena**

- **Fundamental hindrances to this challenge**
  - No comprehensive aeroelastic benchmarking validation standard exists
  - No sustained, successful effort to coordinate validation efforts
- **Approach**
  - Perform comparative computational studies on selected test cases
  - Identify errors & uncertainties in computational aeroelastic methods
  - Identify gaps in existing aeroelastic databases
  - Provide roadmap of path forward

Contents

- RSW Model
- Preliminary Modeling Study
- Workshop Analyses
- Summary & Lessons Learned

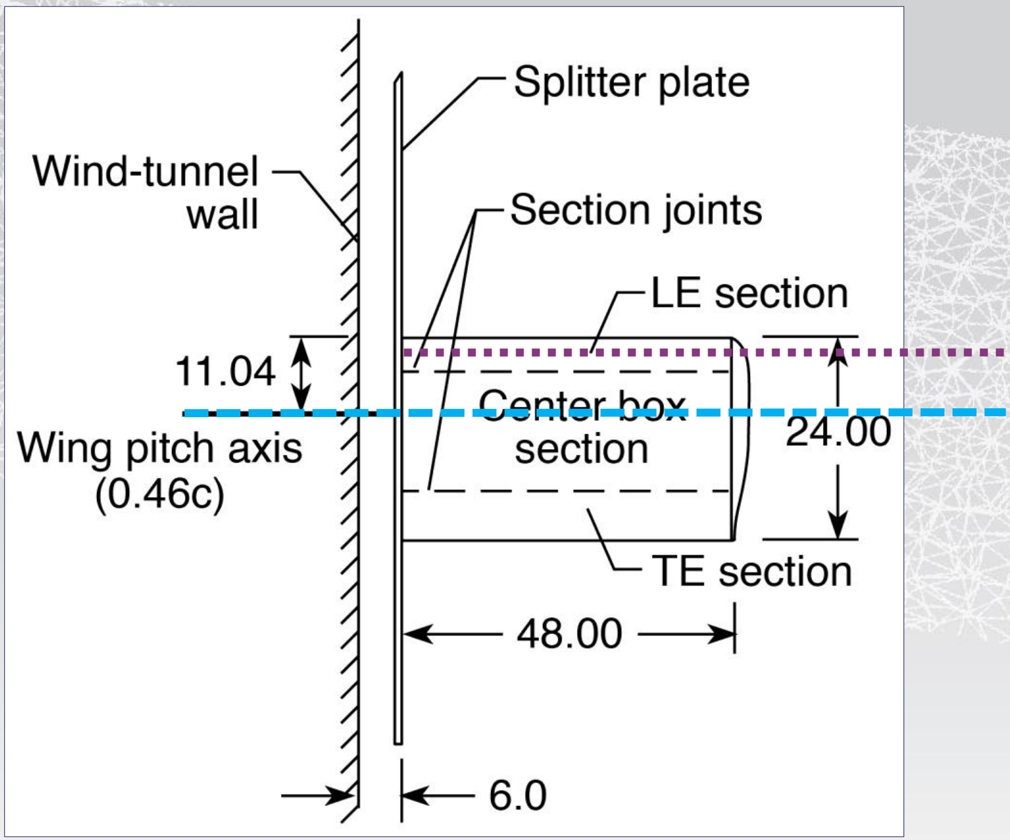
Rectangular Supercritical Wing (RSW)

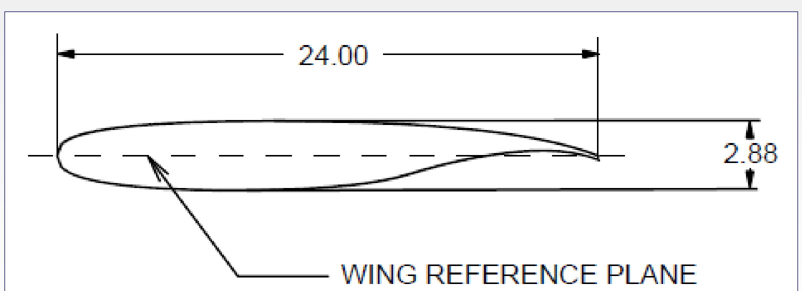
- Simple, rectangular wing
- Structure treated as rigid
- Static and forced oscillation pitching motion

<u>Some deficiencies:</u>

- – Splitter plate deficiencies
- – No time histories

RSW Features





Transition Strip:
6% chord

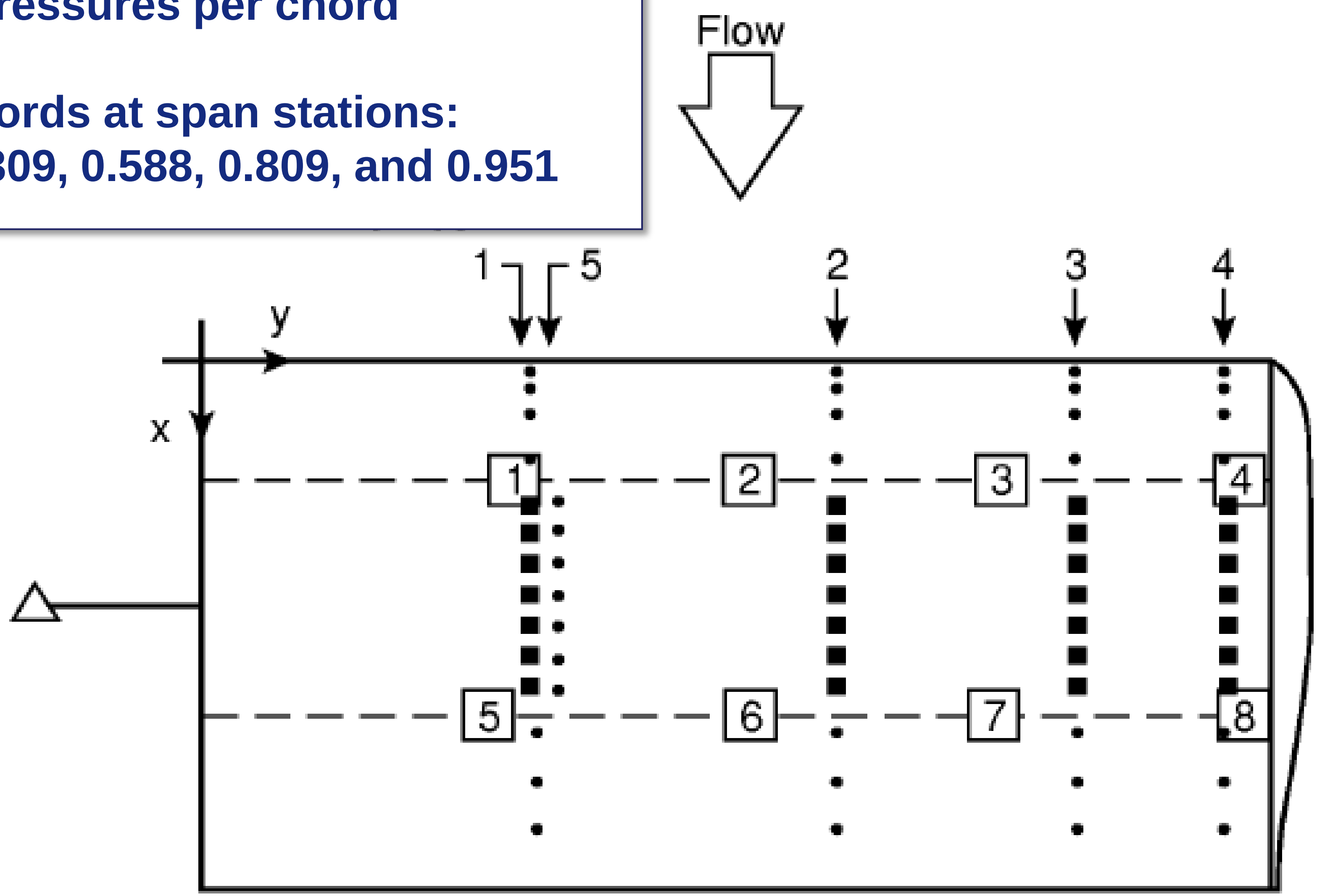
Forced Oscillation:
Pitching motion about 46% chord

Structurally Stiff:
Lowest structural frequency of model and support system = 34.8 Hz

Airfoil:
Supercritical, 12% thick

RSW Unsteady Pressure Transducer Layout

- **29 pressures per chord**
- **4 chords at span stations:**
  0.309, 0.588, 0.809, and 0.951



Rectangular Supercritical Wing Analysis Conditions

M=0.825
Re_c=4.0 million
Test medium: R-12

a) Steady Cases
   i. $\alpha = 2°$
   ii. $\alpha = 4°$
b) Dynamic Cases:
   $\alpha = 2°, \theta = 1°$
   i. f = 10 Hz
   ii. f = 20 Hz

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- RSW Model
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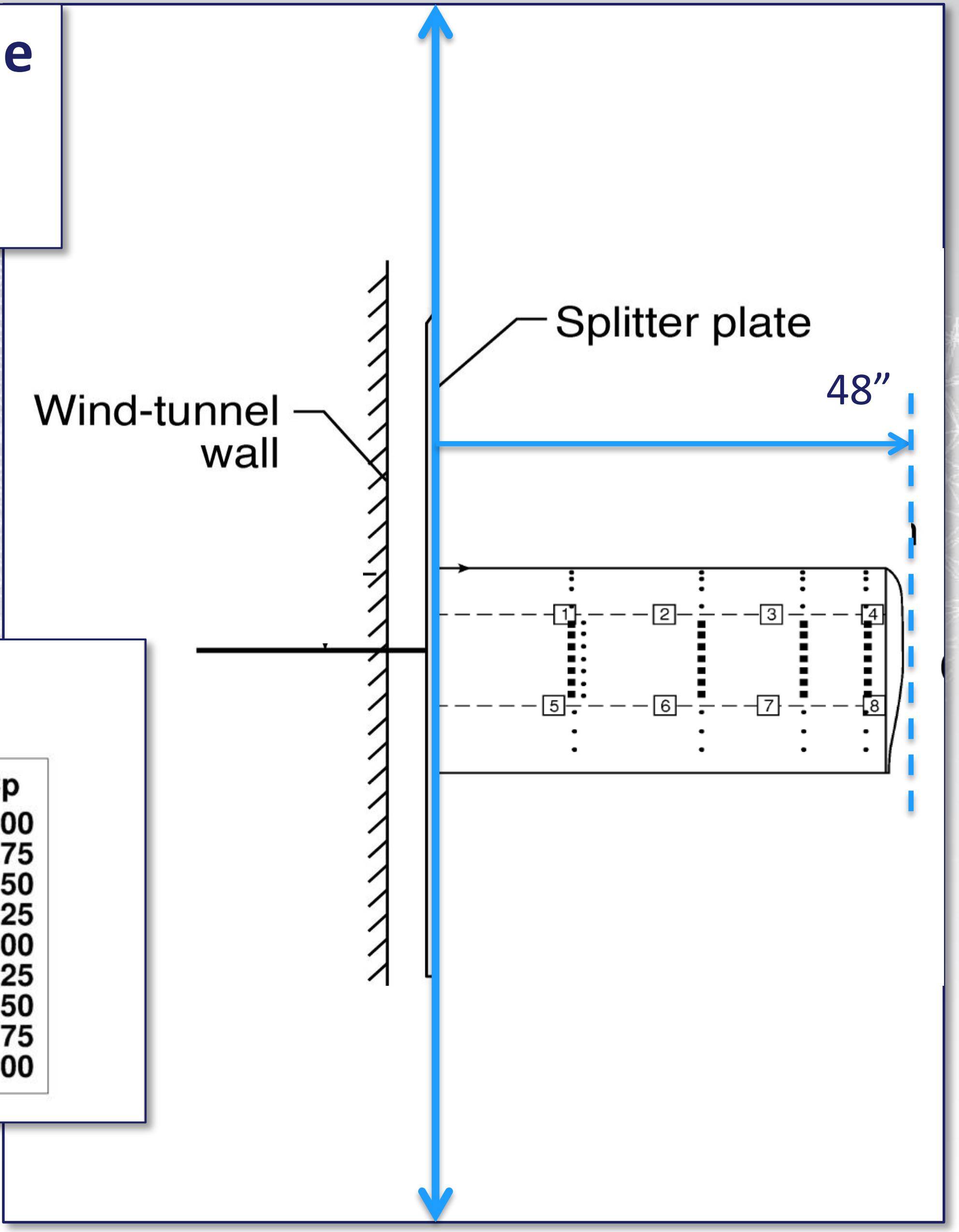
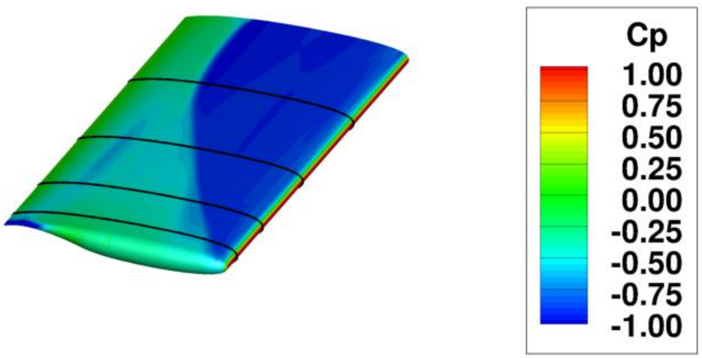
Original computational model recommendation

Wall modeled as symmetry plane
Wing Span = 48”
Upstream BC = 100c_{ref}

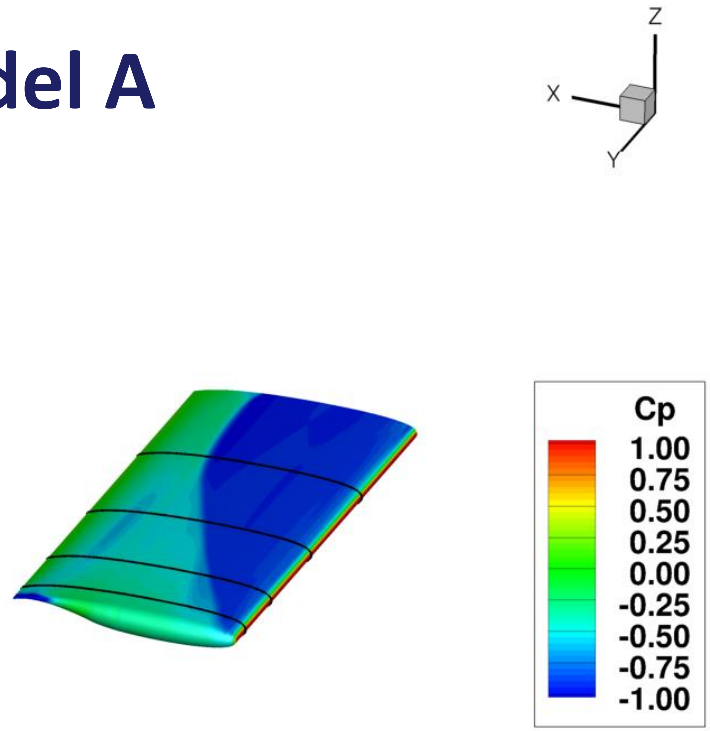


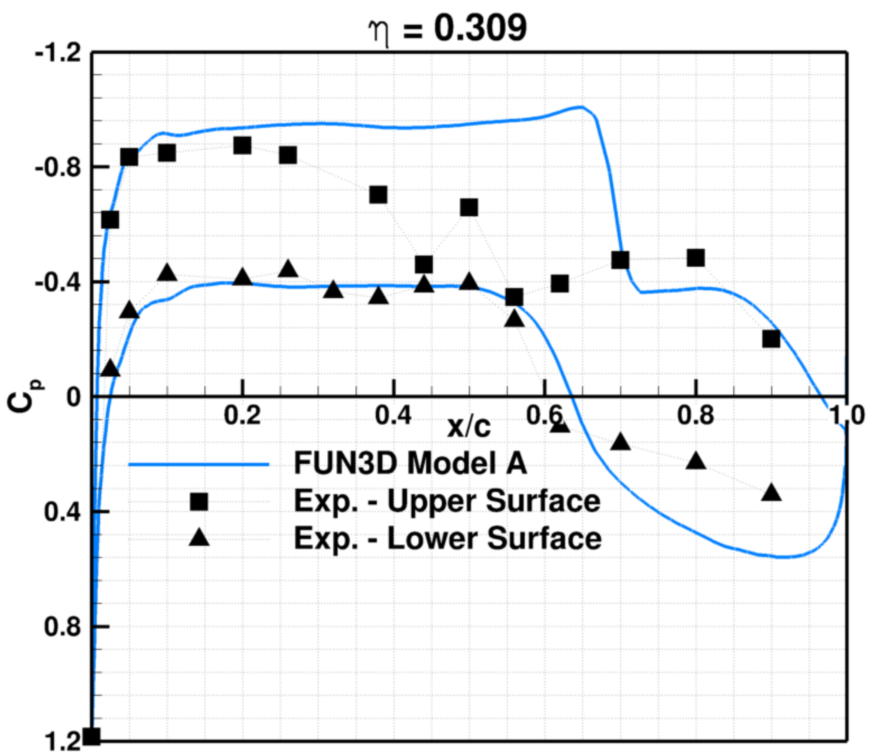
Model A



Original computational model recommendation

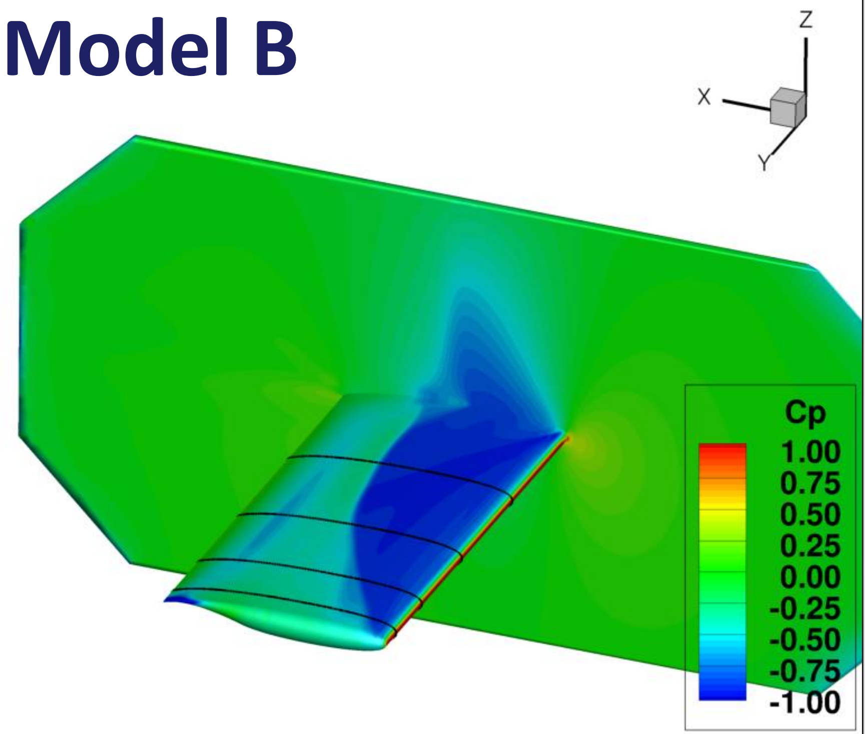
Model A

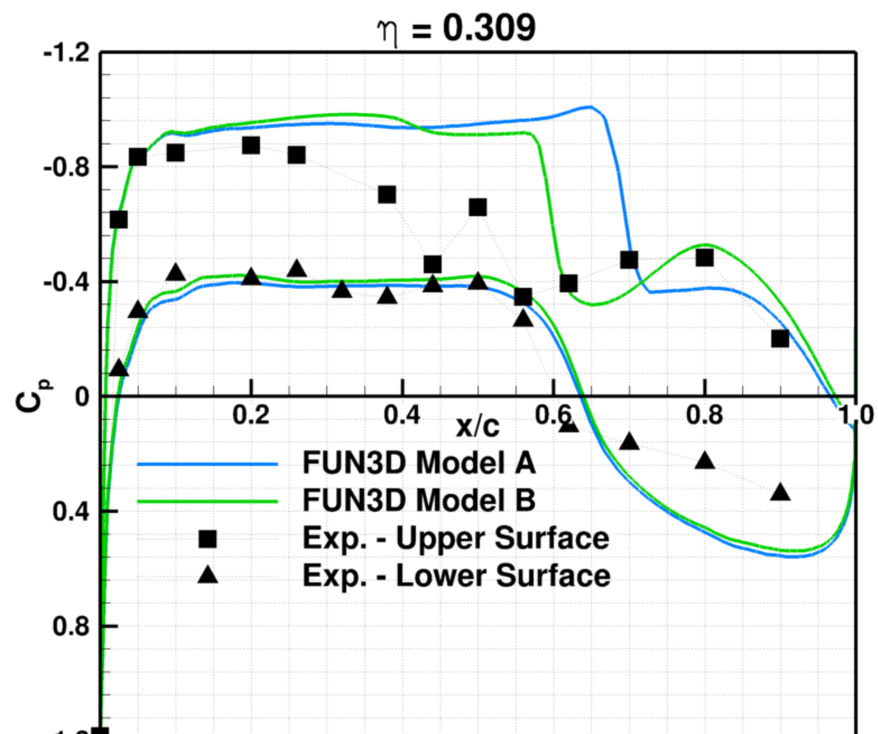




Wall modeled as symmetry plane
Wing Span = 48”
Upstream BC = $100c_{ref}$

Model B: Add Viscous Splitter Plate

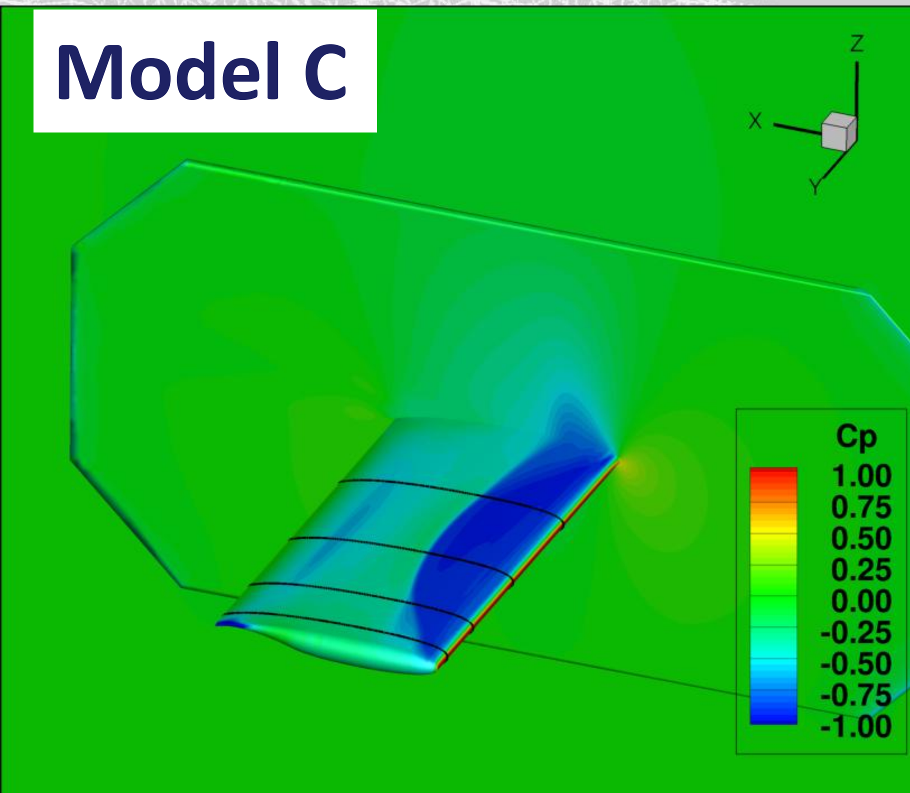


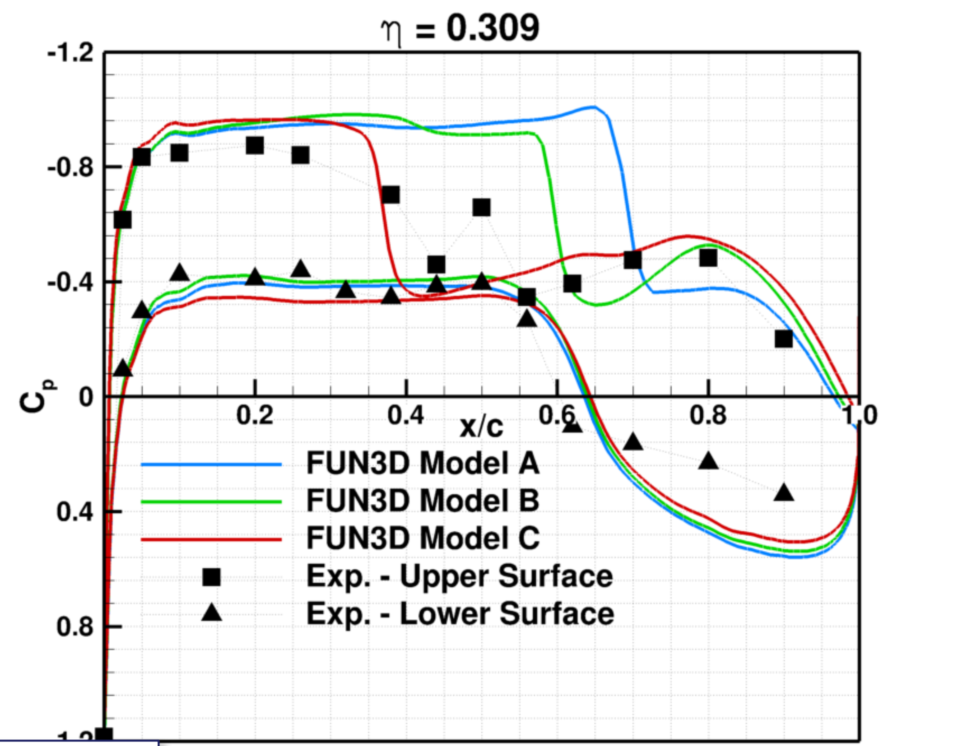


Splitter plate region modeled as viscous surface
Remainder of wall modeled as symmetry plane
Wing Span = 48”
Upstream BC = $100c_{ref}$

Model C: Entire Wall Viscous

Model C



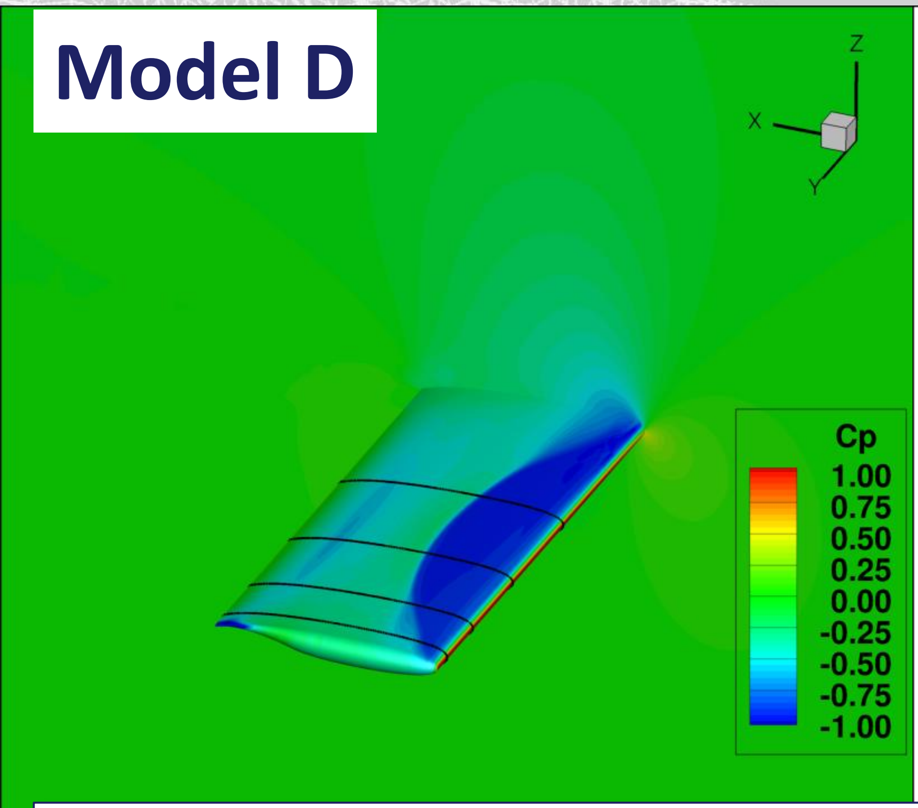


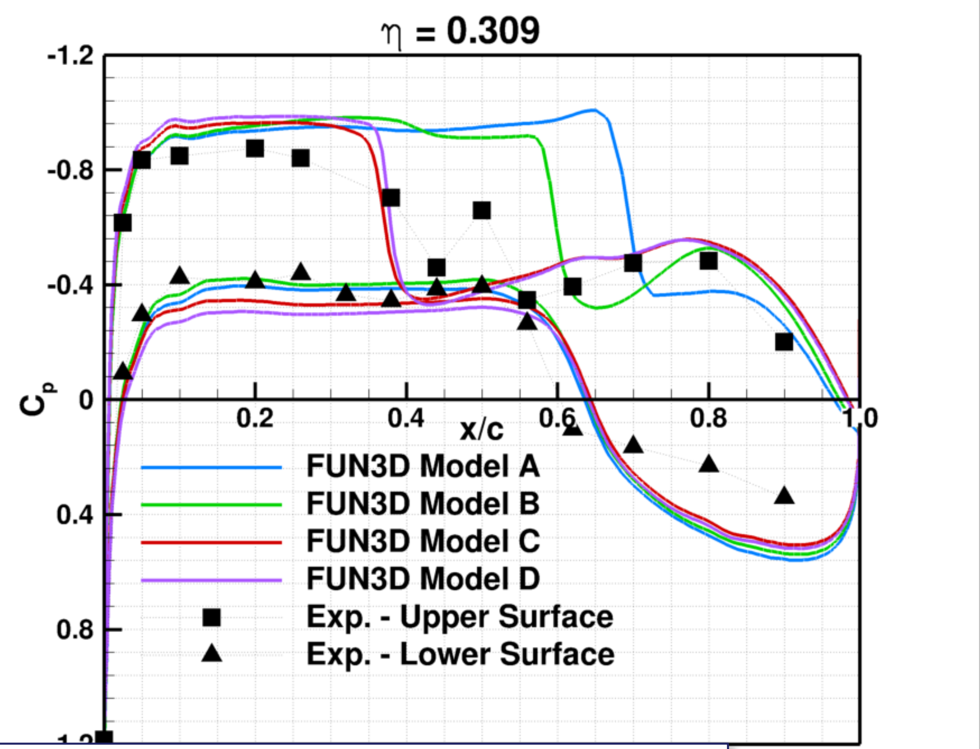
Entire wall modeled as viscous surface

Wing Span = 48”

Upstream BC = $100c_{ref}$

Model D: Wing Extruded to tunnel wall





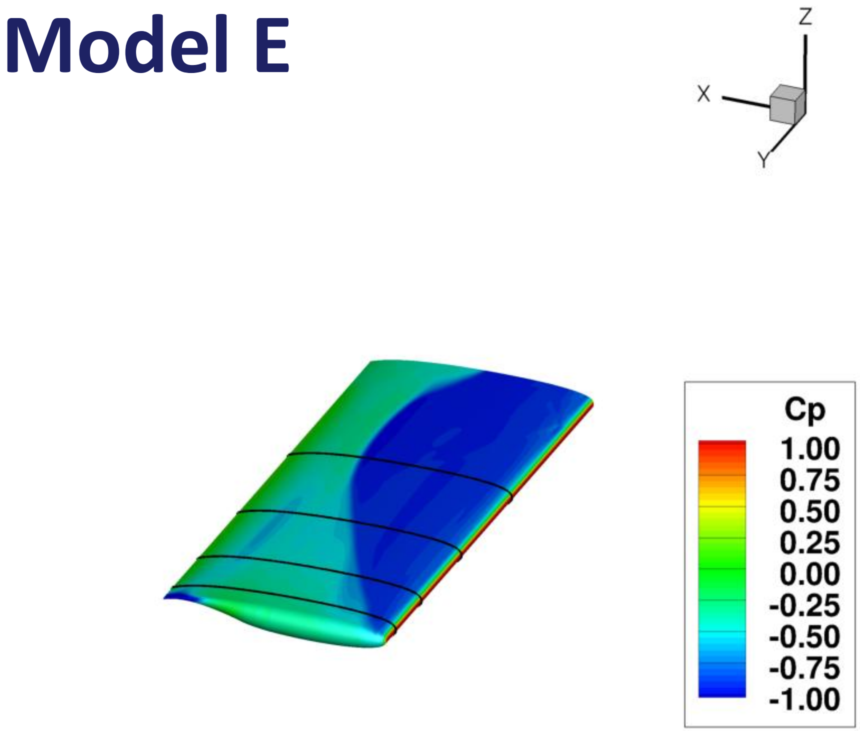
Entire wall modeled as viscous surface

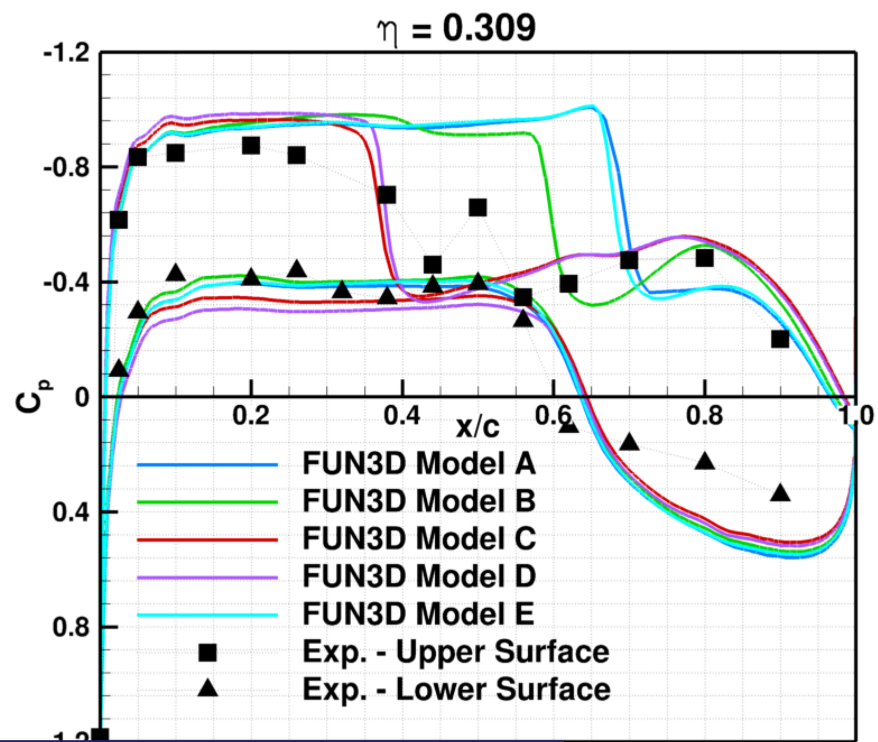
Wing extruded to physical location of wall, Wing Span = 55”

Upstream BC = 100c$_{ref}$

Model E: Remove viscous modeling of wall

Model E



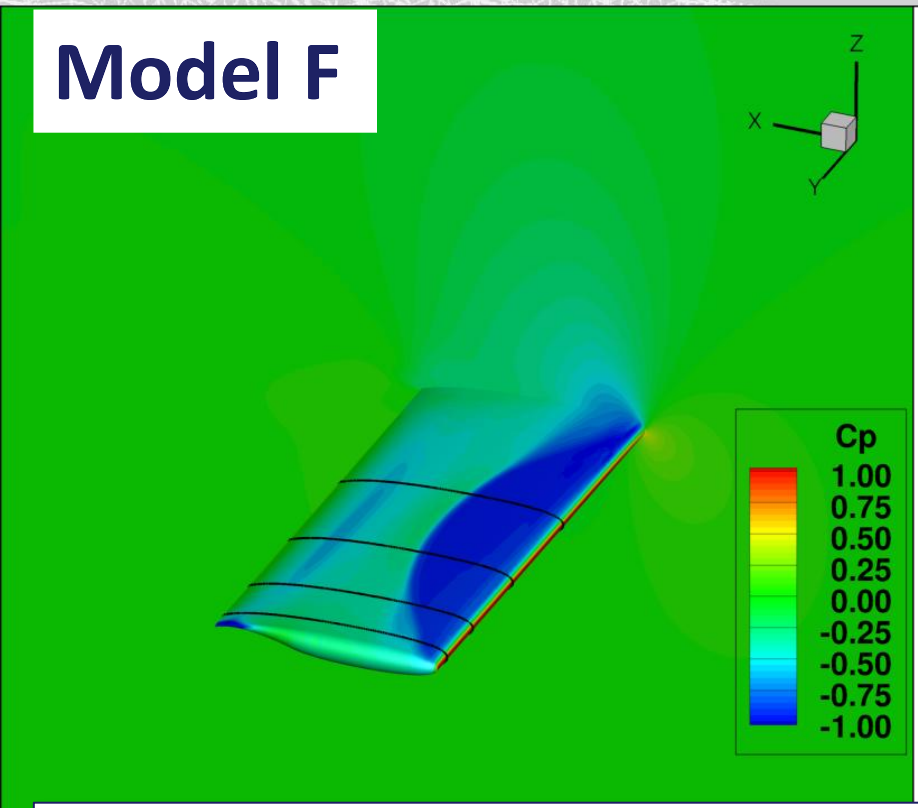


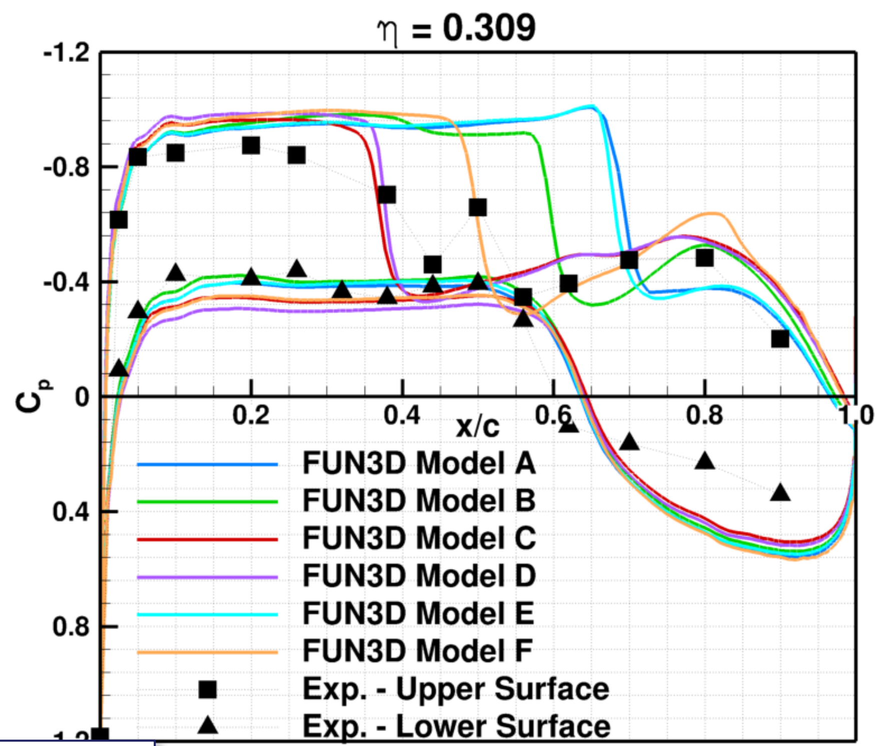
Entire wall modeled as symmetry boundary condition

Wing Span = 55”

Upstream BC = $100c_{ref}$

Model F: Viscous wall reincorporated; Upstream Boundary Location Reduced

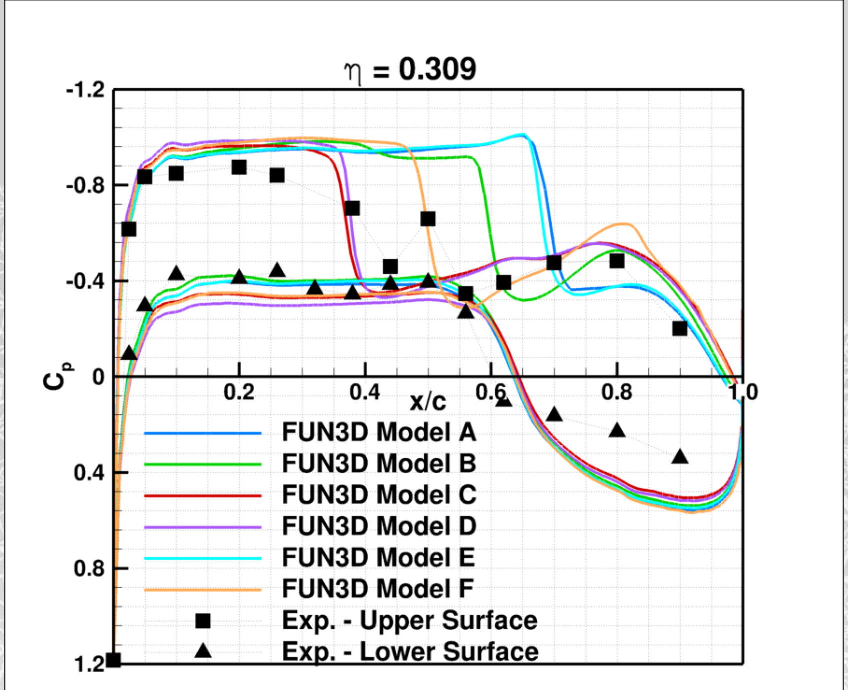


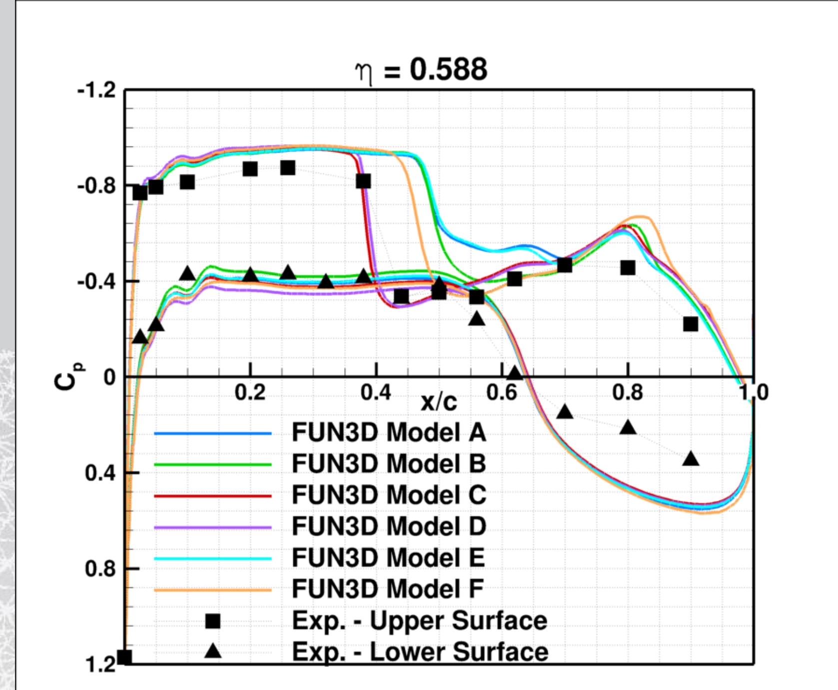


Entire wall modeled as viscous surface

Wing Span = 55”

Upstream BC = $50c_{ref}$


η = 0.309
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
C_p
0.2
0.4
0.6
0.8
1.0
x/c
FUN3D Model A
FUN3D Model B
FUN3D Model C
FUN3D Model D
FUN3D Model E
FUN3D Model F
Exp. - Upper Surface
Exp. - Lower Surface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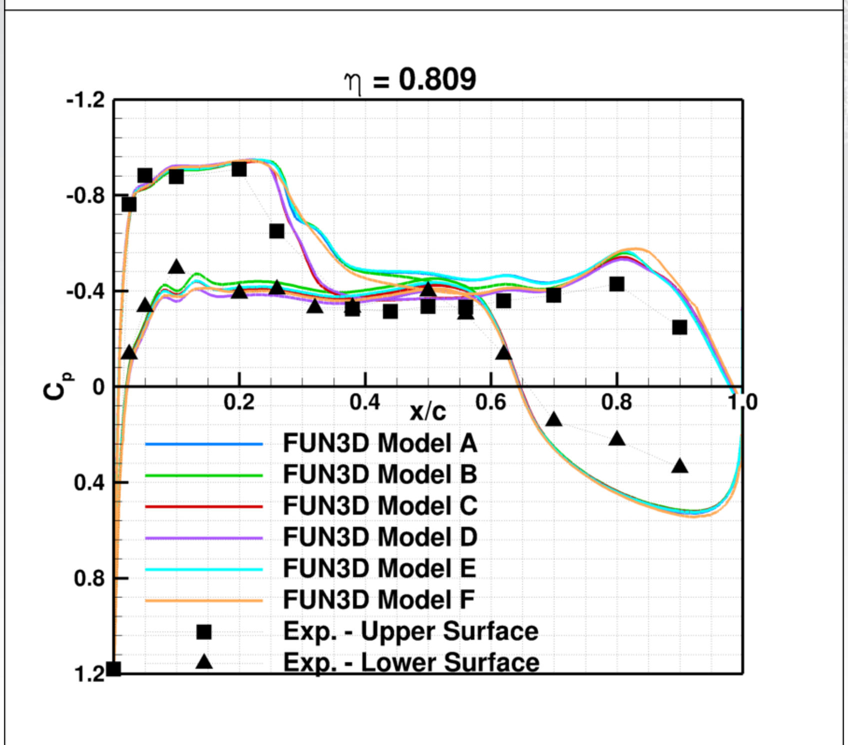
-0.8
-0.4
0
0.4
0.8
1.2
C_p
0.2
0.4
0.6
0.8
1.0
x/c
FUN3D Model A
FUN3D Model B
FUN3D Model C
FUN3D Model D
FUN3D Model E
FUN3D Model F
Exp. - Upper Surface
Exp. - Lower Surface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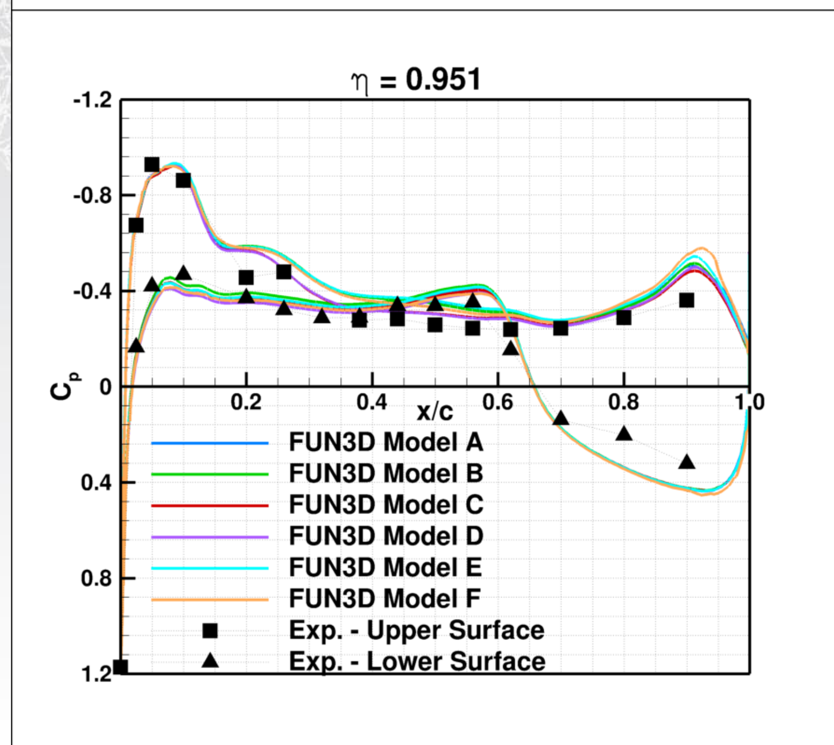
-0.8
-0.4
0
0.4
0.8
1.2
C_p
0.2
0.4
0.6
0.8
1.0
x/c
FUN3D Model A
FUN3D Model B
FUN3D Model C
FUN3D Model D
FUN3D Model E
FUN3D Model F
Exp. - Upper Surface
Exp. - Lower Surface


η = 0.951
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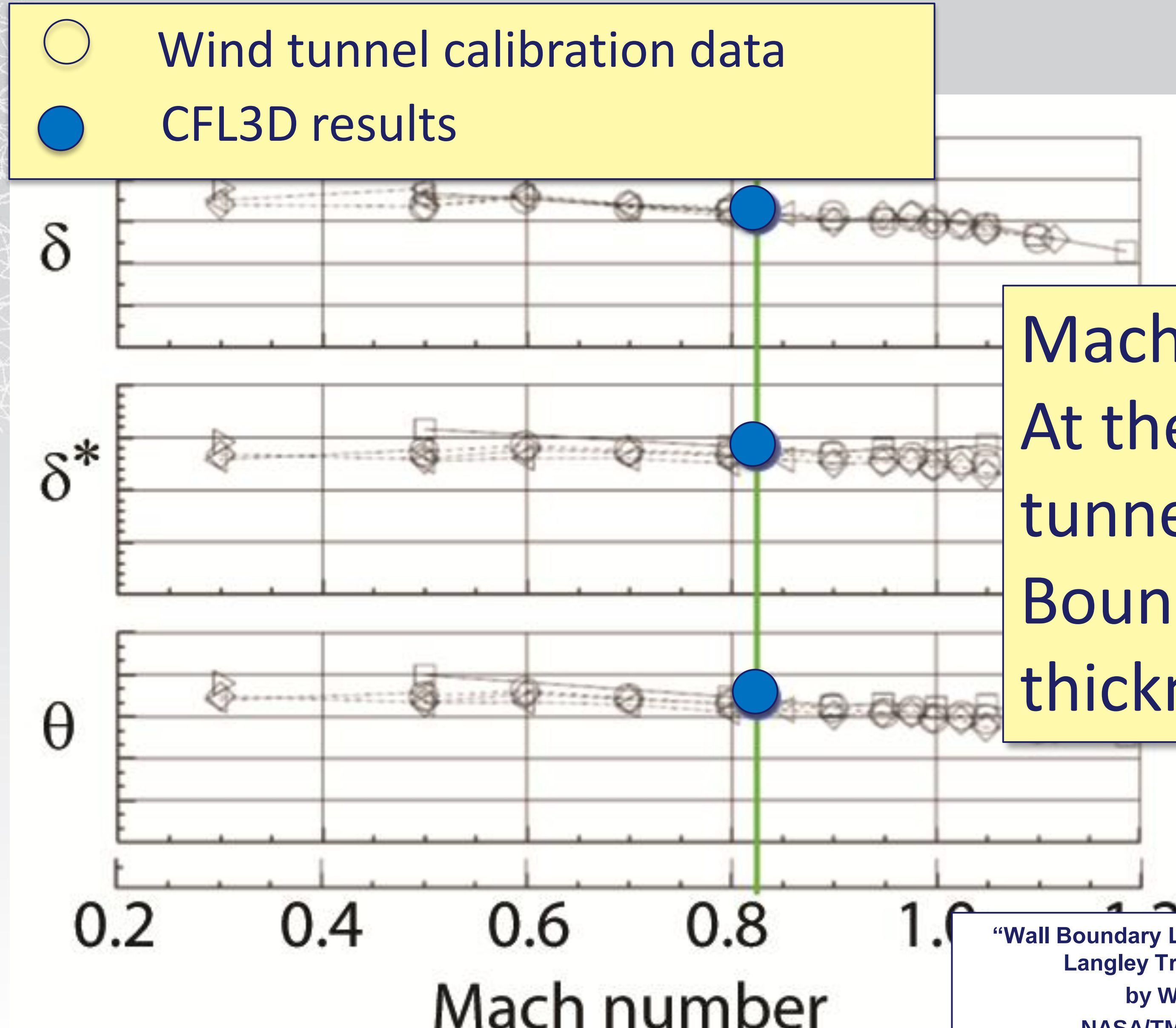
-0.8
-0.4
0
0.4
0.8
1.2
C_p
0.2
0.4
0.6
0.8
1.0
x/c
FUN3D Model A
FUN3D Model B
FUN3D Model C
FUN3D Model D
FUN3D Model E
FUN3D Model F
Exp. - Upper Surface
Exp. - Lower Surface

Tunnel Boundary Layer Thickness Calculations

CFL3D Analysis, Adjusted upstream boundary location

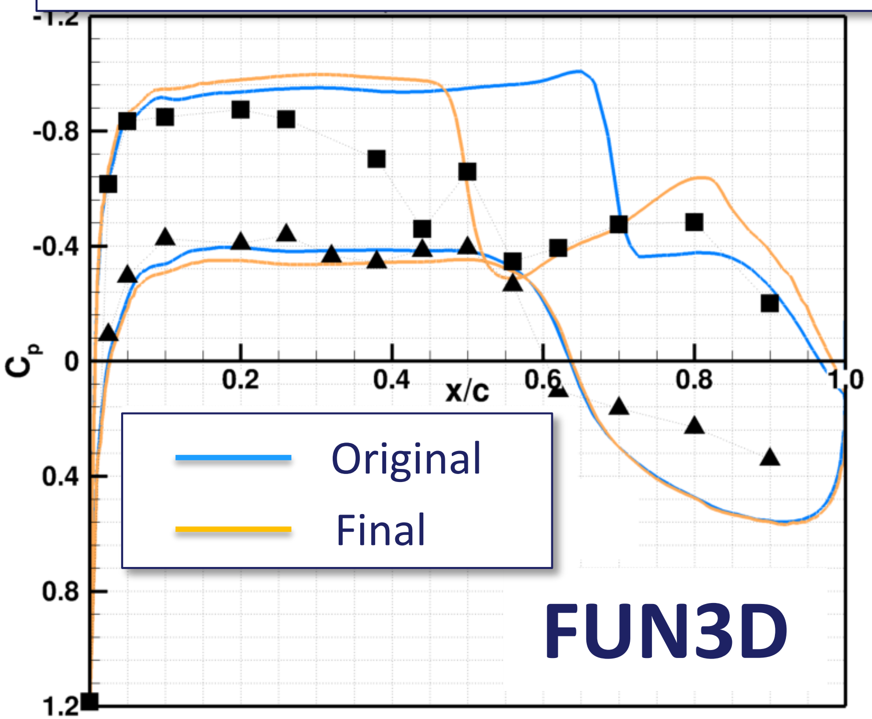


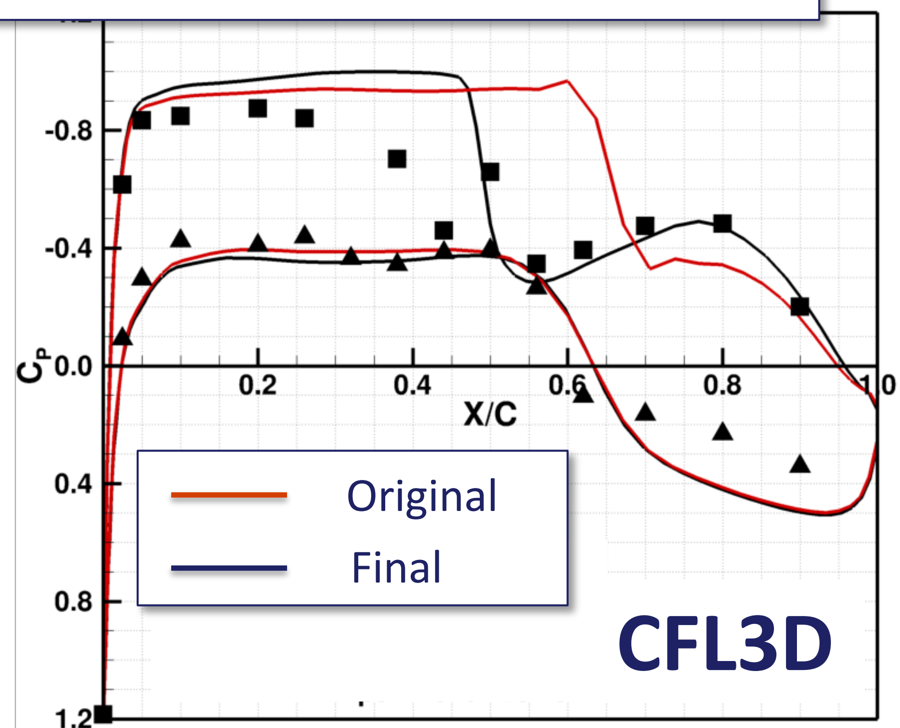
Mach 0.825,
At the model tunnel station:
Boundary layer thickness = 12”

“Wall Boundary Layer Measurements for the NASA Langley Transonic Dynamics Tunnel”
by Wieseman and Bennett
NASA/TM-2007-214867, April, 2007

Final computational model recommendation

- Reduce computational domain from 100 chords ahead of wing to 42 chords ahead of wing
- Viscous model of wall
- No splitter plate
- Extended wing span, 55”





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- **Workshop Analyses**
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RSW Analysis Teams

Affiliation	Analysis Team Members	AePW Designation
RUAG Aviation	Alain Gehri, Daniel Steiling	A
NASA	Pawel Chwalowski	B
NASA	David Schuster, Andrew Prosser	C
ANSYS Germany GMBH	Thorsten Hansen, Angela Lestari	D
University of Wyoming	Dimitri Mavriplis, Mike Long, Zhi Yang, Jay Sitaraman	E
University of Liverpool	Sebastian Timme	F

RSW flow solutions

All RSW Analysis teams used Reynolds'-averaged Navier Stokes flow solvers.

Analysis Team	Software Name	Turbulence Model*	Flux Construction	Flux Limiter	Oscillatory Solution Method
A	NSMB	SA	Unknown	None	Elastic+TFI
B	FUN3D	SA	Roe	Venkat	Elastic
C	CFL3D	SA	Roe	None	Modal+TFI
D	ANSYS CFX	SST	2nd Order Upwind/ Rhie Chow	Barth & Jesperson	Diffusion Equation
E	NSU3D	SA	Matrix Artificial Dissipation	None	Full Grid Motion
F	PMBv1.5	SA	Osher	MUSCL+ van Albada	Full Grid Motion

* Spalart-Allmaras (SA), Shear Stress Transport (SST)

Comparison Data Matrix

CASE	REQUIRED CALCULATIONS		
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Steady-Rigid	C_L, C_D, C_M		• Mean C_p vs. x/c • Means of C_L, C_D, C_M
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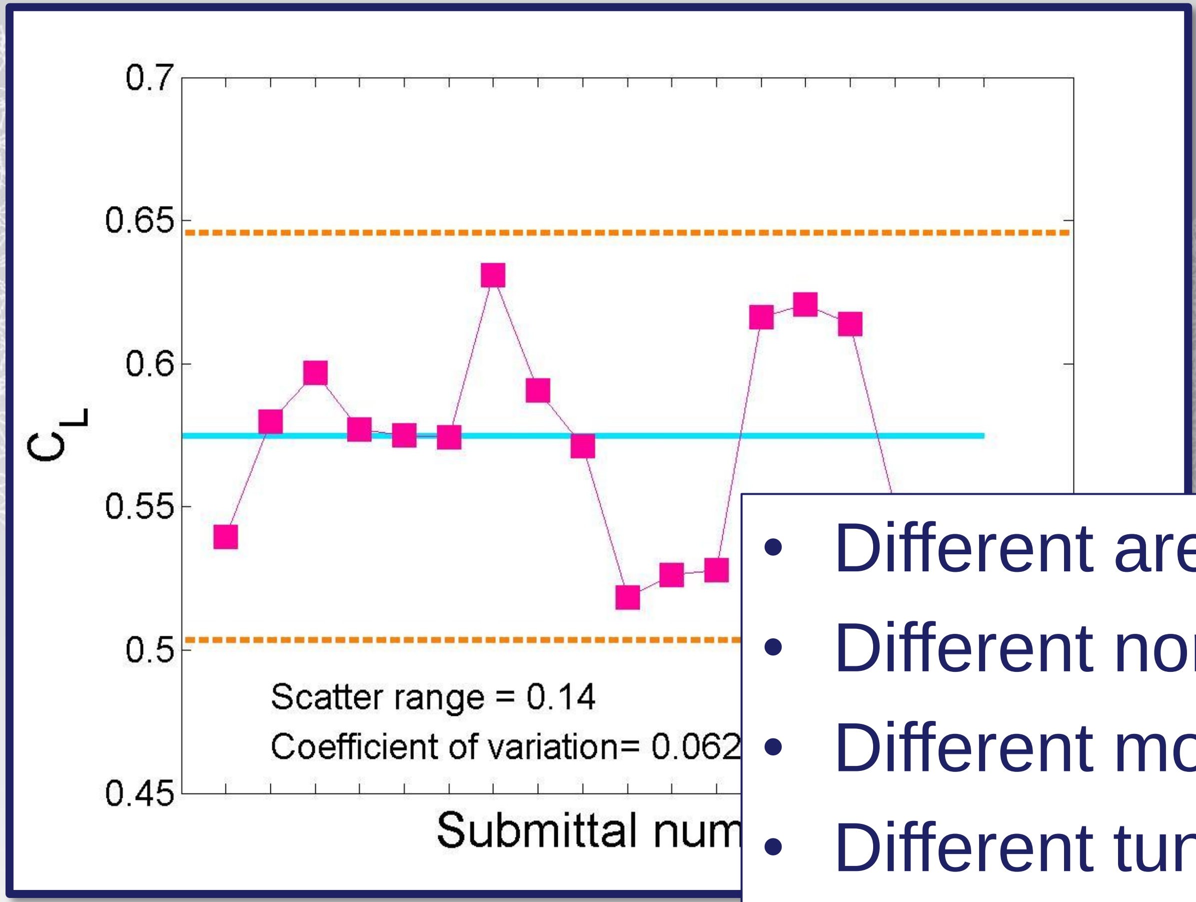
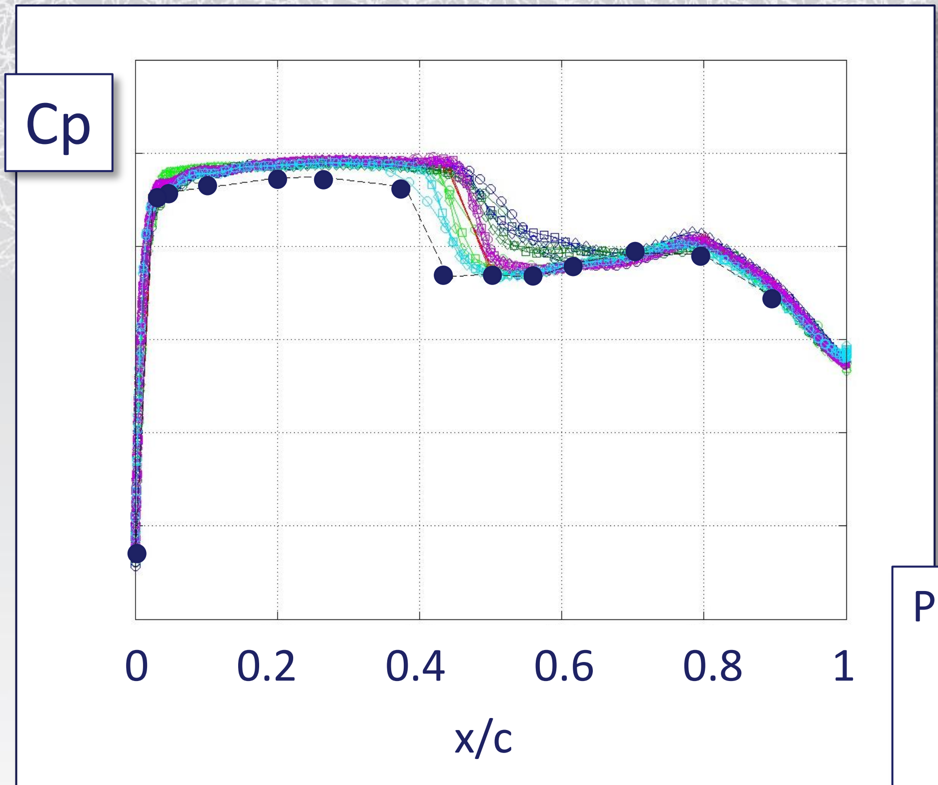
Lift Coefficient



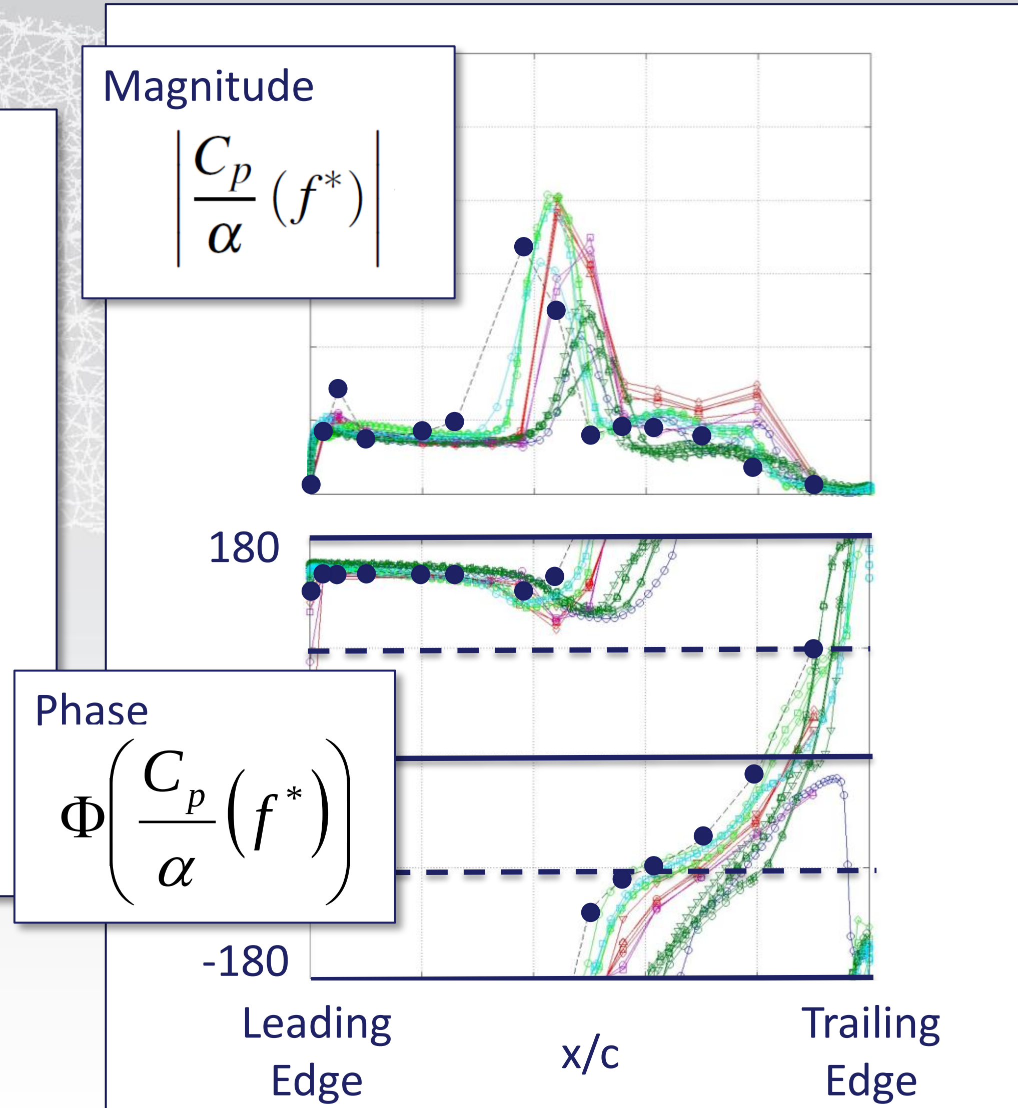
- Different areas of integration
- Different normalization constants
- Different modeled wingspans
- Different tunnel wall treatments
- Different wingtip models
- Different grids
- Solution variables

Example data set

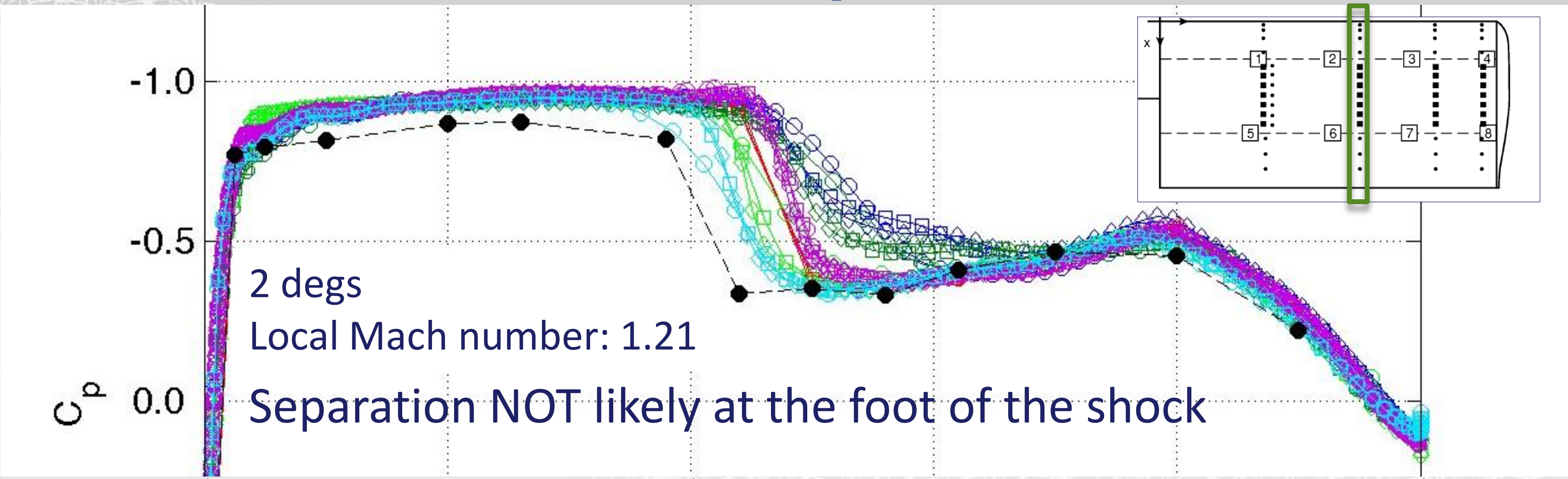
Steady State or Mean Cp distribution

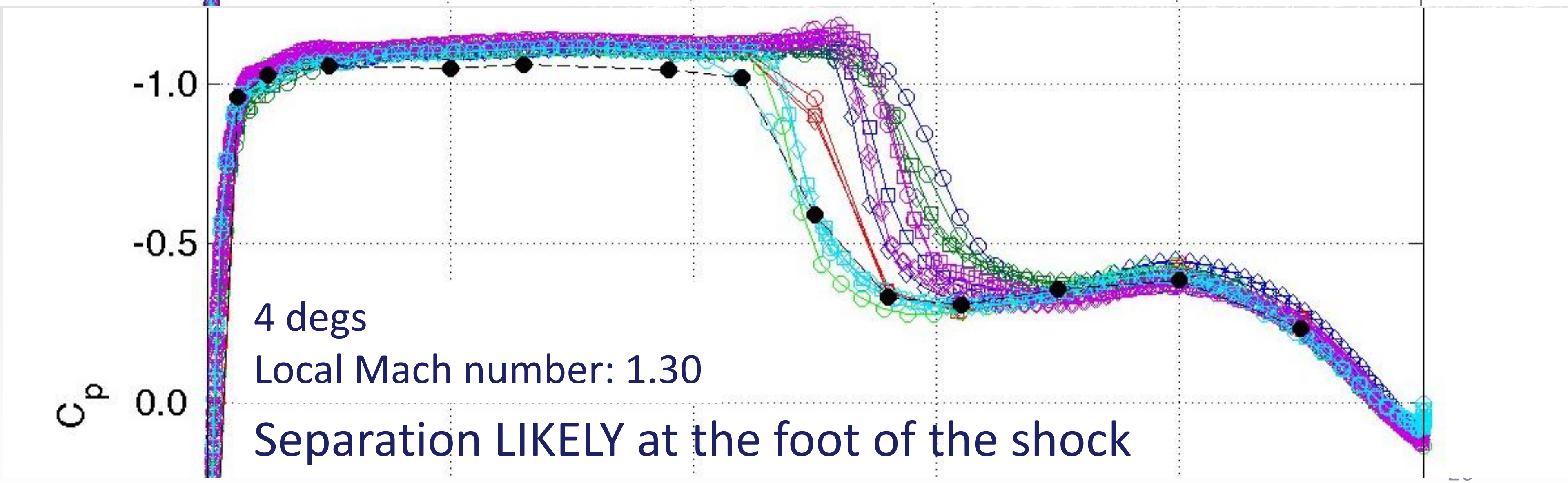


Frequency response function (FRF)

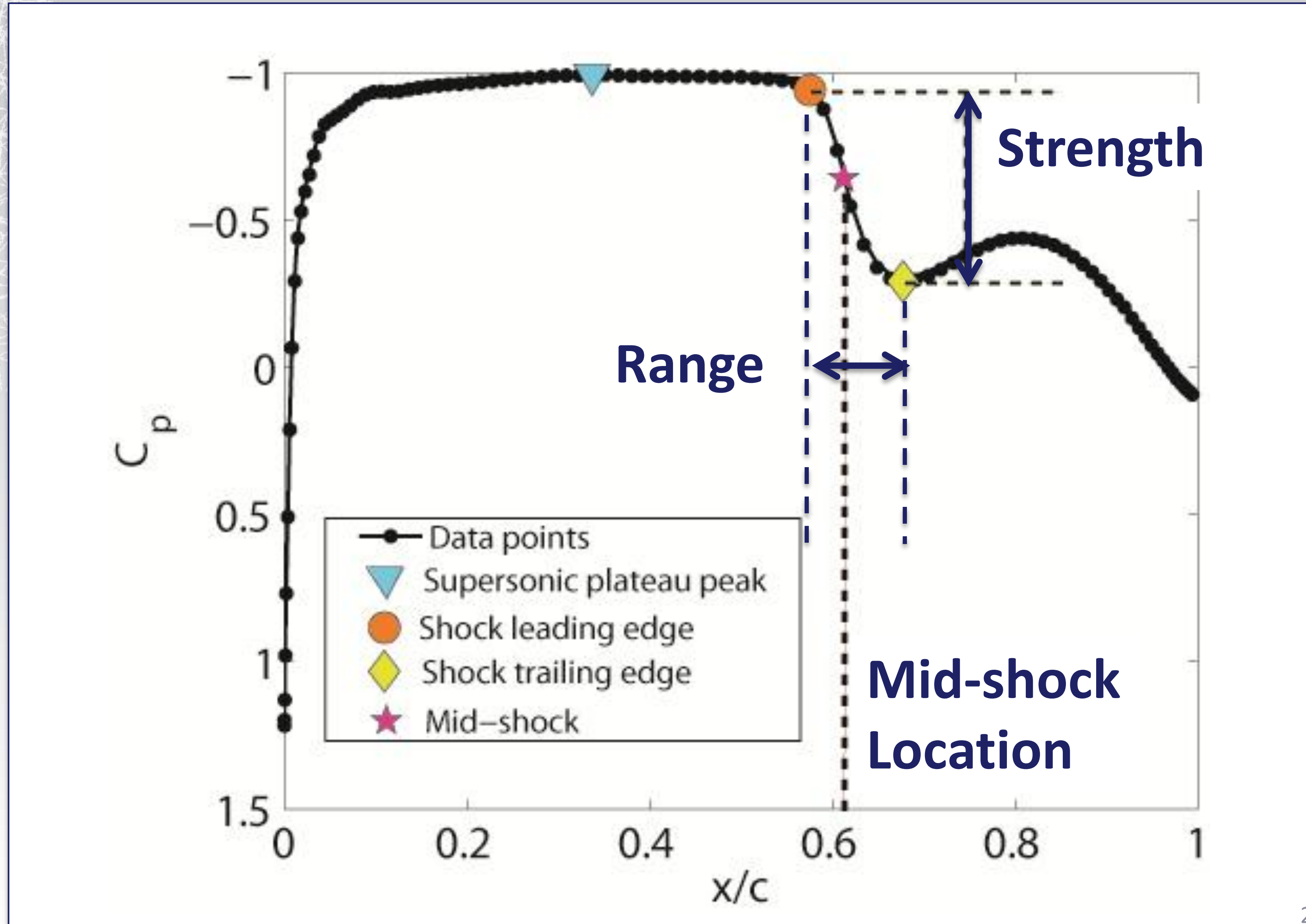


Steady State Pressure Distributions-
Local Shock Induced Separation Assessment

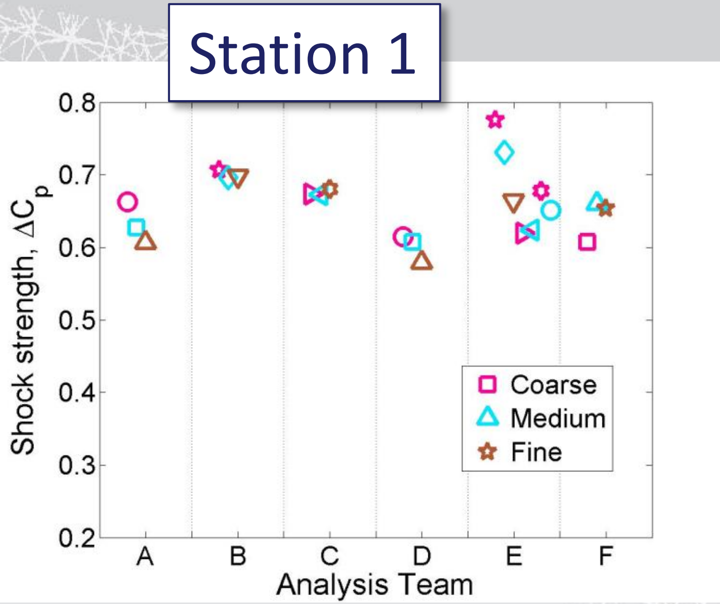


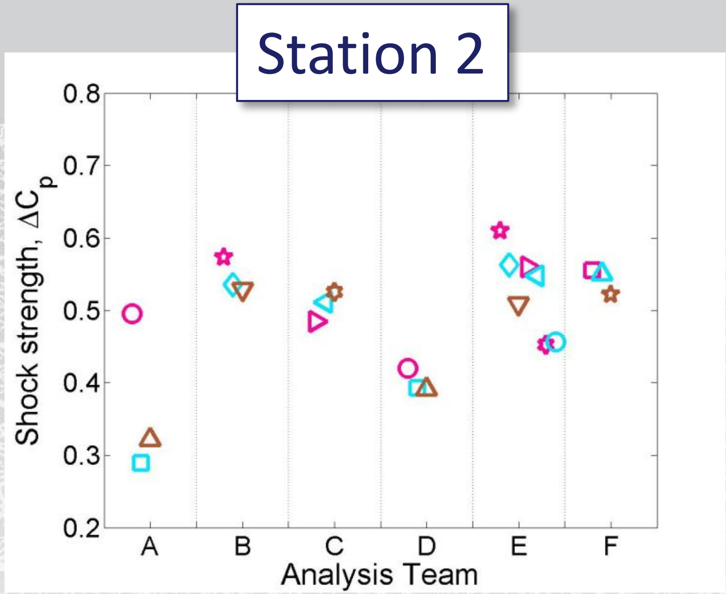


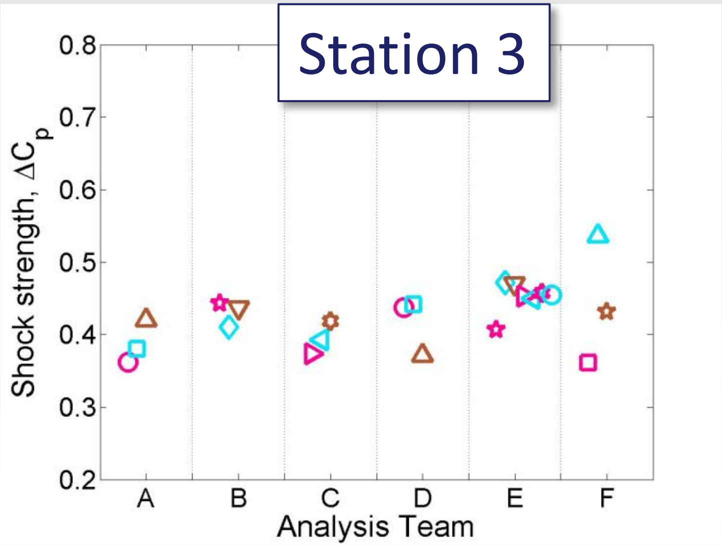
Shock Characterization- Steady State

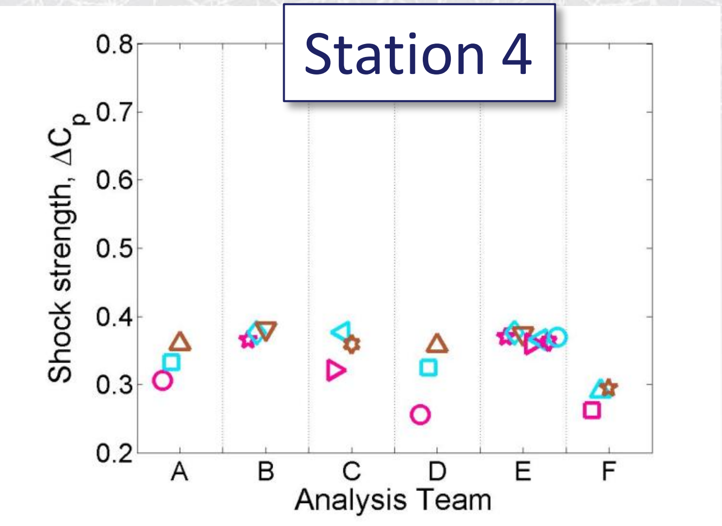


Steady-State Shock Strength









Comparison Data Matrix

CASE	REQUIRED CALCULATIONS		
	GRID CONVERGENCE STUDIES	TIME CONVERGENCE STUDIES	COMPARISON DATA
Steady-Rigid	C_L, C_D, C_M		• Mean C_p vs. x/c • Means of C_L, C_D, C_M
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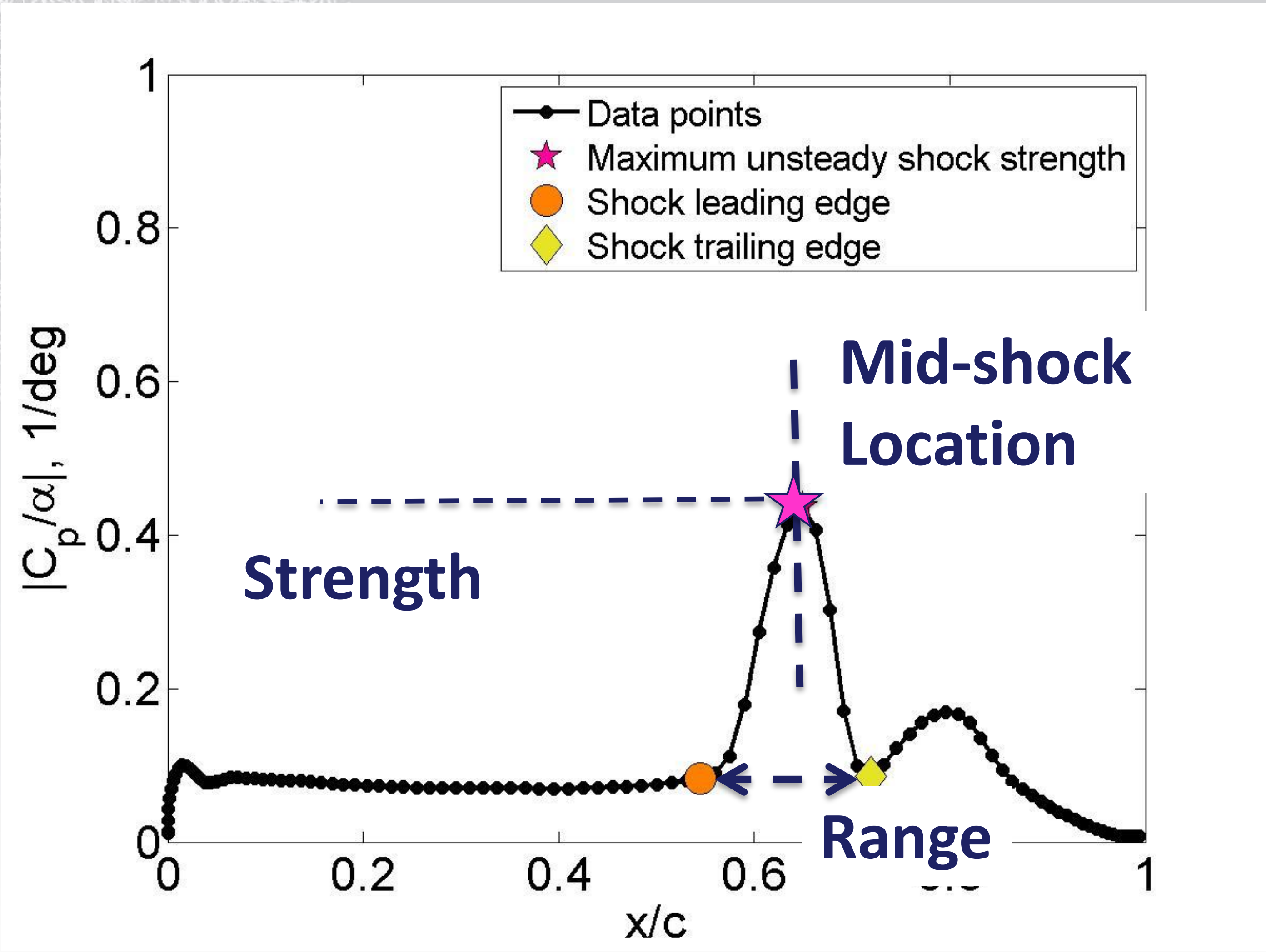
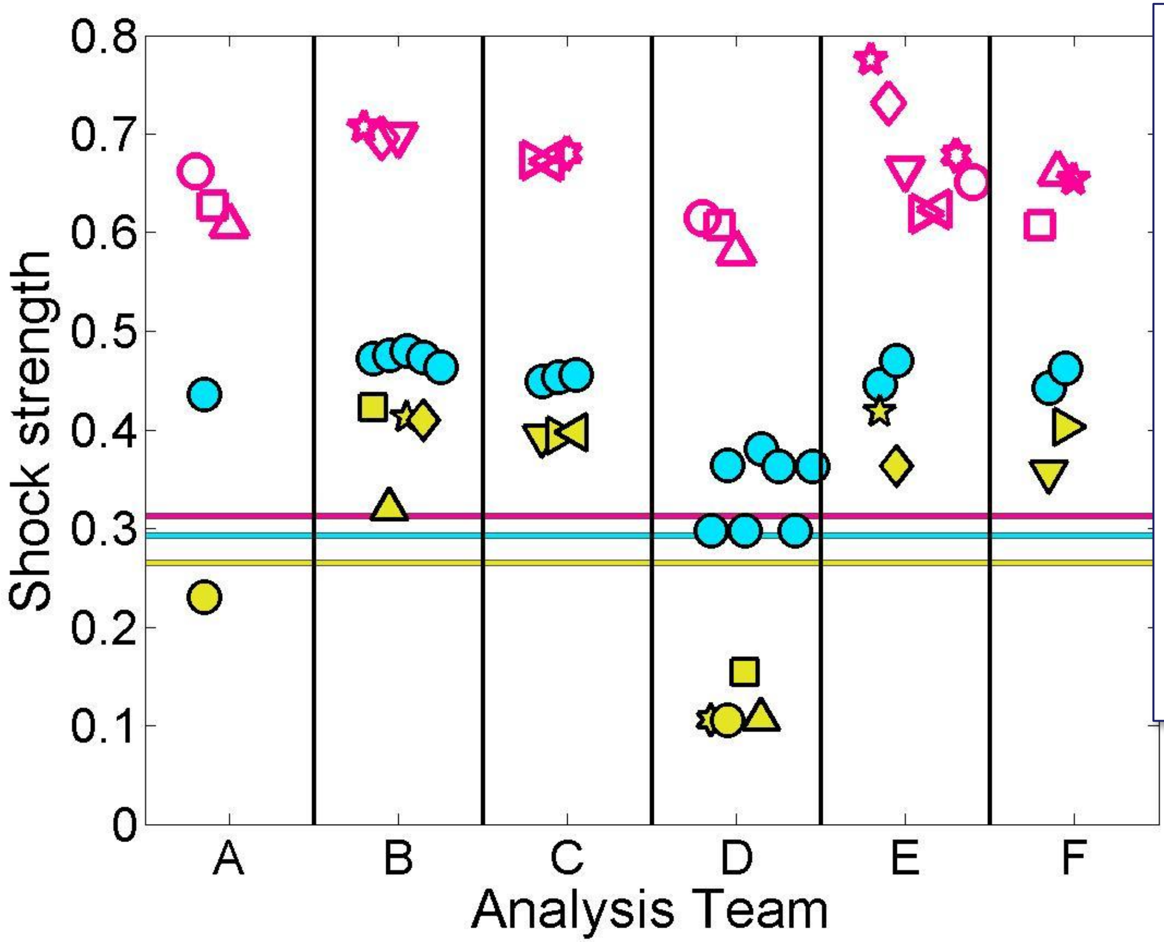
Dominant characteristic:
Upper surface oscillatory shock

Shock Characterization- Forced Oscillation



Shock strength



The steady state (mean) solutions serve as reference points.

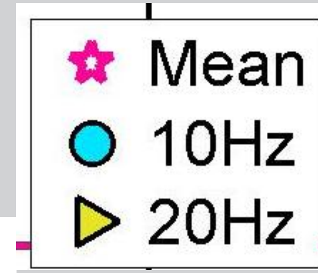
Strength is the amplitude of the dynamic component at the excitation frequency

10 Hz strength > 20Hz strength (At the lower frequency, the oscillatory change in pressure is greater.)

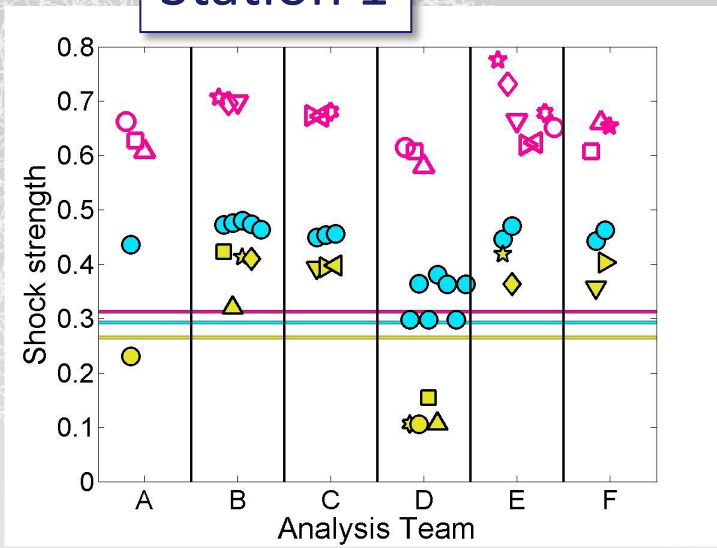
Mean
10Hz
20Hz

Horizontal lines are values from experimental data

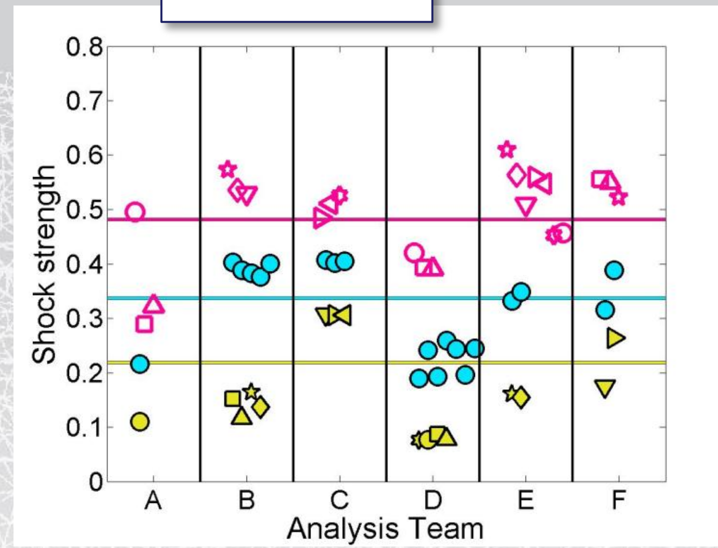
Shock strength



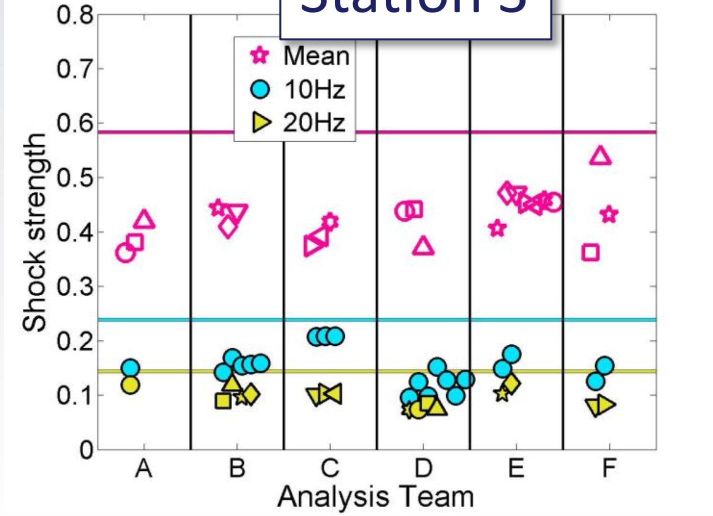
Station 1



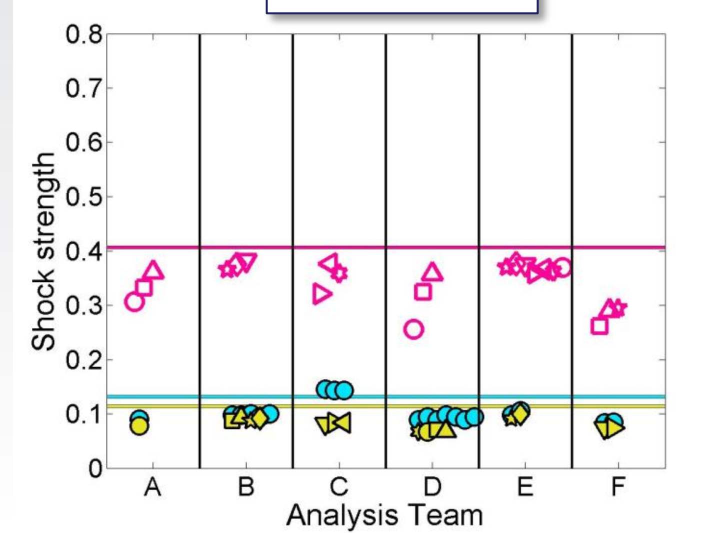
Station 2

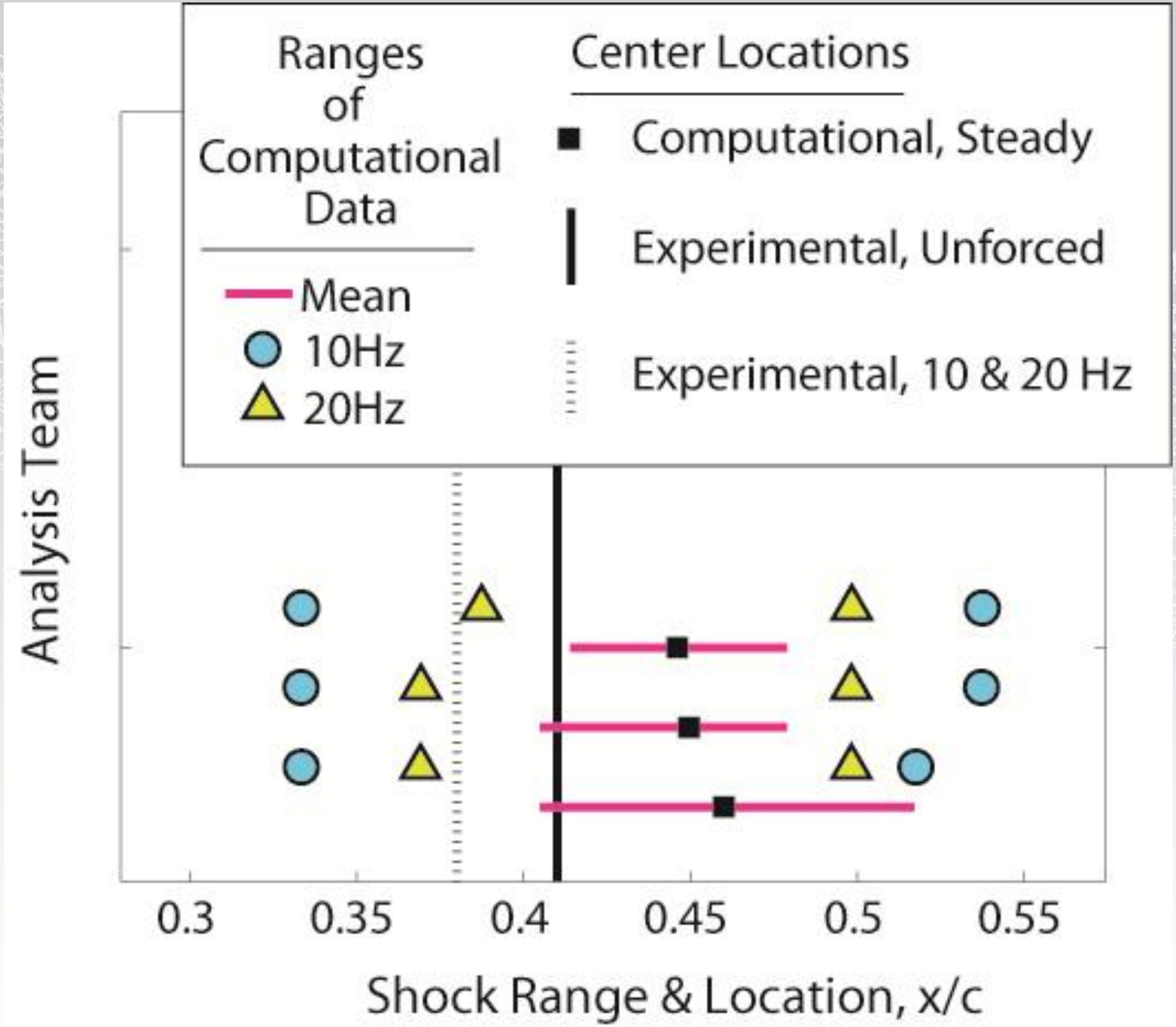


Station 3



Station 4

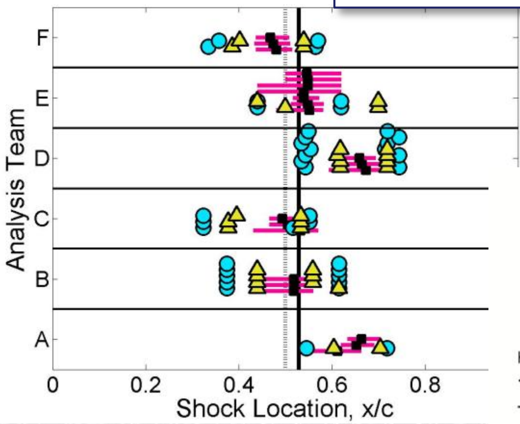




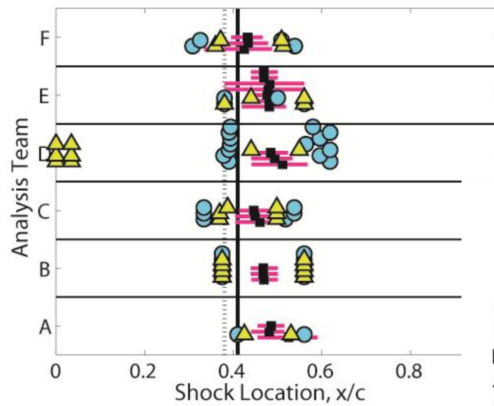
Ranges of Computational Data
Mean
10Hz
20Hz
Center Locations
Computational, Steady
Experimental, Unforced
Experimental, 10 & 20 Hz
Analysis Team
0.3
0.35
0.4
0.45
0.5
0.55
Shock Range & Location, x/c

Shock Locations

Station 1



Station 2



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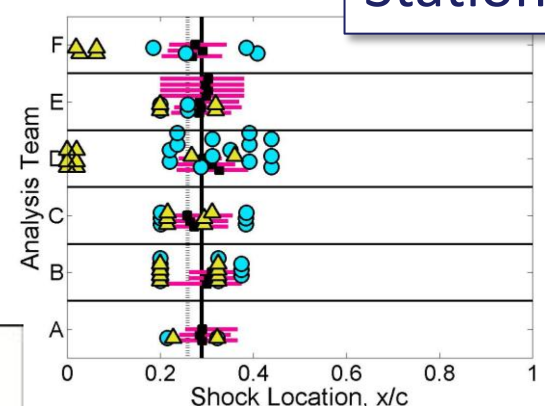
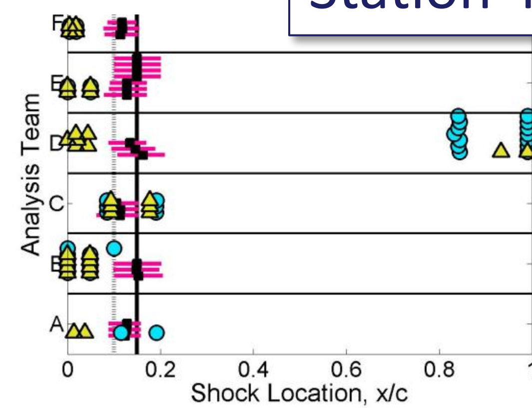
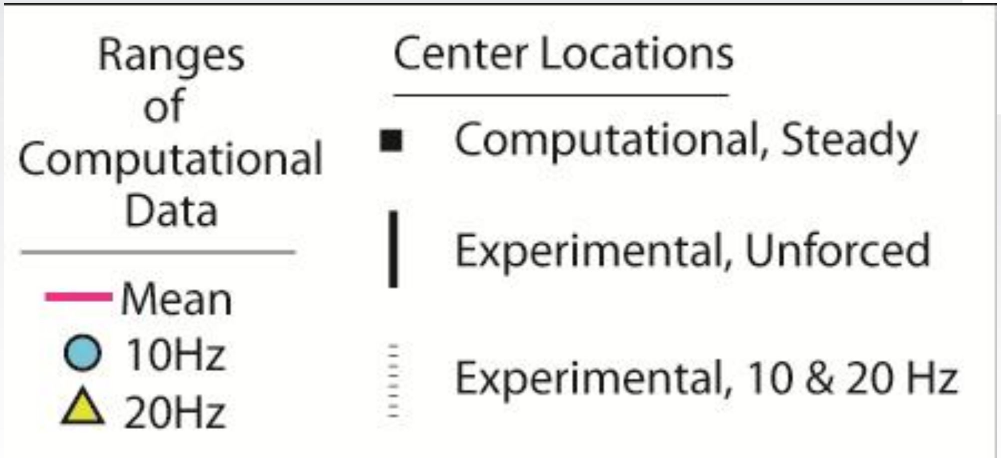
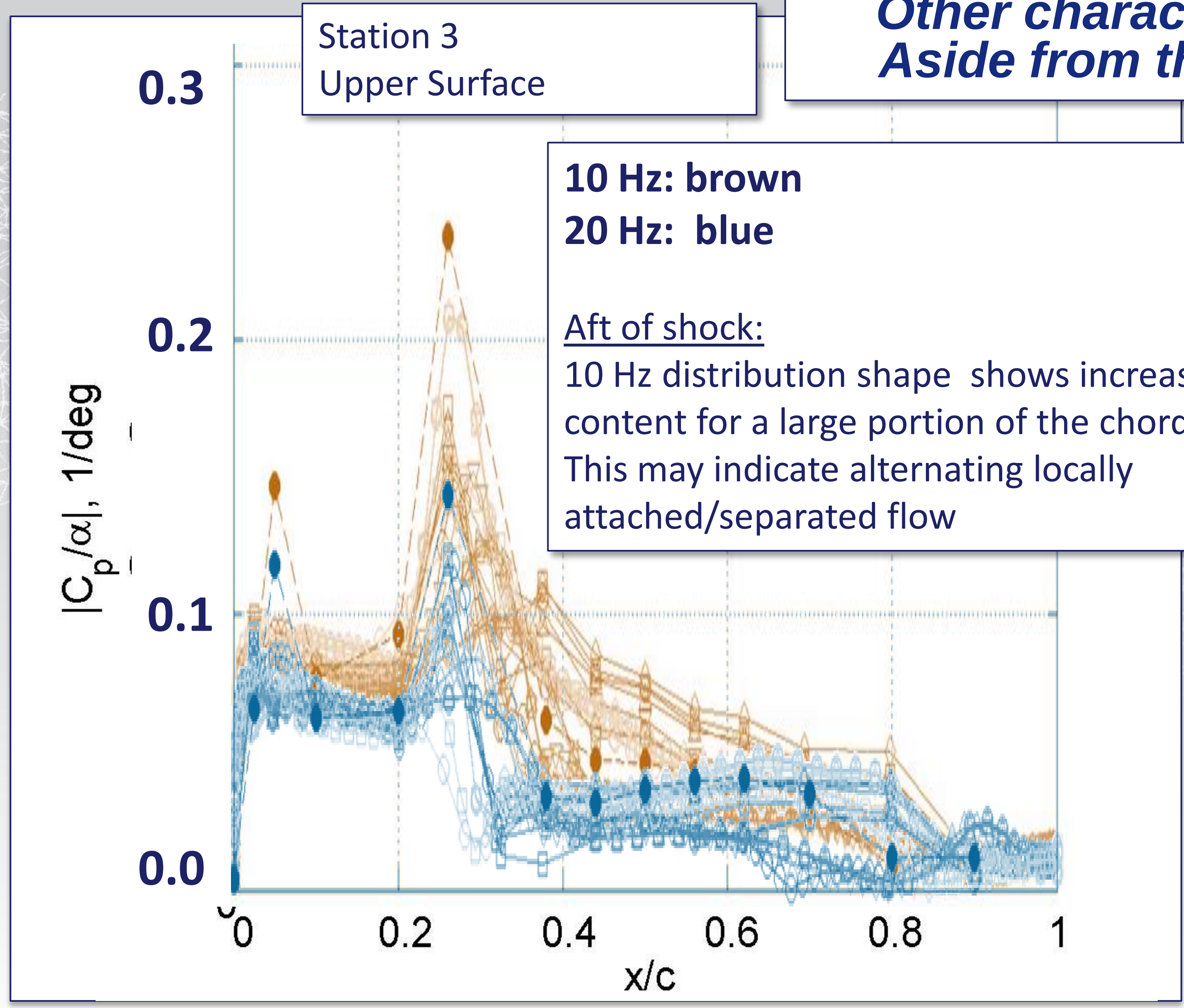


Station 4





FRFs
Other characteristics, Aside from the shock



10 Hz: brown

20 Hz: blue

Aft of shock:

10 Hz distribution shape shows increased dynamic content for a large portion of the chord.
This may indicate alternating locally attached/separated flow

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Forced Oscillation	Magnitude and Phase of CL, CD, CM at excitation frequency	Magnitude and Phase of C_L, C_D, C_M vs. dt at excitation frequency	• Magnitude and Phase of C_p vs. x/c at span stations corresponding to transducer locations • Magnitude and Phase of C_L, C_D, C_M at excitation frequency • Time histories of C_p's at a selected span station for two upper- and two lower-surface transducer locations

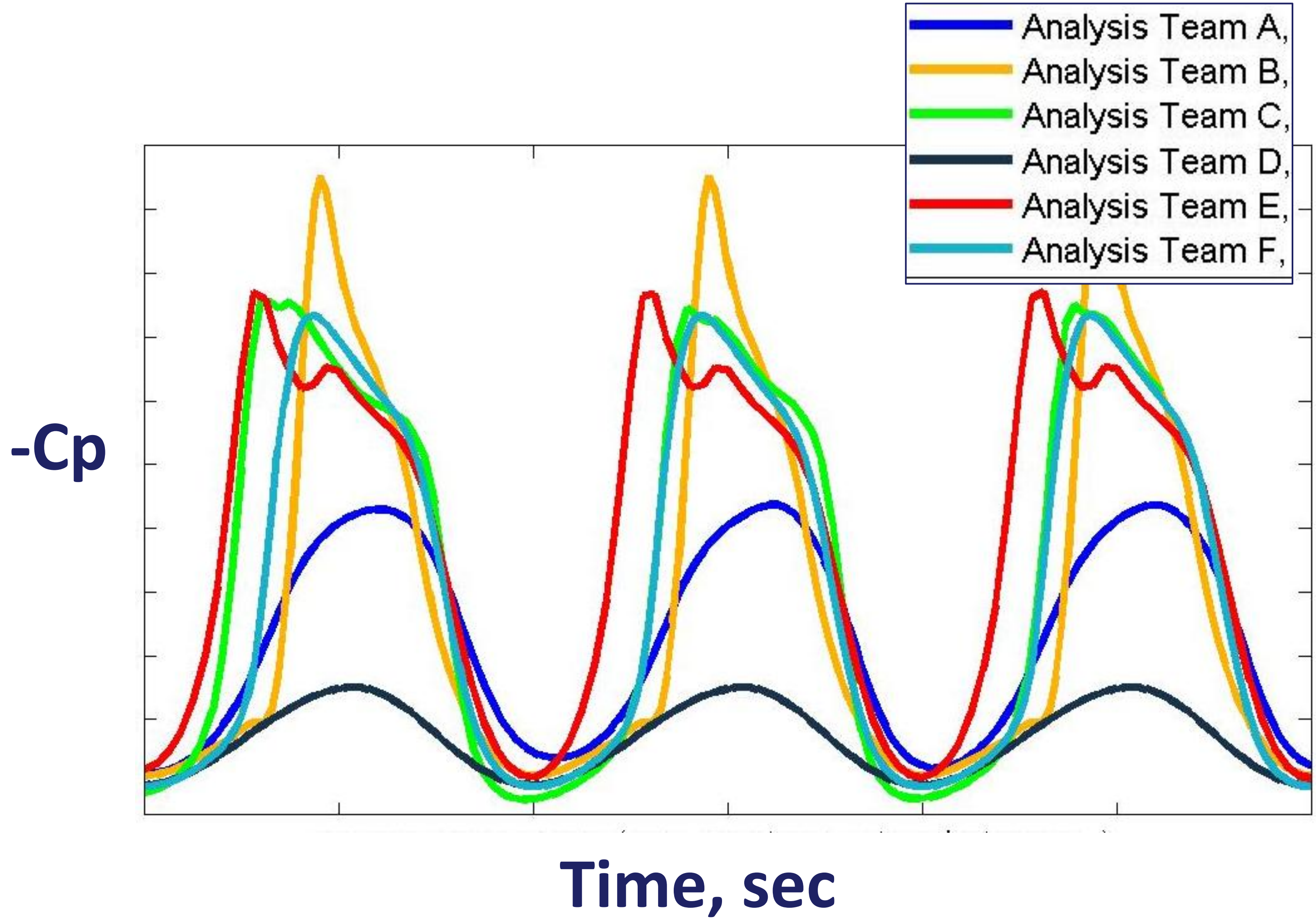
Comparison Data Matrix

CASE	REQUIRED CALCULATIONS		
	GRID CONVERGENCE STUDIES	TIME CONVERGENCE STUDIES	COMPARISON DATA
			• Mean C_p vs. x/c $_D$, C_M
			Phase of C_p n stations to transducer
Forced Oscillation	CD, CM at excitation frequency	C_D, C_M vs. dt at excitation frequency	Phase of C_L, C_D, C_M at excitation frequency • Time histories of C_p's at a selected span station for two upper- and two lower-surface transducer locations

<u>Characteristics:</u>

- Sinusoidal for locations completely ahead of the shock oscillation region
- Nonlinear character in oscillating shock region

Time history comparisons among analyses
Chord location near/at the shock, 10 Hz oscillation



What did we learn from RSW?

- Wall presence effects:
  - The RSW model was too close to the wall
  - The wall effects need to be accounted for
- FRF main contributor- Upper surface oscillatory shock
  - Largest variation among computational results
  - Largest disagreements with experimental data
  - Strength and range of motion change with span station and forcing frequency
- Relationships between steady-state and oscillatory solutions
  - Frequency response functions
  - Nonlinear time history in shock region
- Flow physics of the RSW supercritical airfoil
  - Shock-induced local separation
  - Attached trailing edge flow
  - Lower surface invariance

- CFD solutions vary widely, even for steady state solution; The integrated loads are not an accurate representation of the CFD state of the art

RSW Summary Points

- Assessment of the state of the art in computational tools?
  - Indicates which aspects of the results are most important and which are the most difficult to predict
  - Did not provide a data set for assessing significance of analysis factors (e.g. turbulence model, grid refinement)

Influences on the path forward

- Use this information and these analysis processes as we proceed forward
  - In analyzing the results for BSCW & HIRENASD
  - In our understanding of the aeroelastic behavior

Thank you

RSW Grids

Recommended Gridding

- No splitter plate
- Viscous tunnel wall, extending to 42 wing chords ahead of wing leading edge
- Wing span = 55 inches

Analysis Team	Grid Type*	Element Type†	Solver Type‡	Number of Nodes or Cells, (millions) *Coarse*	*Medium*	*Fine*	Wing Tip Model§	Wing Span, inches
A	Str	Hex	Cell	3.38	9.91	27.0	Revoln	55
B	Unstr	Mix	Node	2.88	7.07	18.23	Revoln	55
C	Str	Hex	Cell	0.18	1.42	11.18	Scarf	55
D	Str	Hex	Node	1.91	5.89	15.42	Revoln	48¶
E	Unstr	Mix	Node	2.87	7.07	18.28	Revoln	55
F	SMB	Hex	Cell	2.32	6.60	18.63	Revoln	55

* Structured (Str), Unstructured (Unstr), Structured MultiBlock (SMB)

† Hexagonal (Hex), Mixed Hexagonal & Tetrahedral (Mix)

‡ Cell-centered (Cell), Node-centered (Node)

§ Model geometry surface of revolution (Revoln), Scarfed tip (Scarf)

¶ Modeled only from splitter plate outboard to wing tip

Review of the RSW Grid Development and Analysis Research by the AePW OC members: Story line

- Wall and splitter plate modeling investigated using **steady** analysis
  - Splitter plate models
    - None
    - Symmetry boundary condition
    - Viscous
  - Wall models
    - Symmetry boundary condition
    - Viscous
  - Wing size
    - Geometric model size
    - Extended wing span to duplicate placement within the test section
- Experimental data utilized to assess computational results:
  - Boundary layer thickness at model location
  - Steady pressure distributions
- Resulting recommended model
  - Reduce computational domain from 100 chords ahead of wing to 42 chords ahead of wing
  - Viscous model of wall
  - No splitter plate
  - Extended wing span

Wind Tunnel Wall Boundary Layer Comparisons