AePW-2: FUN3D Results

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- Robert Biedron, Bil Kleb, Beth Lee-Rausch, and Eric Nielsen from the Aerosciences Branch at NASA Langley
- Steve Massey from Aeroelasticity Branch
- Dave Schuster from NESC
- NAS, NASA Advanced Supercomputing Center

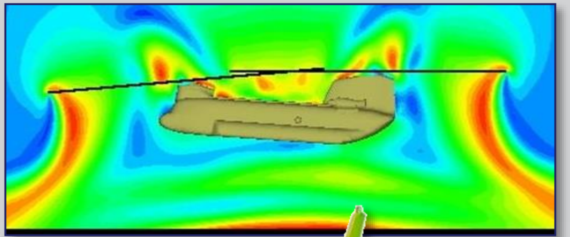
AePW-2 Cases

	Case 1	Case 2	Optional Case 3		
			A	B	C
Mach	0.7	0.74	0.85	0.85	0.85
Angle of attack	3	0	5	5	5
Dynamic Data Type	Forced Oscillation	Flutter	Unforced Unsteady	Forced Oscillation	Flutter
Notes:	• Attached flow solution • Oscillating Turn Table (OTT) exp. data	• Unknown flow state • Pitch and Plunge Apparatus (PAPA) exp. data	• Separated flow effects • Oscillating Turn Table (OTT) experimental data	• Separated flow effects • Oscillating Turn Table (OTT) experimental data	• Separated flow effects on aeroelastic solution • No experimental data for comparison

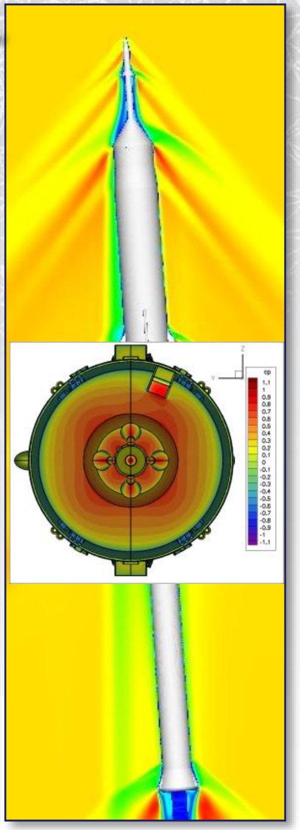
FUN3D Core Capabilities

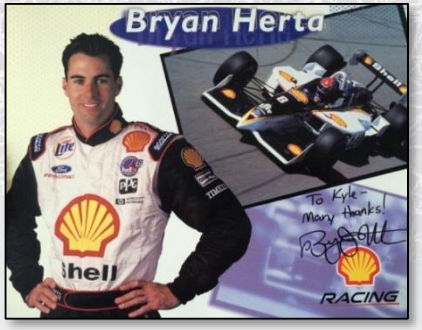
http://fun3d.larc.nasa.gov/

- Established as a research code in late 1980s; now supports numerous internal and external efforts across the speed range
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows
- General dynamic mesh capability: any combination of rigid / overset / morphing grids, including 6-DOF effects
- Aeroelastic modeling using mode shapes, full FEM, etc.
- Constrained / multipoint adjoint-based design and mesh adaptation
- Distributed development team using agile/extreme software practices including 24/7 regression, performance testing
- Capabilities fully integrated, online documentation, training videos, tutorials

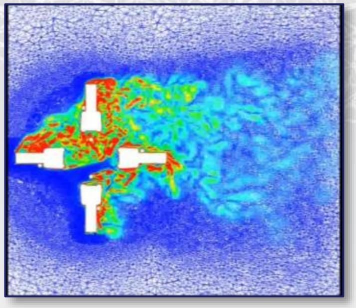


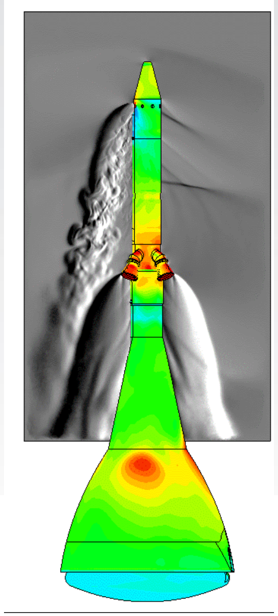
US Army

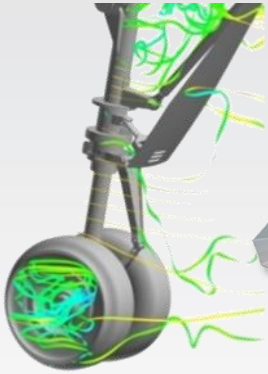


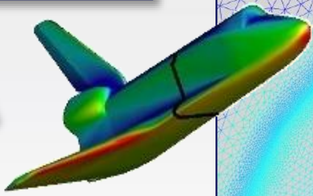


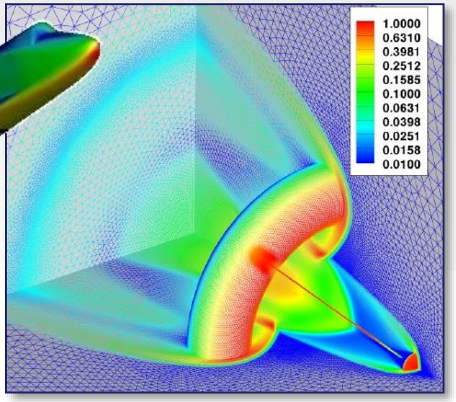
Georgia Tech





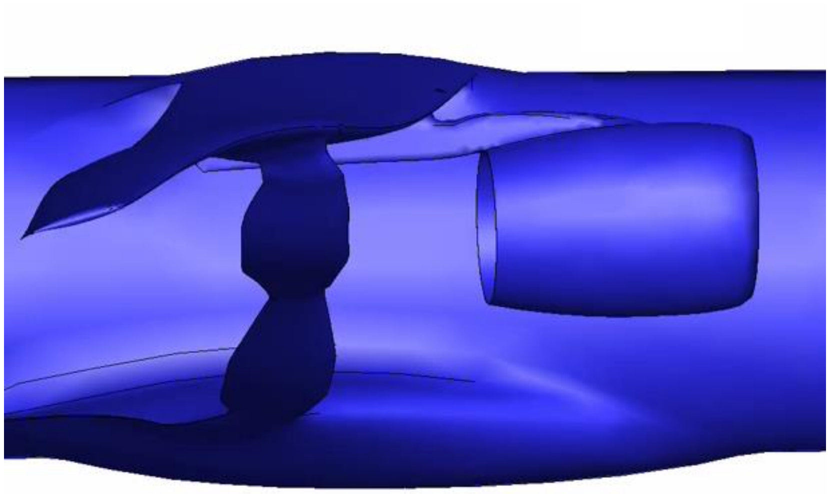






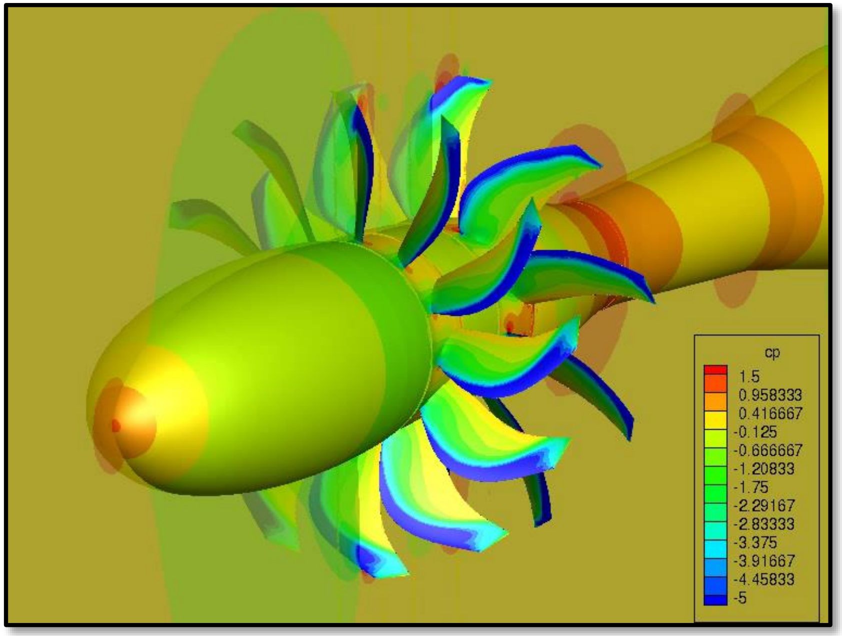
Some Recent NASA Applications

Courtesy Bob Bartels



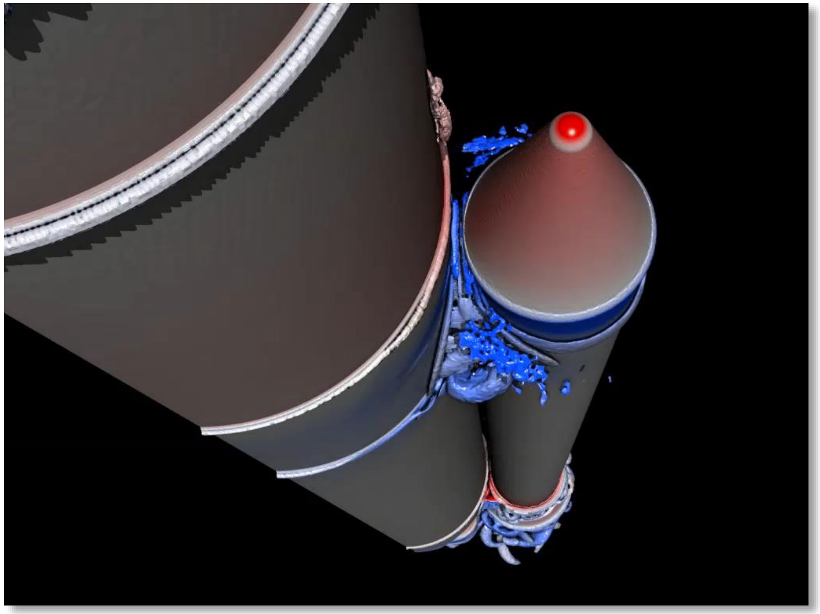
Aeroelastic Analysis of the Boeing SUGAR Truss-Braced Wing Concept

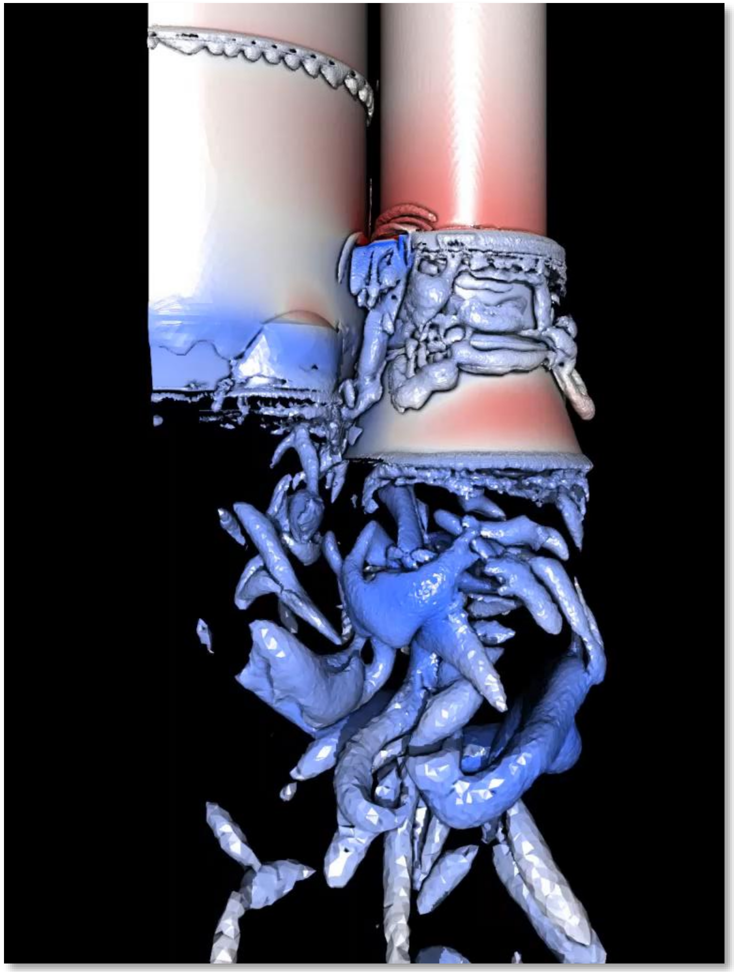
Open-Rotor Concepts



Courtesy Bill Jones

Some Recent NASA Applications

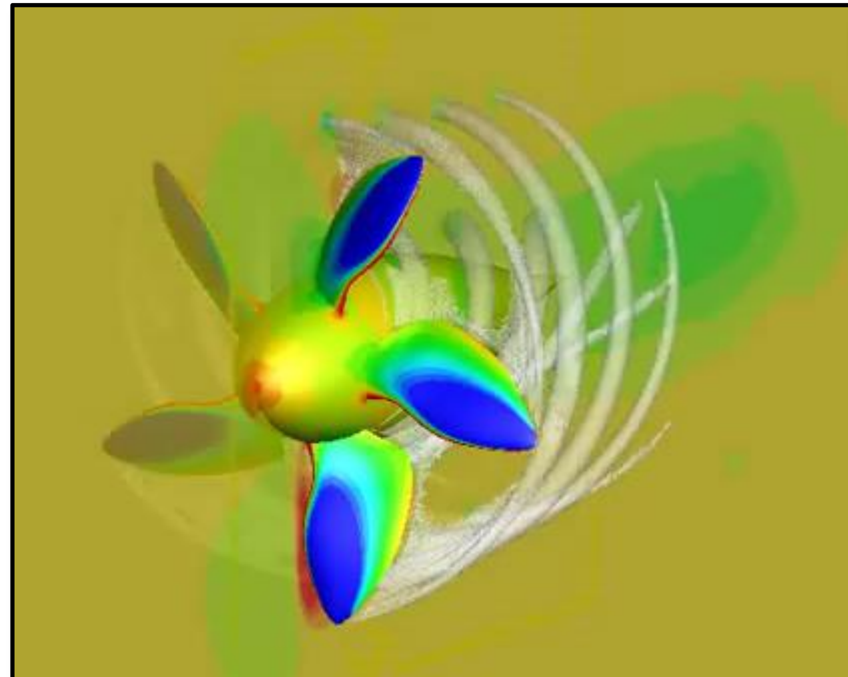




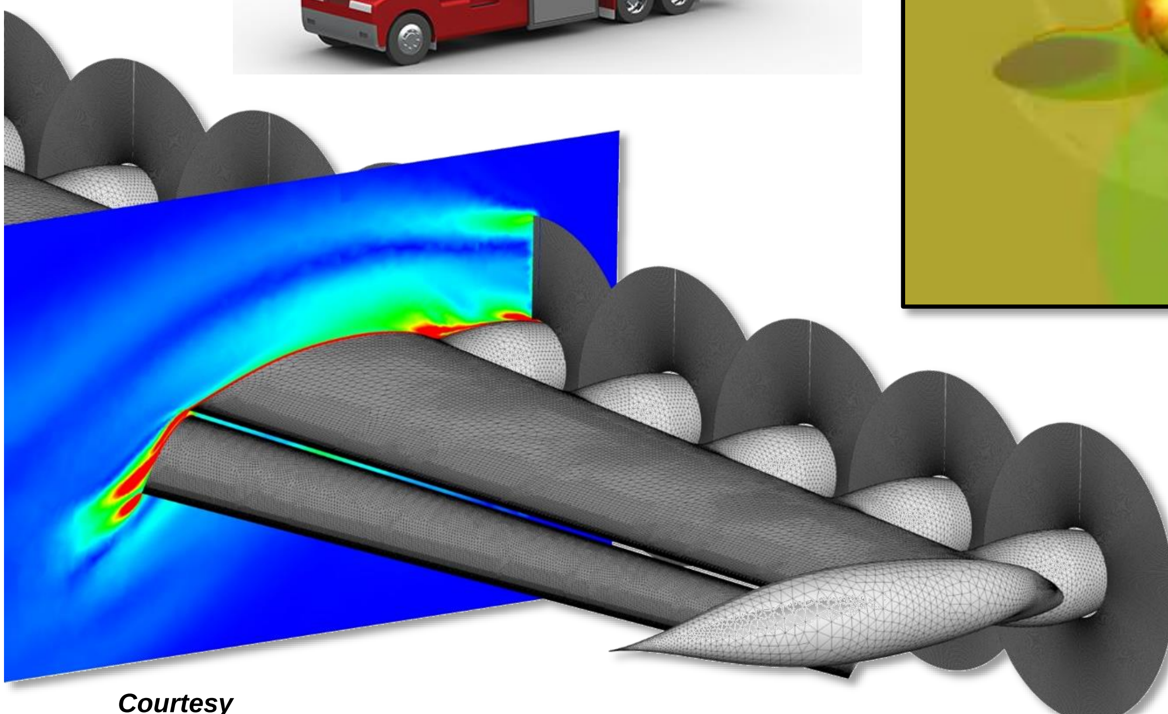
Transonic Buffet Characterization for Space Launch System

Courtesy
Greg Brauckmann,
Steve Alter, Bil Kleb

Some Recent NASA Applications



Courtesy Bill Jones



Distributed Electric Propulsion

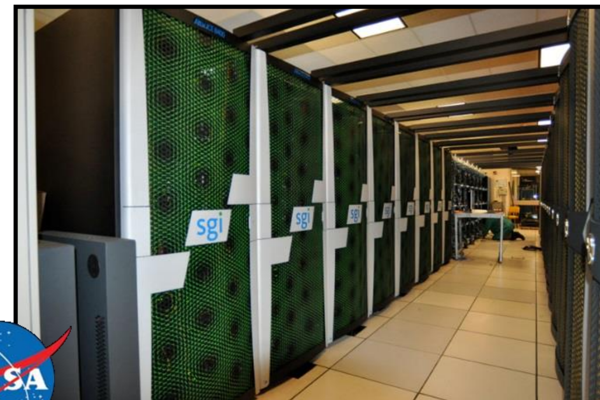
Courtesy
Mike Park, Sally Viken,
Karen Deere, Mark Moore

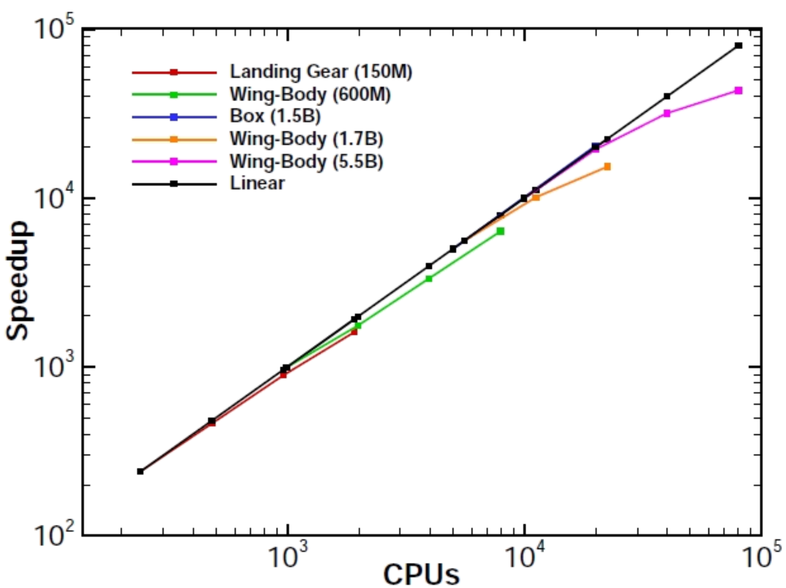
FUN3D and High-Performance Computing

FUN3D is used on a broad range of HPC installations around the country

DOD HPC

OLCF
Oak Ridge Leadership Computing Facility





Scaled to 80,000 cores

FUN3D Aeroelastic Capabilities

- Built upon elasticity PDE-based mesh deformation
- Built in modal structural solver, same as in CAP-TSD, CFL3D, Overflow
  - Typically uses mode shapes from NASTRAN normal modes analysis
- Coupling to external FEM/CSD codes
  - Read surface displacements obtained from FEM
  - Write aerodynamic loads (C_p, C_{fx}, C_{fy}, C_{fz}) for FEM
  - Requires CFD/CSD transfer middleware
  - Special case: rotorcraft comprehensive CSD codes, CAMRAD, DYMORE

FUN3D Mesh Deformation

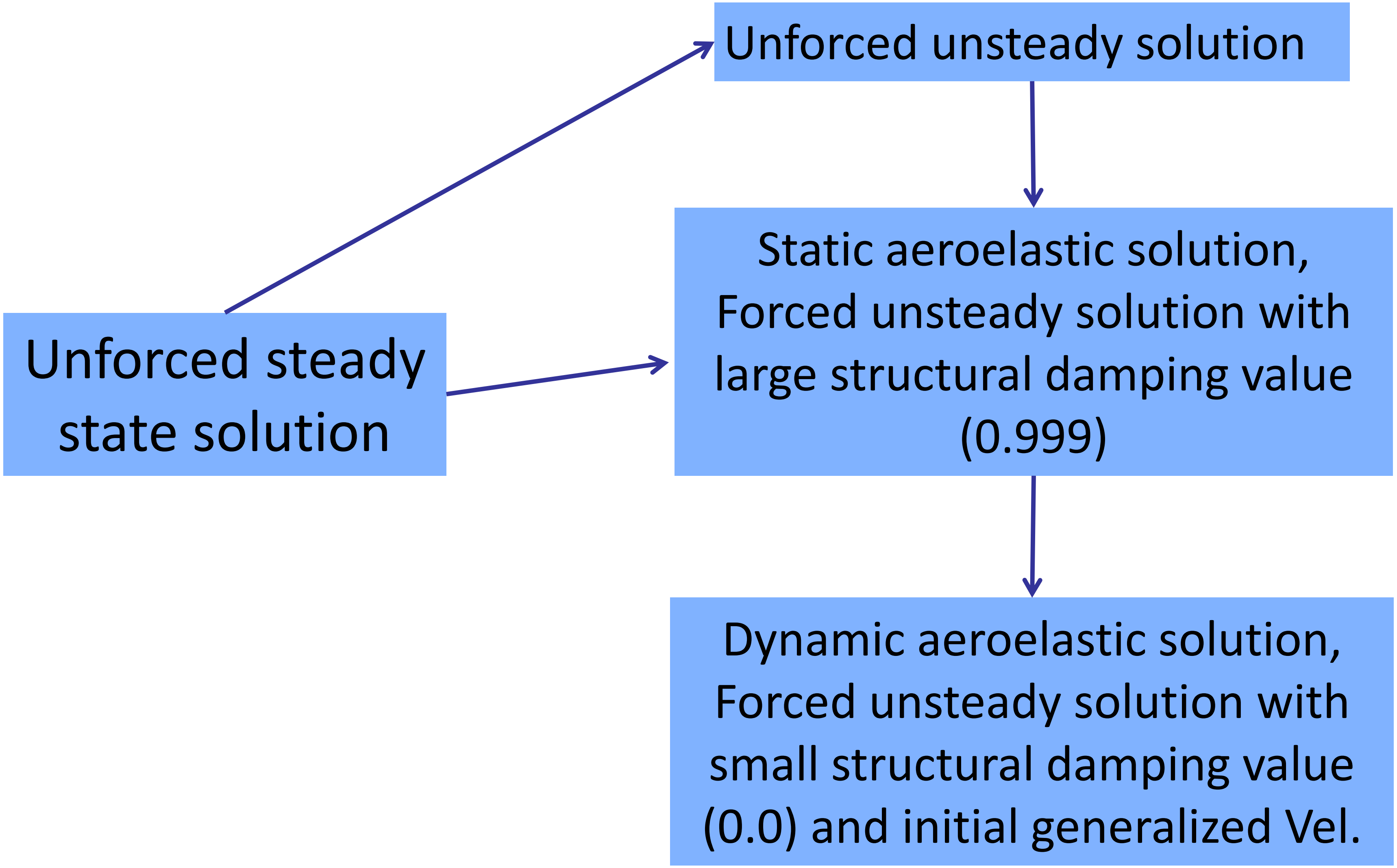
- Model the mesh as a linear elastic solid governed by

$$\nabla \cdot [\mu(\nabla u + \nabla u^T) + \lambda(\nabla \cdot u)I] = f = 0$$

$$/ = \frac{Eu}{(1+u)(1-2u)} \qquad m = \frac{E}{2(1+u)}$$

- Choose Poisson's ratio and Young's modulus to close system
  - $u = const, E = E(1/V) \; or \; E(1/d)$
  - Smaller cells or cells closer to surface are stiffer
- Solve linear PDE
  - Large fraction (typ. 30% or more) of cost of flow-solver step
  - Eventually will employ multigrid to speed up solution
- Geometric Conservation Law (ALE formulation) accounted for
  - Essential for free stream preservation on deforming meshes
  - Appears as a source term in flow equation residuals

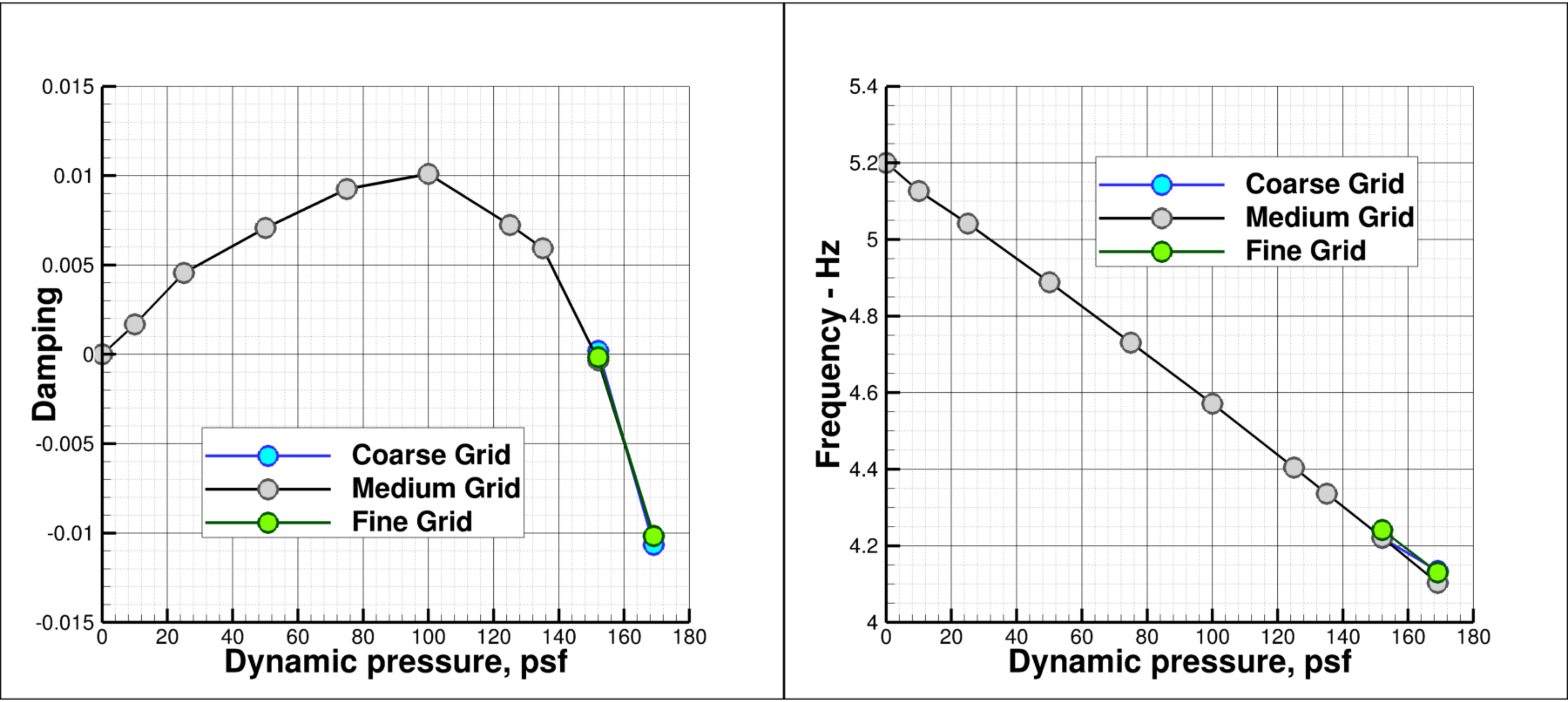
FUN3D Analysis Process



AePW-2 Case 2, Mach 0.74, AoA = 0°

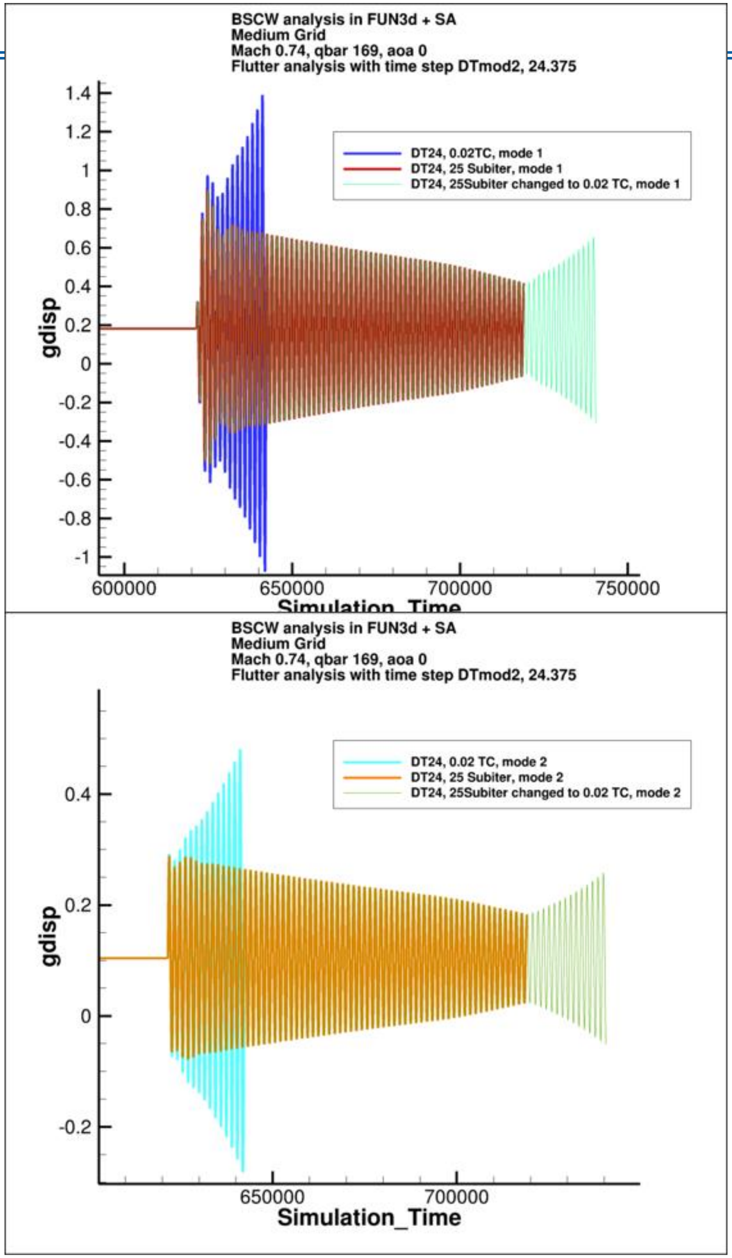
	Case 1	Case 2	Optional Case 3		
			A	B	C
Mach	0.7	0.74	0.85	0.85	0.85
Angle of attack	3	0	5	5	5
Dynamic Data Type	Forced Oscillation	Flutter	Unforced Unsteady	Forced Oscillation	Flutter
Notes:	• Attached flow solution • Oscillating Turn Table (OTT) exp. data	• Unknown flow state • Pitch and Plunge Apparatus (PAPA) exp. data	• Separated flow effects • Oscillating Turn Table (OTT) experimental data	• Separated flow effects • Oscillating Turn Table (OTT) experimental data	• Separated flow effects on aeroelastic solution • No experimental data for comparison

AePW-2 Case 2, Mach 0.74, AoA = 0°

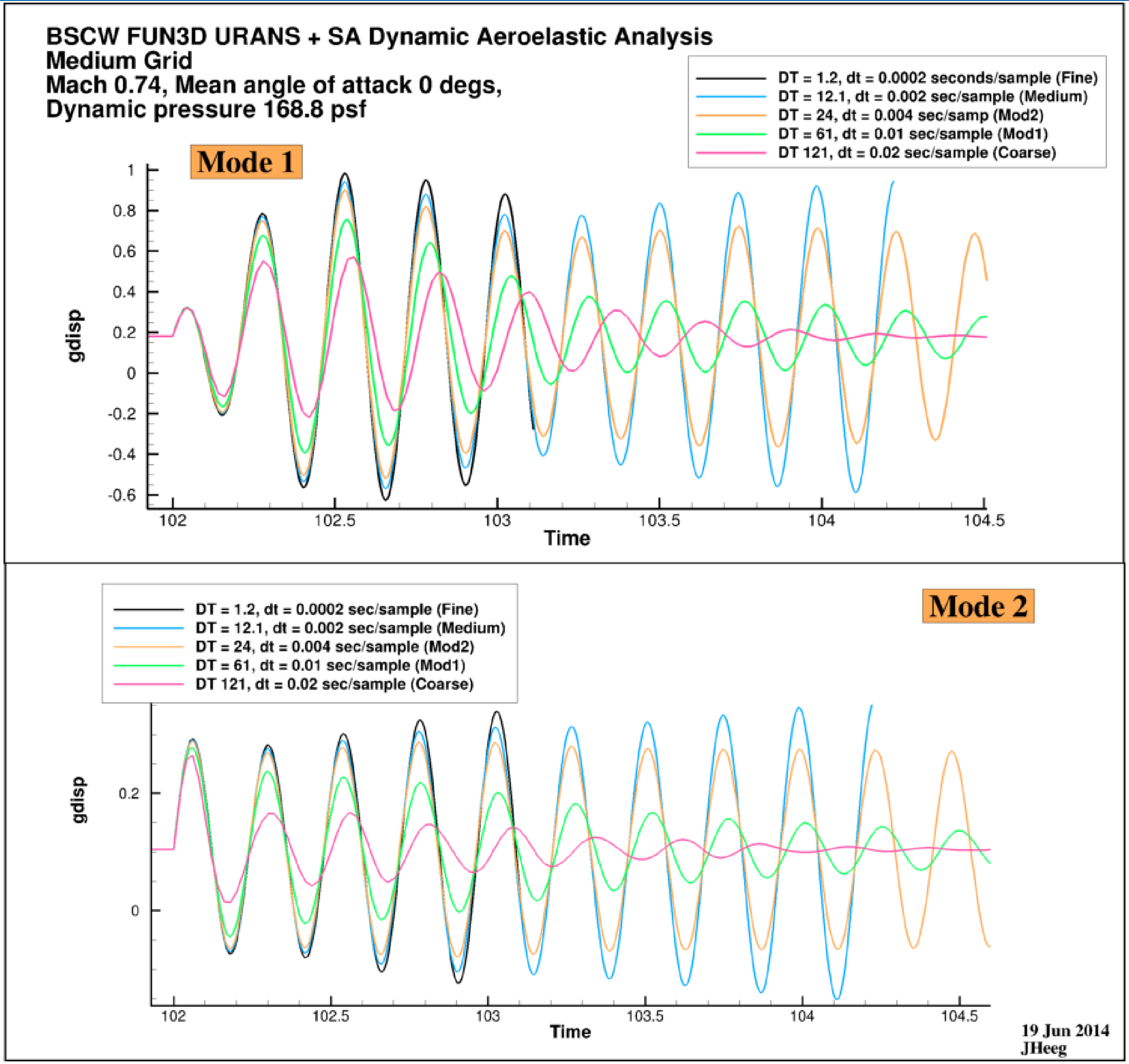


Predicted flutter onset: q = 152 psf and f = 4.23 Hz

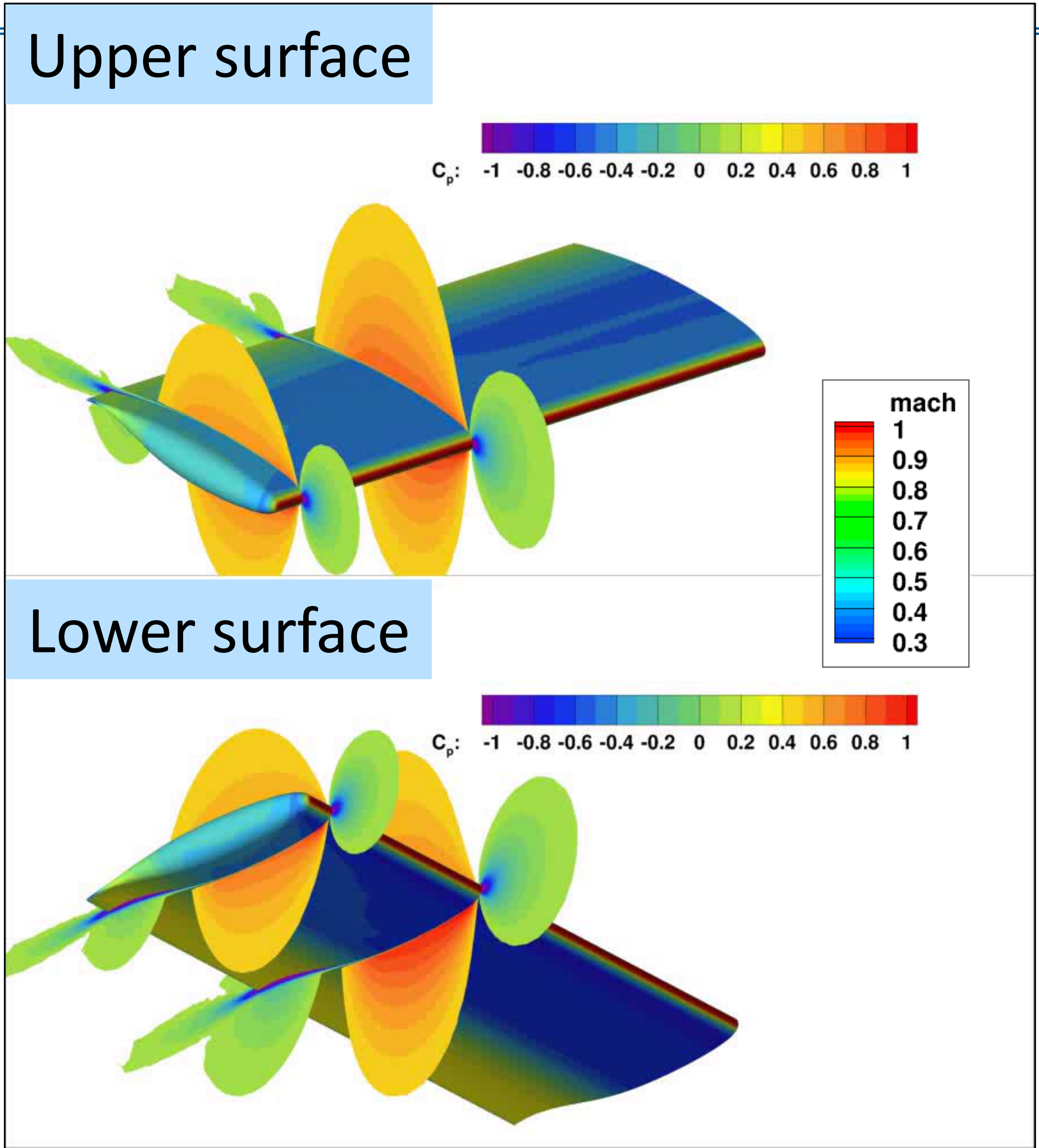
AePW-2 Case 2, Mach 0.74, AoA = 0°



AePW-2 Case 2, Mach 0.74, AoA = 0°



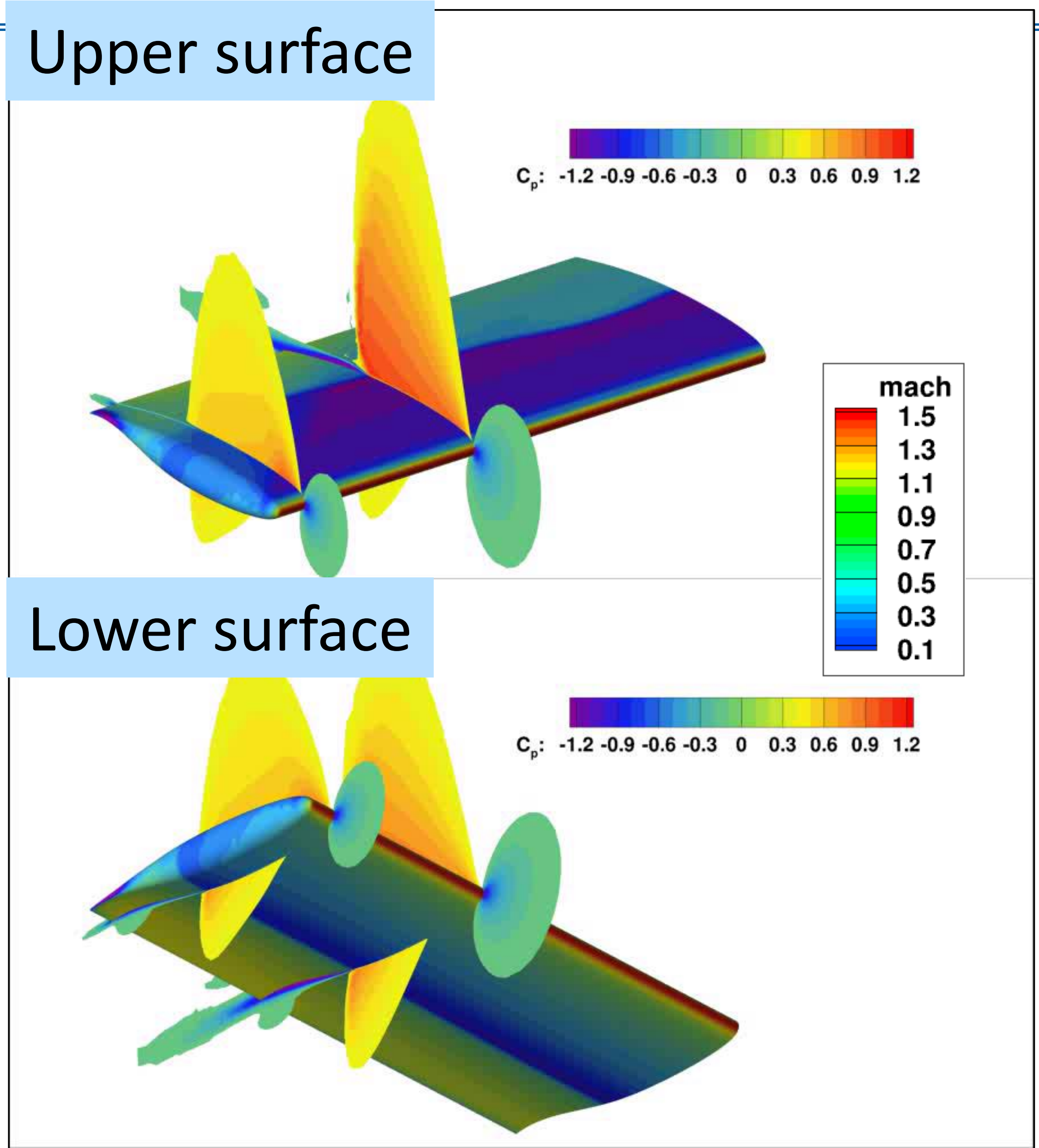
AePW-2 Case 2, Mach 0.74, AoA = 0°, q=169 psf



AePW-2 Case 3B, Mach 0.85, AoA = 5°

	Case 1	Case 2		Optional Case 3	
			A	B	C
Mach	0.7	0.74	0.85	0.85	0.85
Angle of attack	3	0	5	5	5
Dynamic Data Type	Forced Oscillation	Flutter	Unforced Unsteady	Forced Oscillation	Flutter
Notes:	• Attached flow solution • Oscillating Turn Table (OTT) exp. data	• Unknown flow state • Pitch and Plunge Apparatus (PAPA) exp. data	• Separated flow effects • Oscillating Turn Table (OTT) experimental data	• Separated flow effects • Oscillating Turn Table (OTT) experimental data	• Separated flow effects on aeroelastic solution • No experimental data for comparison

AePW-2 Case 3B, Mach 0.85, AoA = 5°



AePW-2 Case 3C, Mach 0.85, AoA = 5°

	Case 1	Case 2		Optional Case 3	
			A	B	C
Mach	0.7	0.74	0.85	0.85	0.85
Angle of attack	3	0	5	5	5
Dynamic Data Type	Forced Oscillation	Flutter	Unforced Unsteady	Forced Oscillation	Flutter
Notes:	• Attached flow solution • Oscillating Turn Table (OTT) exp. data	• Unknown flow state • Pitch and Plunge Apparatus (PAPA) exp. data	• Separated flow effects • Oscillating Turn Table (OTT) experimental data	• Separated flow effects • Oscillating Turn Table (OTT) experimental data	• Separated flow effects on aeroelastic solution • No experimental data for comparison

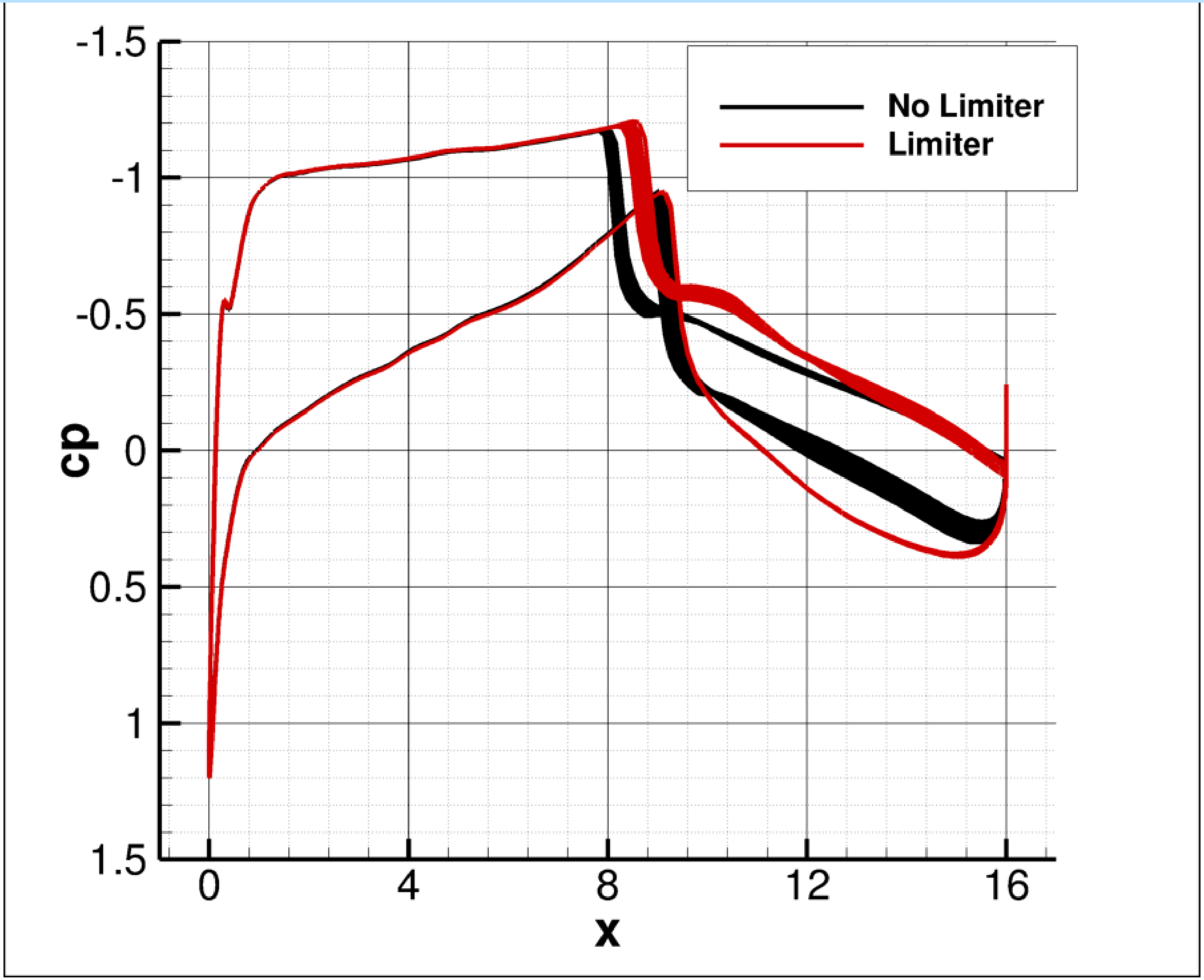
AePW-2 Case 3C, Mach 0.85, AoA = 5°

	Flutter dynamic pressure, psf		Flutter frequency, Hz	
Mesh / Turb. Model	No Limiter	Limiter	No Limiter	Limiter
Coarse / SA	455	665	4.85	4.65
Medium / SA	477	503	5.2	5.1
Fine / SA	390	482	5.0	4.8
Fine / DDES	565	x	5.1	x

Note: Venkatakrishnan Limiter

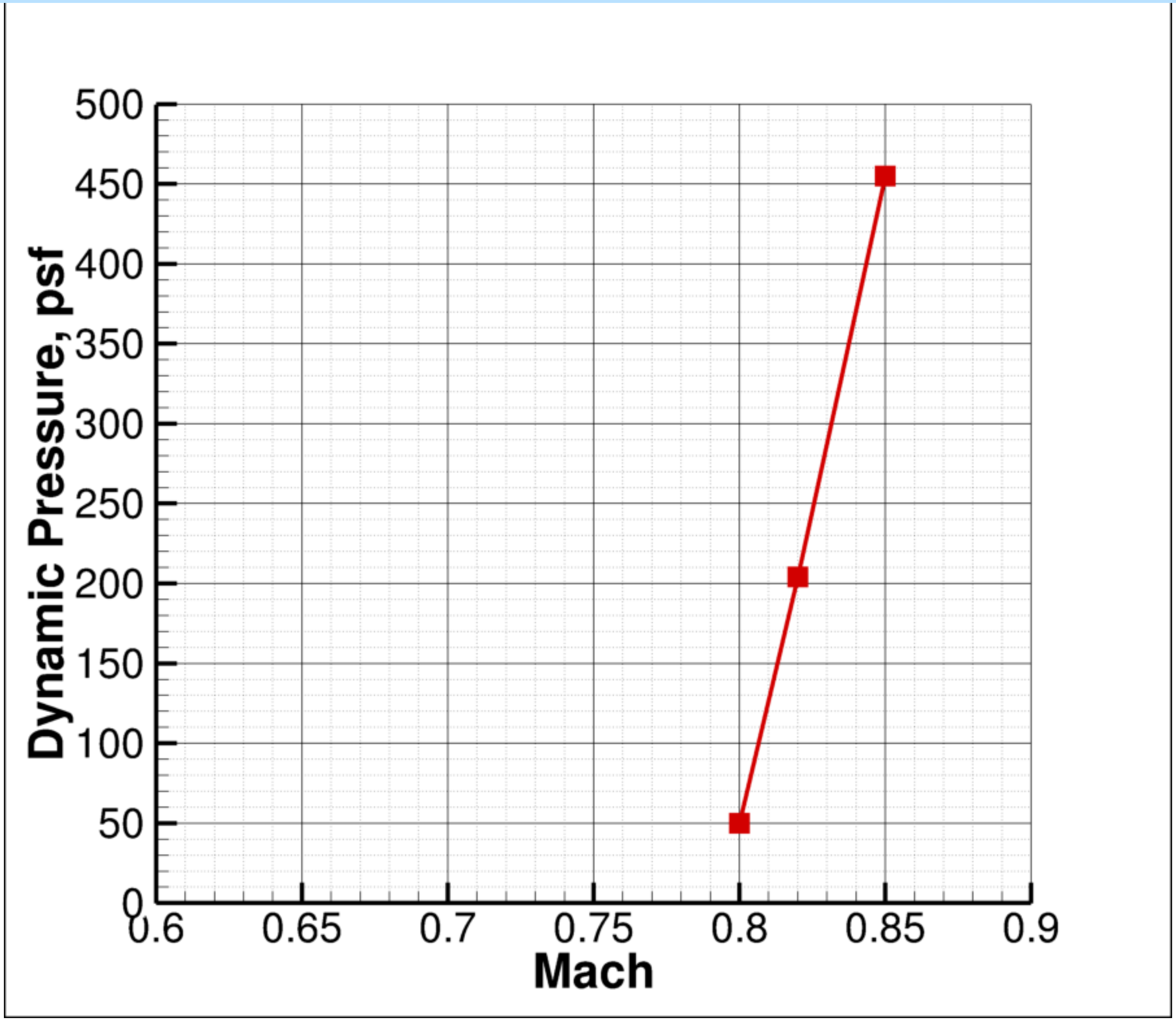
AePW-2 Case 3C, Mach 0.85, AoA = 5°

Static aeroelastic solution at q's near flutter onset: fine grids



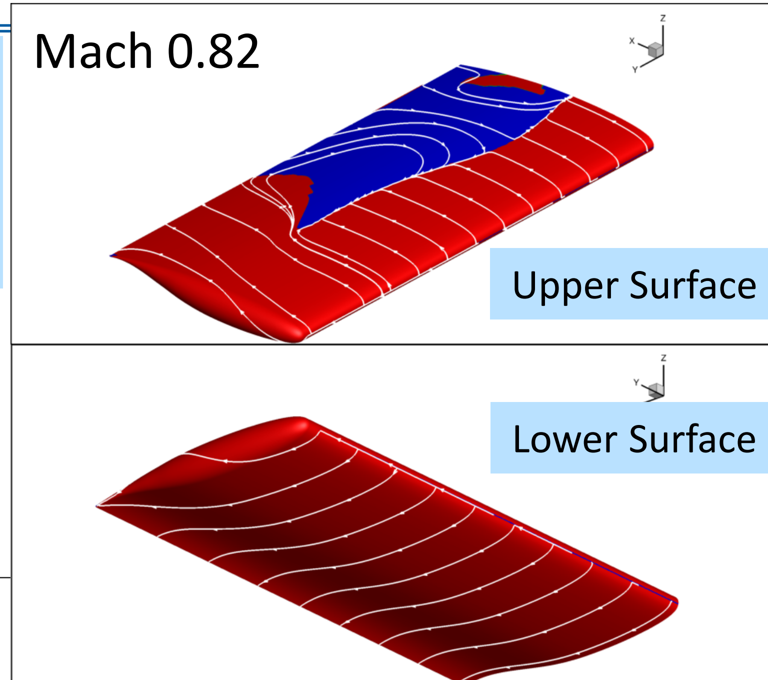
AePW-2 Case 3C, Mach 0.85, AoA = 5°

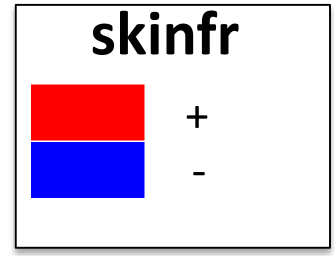
Flutter Onset at AoA = 5°, Coarse Grid, No Limiter

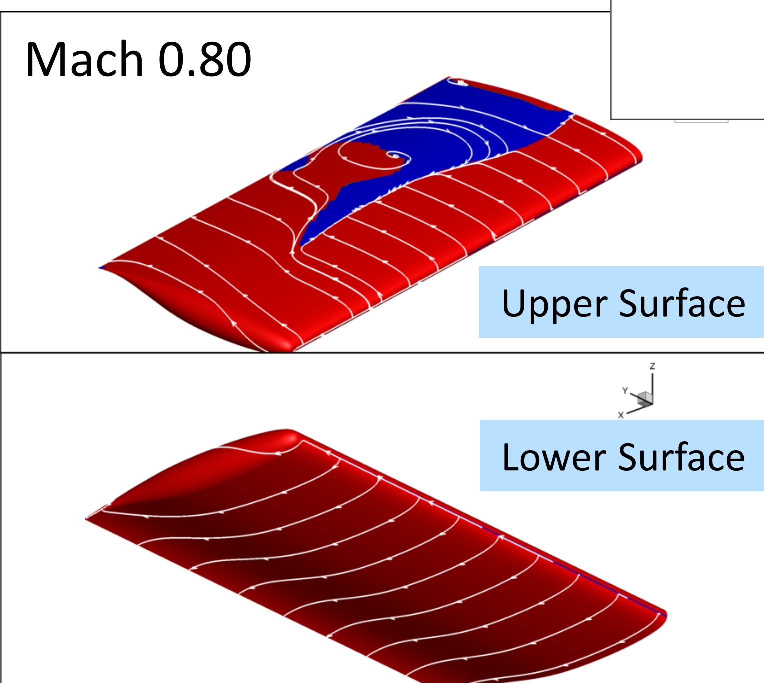


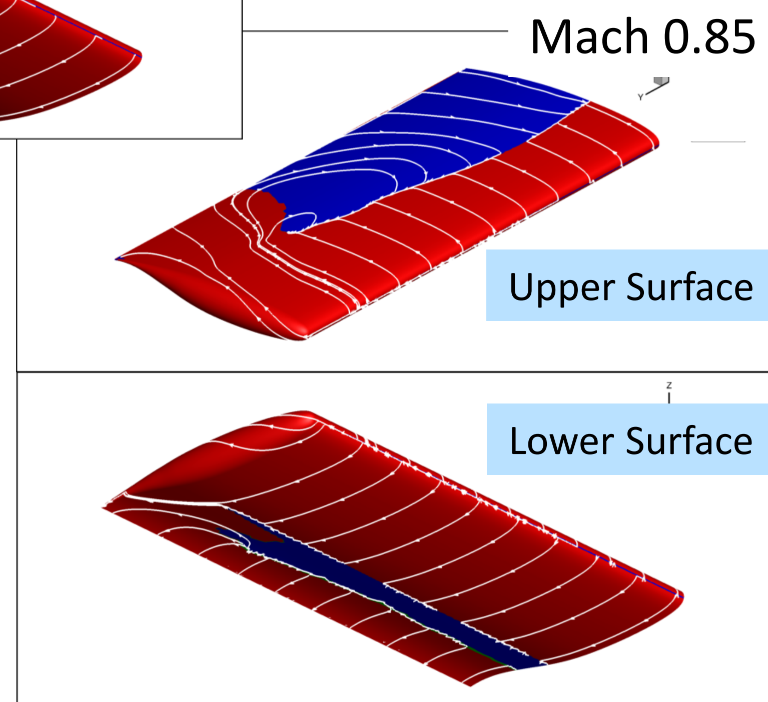
AePW-2 Case 3C, Mach 0.85, AoA = 5°

Static aeroelastic solutions: Skin friction and streamlines at dynamic pressure near flutter onset









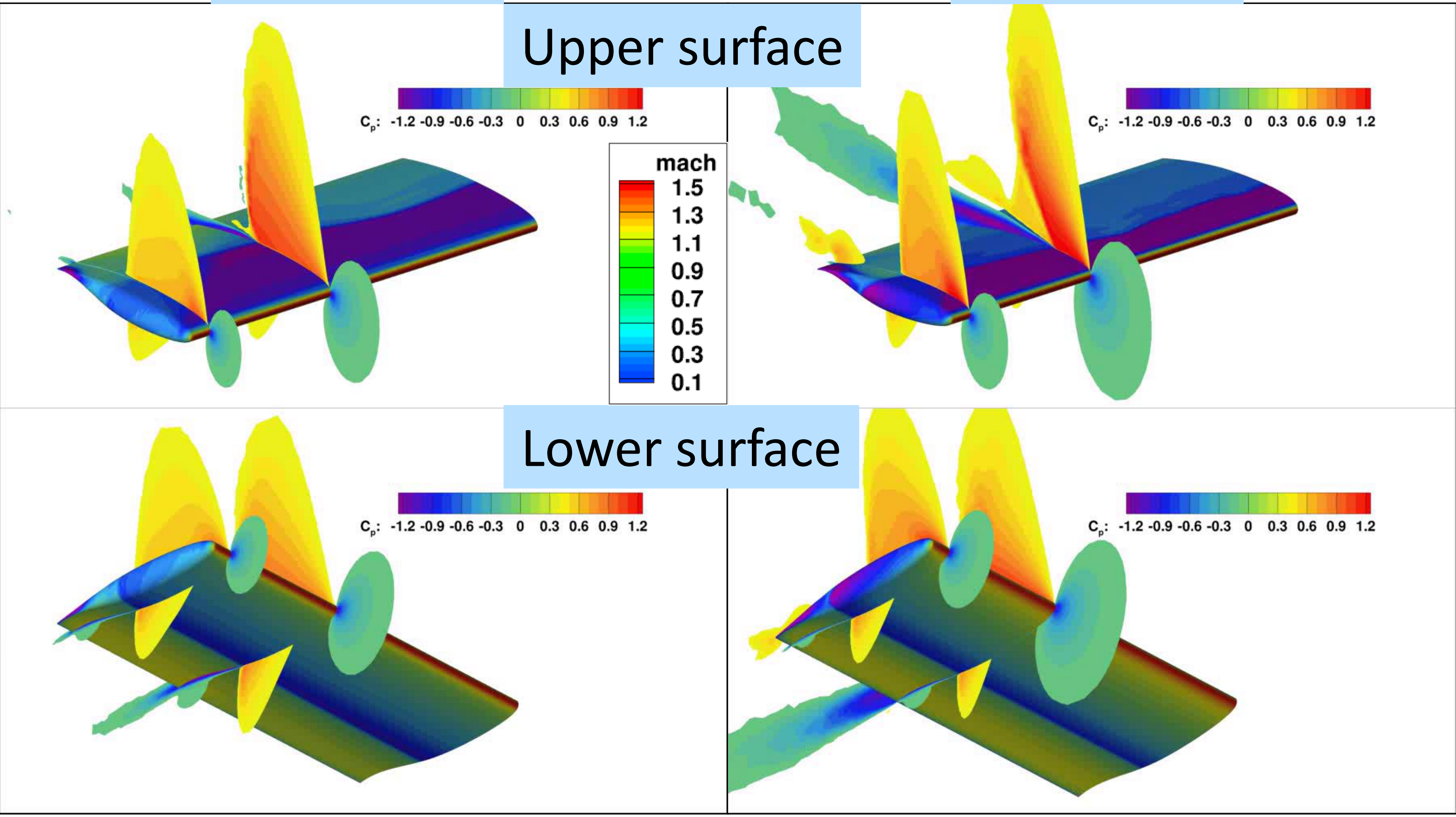
AePW-2 Case 3C, Mach 0.85, AoA = 5°

Q = 204 psf

Q = 816 psf

Upper surface

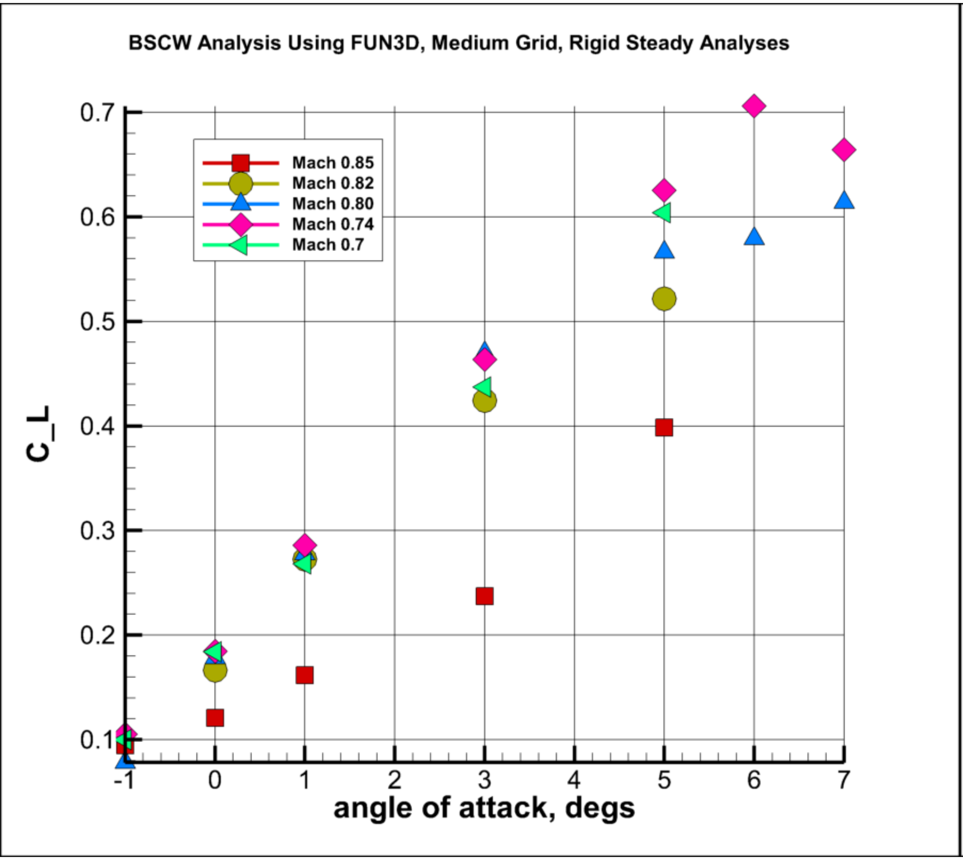
Lower surface



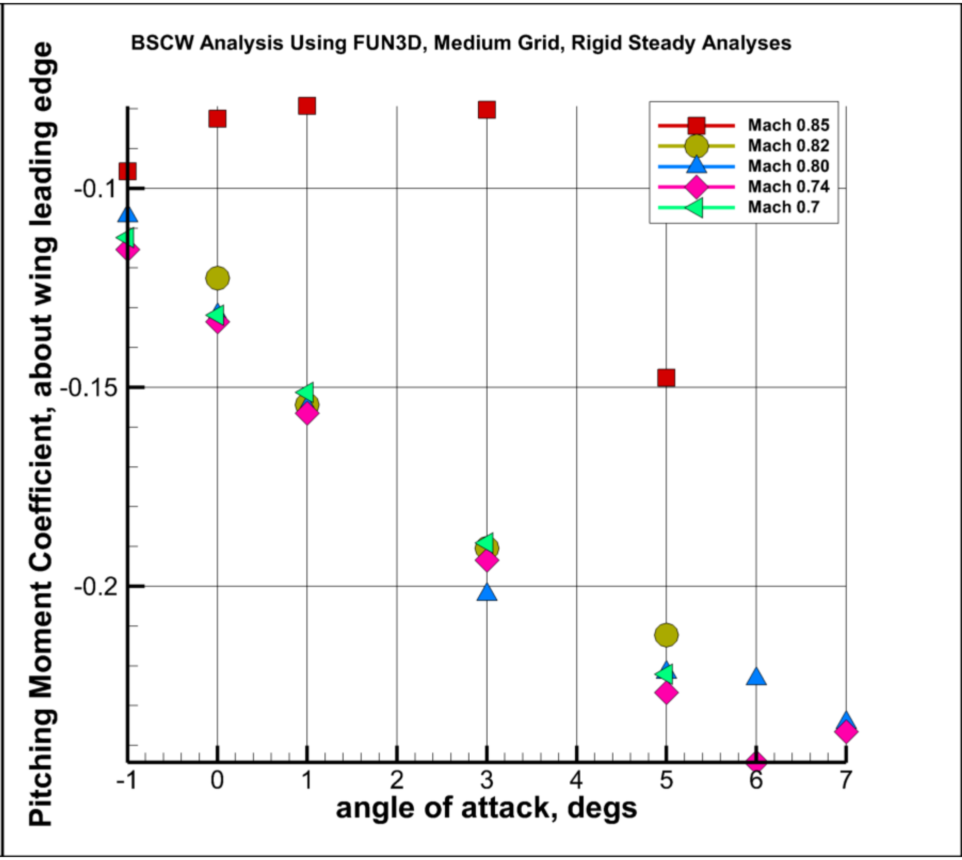
Conclusions

- It takes too long and significant computational resources are required to obtain flutter boundary prediction on a simple configuration like BSCW.
- There is need for tools like Reduced Order Methods to obtain flutter boundary prediction quickly.
- Spatial and temporal convergence analysis are necessary.
- 2D airfoil section analysis vs. 3D analysis.

Backup

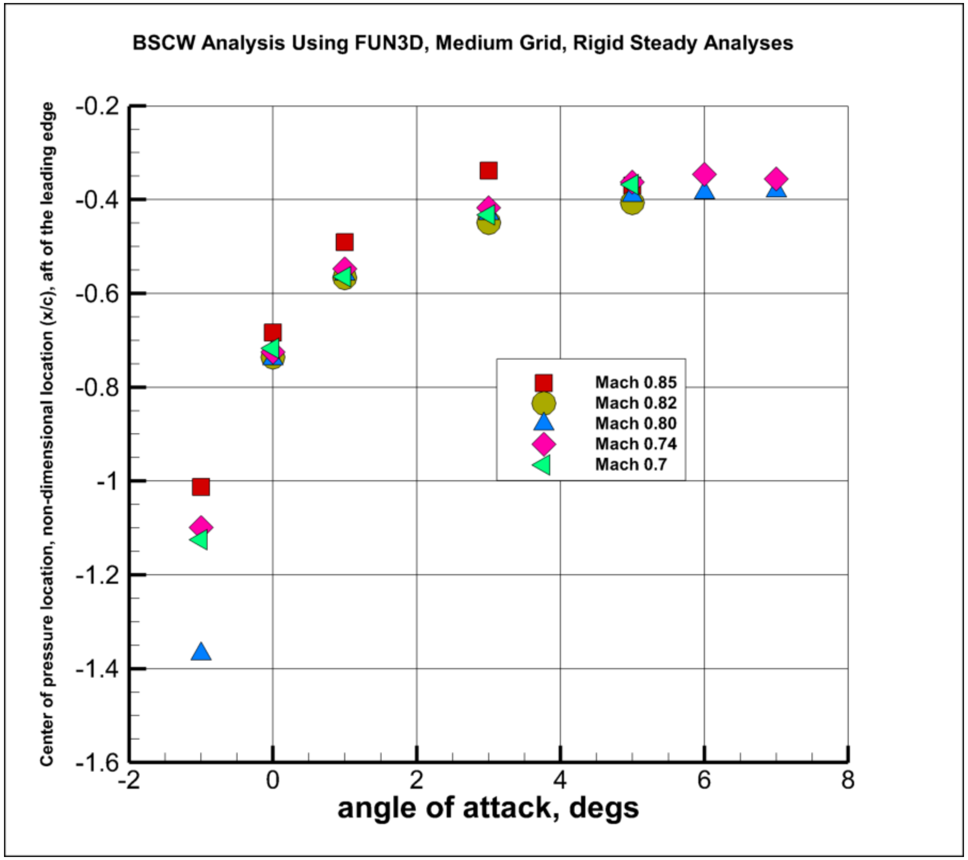


BSCW Analysis Using FUN3D, Medium Grid, Rigid Steady Analyses
C_L
angle of attack, degs
Mach 0.85
Mach 0.82
Mach 0.80
Mach 0.74
Mach 0.7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
-1
0
1
2
3
4
5
6
7



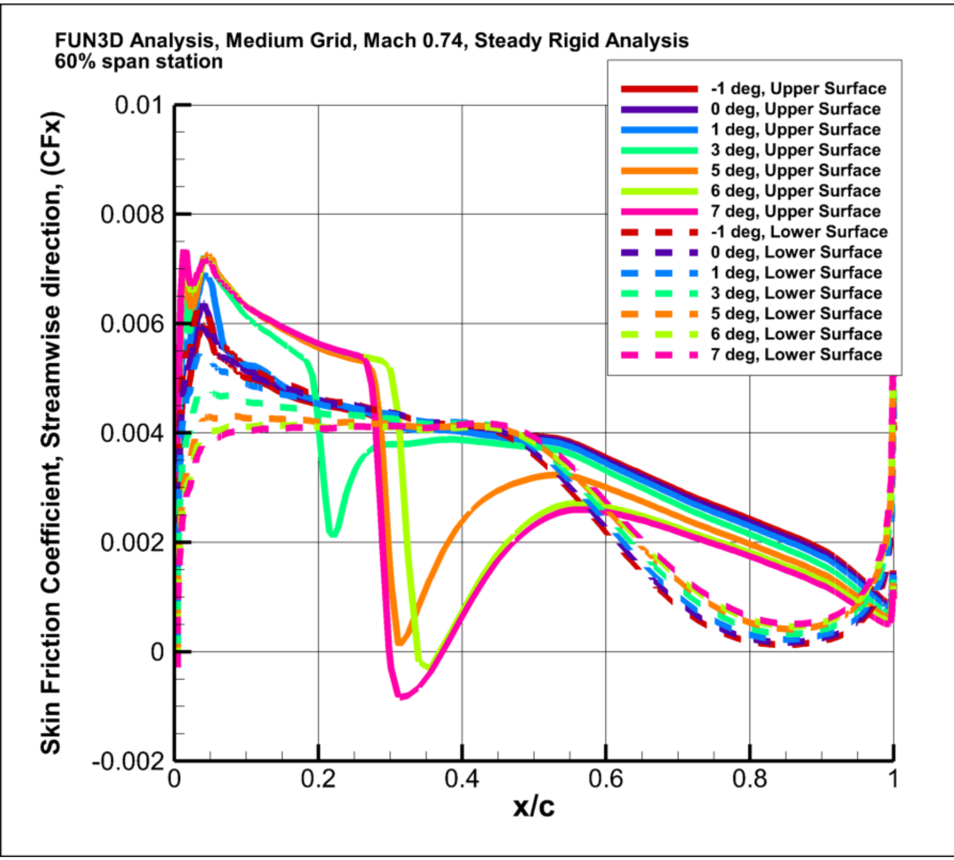
BSCW Analysis Using FUN3D, Medium Grid, Rigid Steady Analyses
Pitching Moment Coefficient, about wing leading edge
angle of attack, degs
Mach 0.85
Mach 0.82
Mach 0.80
Mach 0.74
Mach 0.7
-0.1
-0.15
-0.2
-1
0
1
2
3
4
5
6
7

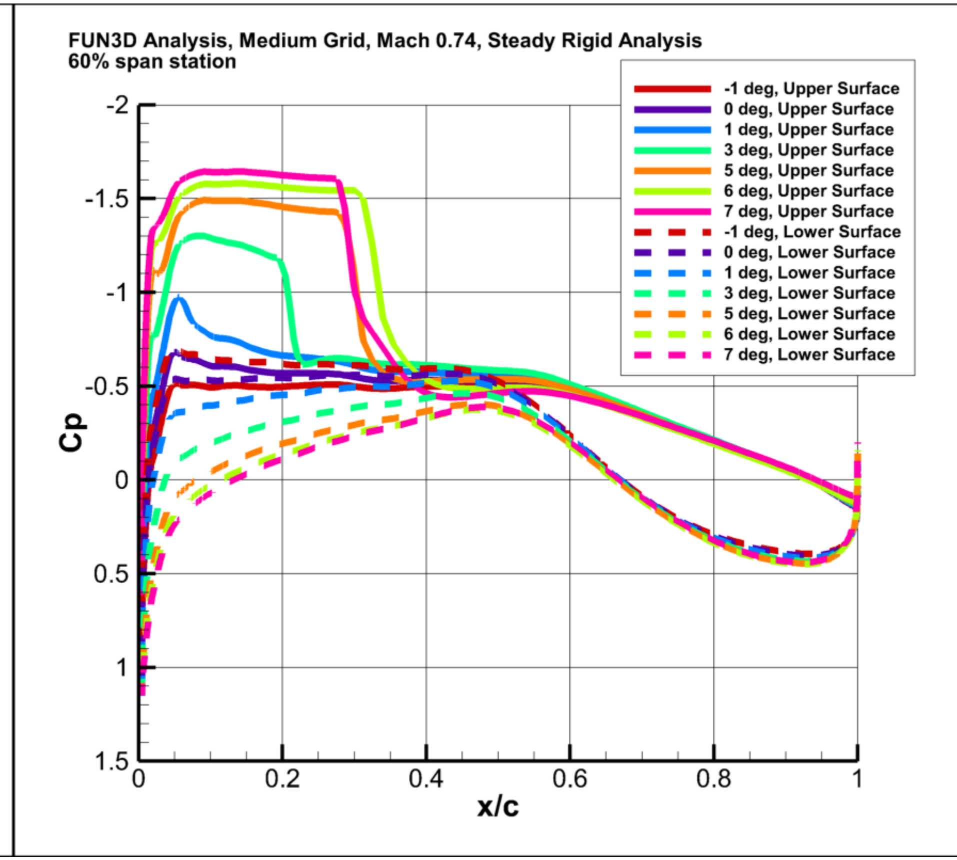
Backup



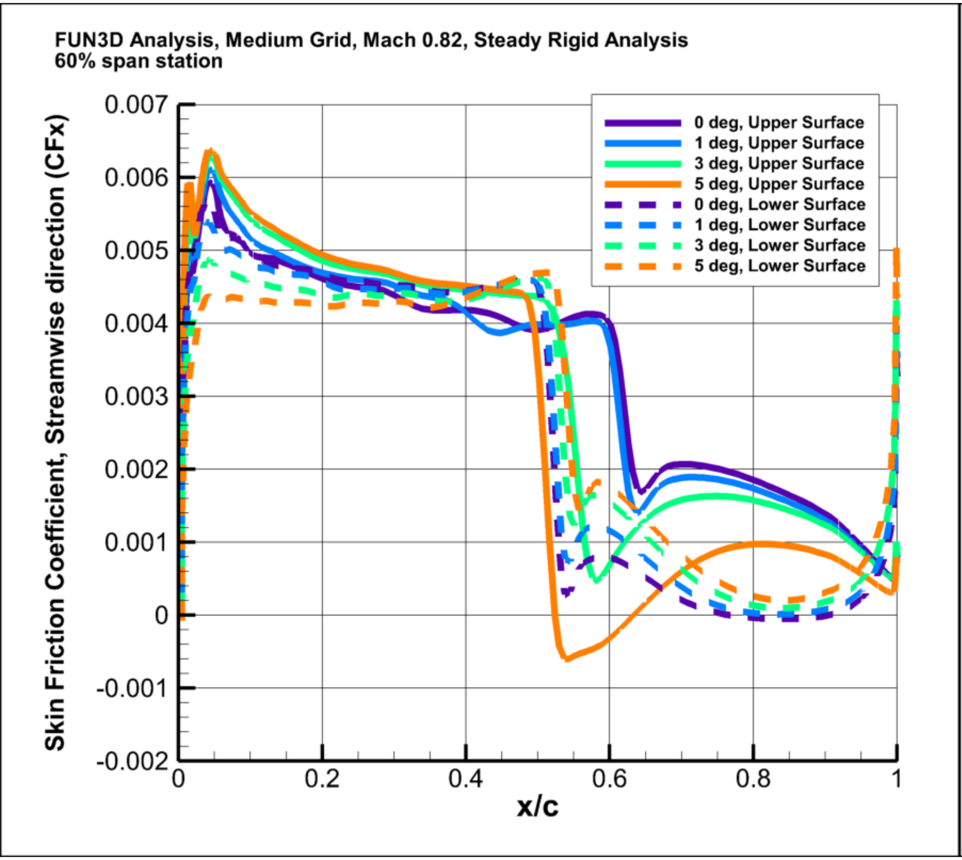
BSCW Analysis Using FUN3D, Medium Grid, Rigid Steady Analyses
Center of pressure location, non-dimensional location (x/c), aft of the leading edge
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-2
0
2
4
6
8
angle of attack, degs
Mach 0.85
Mach 0.82
Mach 0.80
Mach 0.74
Mach 0.7

Backup

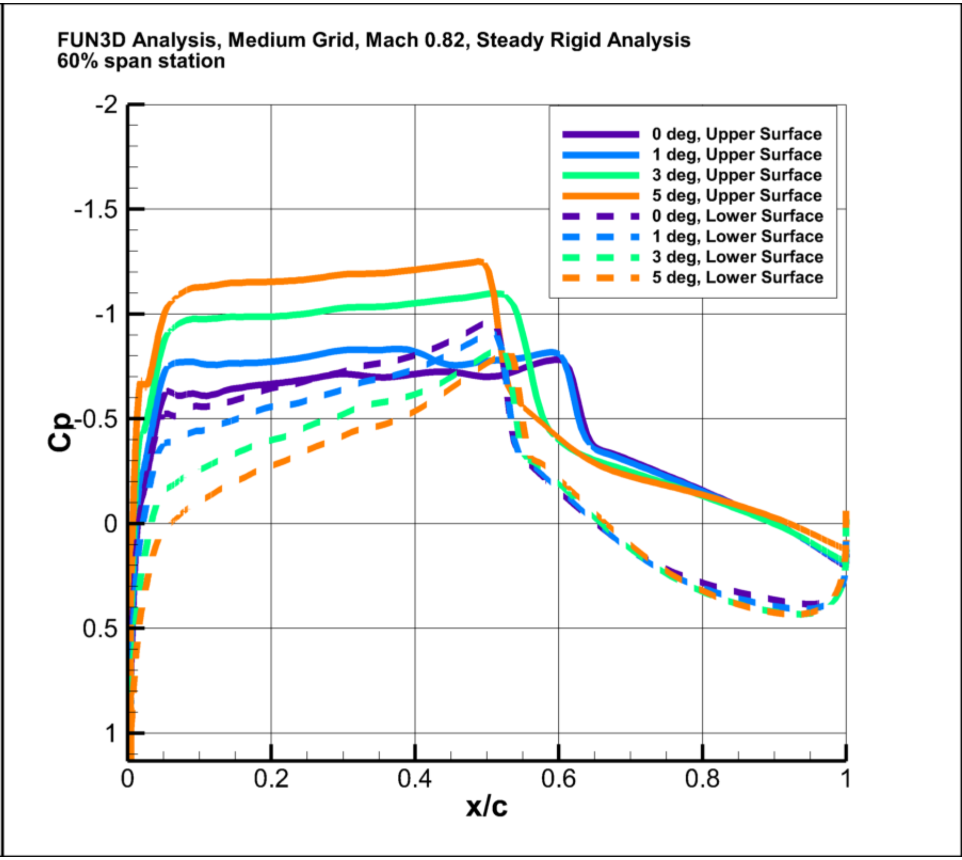

FUN3D Analysis, Medium Grid, Mach 0.74, Steady Rigid Analysis
60% span station
-1 deg, Upper Surface
0 deg, Upper Surface
1 deg, Upper Surface
3 deg, Upper Surface
5 deg, Upper Surface
6 deg, Upper Surface
7 deg, Upper Surface
-1 deg, Lower Surface
0 deg, Lower Surface
1 deg, Lower Surface
3 deg, Lower Surface
5 deg, Lower Surface
6 deg, Lower Surface
7 deg, Lower Surface
Skin Friction Coefficient, Streamwise direction, (CFx)
0.01
0.008
0.006
0.004
0.002
0
-0.002
0
0.2
0.4
0.6
0.8
1
x/c


FUN3D Analysis, Medium Grid, Mach 0.74, Steady Rigid Analysis
60% span station
-1 deg, Upper Surface
0 deg, Upper Surface
1 deg, Upper Surface
3 deg, Upper Surface
5 deg, Upper Surface
6 deg, Upper Surface
7 deg, Upper Surface
-1 deg, Lower Surface
0 deg, Lower Surface
1 deg, Lower Surface
3 deg, Lower Surface
5 deg, Lower Surface
6 deg, Lower Surface
7 deg, Lower Surface
Cp
-2
-1.5
-1
-0.5
0
0.5
1
1.5
0
0.2
0.4
0.6
0.8
1
x/c

Backup

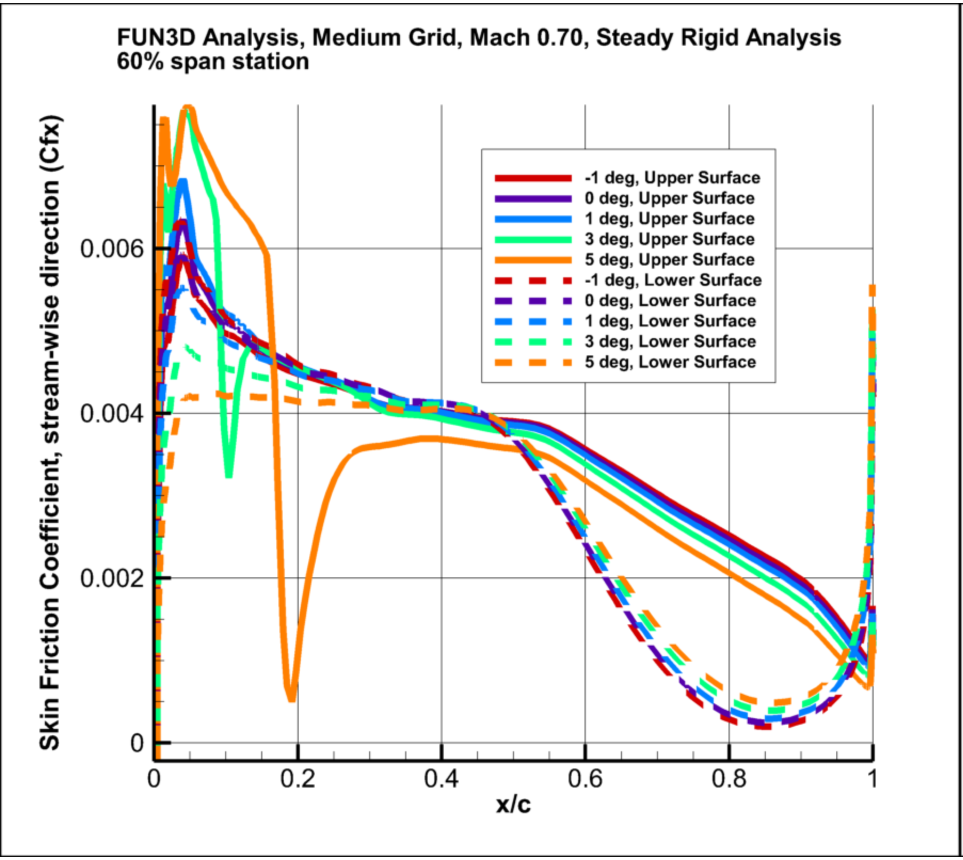


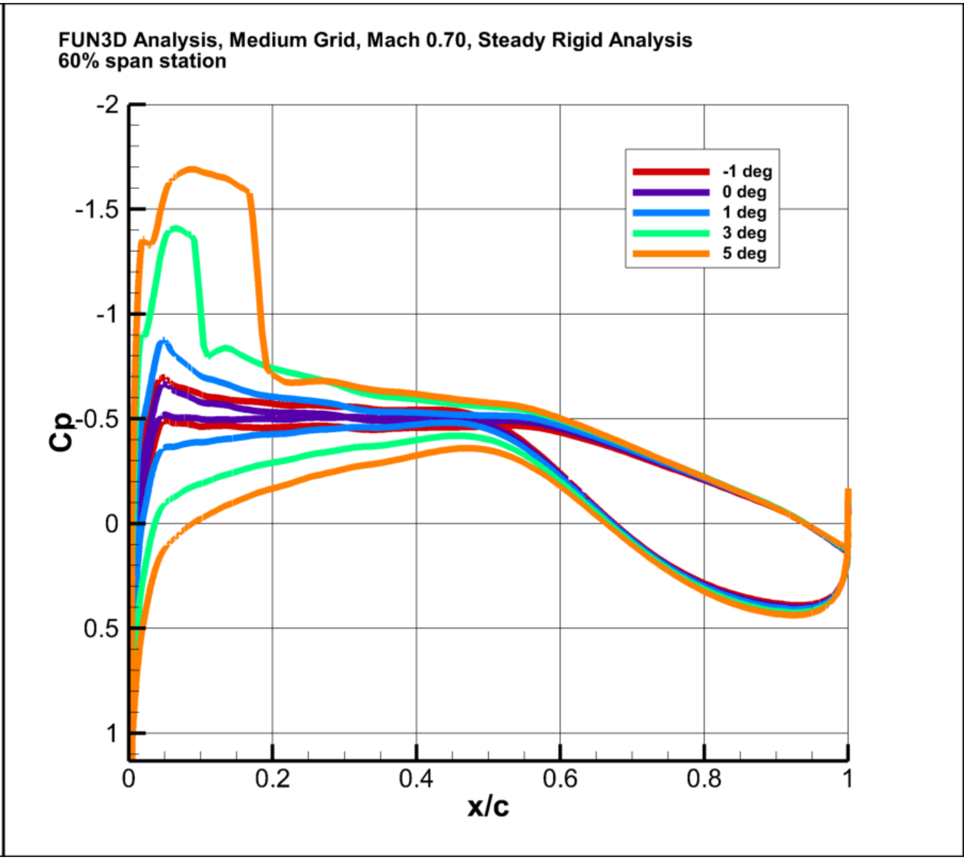
FUN3D Analysis, Medium Grid, Mach 0.82, Steady Rigid Analysis
60% span station
Skin Friction Coefficient, Streamwise direction (CFx)
x/c
0 deg, Upper Surface
1 deg, Upper Surface
3 deg, Upper Surface
5 deg, Upper Surface
0 deg, Lower Surface
1 deg, Lower Surface
3 deg, Lower Surface
5 deg, Lower Surface
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
0
0.2
0.4
0.6
0.8
1



FUN3D Analysis, Medium Grid, Mach 0.82, Steady Rigid Analysis
60% span station
Cp
x/c
0 deg, Upper Surface
1 deg, Upper Surface
3 deg, Upper Surface
5 deg, Upper Surface
0 deg, Lower Surface
1 deg, Lower Surface
3 deg, Lower Surface
5 deg, Lower Surface
-2
-1.5
-1
-0.5
0
0.5
1
0
0.2
0.4
0.6
0.8
1

Backup


FUN3D Analysis, Medium Grid, Mach 0.70, Steady Rigid Analysis
60% span station
Skin Friction Coefficient, stream-wise direction (Cfx)
x/c
0.006
0.004
0.002
0
0
0.2
0.4
0.6
0.8
1
-1 deg, Upper Surface
0 deg, Upper Surface
1 deg, Upper Surface
3 deg, Upper Surface
5 deg, Upper Surface
-1 deg, Lower Surface
0 deg, Lower Surface
1 deg, Lower Surface
3 deg, Lower Surface
5 deg, Lower Surface


FUN3D Analysis, Medium Grid, Mach 0.70, Steady Rigid Analysis
60% span station
Cp
x/c
-2
-1.5
-1
-0.5
0
0.5
1
0
0.2
0.4
0.6
0.8
1
-1 deg
0 deg
1 deg
3 deg
5 deg