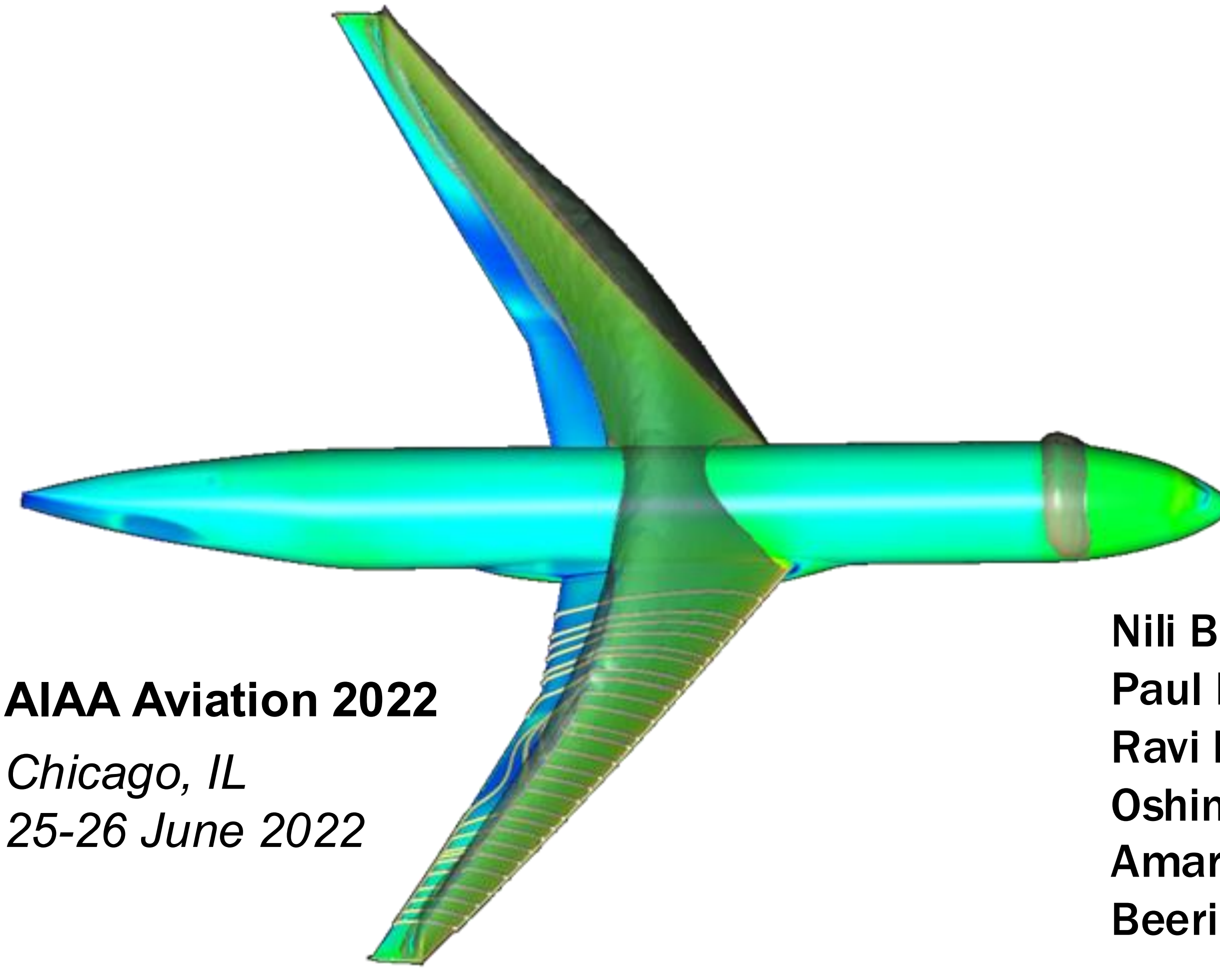
7th AIAA Drag Prediction Workshop
Metacomp Technologies, Inc.



AIAA Aviation 2022

Chicago, IL
25-26 June 2022

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Amar Potturi
Beerinder Singh

Overview

- Solver, settings & models
- ✓ Case 1a: Grid Convergence Study
- ✓ Case 2a: Alpha Sweep (Re=20M)
- ✓ Case 3: Re sweep (C_L=0.50)
- ✓ Case 6: Coupled aero-structural
- Summary

Solver & Settings

- CFD++ Version 20.1
- Bounded nodal-reconstruction transport
- HLLC Riemann solver
- Self-tuning far-field absorbing layers
- Implicit solver with algebraic multi-grid acceleration
- C_L-driver option (for imposed C_L cases)
- SARC+QCR2013 and SST models

Case 1a: Grid Convergence Study

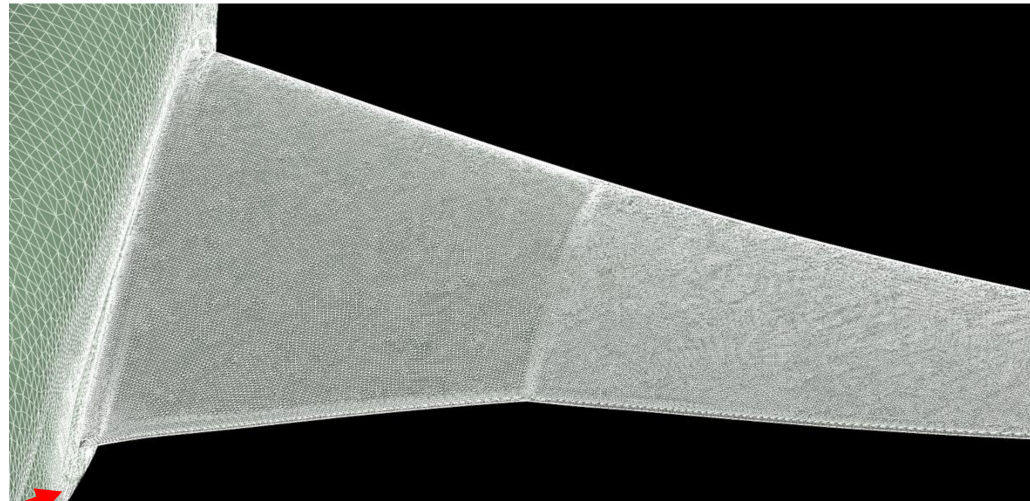
- 6 Simulations performed – one with each grid from the JAXA hybrid mesh family: **tiny, coarse, medium, fine, extra fine and ultra fine**

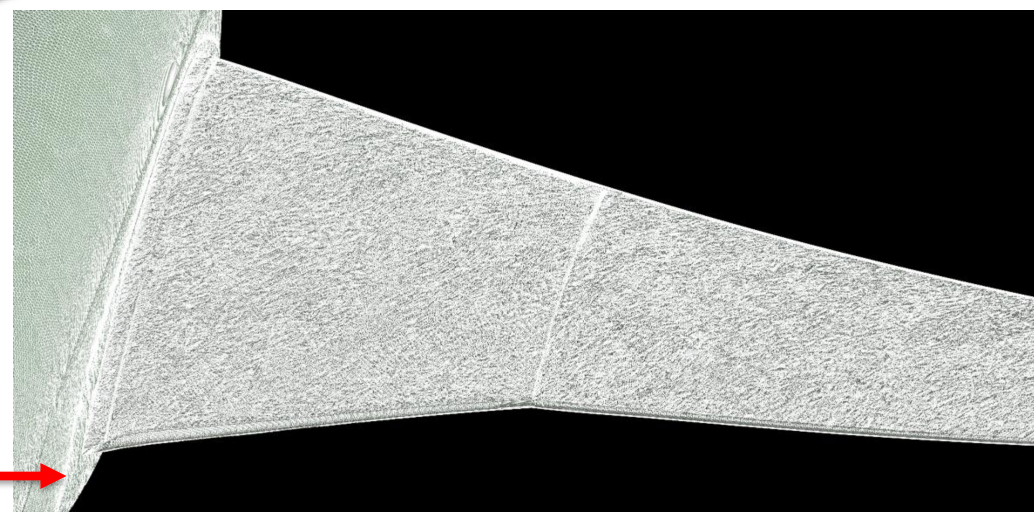
- **CFD++'s C_L-driver** used to automatically adjust the angle-of-attack to achieve desired $C_L = 0.58$ ($\pm$ 0.0001)

Grids

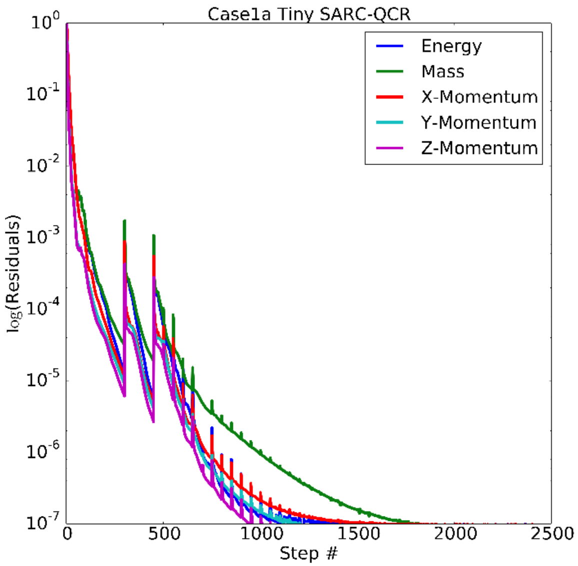
JAXA hybrid mesh family with tetrahedrals, pyramids, prisms, and hexahedrals

Grid Level	# Cells
Tiny	25,294,690
Coarse	76,058,884
Medium	164,065,758
Fine	295,240,476
Extra fine	476,358,610
Ultra fine	739,171,907

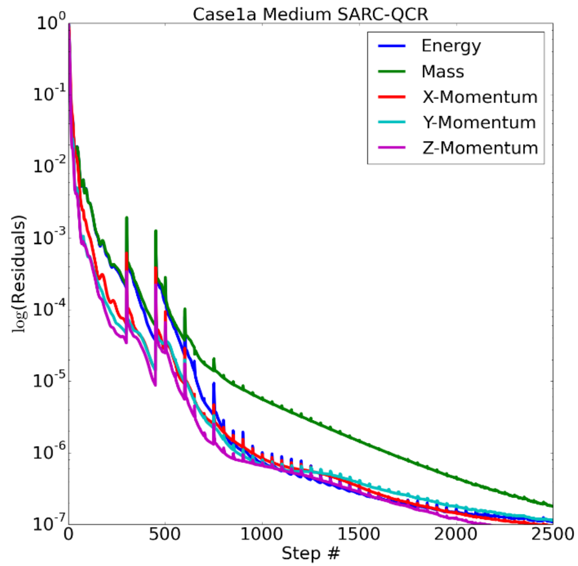




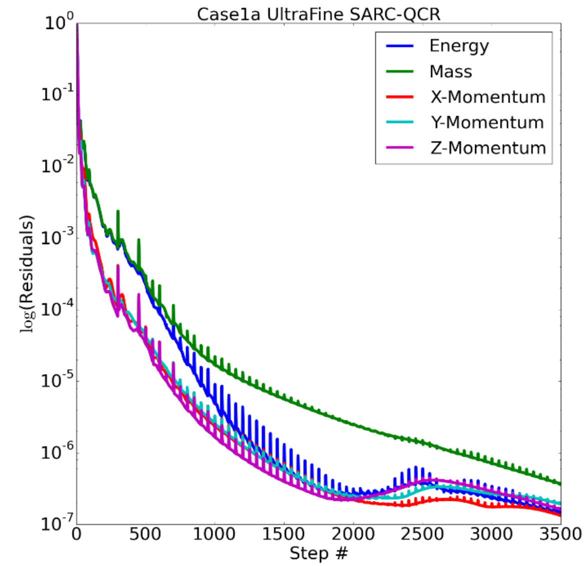
Sample Residual Convergence



Tiny

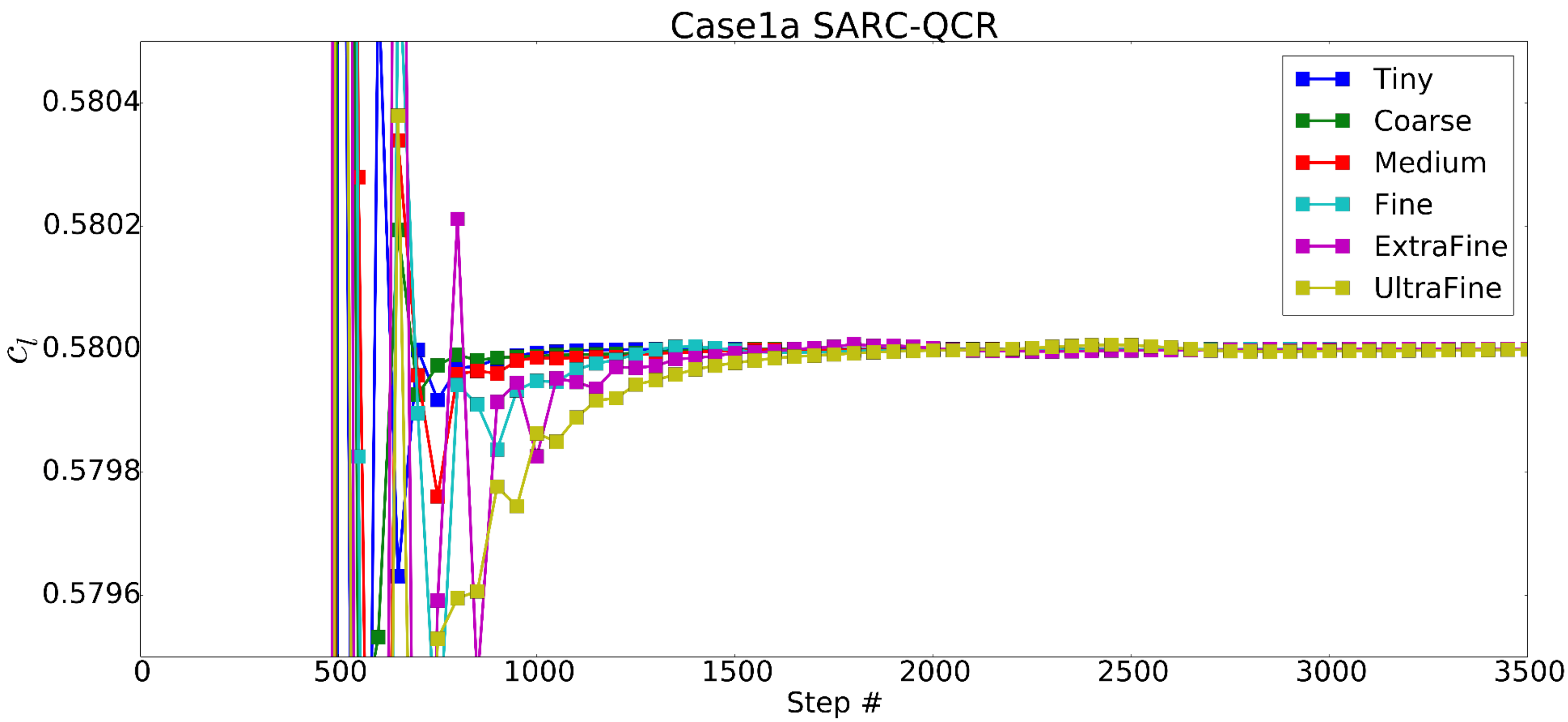


Medium



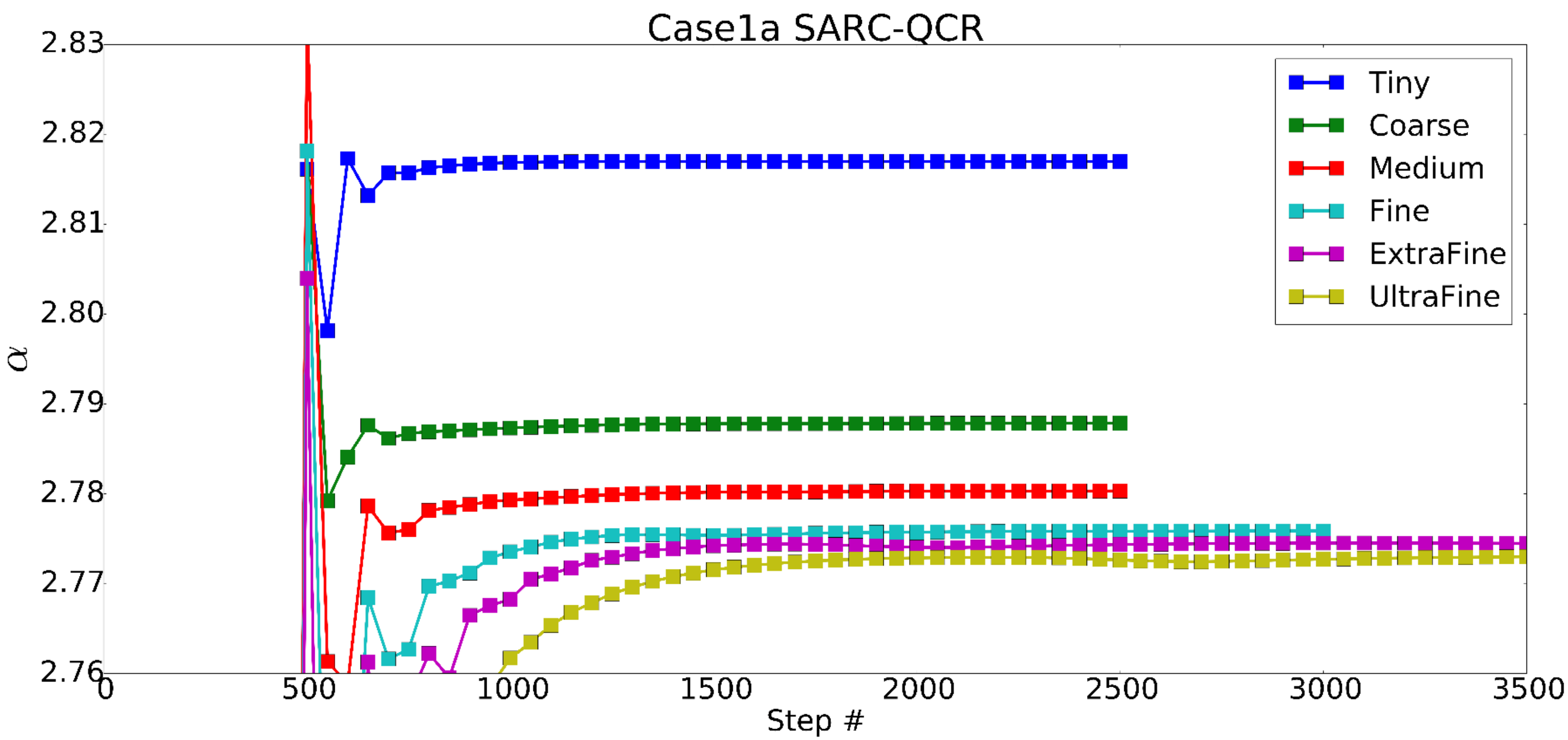
Ultra Fine

C_L History



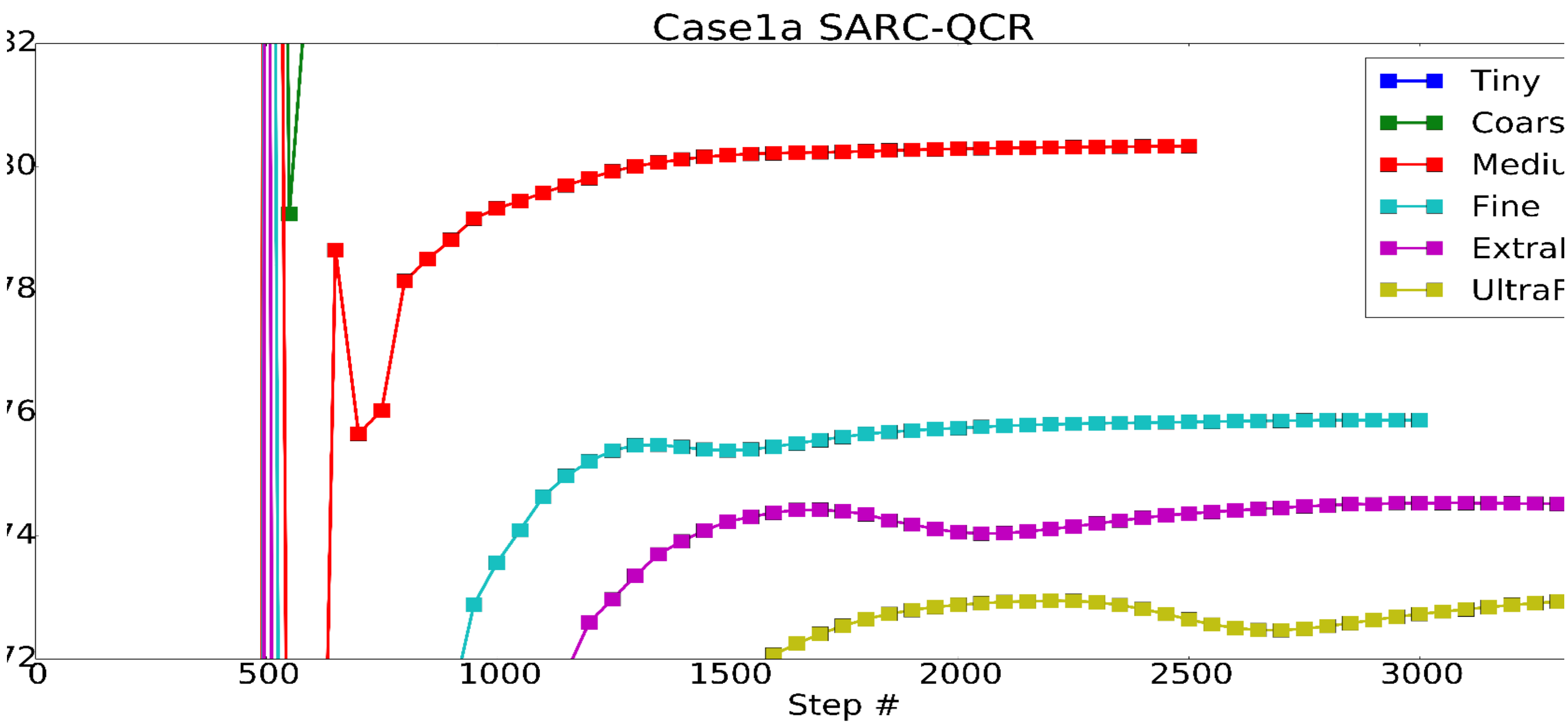
Case1a SARC-QCR
Tiny
Coarse
Medium
Fine
ExtraFine
UltraFine
c_l
0.5804
0.5802
0.5800
0.5798
0.5796
0
500
1000
1500
2000
2500
3000
3500
Step #

α History

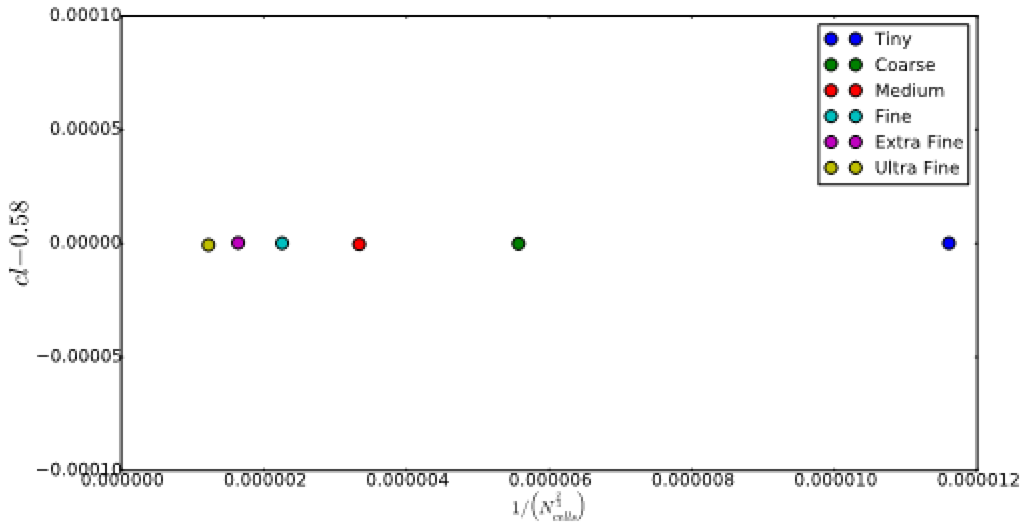


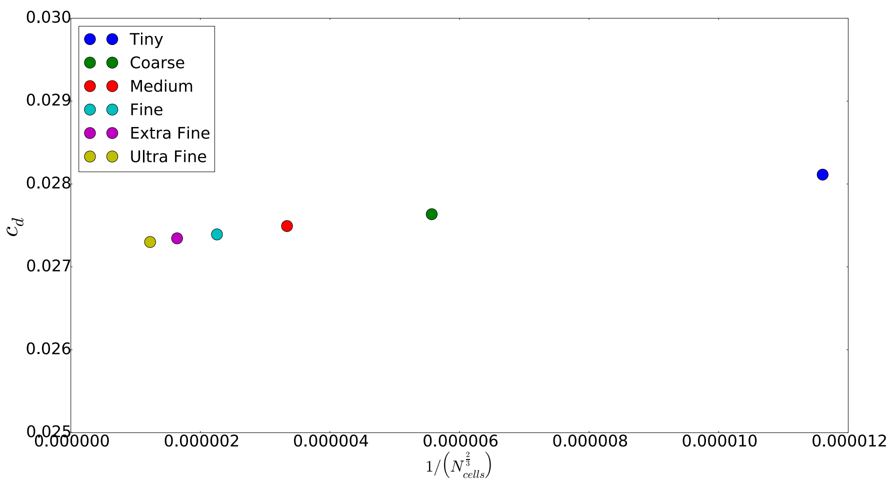
Case1a SARC-QCR
2.83
2.82
2.81
2.80
2.79
2.78
2.77
2.76
α
0
500
1000
1500
2000
2500
3000
3500
Step #
Tiny
Coarse
Medium
Fine
ExtraFine
UltraFine

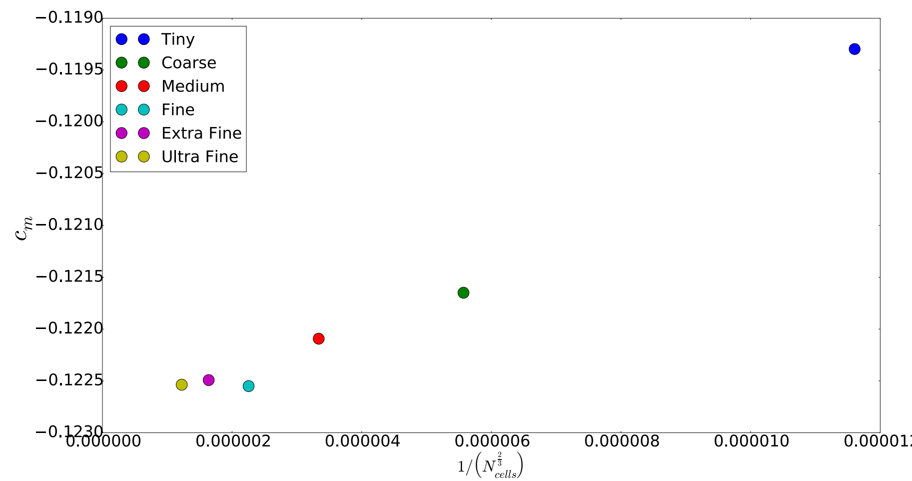
α History (Zoomed-in)



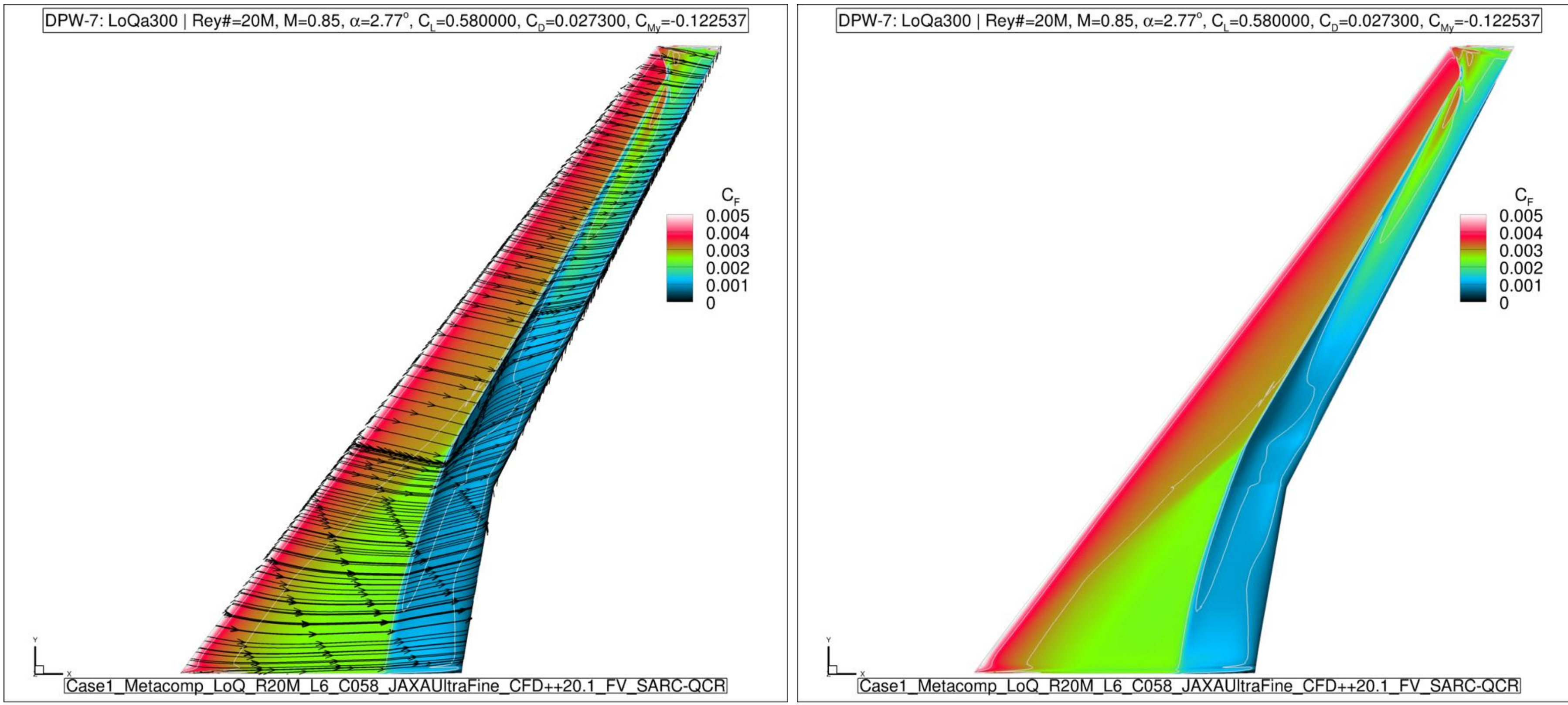
Grid Convergence





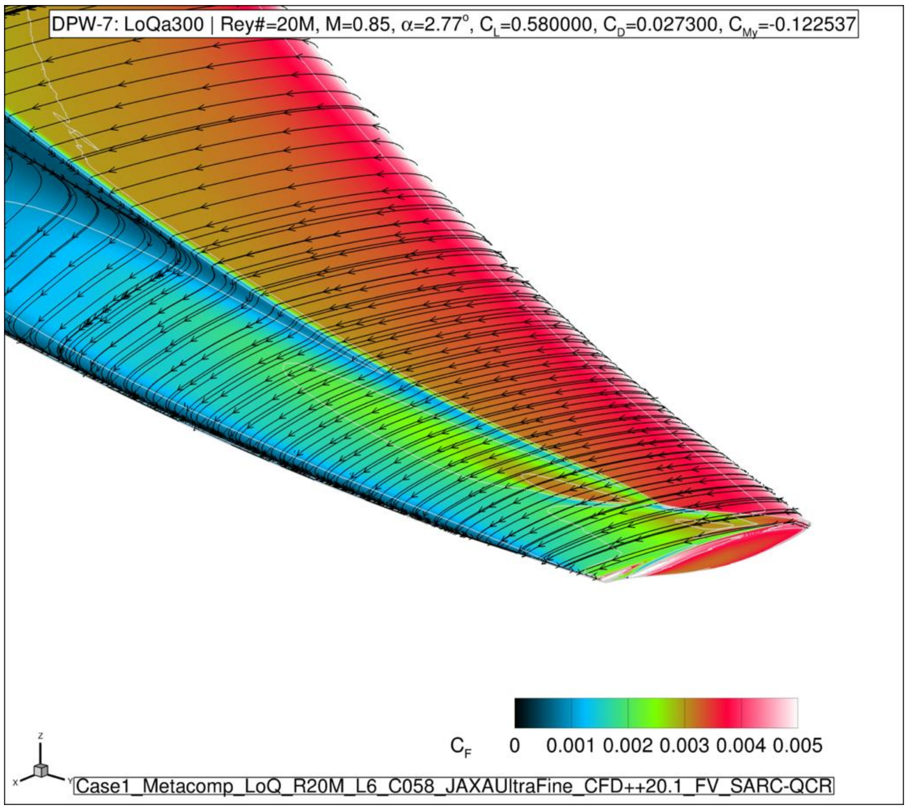


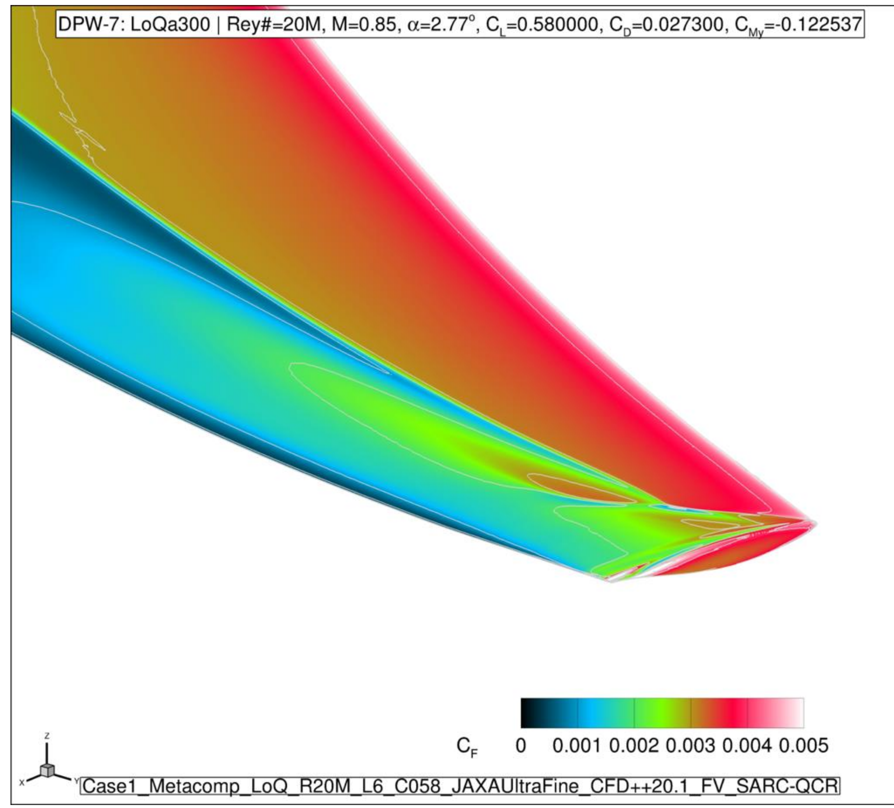
Case 2a : Wing-Body Alpha Sweep



α=2.75˚Cl =0.580000 SARC-QCR

Case 2a : Wing-Body Alpha Sweep





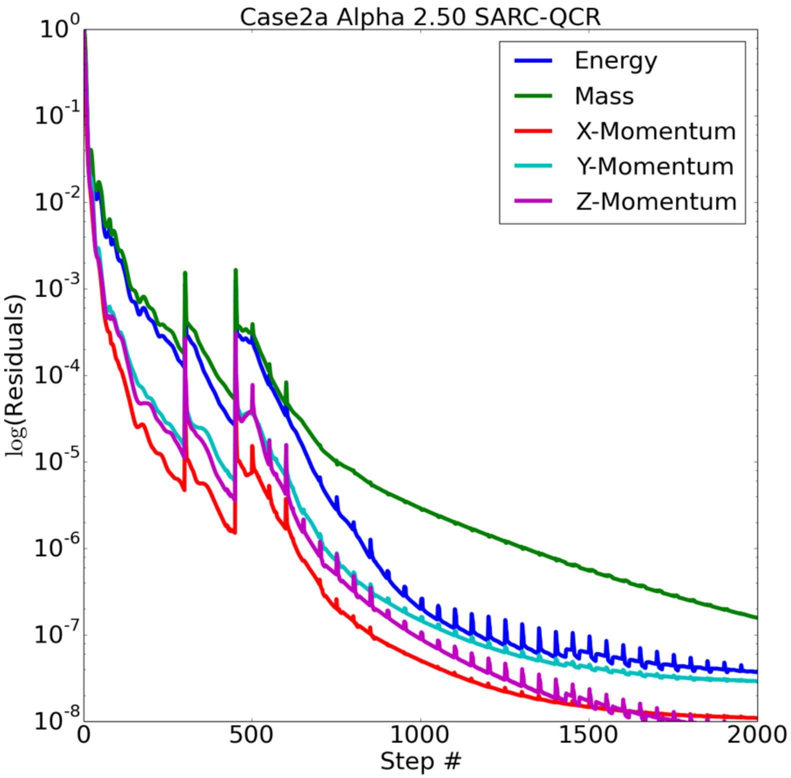
α=2.75˚Cl =0.580000 SARC-QCR

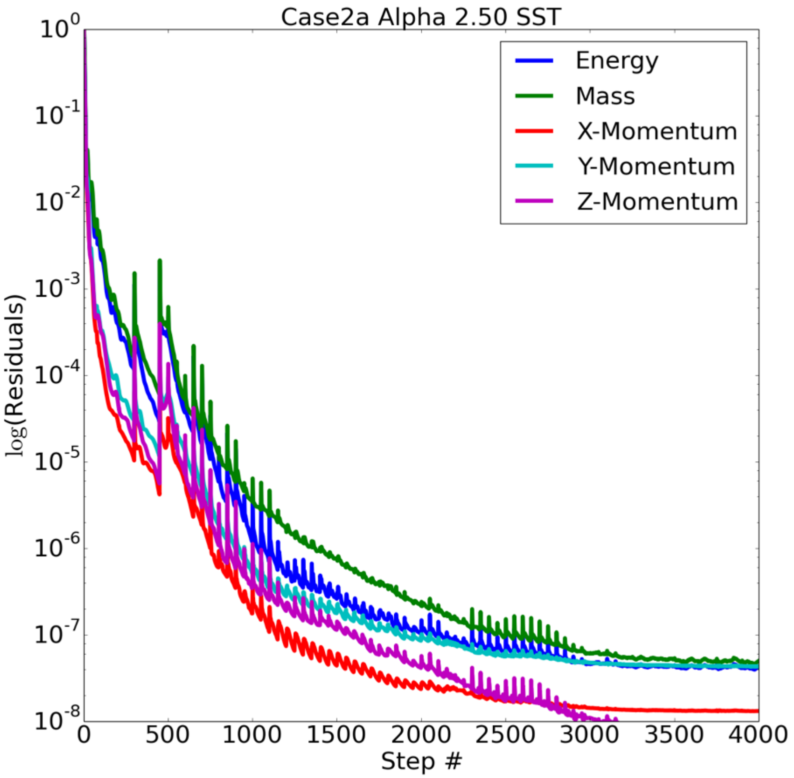
Case 2a : Wing-Body Alpha Sweep

- **Flow conditions: Mach 0.85, Re=20M, T_{total}= -250˚F**
- **CFD++ Compressible RANS (Air, Perfect Gas)**

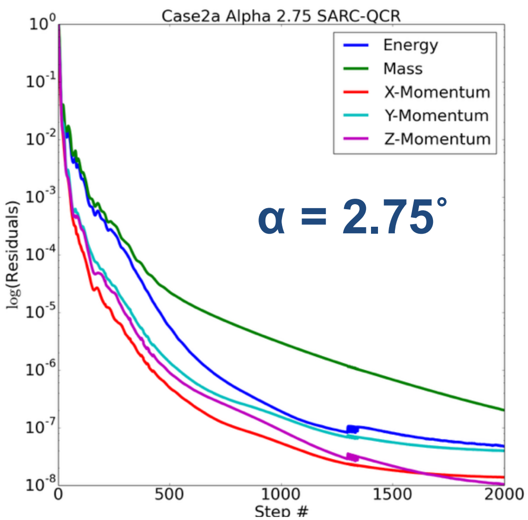
α	Mesh
2.23˚ (C_L=0.50)	2.50˚ LoQ JAXA Medium
2.75˚	2.75˚ LoQ JAXA Medium
3.00˚	3.00˚ LoQ JAXA Medium
3.25˚	3.25˚ LoQ JAXA Medium
3.50˚	3.50˚ LoQ JAXA Medium
3.75˚	3.75˚ LoQ JAXA Medium
4.00˚	4.00˚ LoQ JAXA Medium
4.25˚	4.25˚ LoQ JAXA Medium

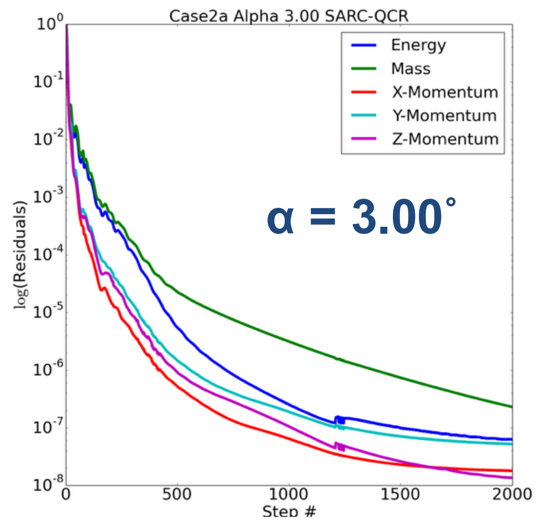
Residuals: α = 2.50˚ (C_L-driver active)

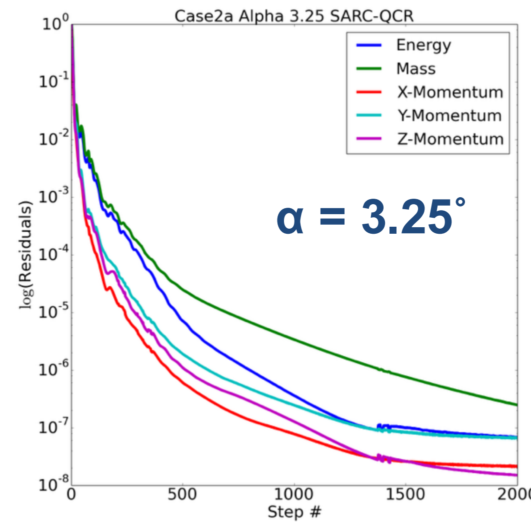


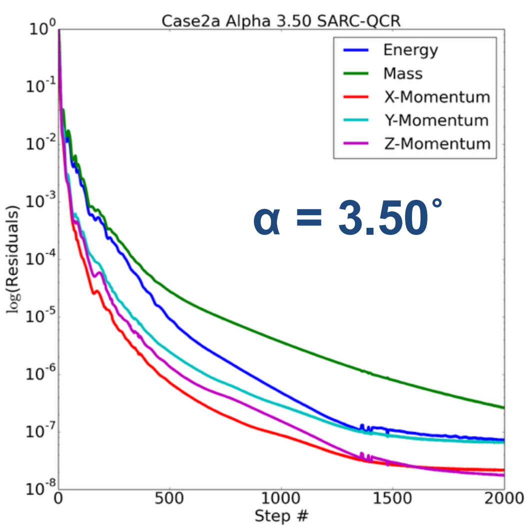


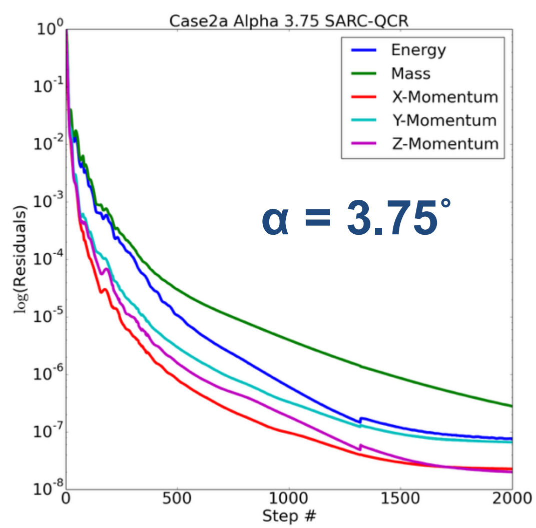
Alpha-Sweep Residuals: SARC+QCR, Re=4M

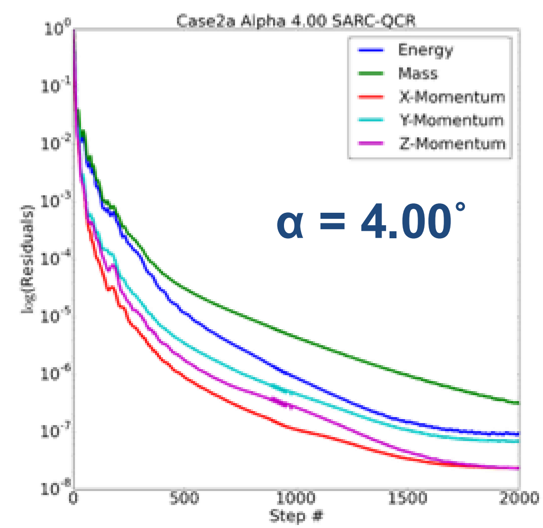




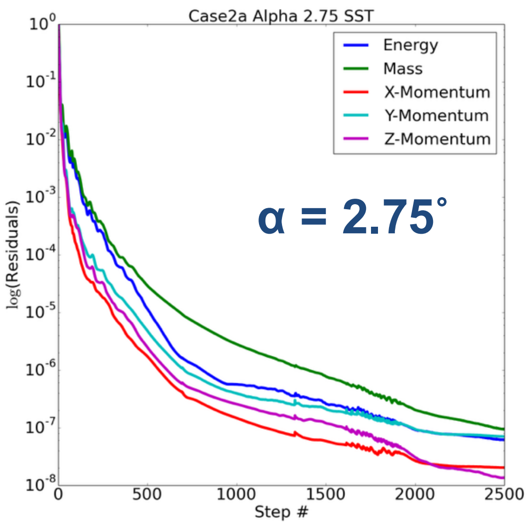


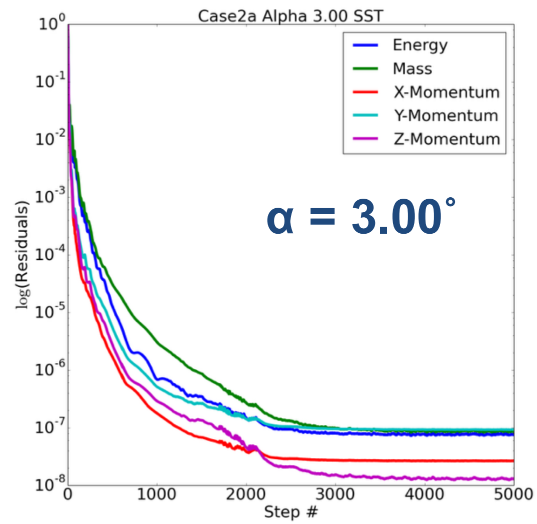


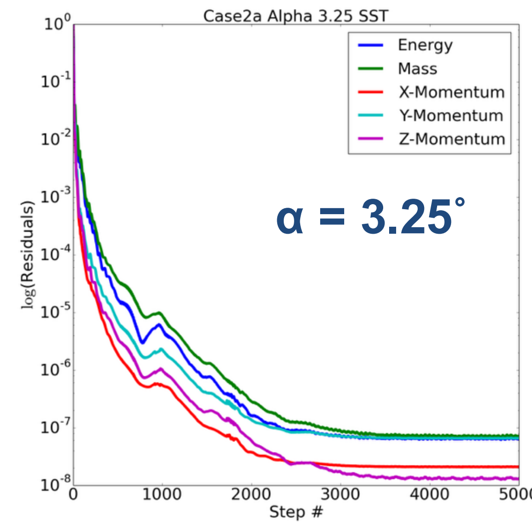


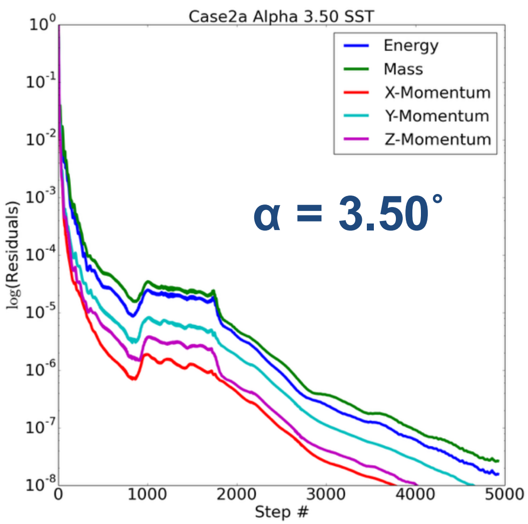


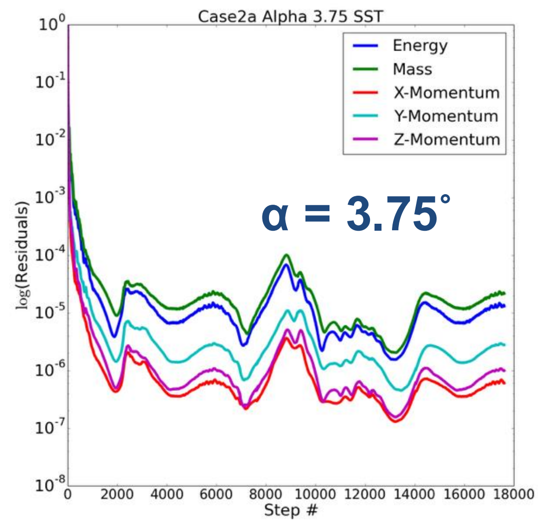
Alpha-Sweep Residuals: SST, Re=4M

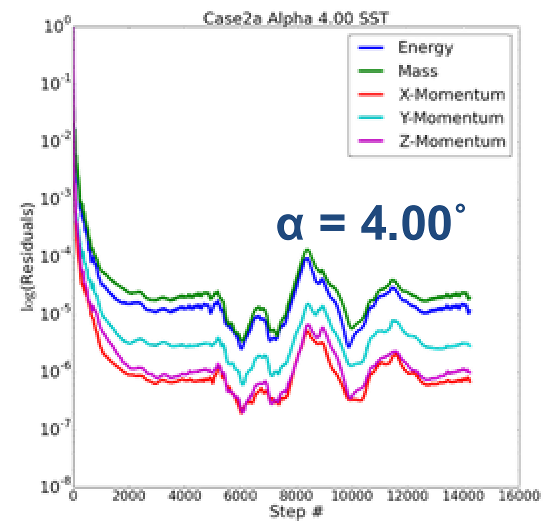






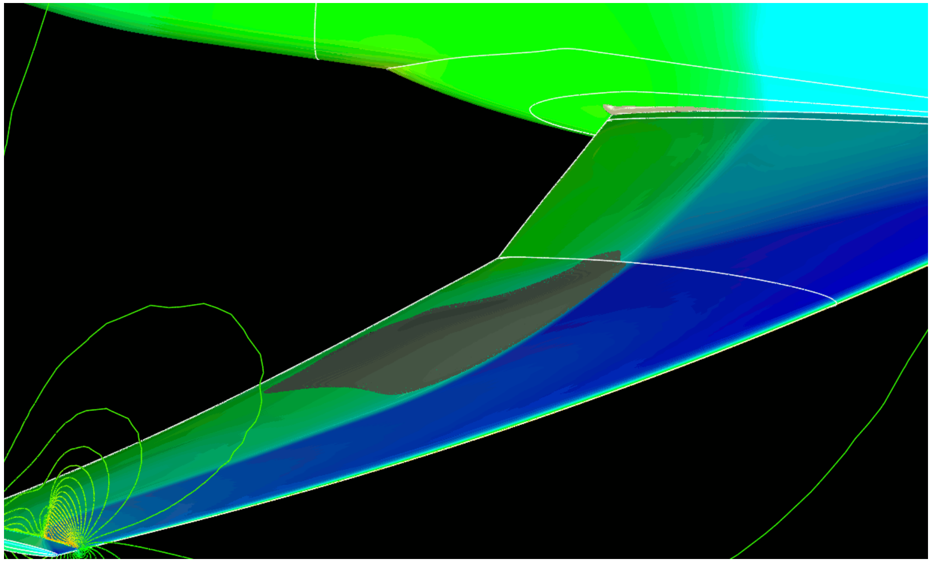


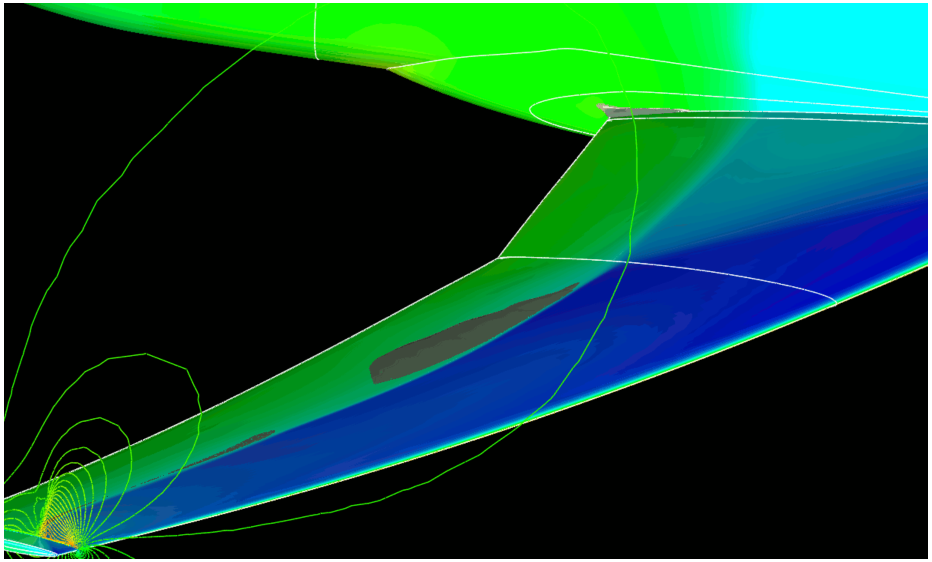




Cross-Section Mach Contours and Separation Re=4M Isosurface Comparisons

α=4.00˚: SARC-QCR (*Left*) and SST/Start Soln nt=8900 (*Right*)

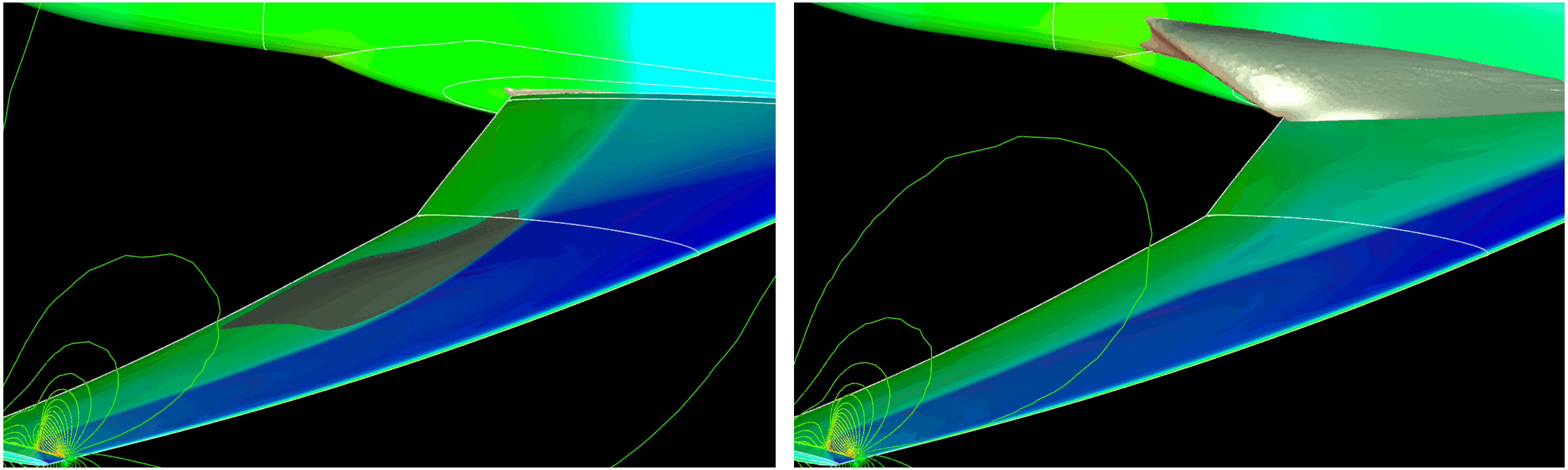




Aircraft surface: Pressure
Isosurface: -1 m/s x-velocity component
Cutplane: Mach number

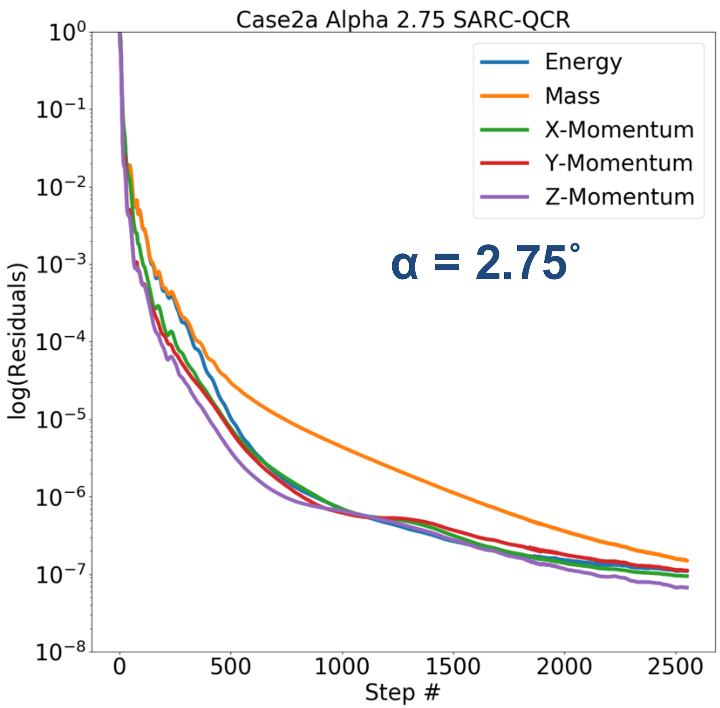
Cross-Section Mach Contours and Separation Re=4M Isosurface Comparisons

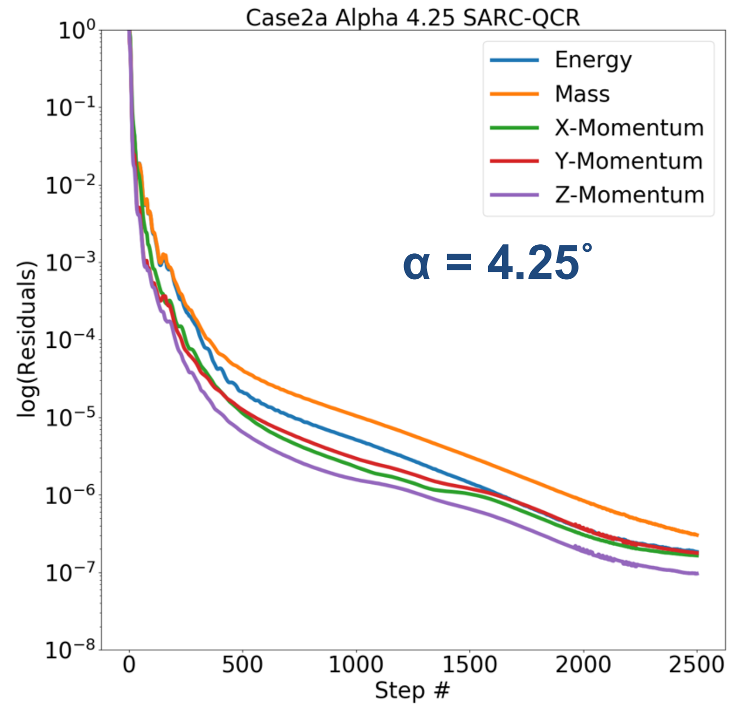
α=4.00˚: SARC-QCR *(Left)* and SST/Cont Soln nt=14200 *(Right)*



Aircraft surface: Pressure
Isosurface: -1 m/s x-velocity component
Cutplane: Mach number

Alpha-Sweep Residuals: SARC+QCR, Re=20M





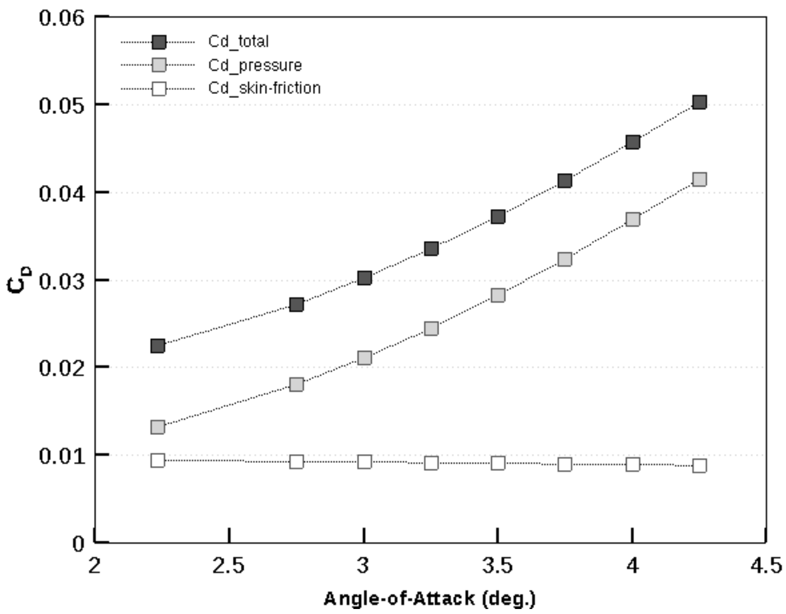
Case 2a : Wing-Body Alpha Sweep

- ✓ **Shock-induced separation from 2.75˚**
- ✓ **Side-of-body separation in all cases**

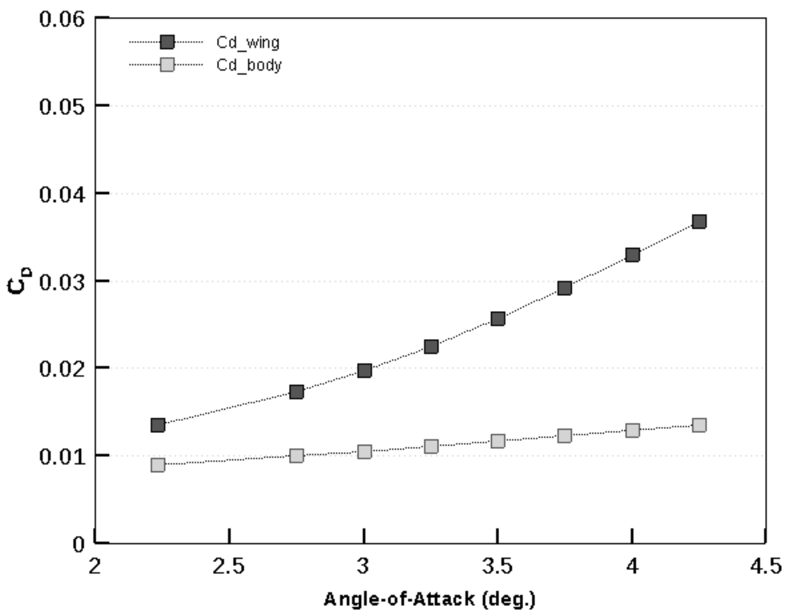
α	C_L	C_D
2.23˚	0.50	0.022517
2.75˚	0.577272	0.027241
3.00˚	0.609559	0.030213
3.25˚	0.633715	0.033557
3.50˚	0.651930	0.038059
3.75˚	0.669637	0.041414
4.00˚	0.686953	0.045781
4.25˚	0.703539	0.050348

Case 2a : Wing-Body Alpha Sweep

Drag Components

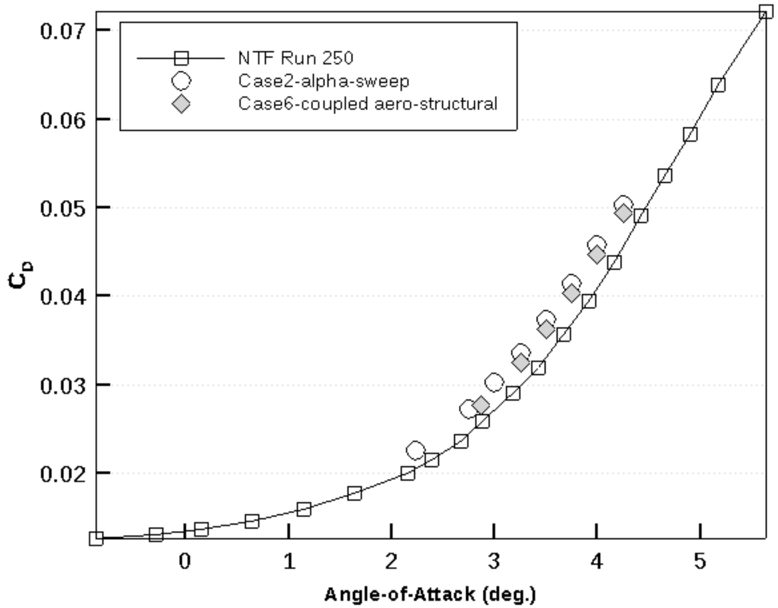


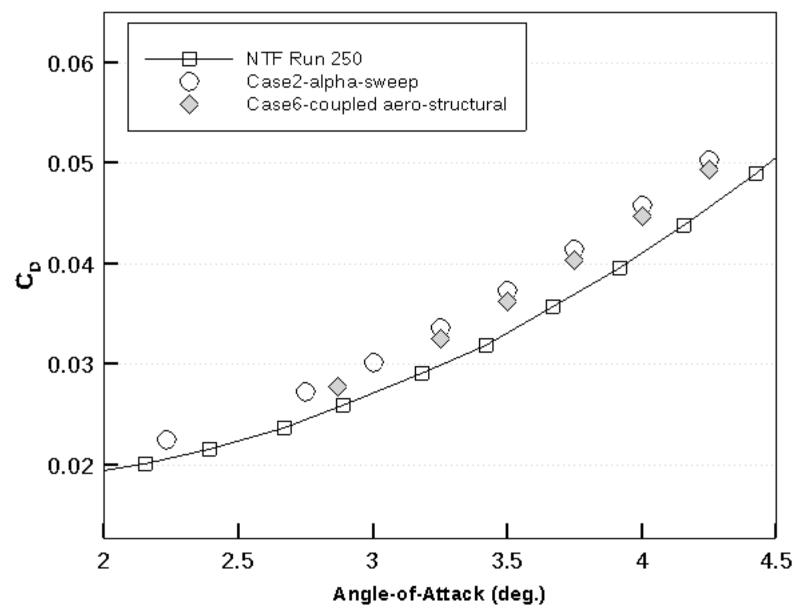
Wing/Body Contribution



Case 2a : Wing-Body Alpha Sweep

Drag Coefficient

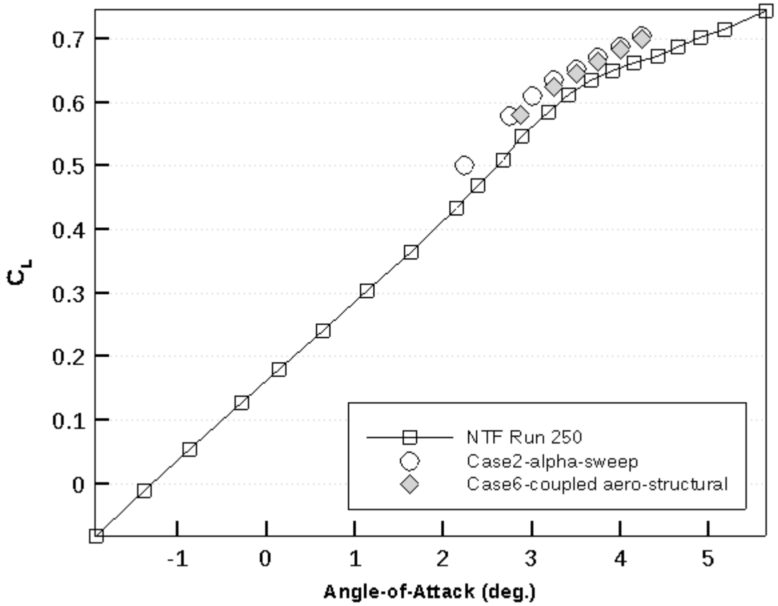


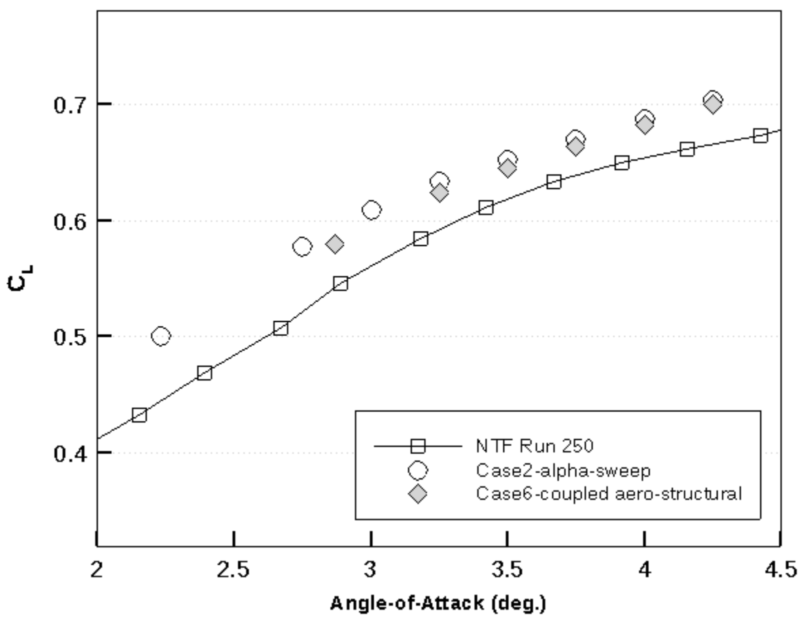


No sting correction applied to NTF data

Case 2a : Wing-Body Alpha Sweep

Lift Coefficient

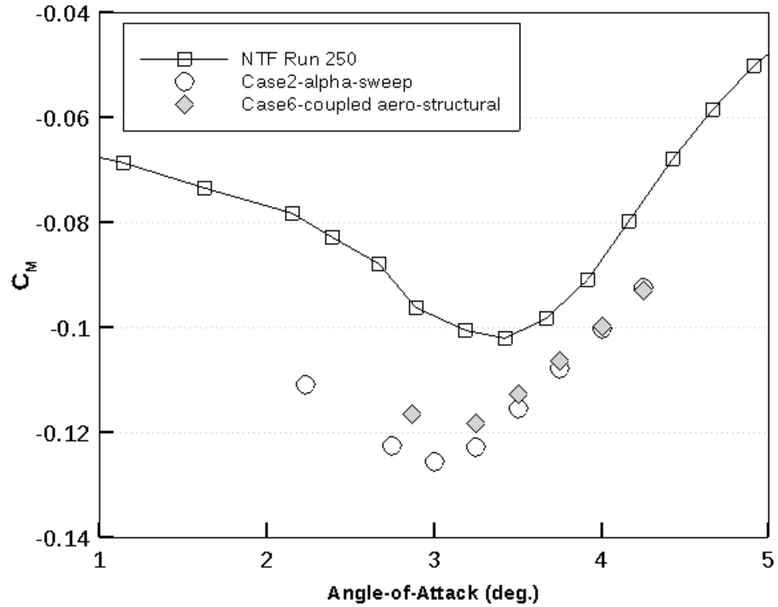




No sting correction applied to NTF data

Case 2a : Wing-Body Alpha Sweep

Pitching Moment Coefficient



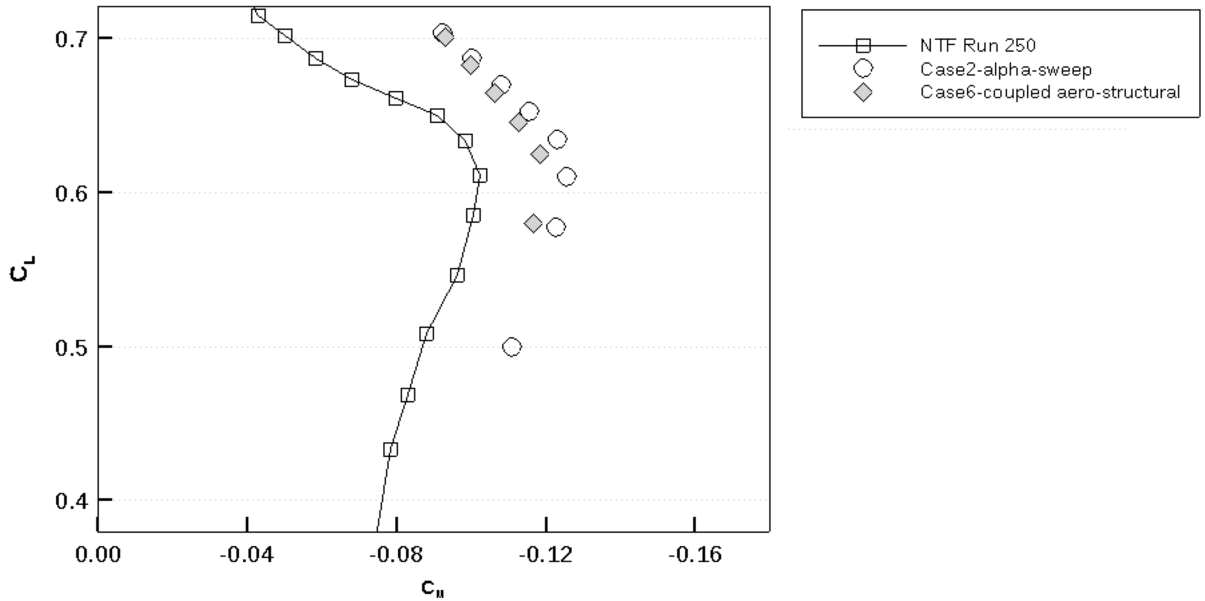
Corrections applied to NTF tunnel data:

- **Model blockage**
- **Wake blockage**
- **Tunnel buoyancy**
- **Lift interference**

No sting correction applied to NTF data

Case 2a : Wing-Body Alpha Sweep

C_M vs C_L



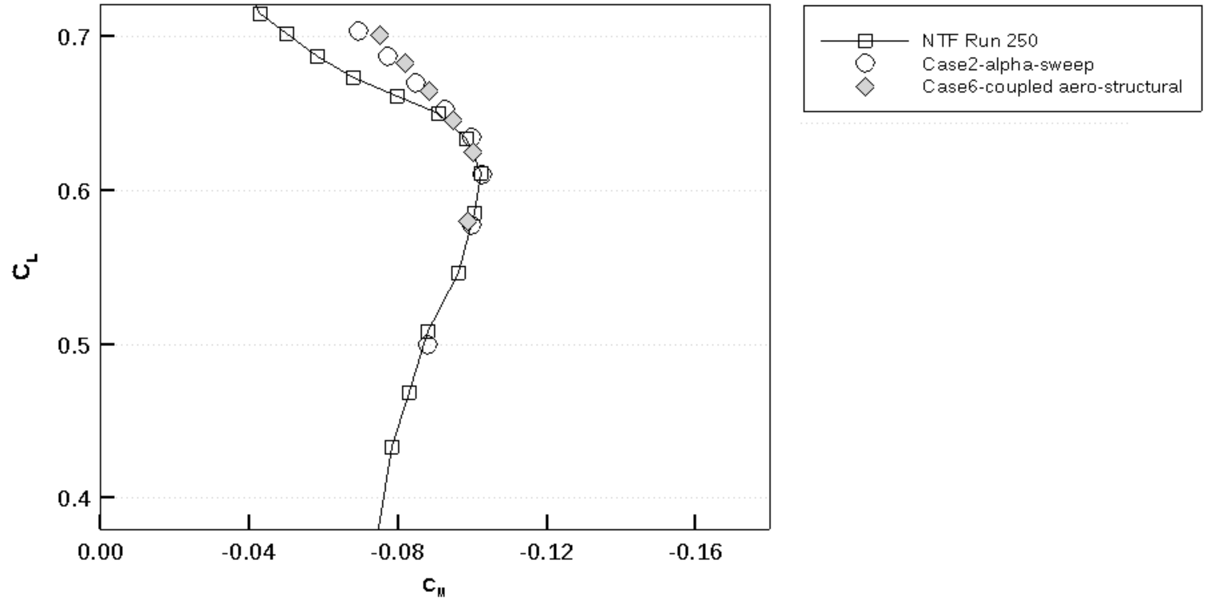
Many tunnel installation effects can cause a shift:

- **Error in true alpha measurement**
- **Error in moment-center offset**
- **Model/mount aeroelastic effects**
- **Unknown effects of tunnel corrections**

No sting correction applied to NTF data

Case 2a : Wing-Body Alpha Sweep

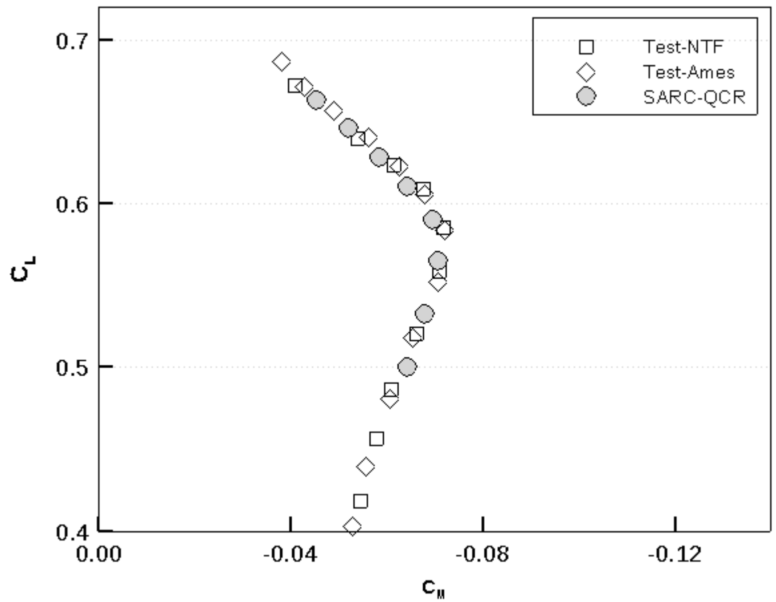
C_M vs C_L – with shift in C_M



No sting correction applied to NTF data

Case 2a : Wing-Body Alpha Sweep

C_M vs C_L – with shift in C_M



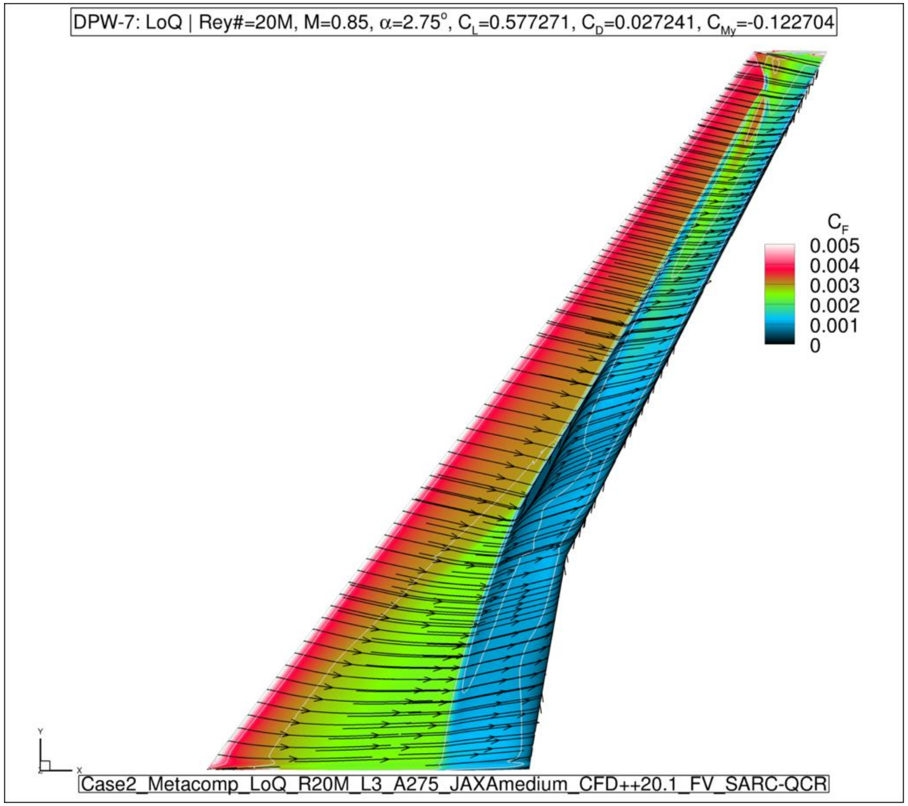
Re: **4 million**
Mach 0.85
T = -250˚ F
Angle-of-Attack Sweep from 2.50˚ to 4.25˚

Test-NTF : (Re 5M)
Test-Ames : (Re 5M)

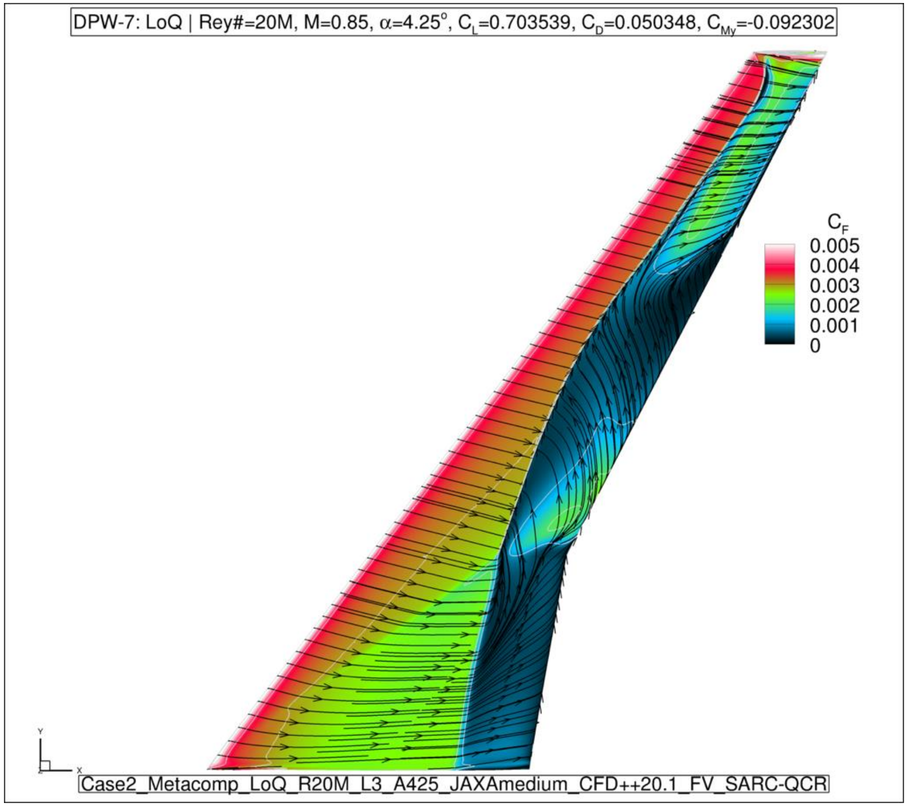
No sting correction applied to NTF data

Case 2a : Wing-Body Alpha Sweep

α=2.75˚SARC-QCR

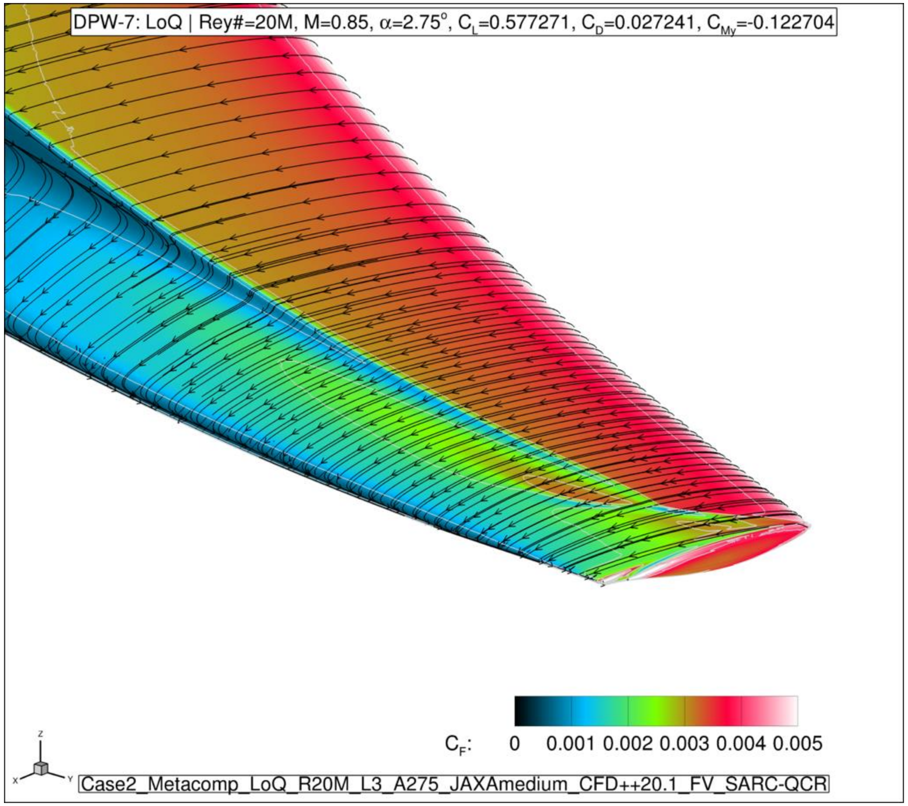


α=4.25˚SARC-QCR

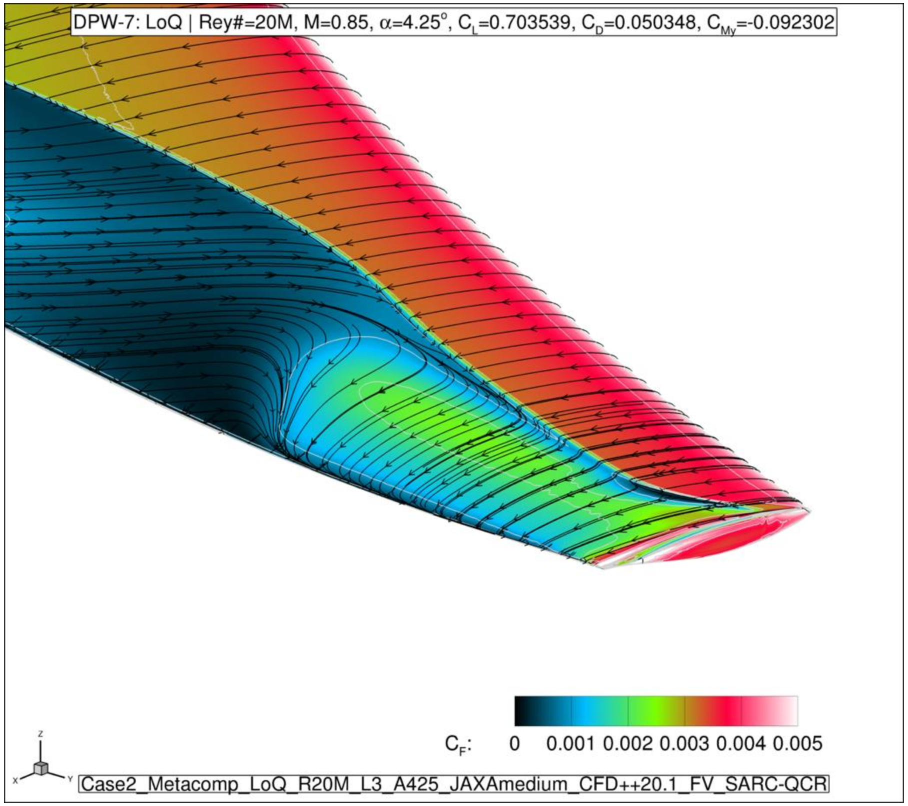


Case 2a : Wing-Body Alpha Sweep

α=2.75˚SARC-QCR



α=4.25˚SARC-QCR



Case 3 : Reynolds Number Sweep (C_L=0.50)

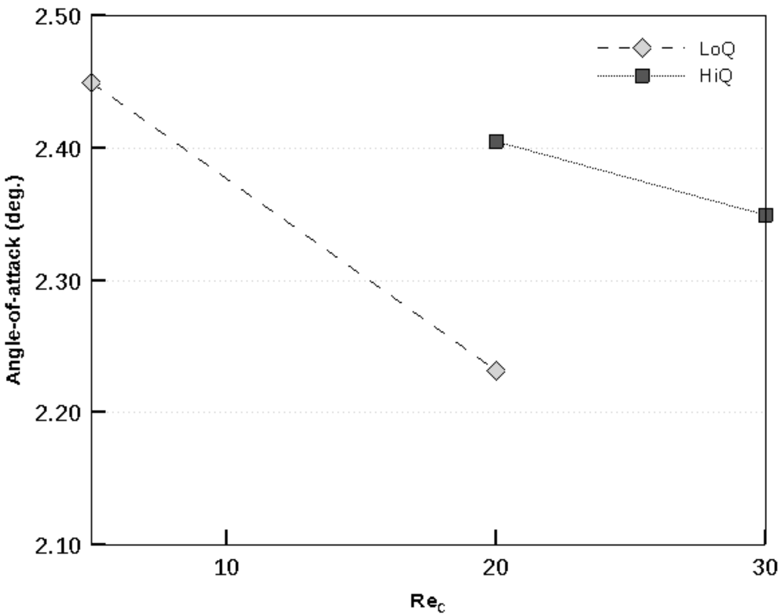
- **Reynolds Sweep at Constant Cl=0.50 and Mach 0.85**
- **Medium JAXA grids**
- **CFD++ Compressible RANS (Air, Perfect Gas)**
- **Turbulence Model: SARC-QCR**
- **All simulations run with C_L-driver**

Reynolds #	P_{static} (kPa)	T_{static} (˚K)	U_∞ (m/s)	q (kPa)
5M LoQ	125	271.67	280.92	63
20M LoQ	127	101.77	171.94	64
20M HiQ	192	134.78	197.87	97
30M HiQ	189	101.78	171.94	96

Case 3 : Reynolds Number Effects

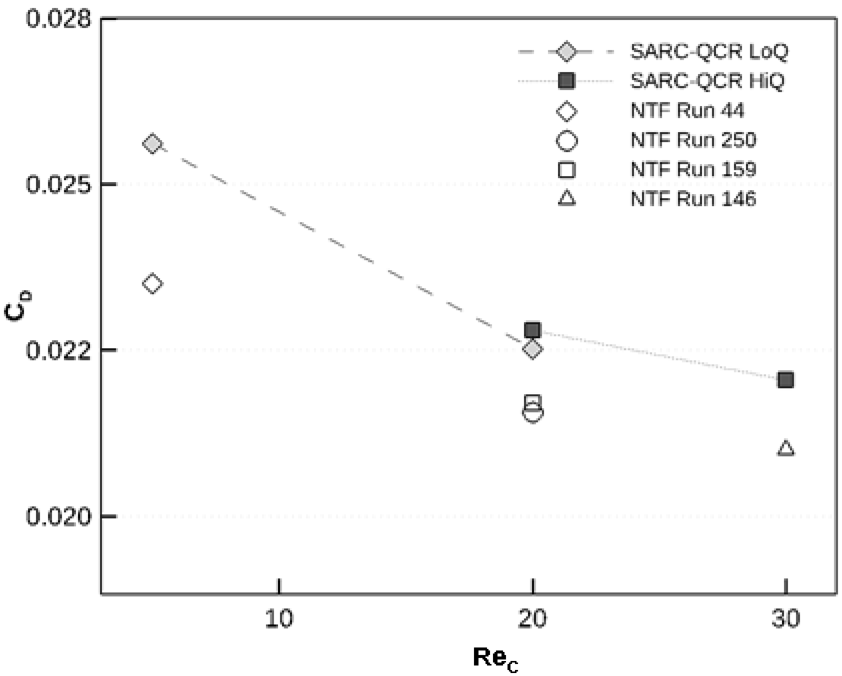
- ✓ No shock induced separation in all cases
- ✓ Angles-of-attack settle below 2.45˚

Reynolds #	C_L	α
5M LoQ	0.50	2.4495˚
20M LoQ	0.50	2.2314˚
20M HiQ	0.50	2.4046˚
30M HiQ	0.50	2.3489˚

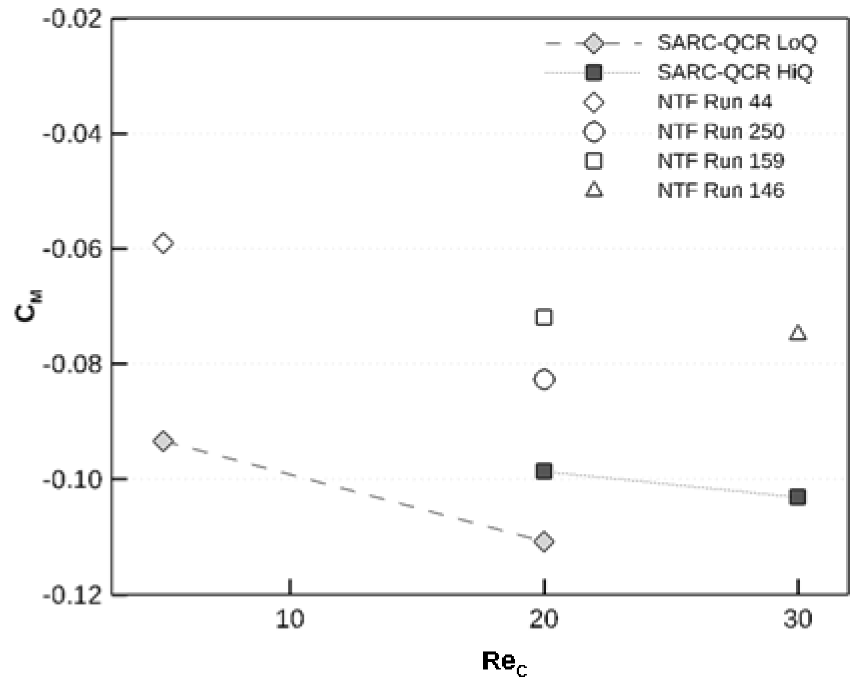


Case 3 : Reynolds Number Effects

Drag Coefficient



Pitching Moment Coefficient



N.B.

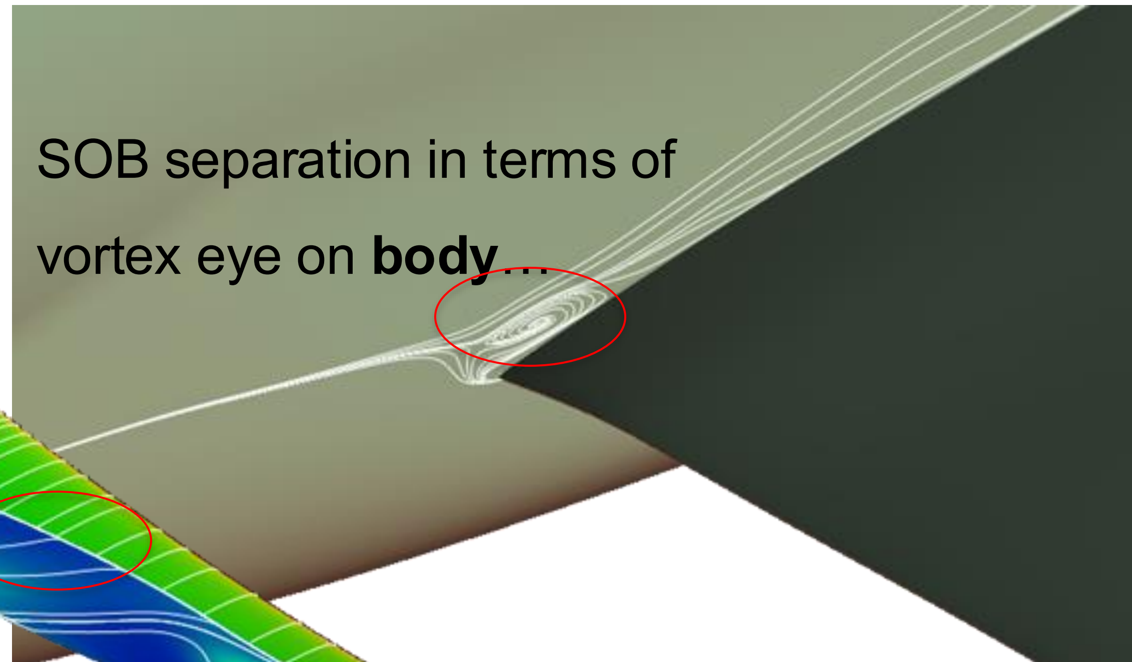
5millionLoQ CFD Q=1325 / NTF Run 44 Q=1388
20millionLoQ CFD Q=1338 / NTF Run 250 Q=1313
20millionHiQ CFD Q=2031 / NTF Run 159 Q=1988
30millionHiQ CFD Q=2007 / NTF Run 146 Q=1989

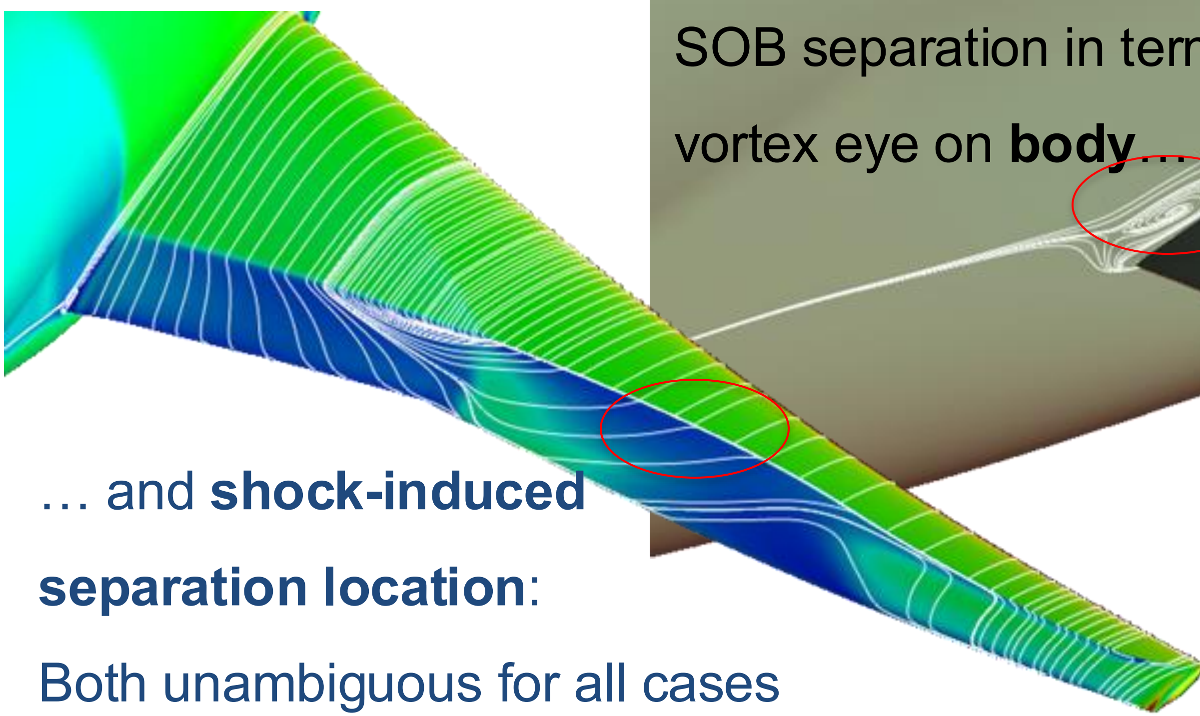
&

Alphas are approximate and no sting correction applied to NTF data

Misc. Observations 1

#1: TE (Shock) & SOB/Wing Separations





SOB separation in terms of vortex eye on **body**…

… and **shock-induced separation location**:

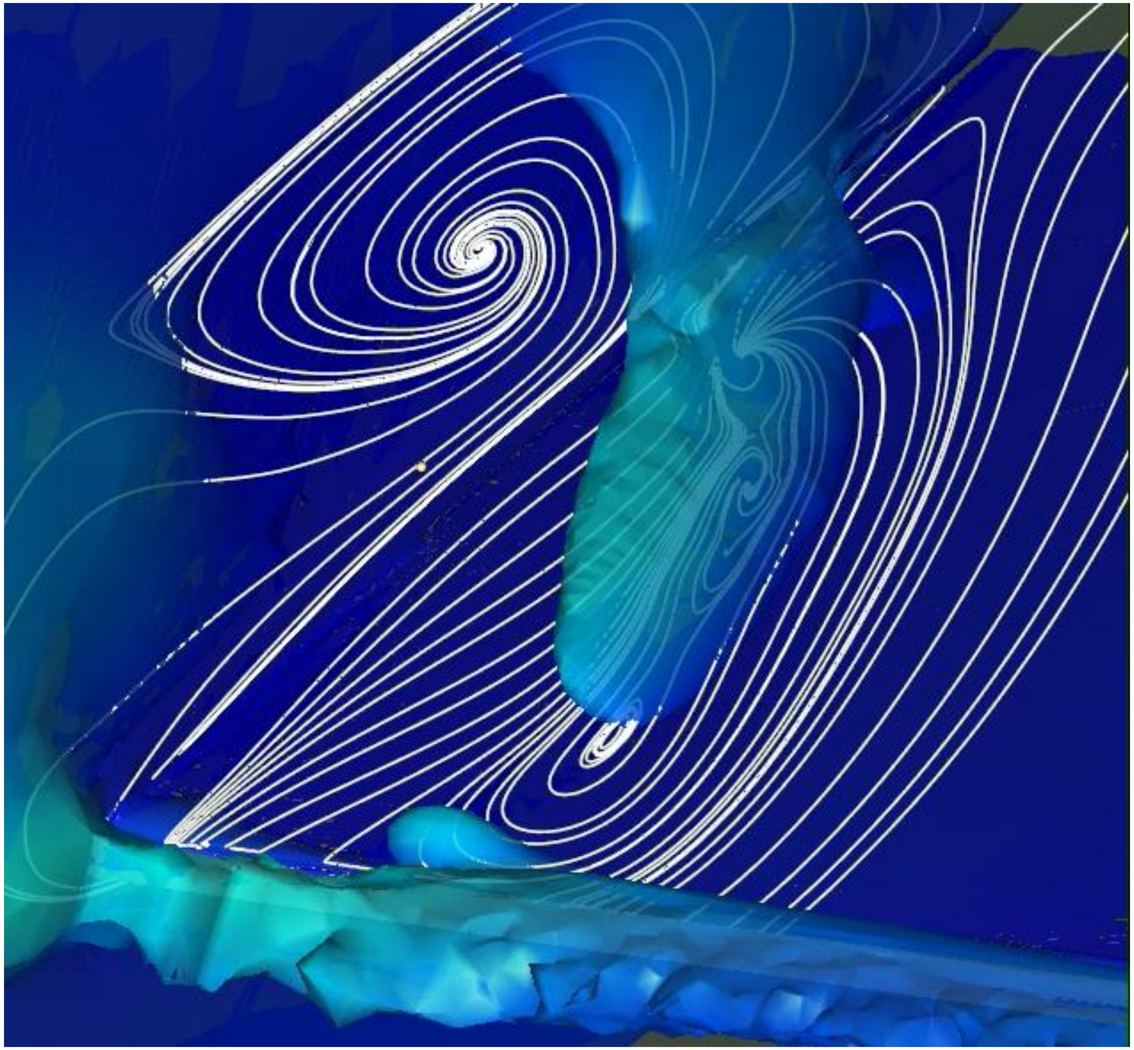
Both unambiguous for all cases

In most cases wing separation is more complicated…

Which Vortex Eye Do We Want?

λ_2 /Q-criterion

isosurfaces:



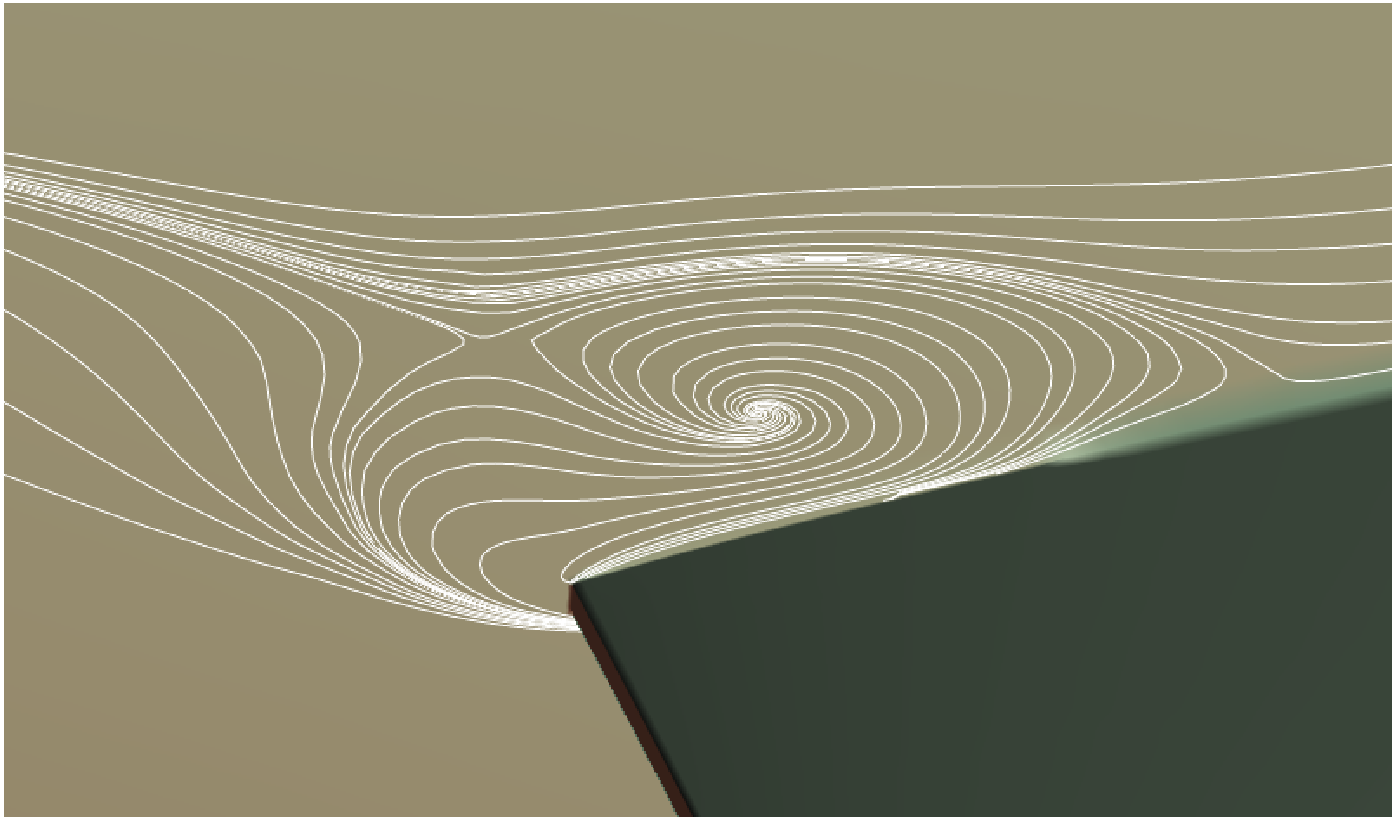
Case 1a : Juncture-Region SOB Separation

Case 1a : Juncture-Region

SOB Separation

SOB separation:

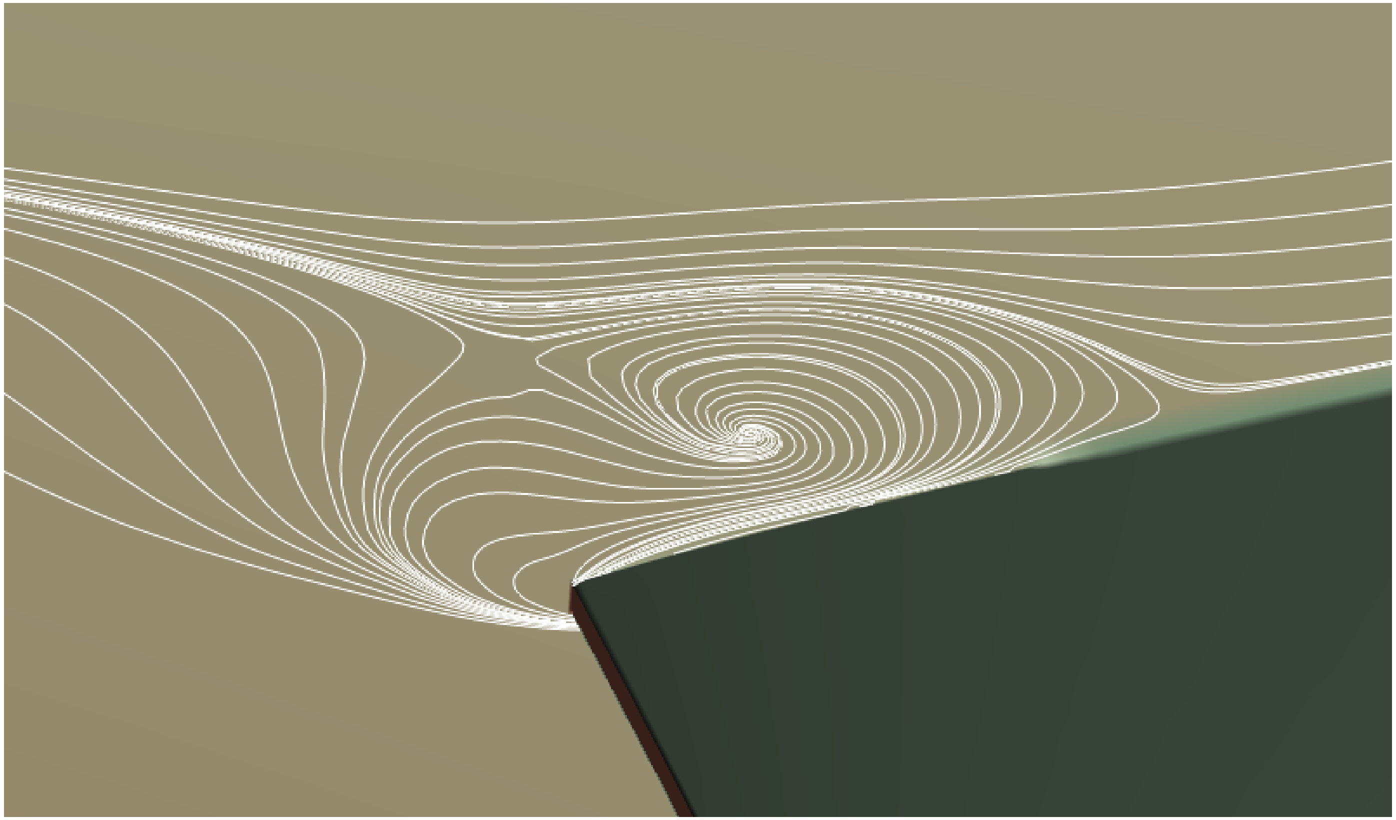
Tiny mesh



Case 1a : Juncture-Region
SOB Separation

SOB separation:

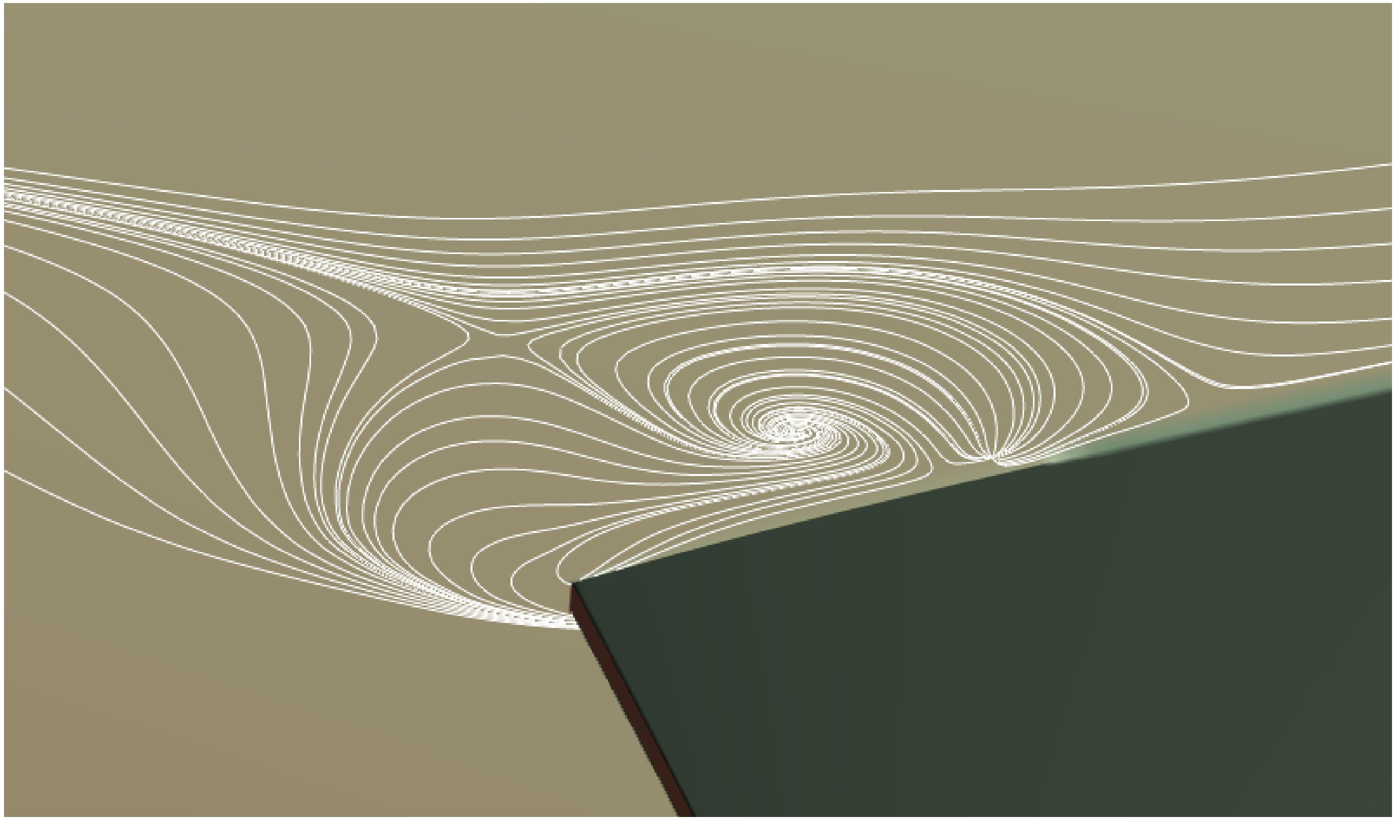
Coarse mesh



Case 1a : Juncture-Region
SOB Separation

SOB separation:

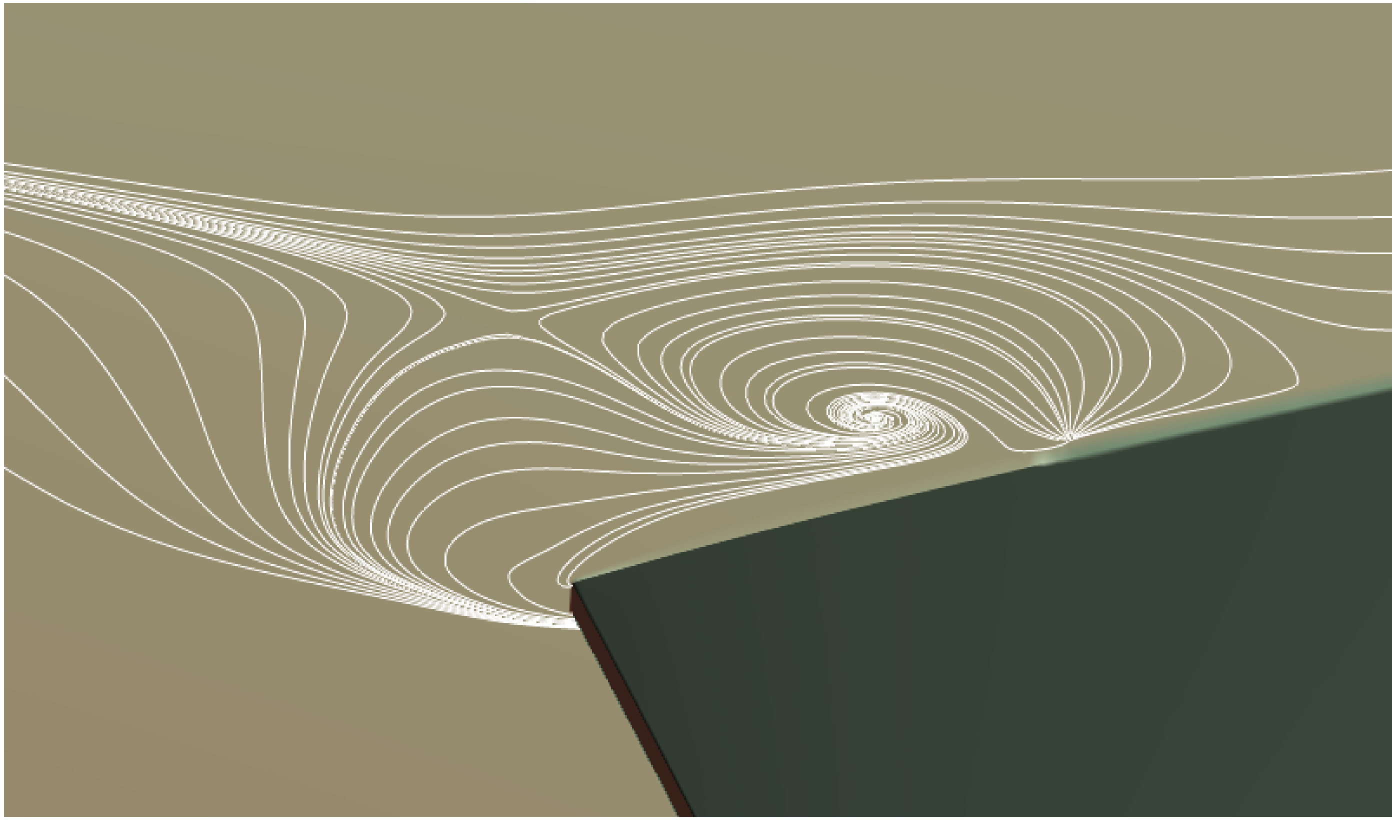
Medium mesh



Case 1a : Juncture-Region
SOB Separation

SOB separation:

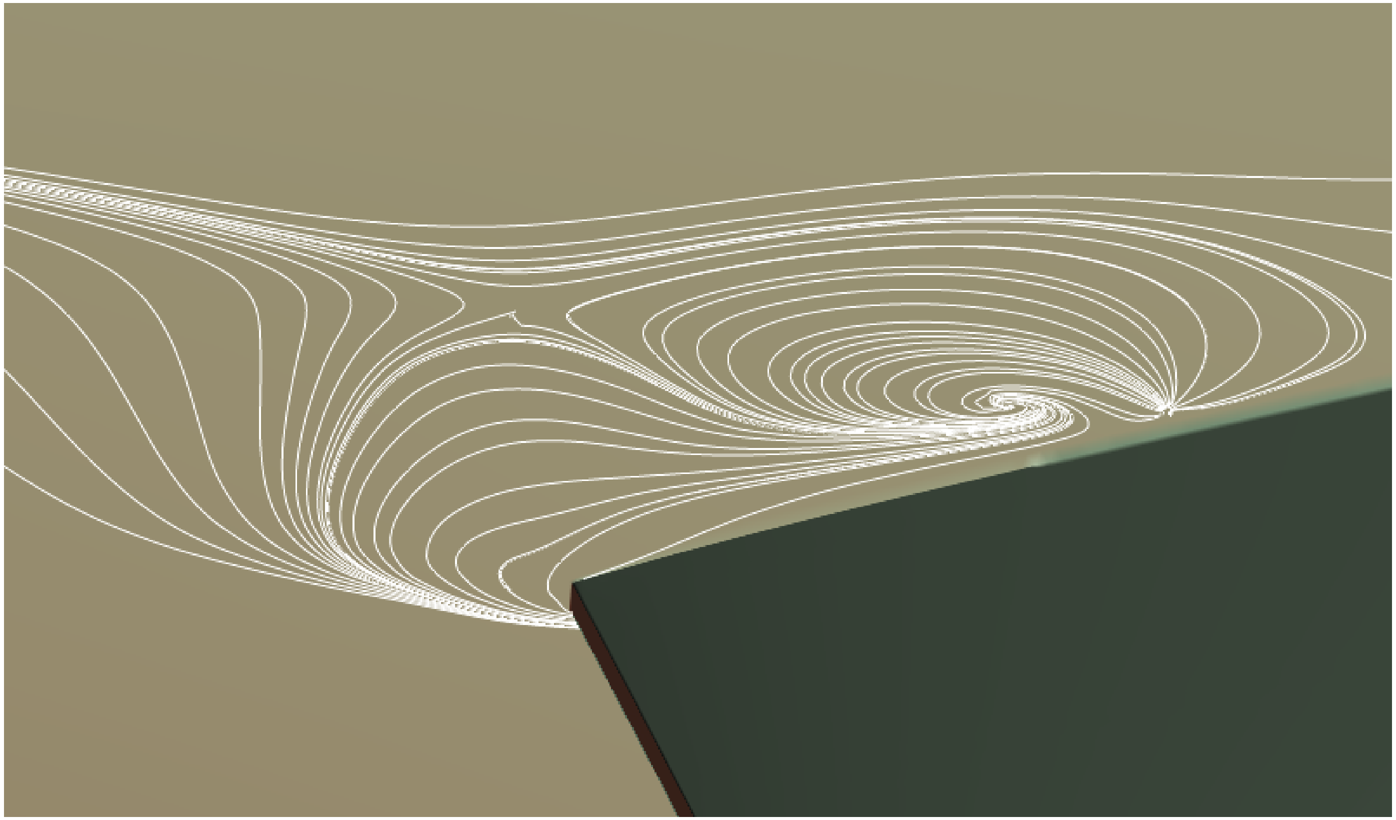
Fine mesh



Case 1a : Juncture-Region
SOB Separation

SOB separation:

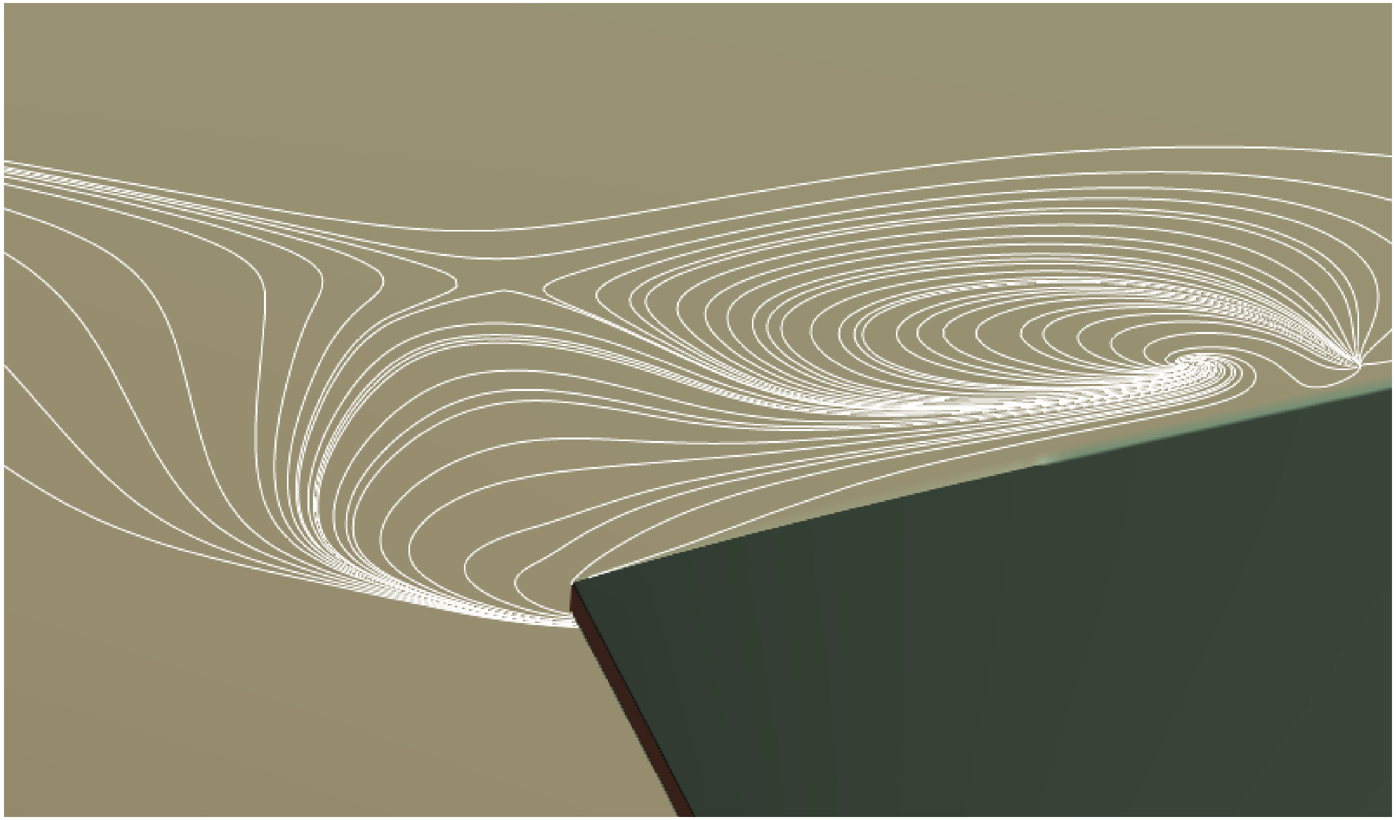
Extra Fine mesh



Case 1a : Juncture-Region
SOB Separation

SOB separation:

Ultra Fine mesh

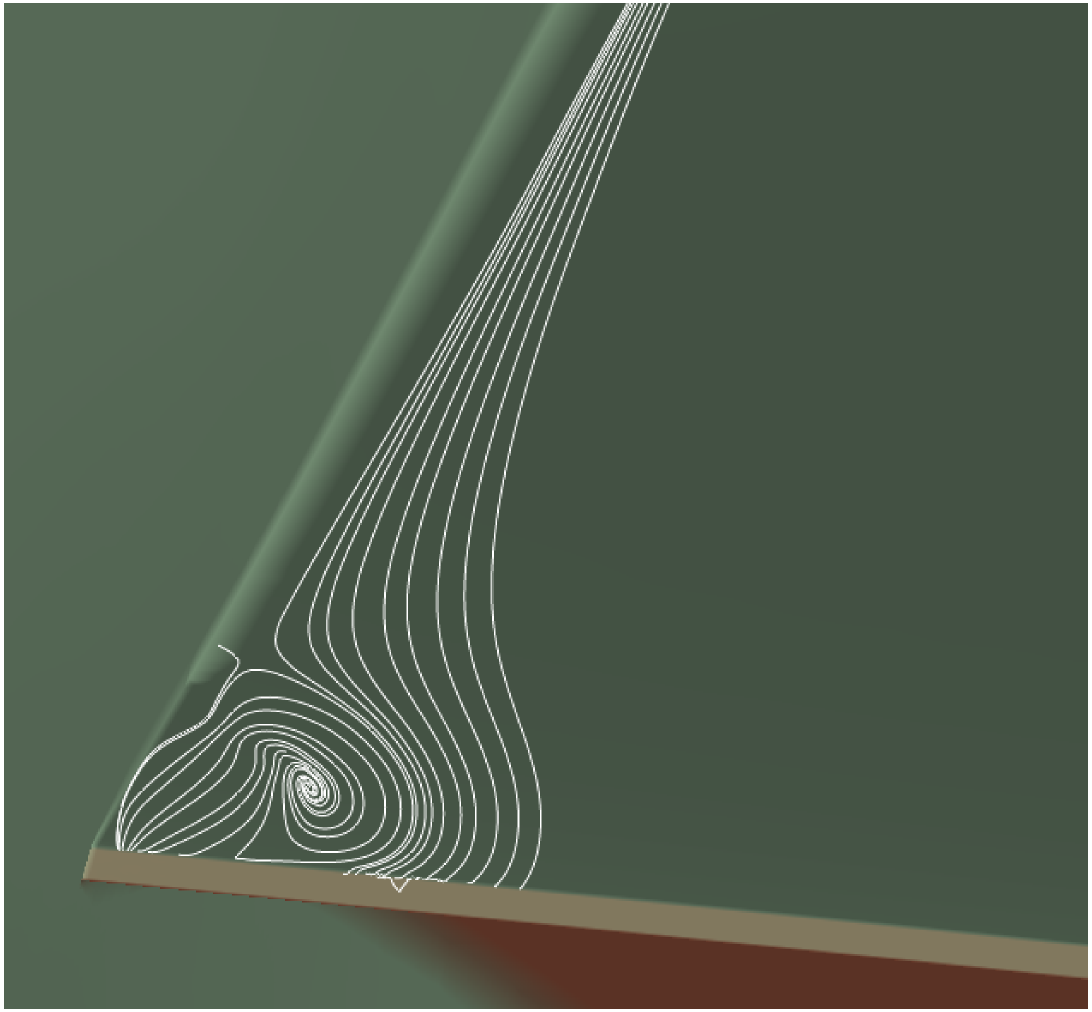


Case 1a : Juncture-Region Wing Separation

Case 1a : Juncture-Region
Wing Separation

Wing separation:

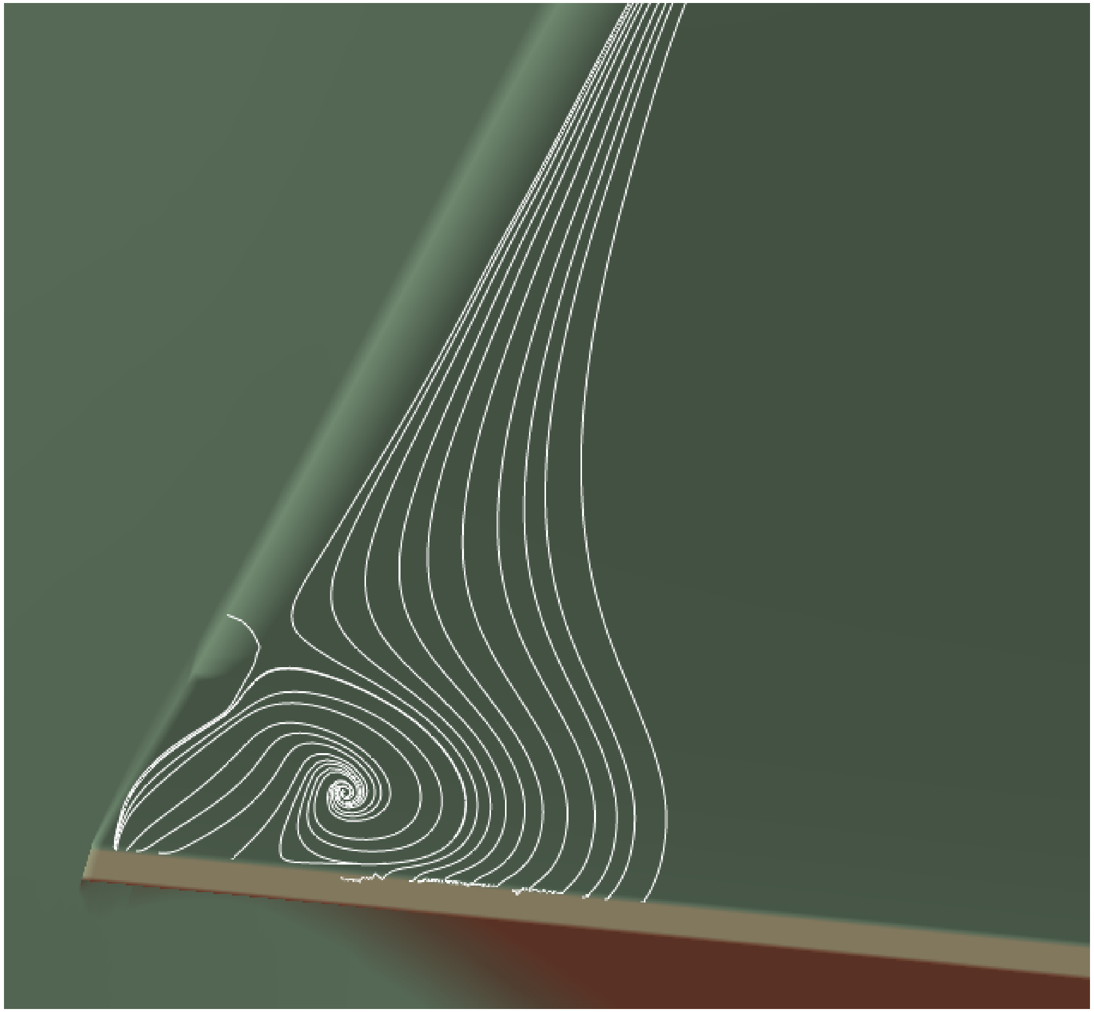
Tiny mesh



Case 1a : Juncture-Region
Wing Separation

Wing separation:

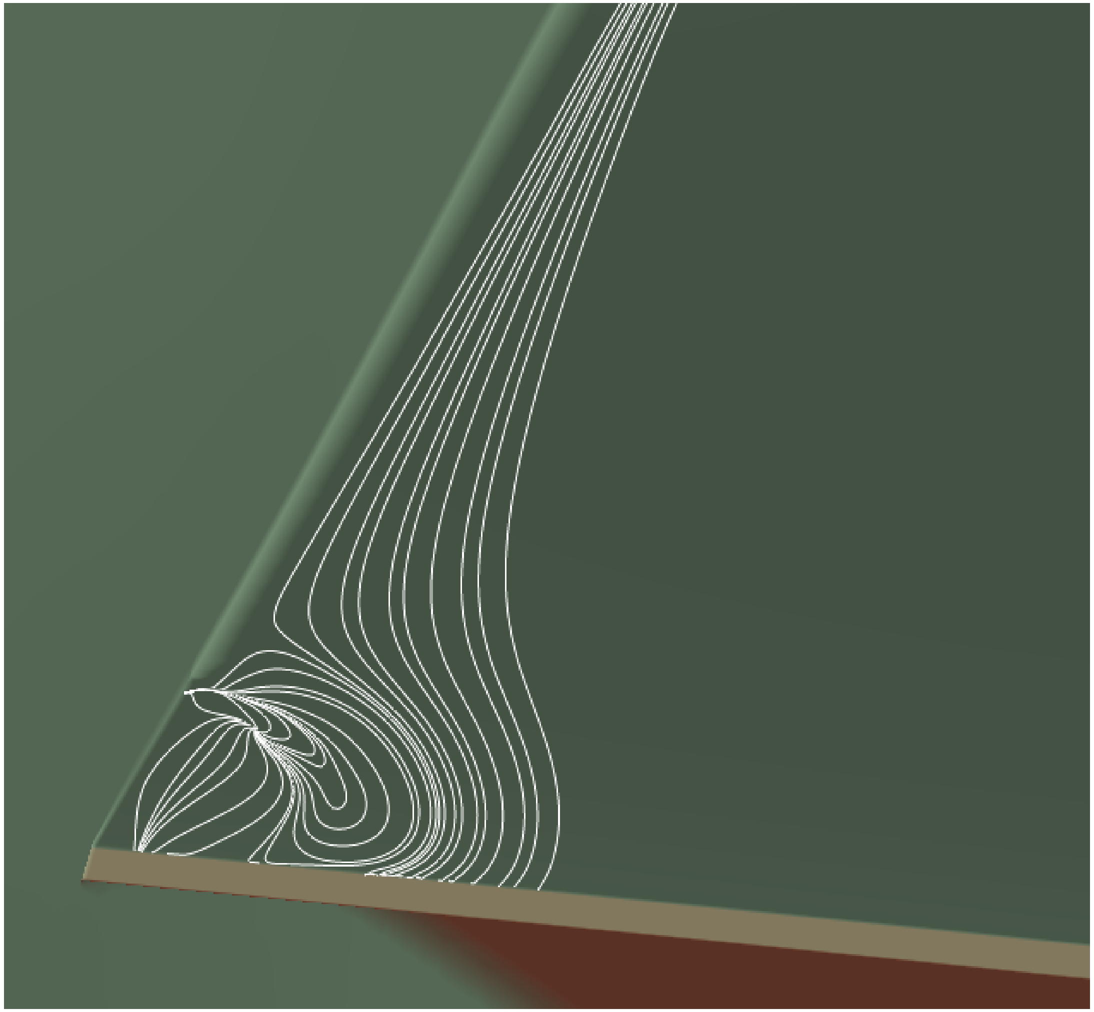
Coarse mesh



Case 1a : Juncture-Region
Wing Separation

Wing separation:

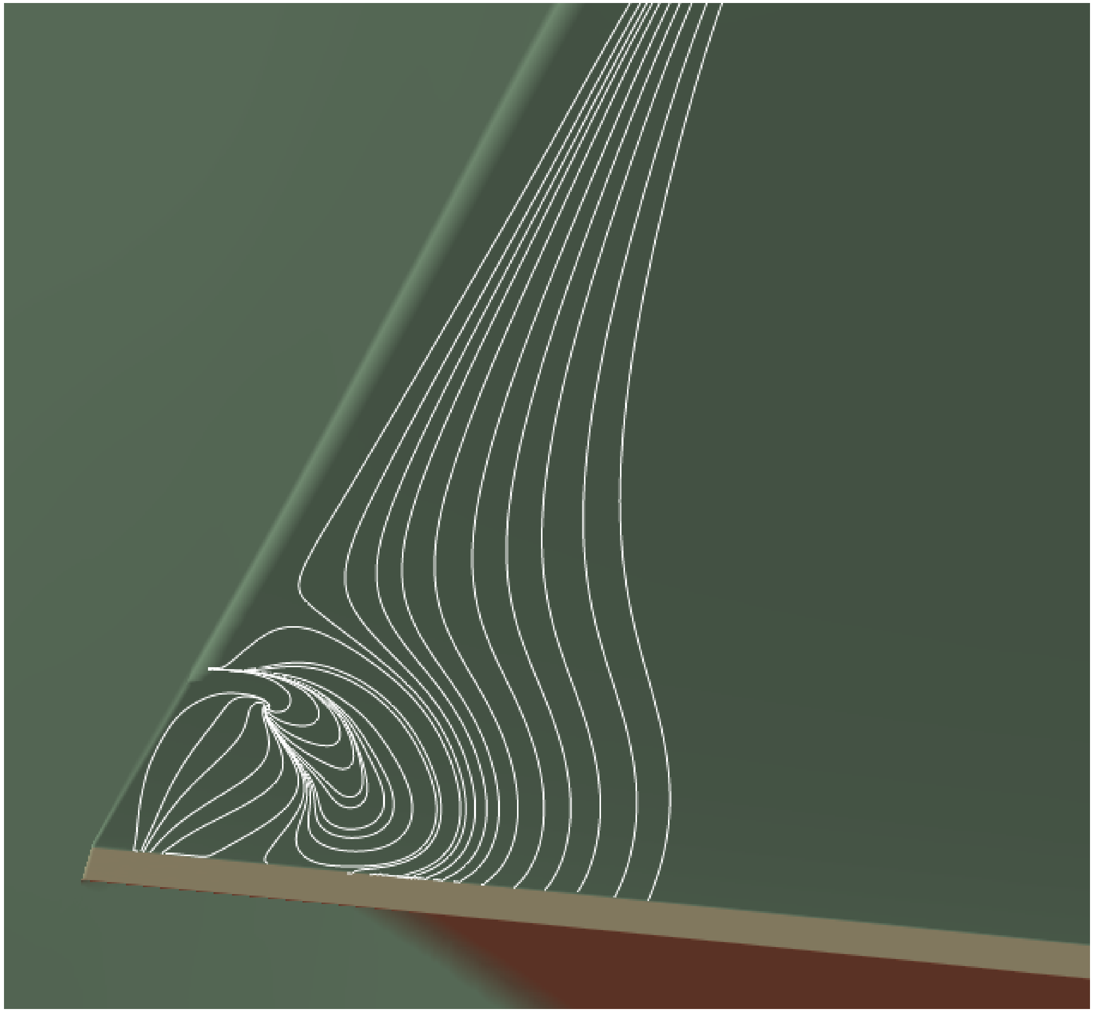
Medium mesh



Case 1a : Juncture-Region
Wing Separation

Wing separation:

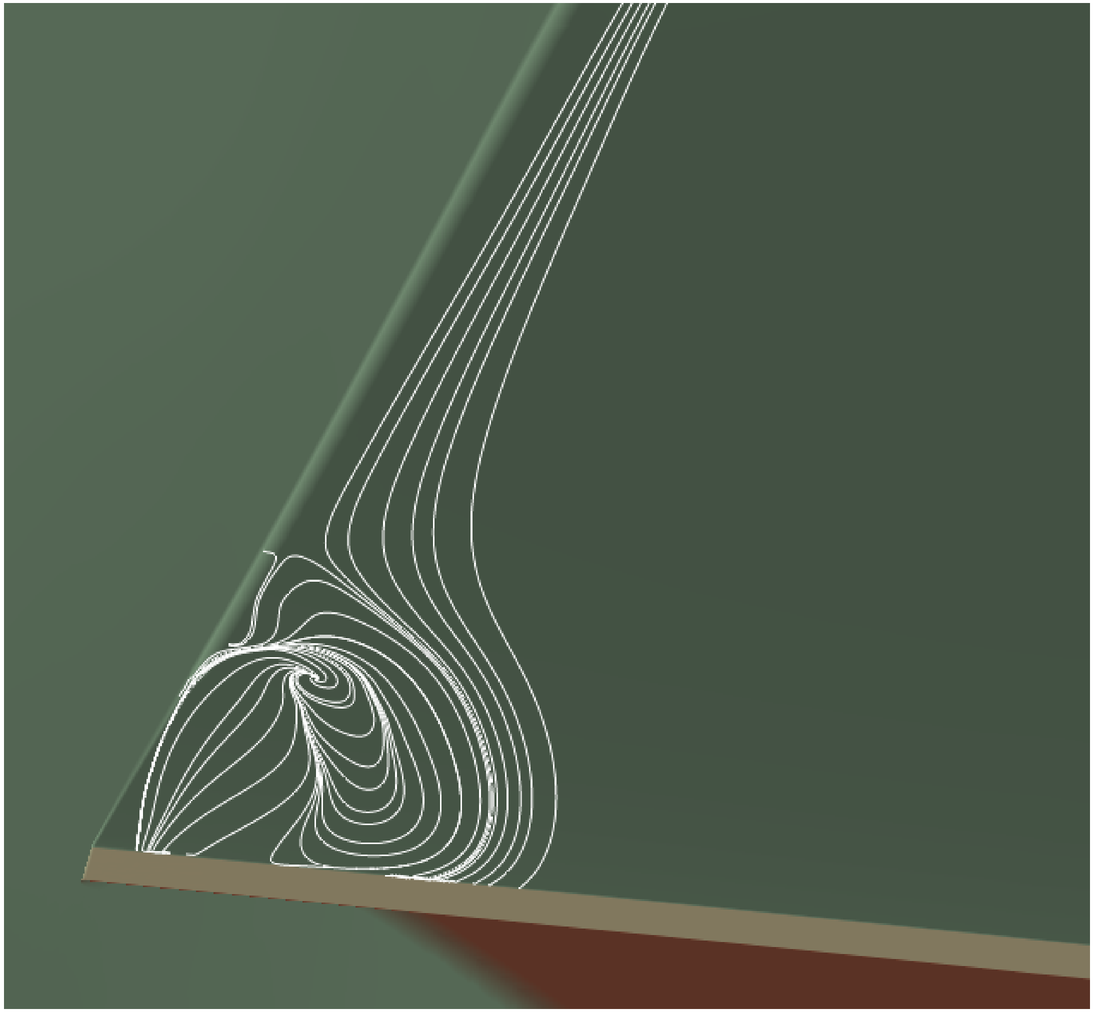
Fine mesh



Case 1a : Juncture-Region
Wing Separation

Wing separation:

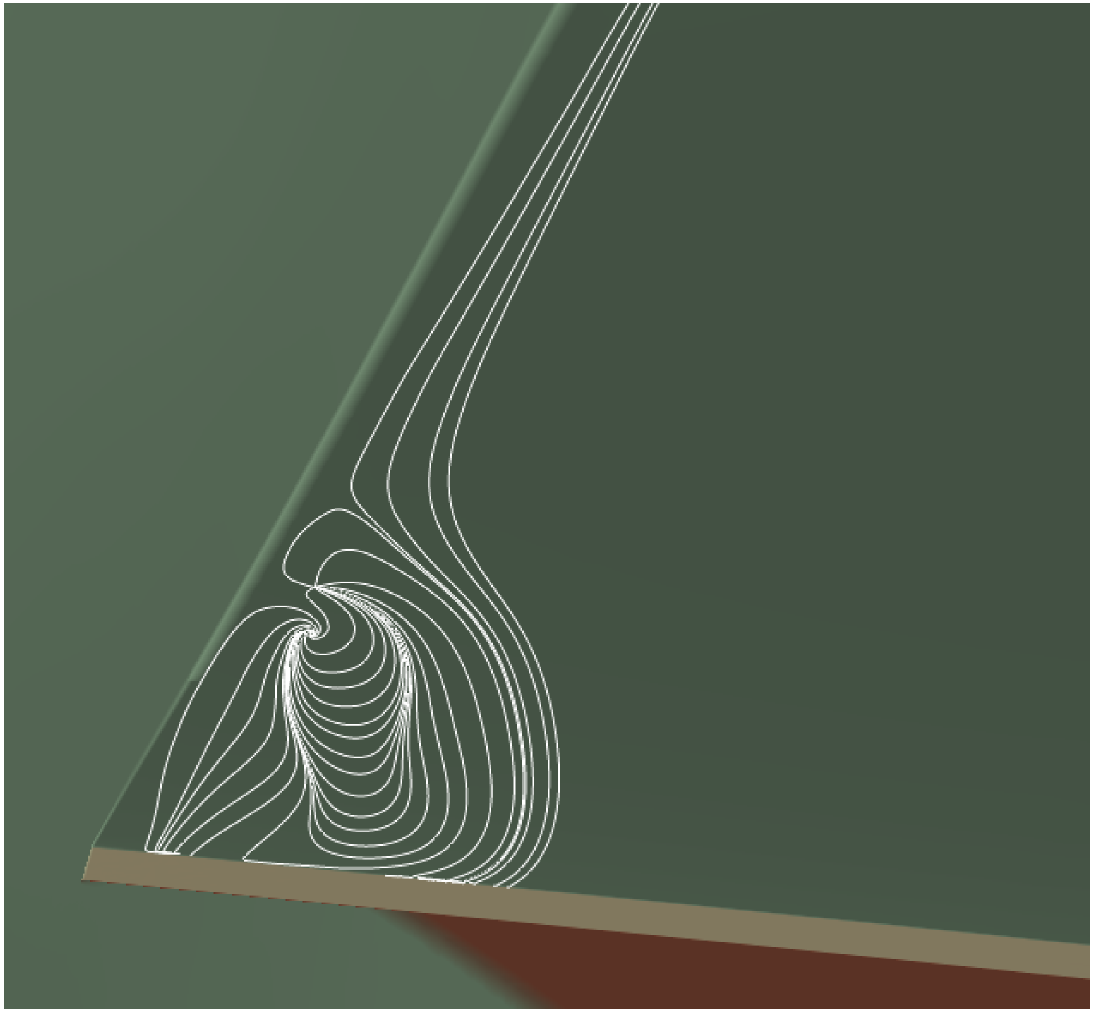
Extra Fine mesh



Case 1a : Juncture-Region
Wing Separation

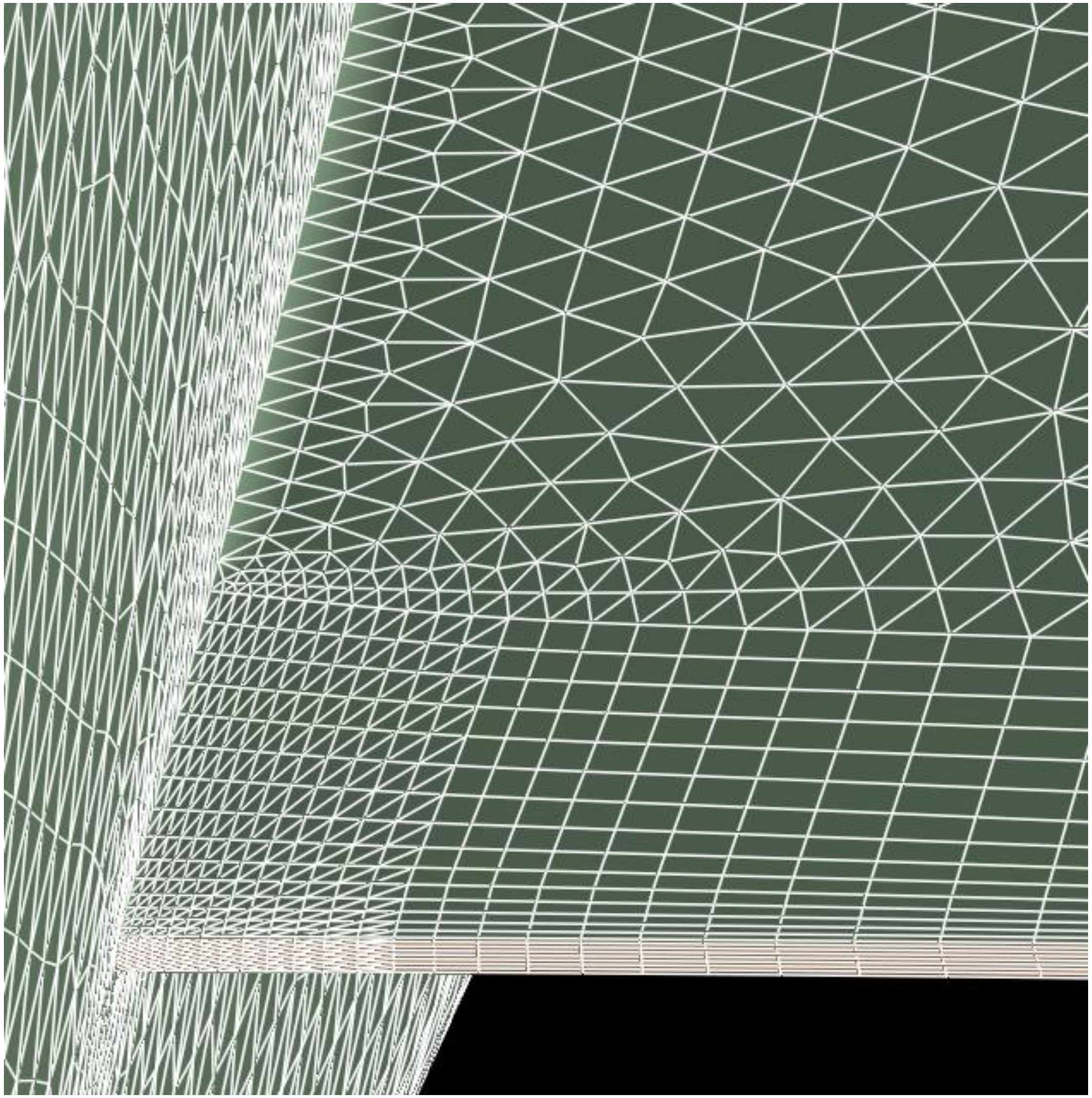
Wing separation:

Ultra Fine mesh



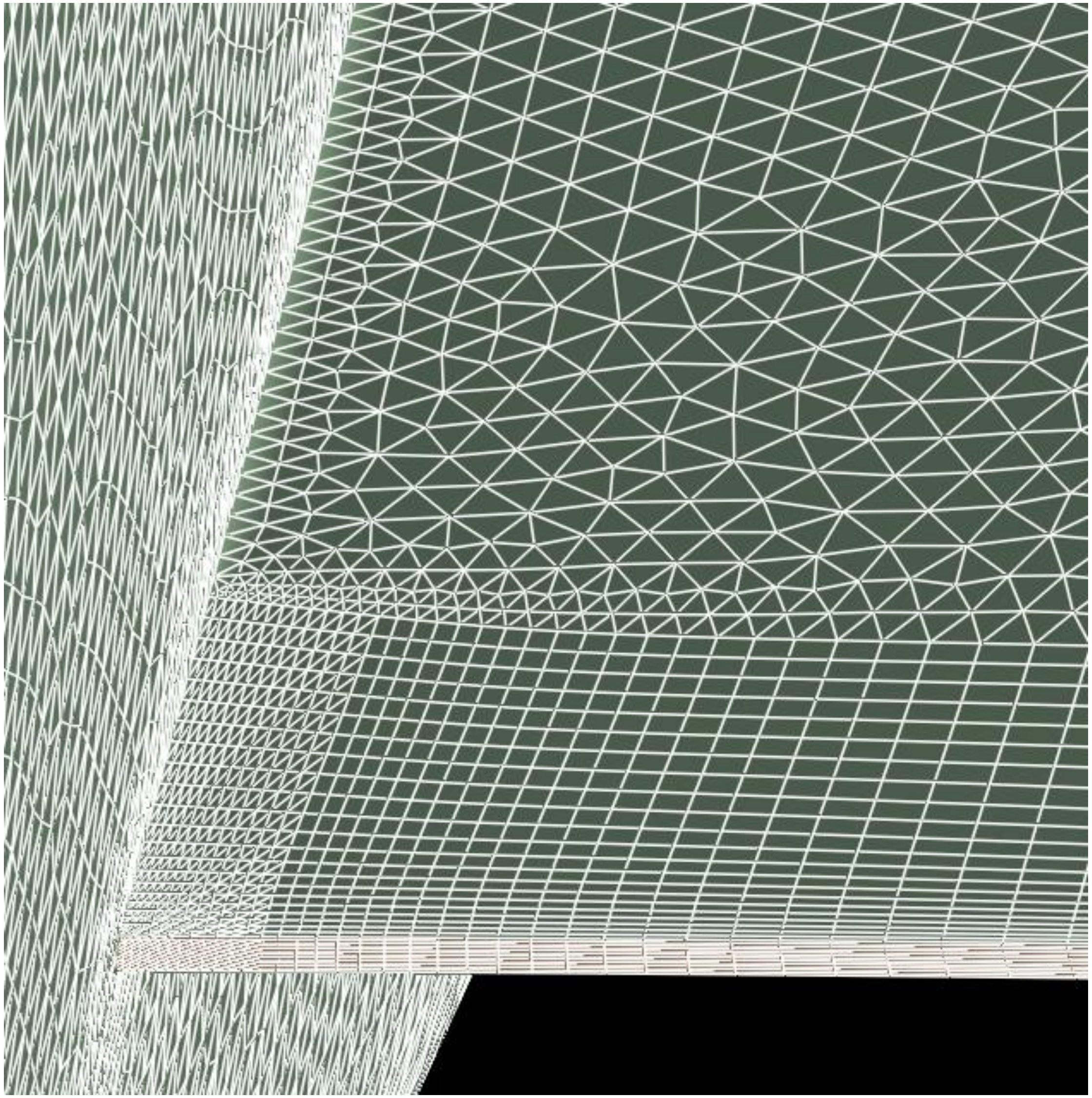
Case 1a : Juncture-Region Mesh

Tiny mesh



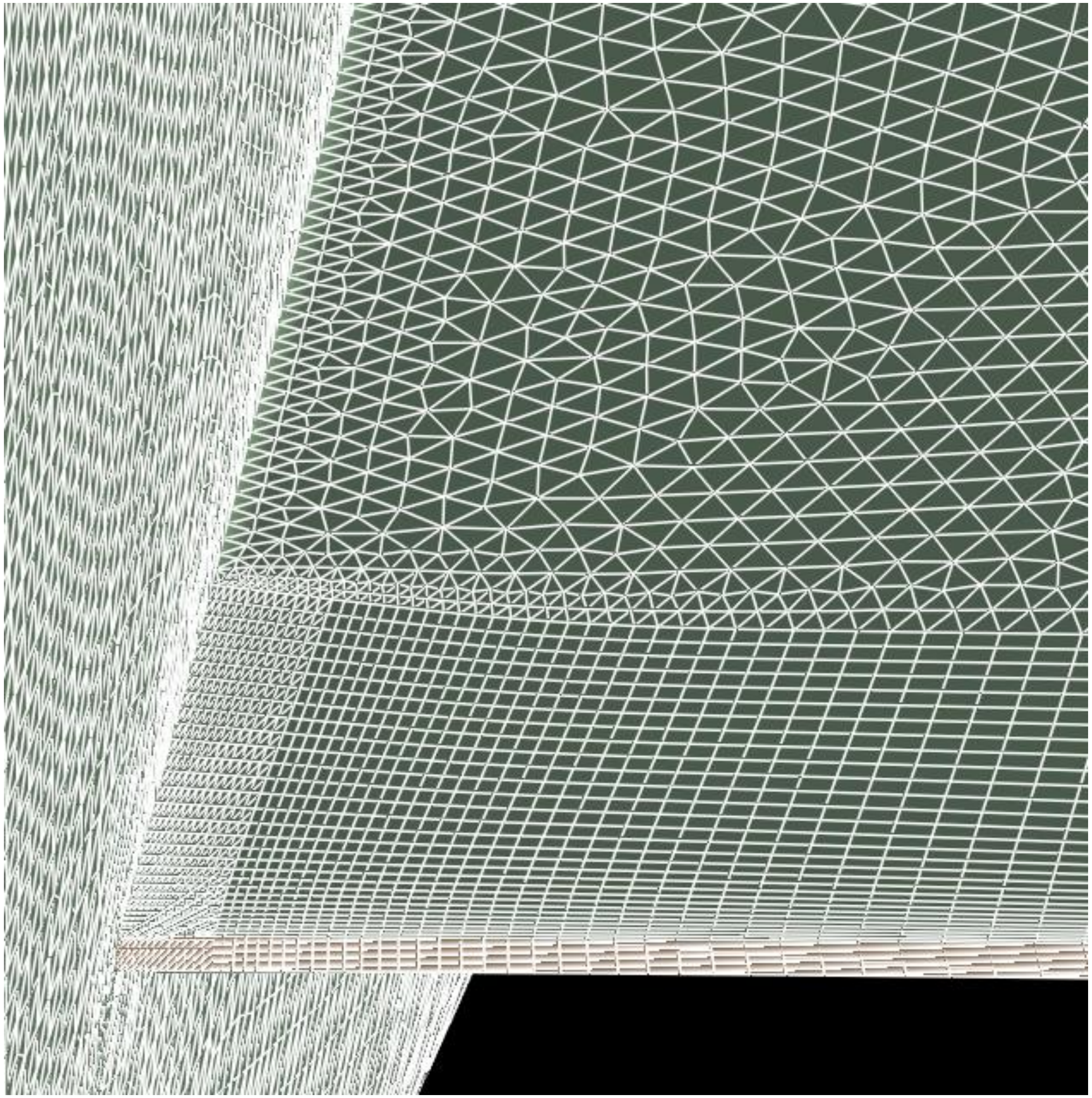
Case 1a : Juncture-Region Mesh

Coarse mesh



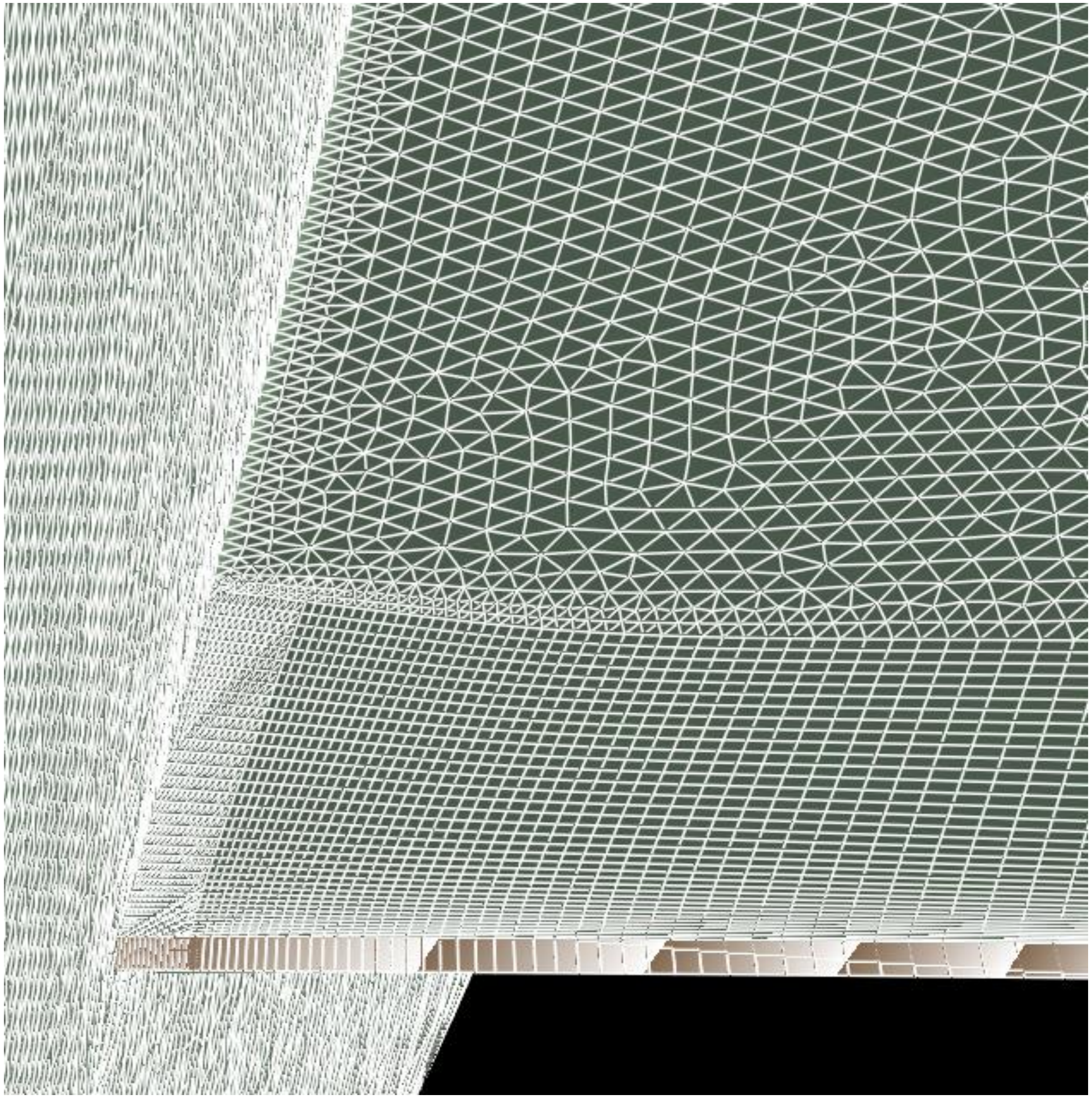
Case 1a : Juncture-Region Mesh

Medium mesh



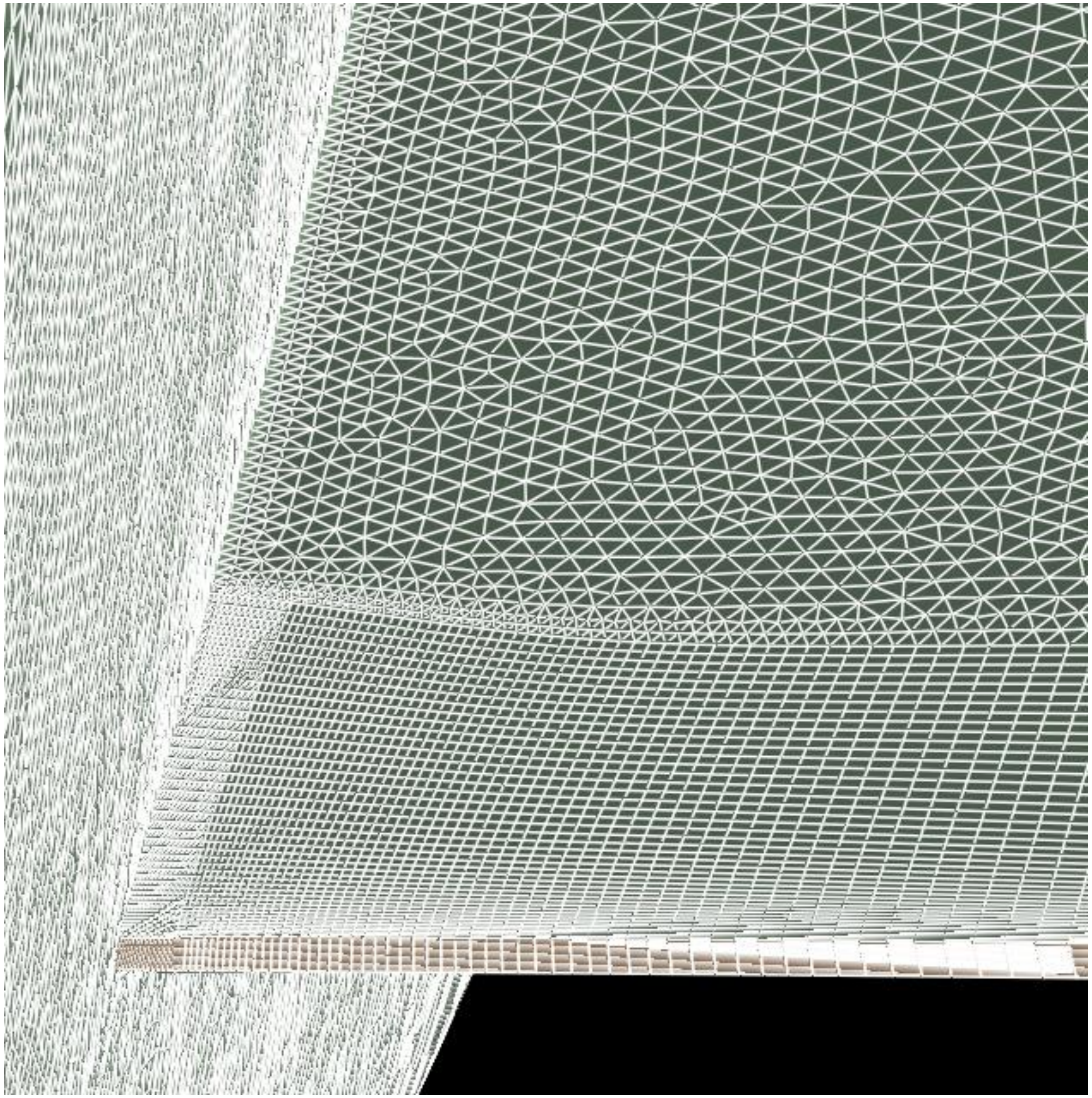
Case 1a : Juncture-Region Mesh

Fine mesh



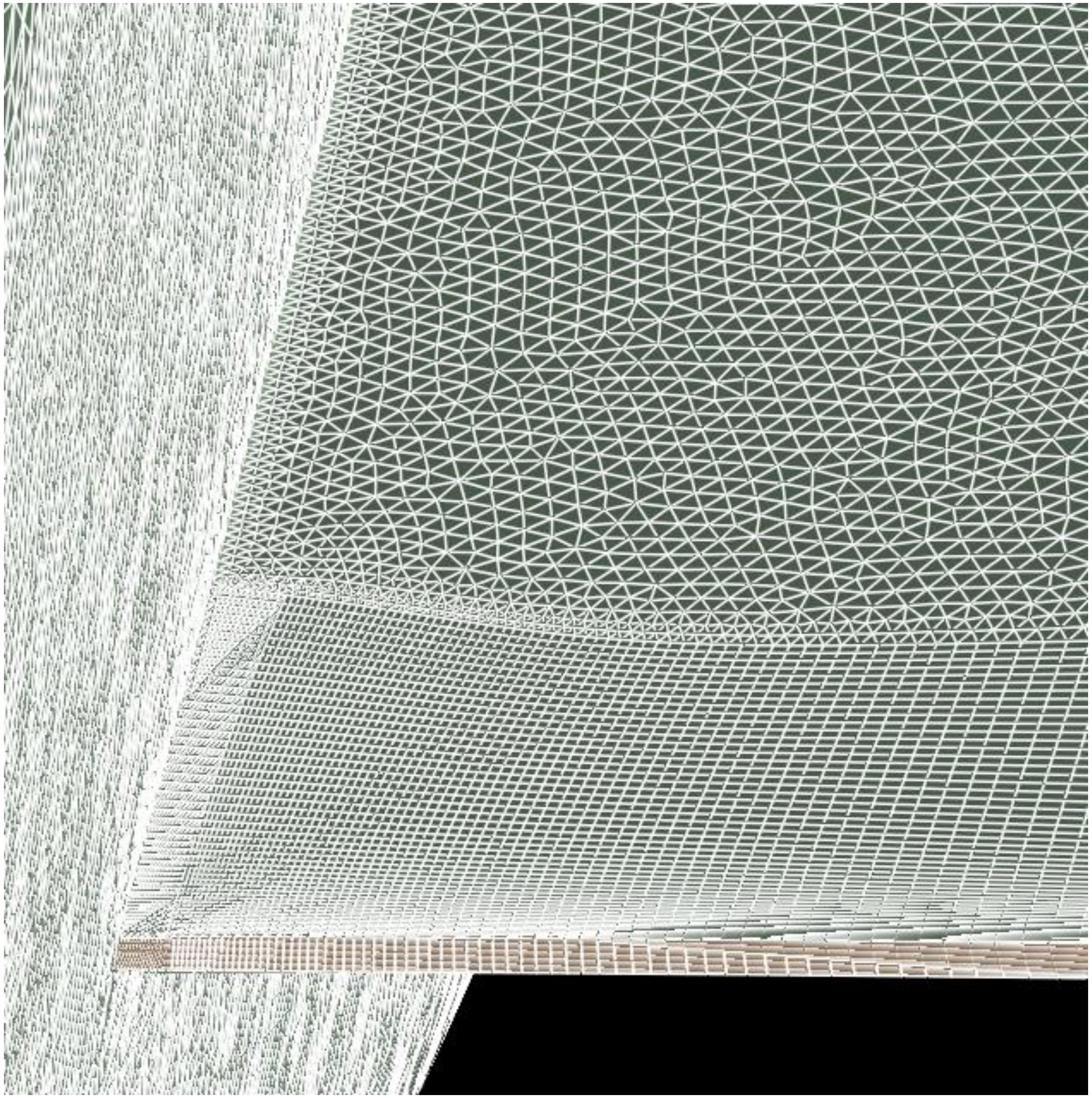
Case 1a : Juncture-Region Mesh

ExtraFine mesh



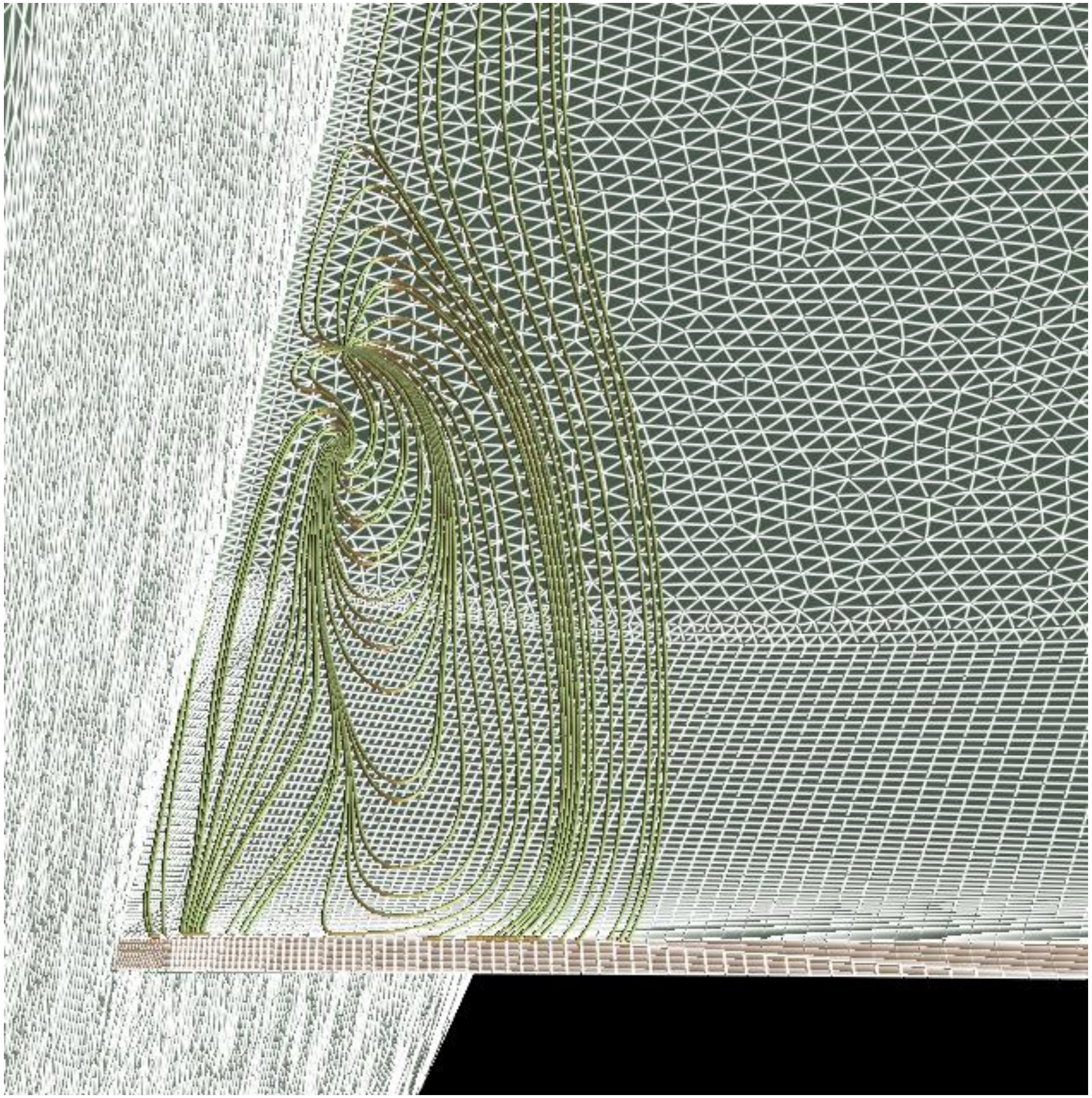
Case 1a : Juncture-Region Mesh

UltraFine mesh



Case 1a : Juncture-Region Mesh

UltraFine mesh + surface srteamlines



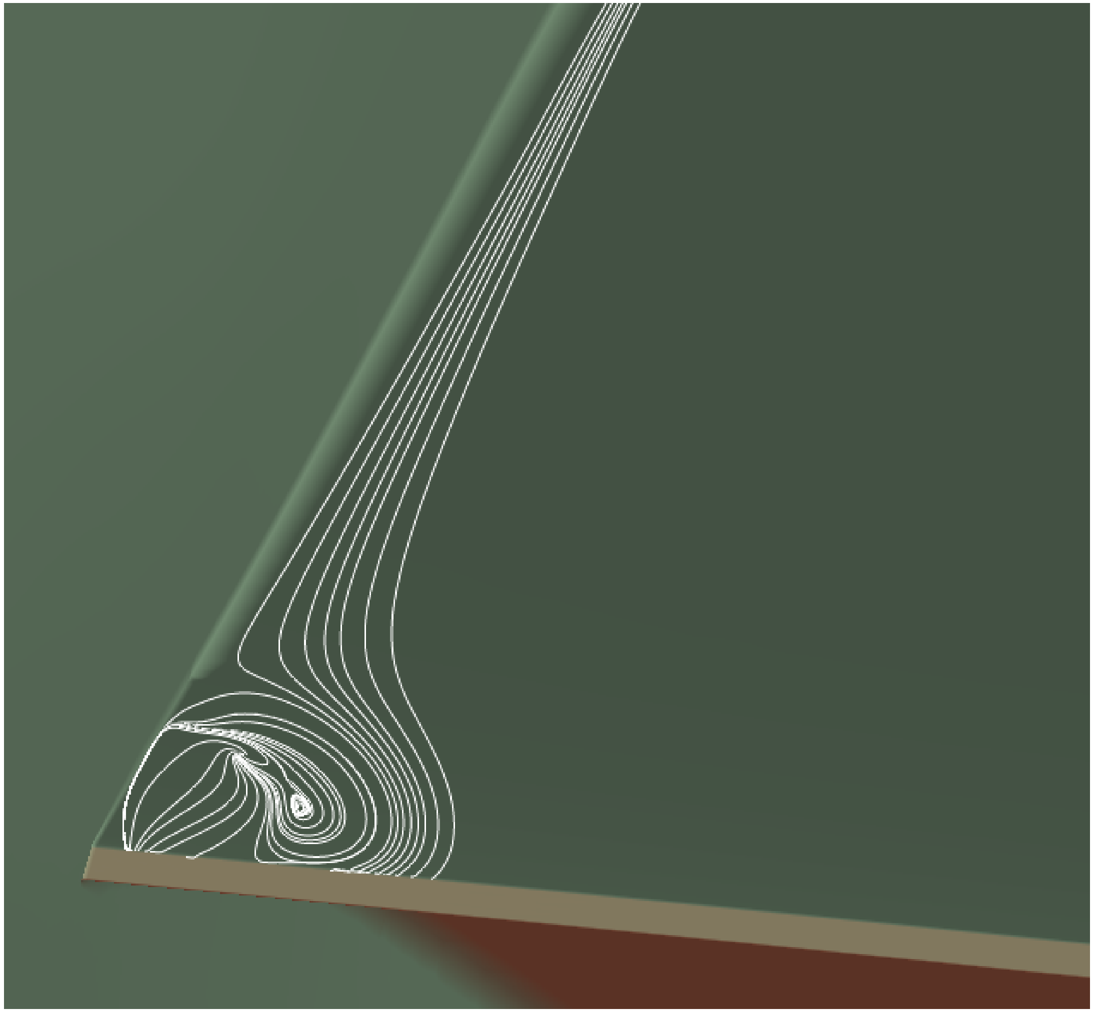
Case 2a : Juncture-Region Wing Separation

Case 2a : Juncture-Region
Wing Separation

Wing separation:

C_L=0.50

2.50° LoQ AE CRM geometry

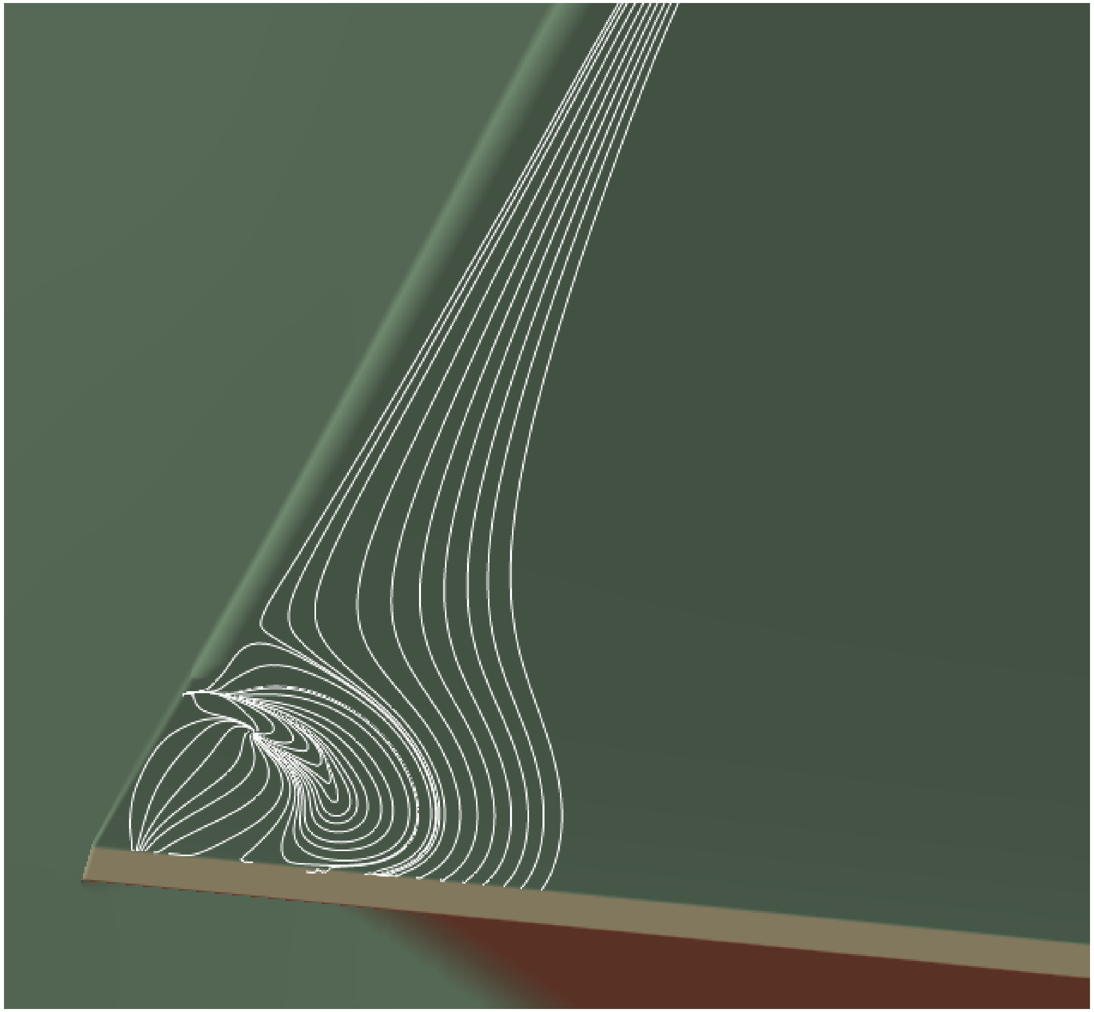


Case 2a : Juncture-Region
Wing Separation

Wing separation:

α=2.75˚

2.75˚ LoQ AE CRM geometry

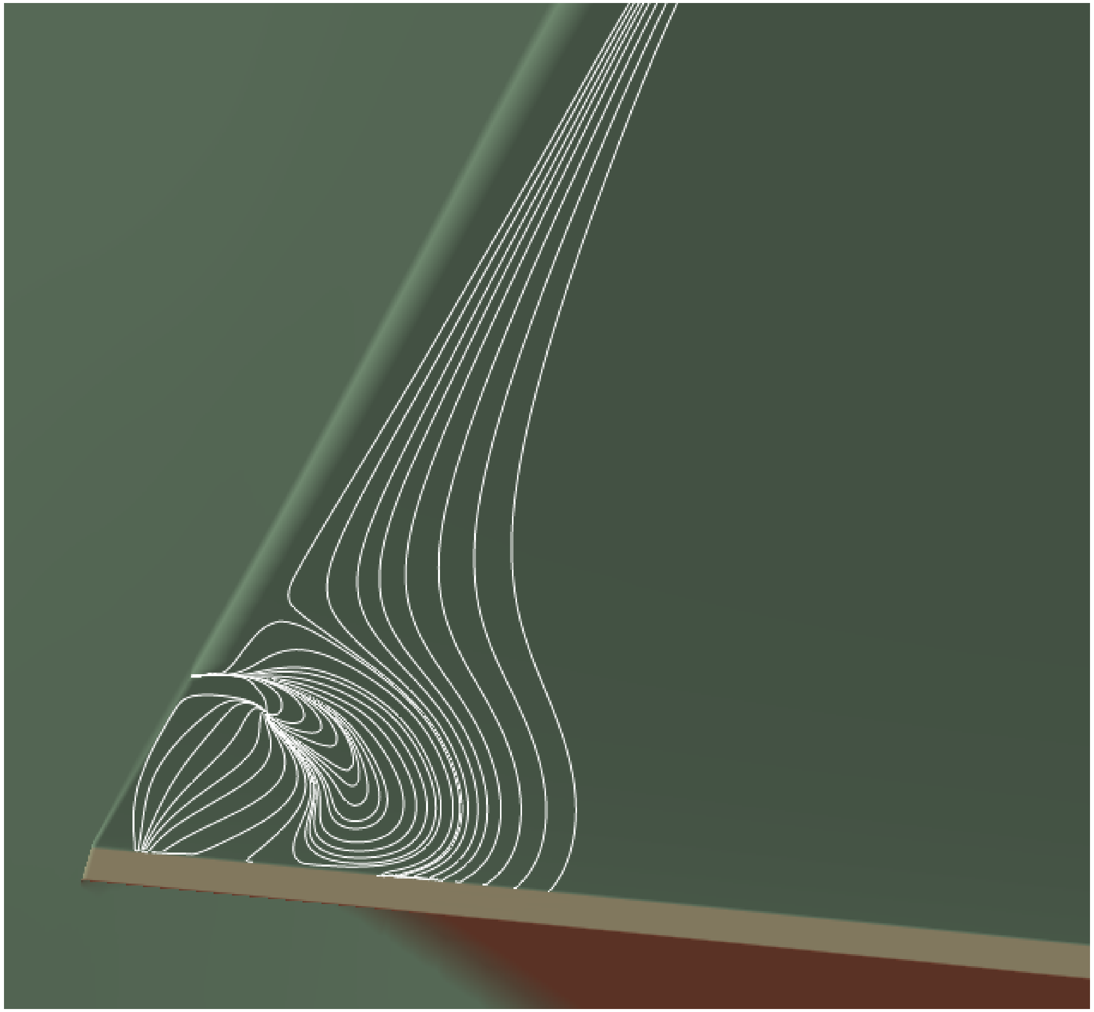


Case 2a : Juncture-Region
Wing Separation

Wing separation:

α=3.00˚

3.00˚ LoQ AE CRM geometry

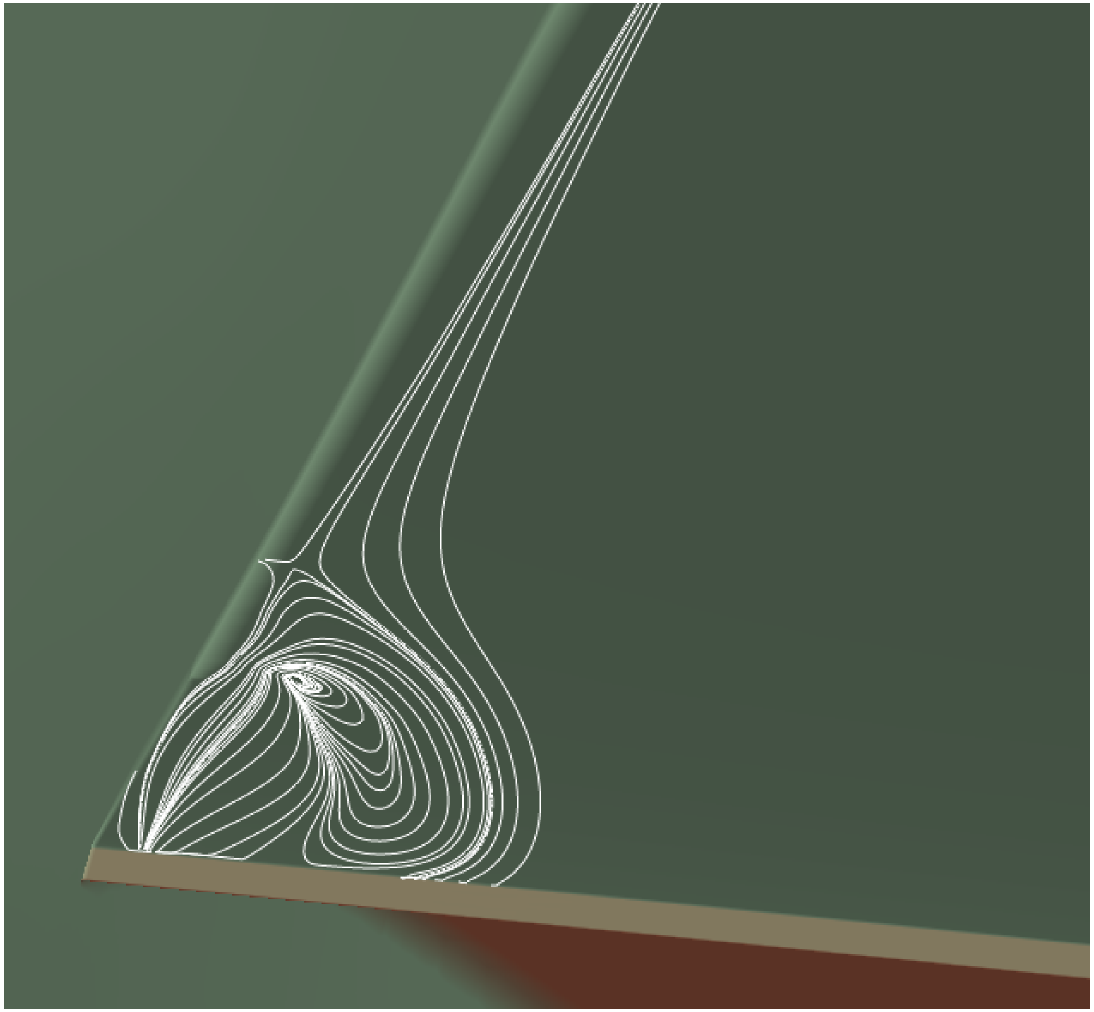


Case 2a : Juncture-Region
Wing Separation

Wing separation:

α=3.25˚

3.25˚ LoQ AE CRM geometry

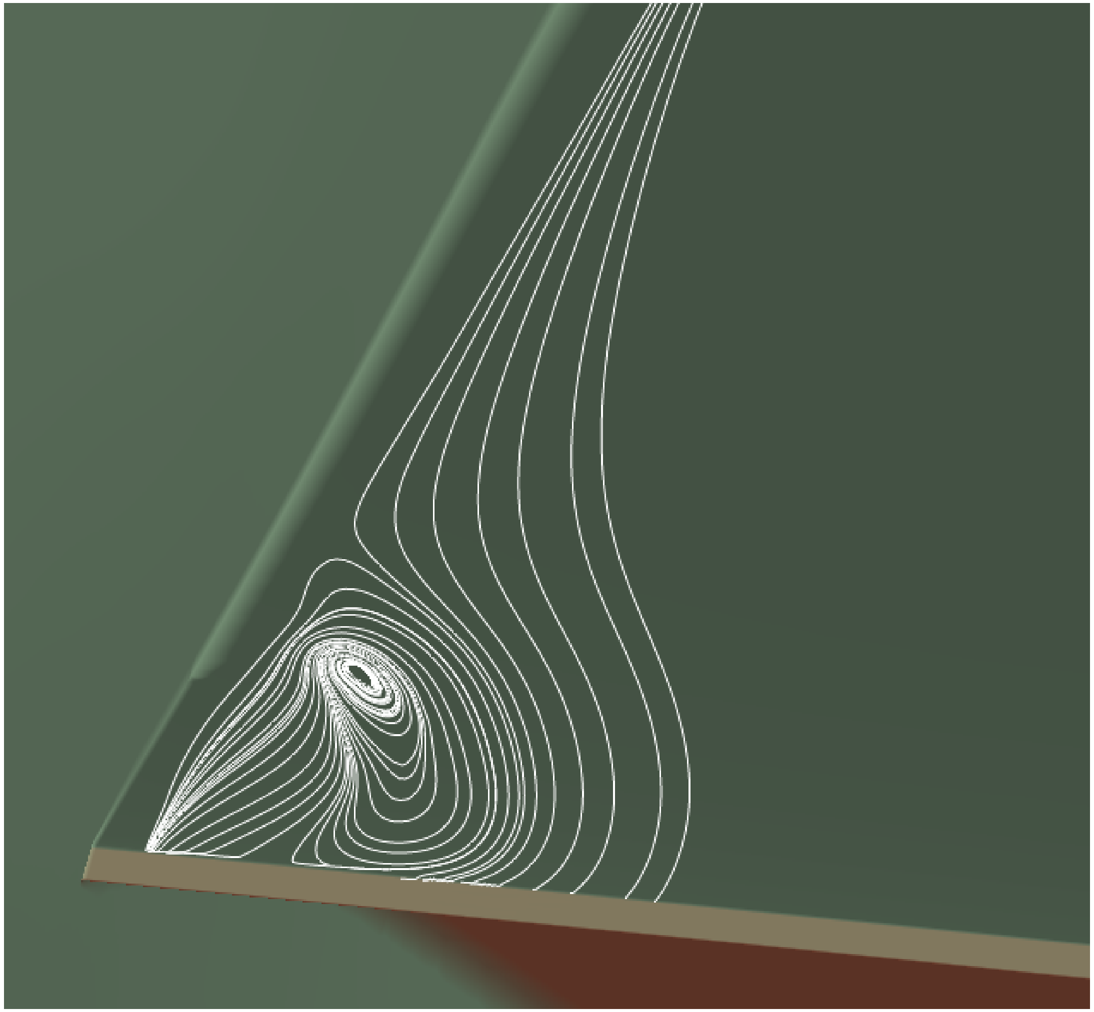


Case 2a : Juncture-Region
Wing Separation

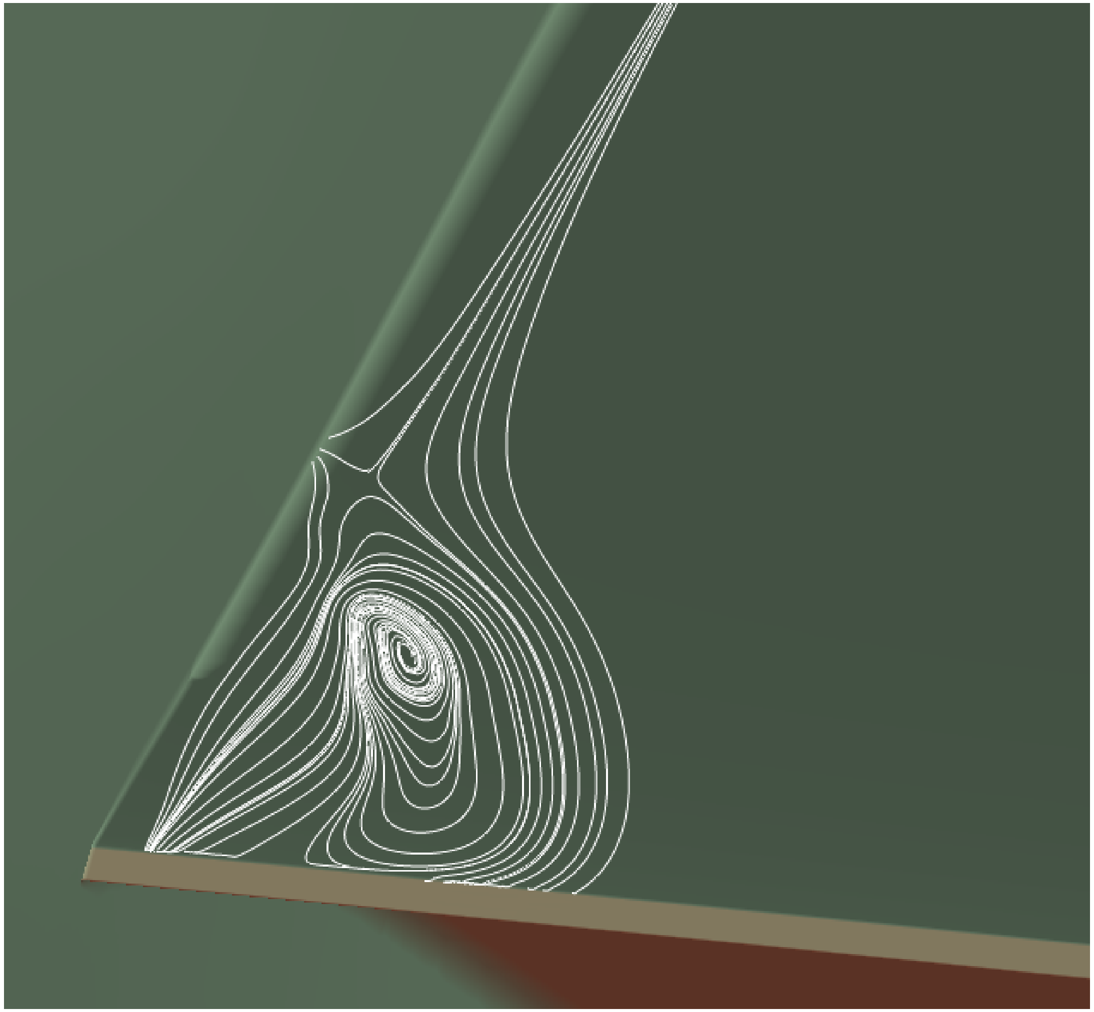
Wing separation:

α=3.50˚

3.50˚ LoQ AE CRM geometry



Case 2a : Juncture-Region
Wing Separation



Wing separation:

α=3.75˚

3.75˚ LoQ AE CRM geometry

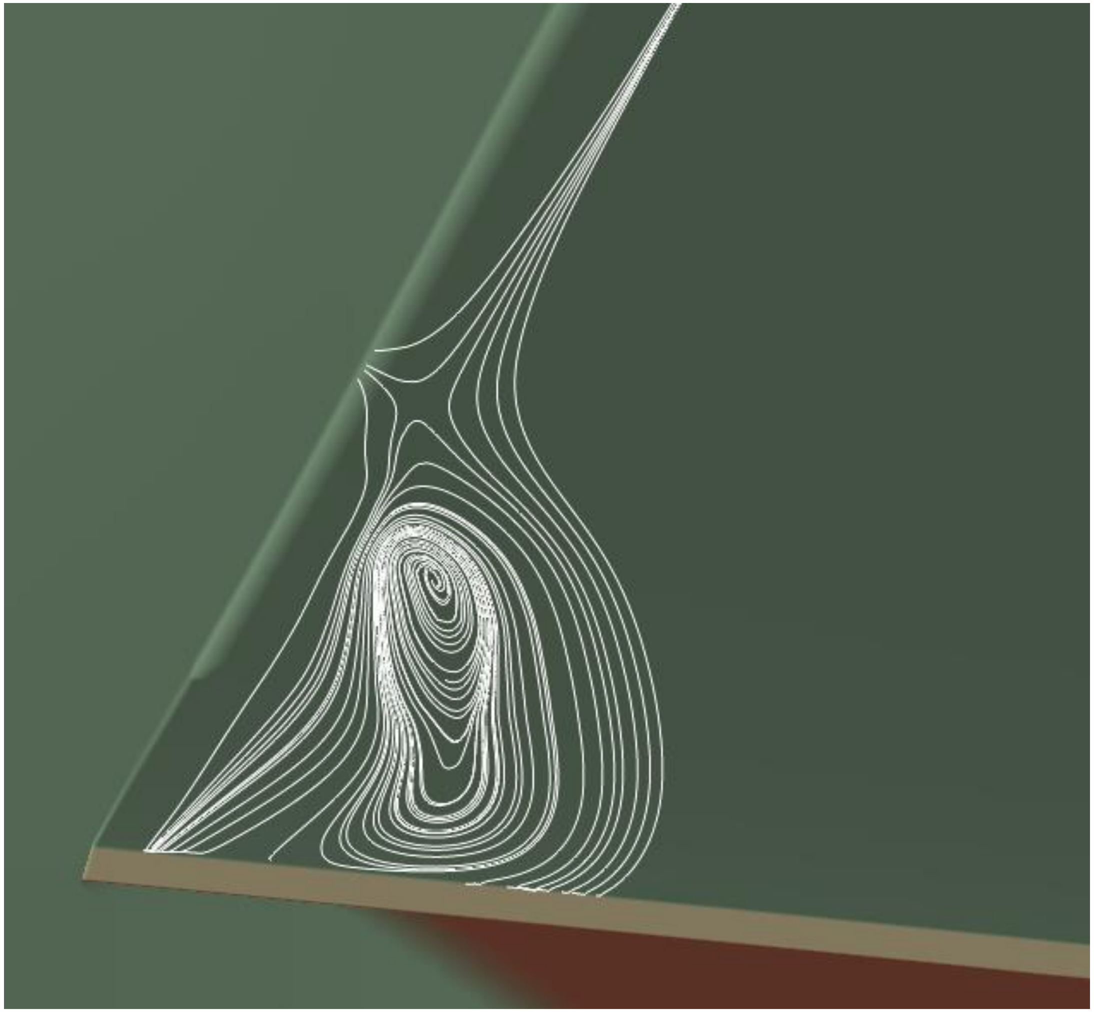
Case 2a : Juncture-Region
Wing Separation

Wing separation:

α=4.00˚

4.00˚ LoQ AE CRM

geometry

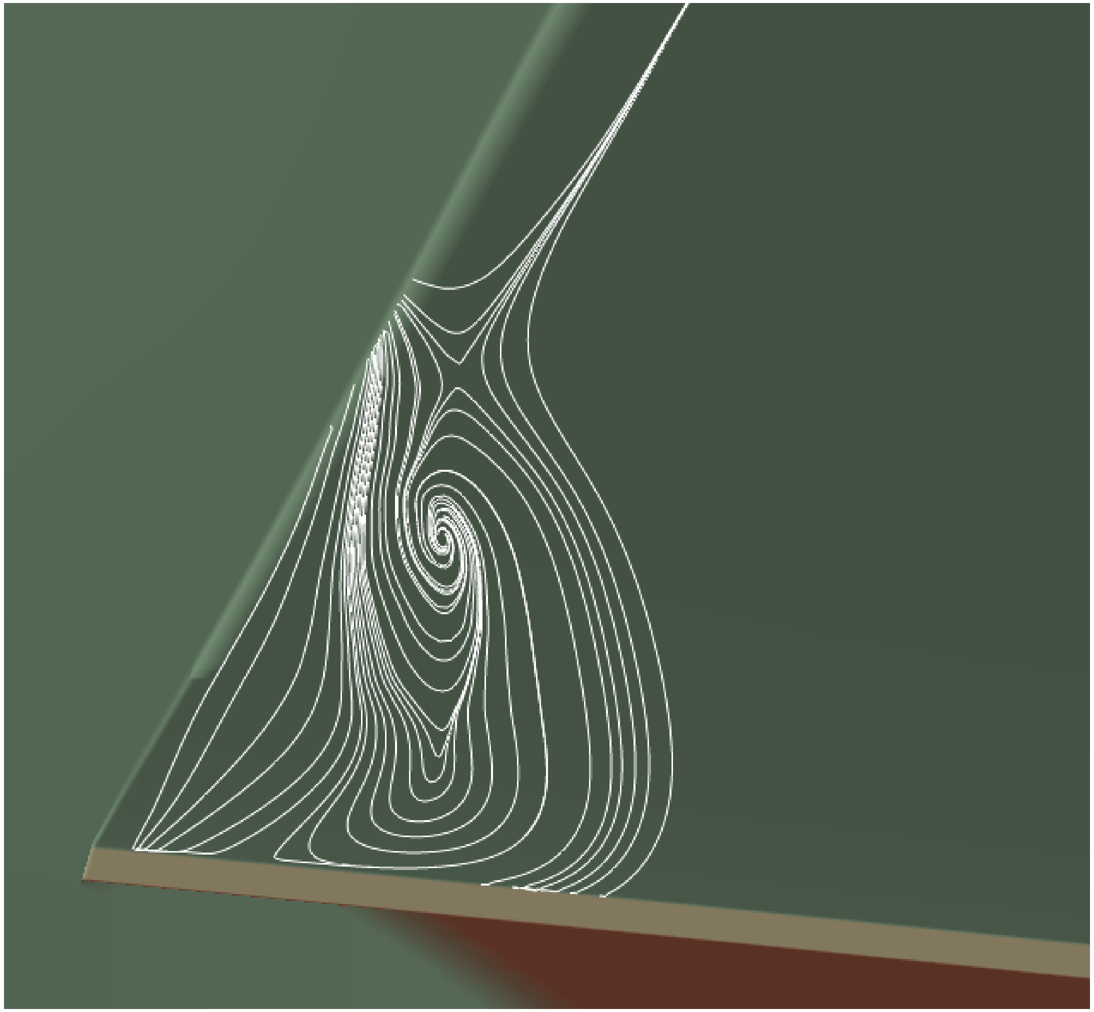


Case 2a : Juncture-Region
Wing Separation

Wing separation:

α=4.25˚

4.25˚ LoQ AE CRM geometry



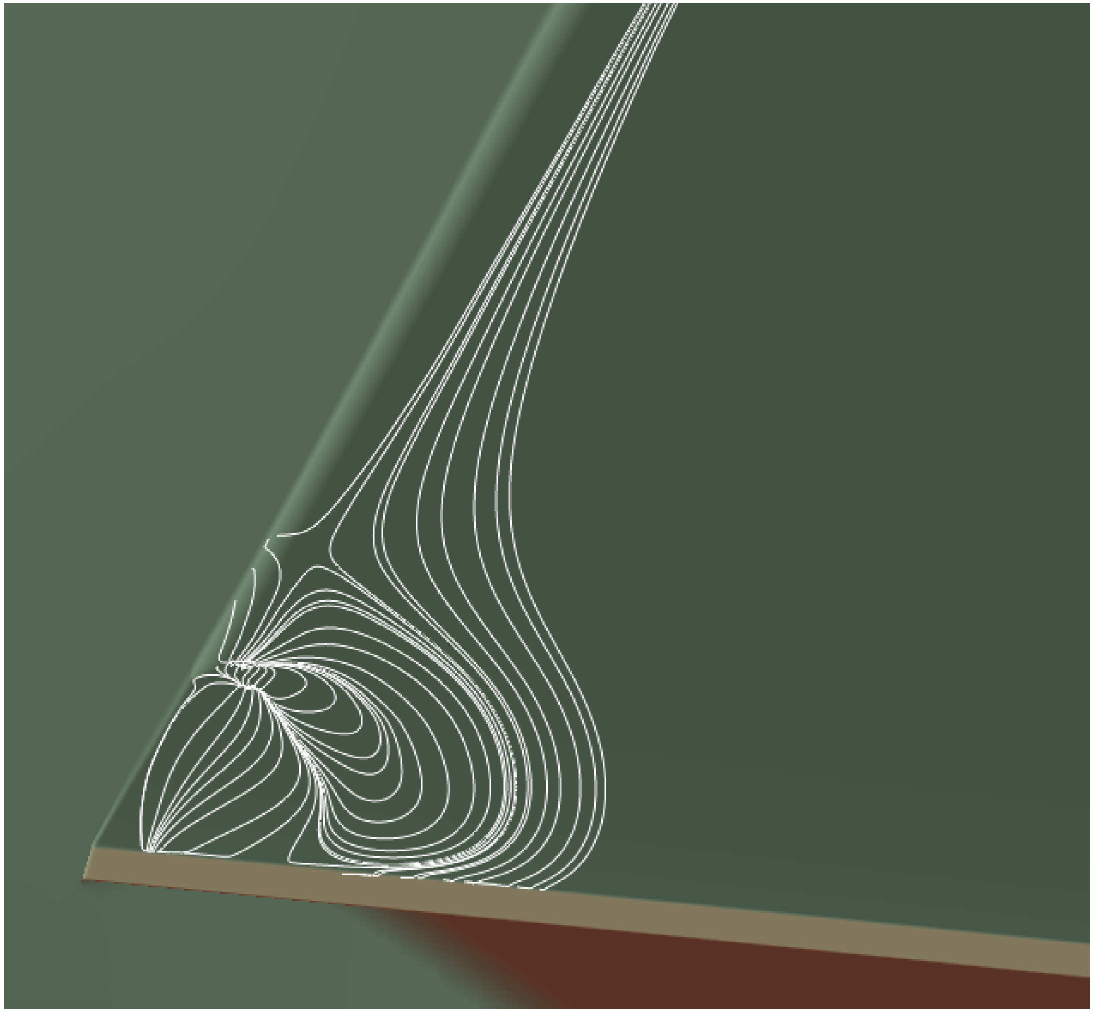
Case 3 : Juncture-Region Wing Separation

Case 3 : Juncture-Region
Wing Separation

Wing separation:

Re=5M, C_L=0.50

2.50˚ LoQ AE CRM geometry



Case 3 : Juncture-Region
Wing Separation

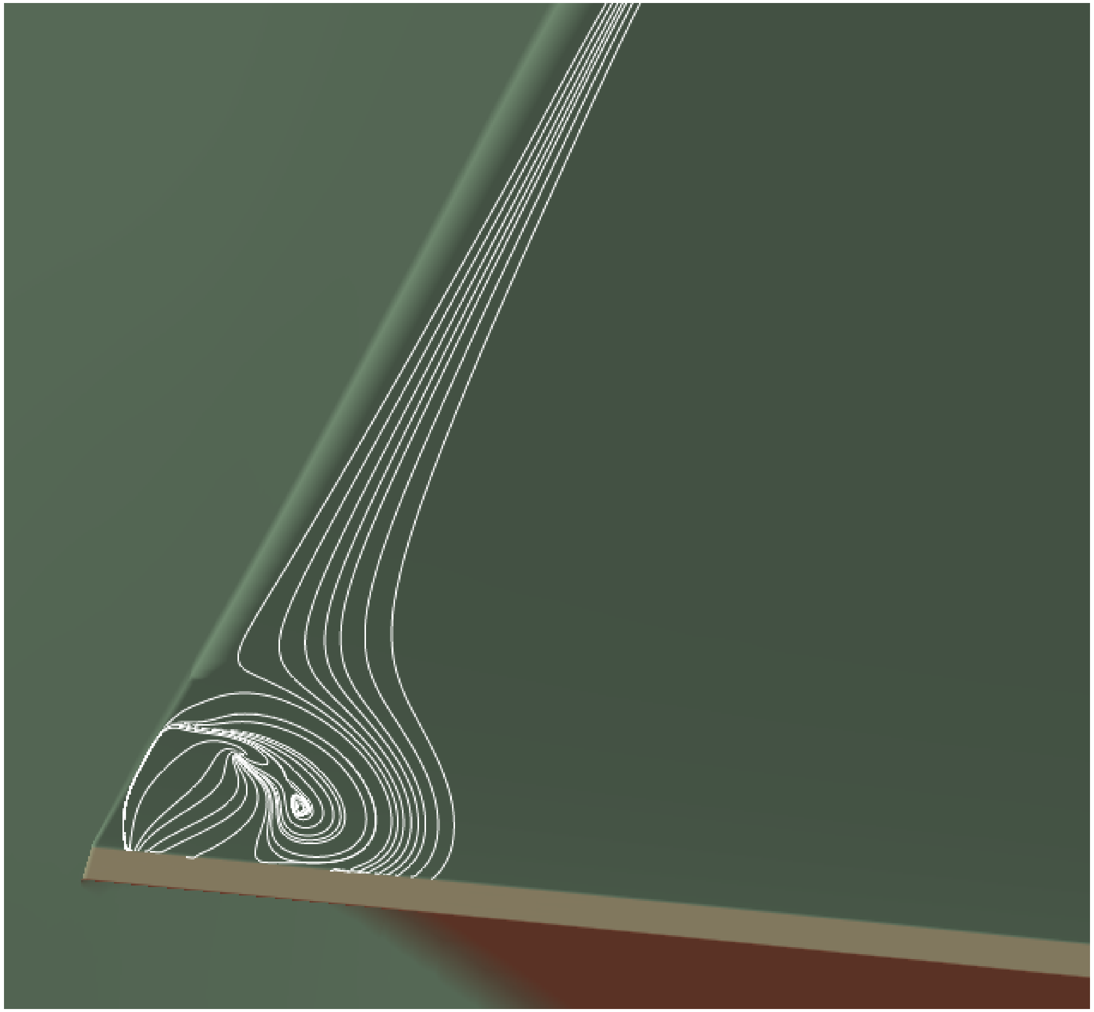
Wing separation:

Re=20M, C_L=0.50*

2.50° LoQ AE CRM

geometry

(same as Case 2a, C_L=0.50)



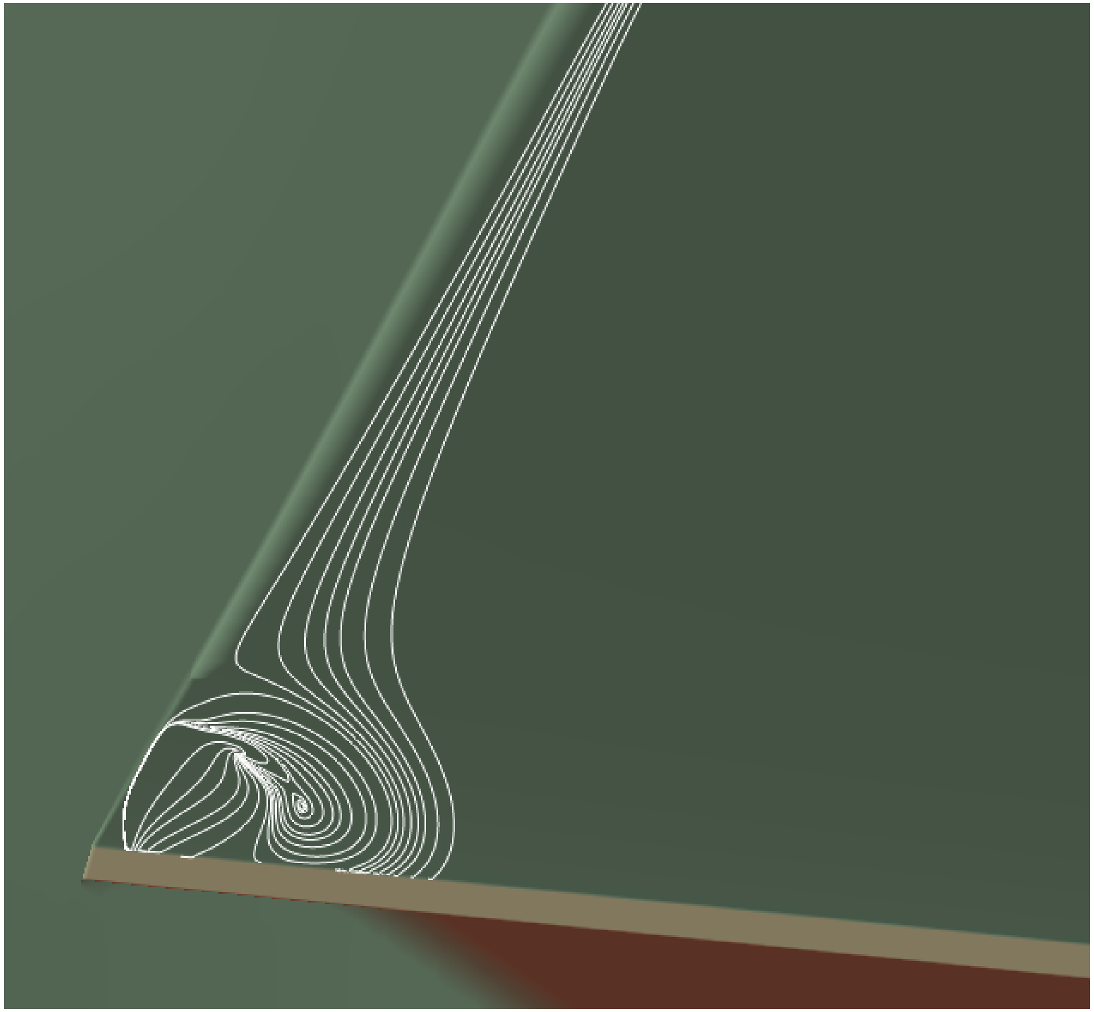
Case 3 : Juncture-Region
Wing Separation

Wing separation:

Re=20M, C_L=0.50

2.50˚ HiQ AE CRM

geometry



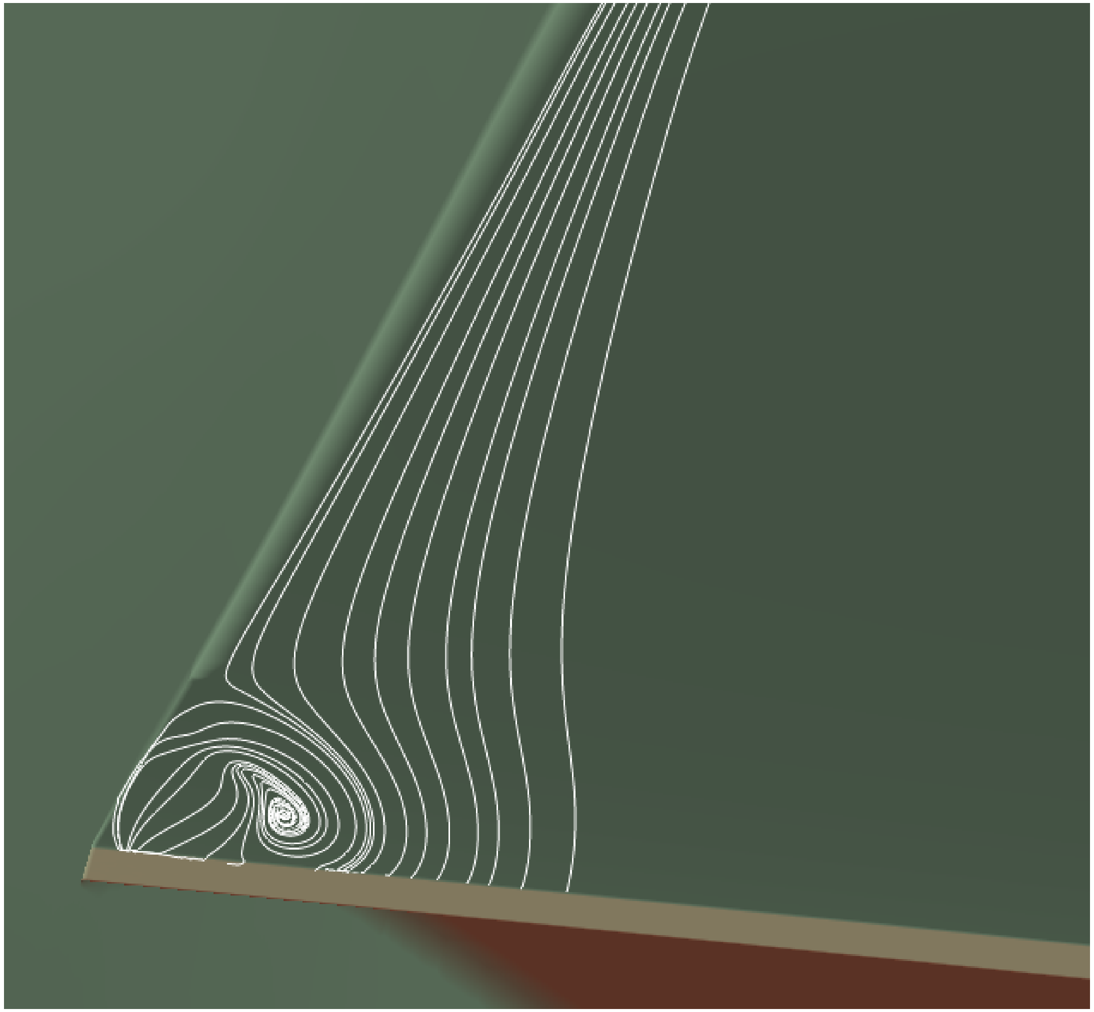
Case 3 : Juncture-Region
Wing Separation

Wing separation:

Re=30M, C_L=0.50

2.50° HiQ AE CRM

geometry



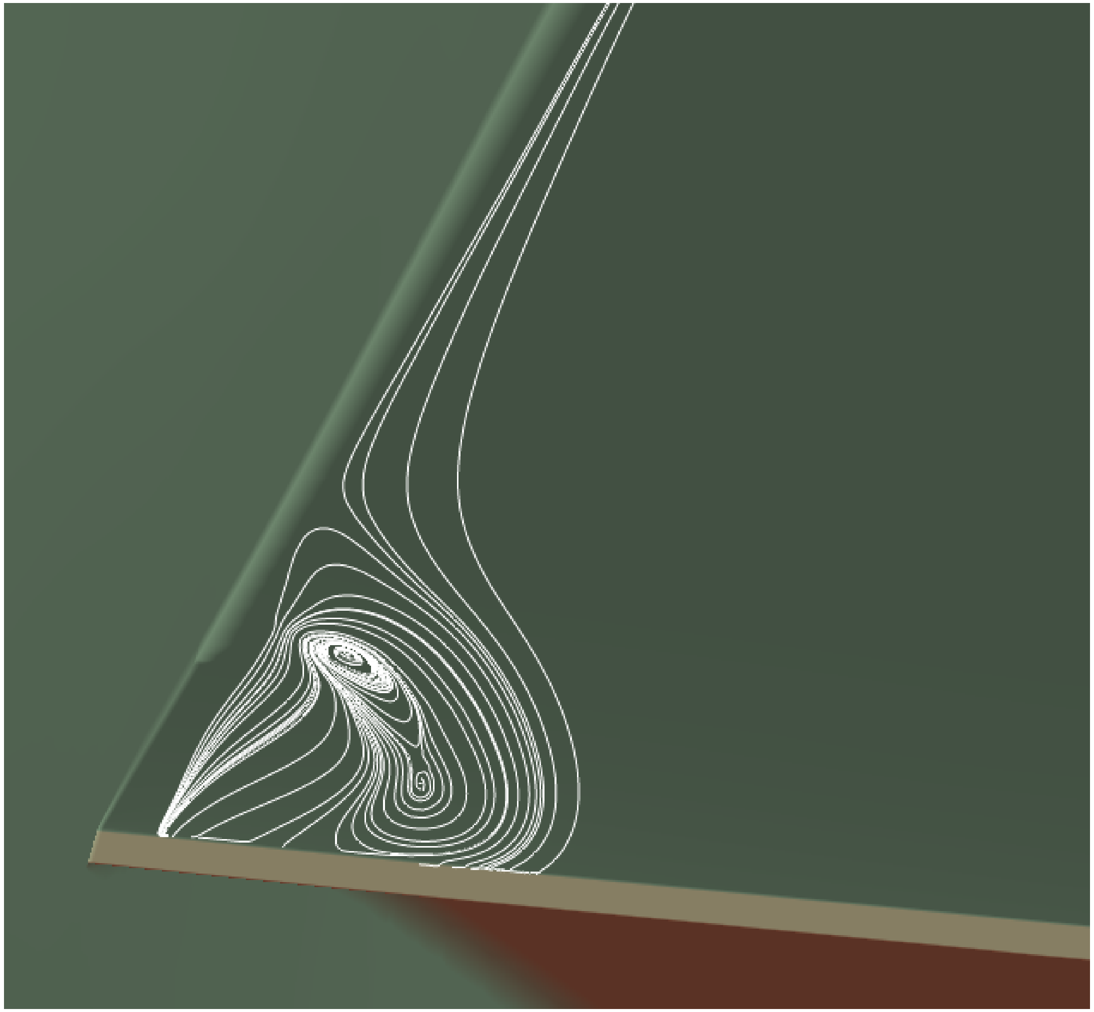
Case 6 : Juncture-Region Wing Separation

Case 6 : Juncture-Region
Wing Separation

Wing separation:

C_L=0.58

q/E=0.334 x10^{-6}

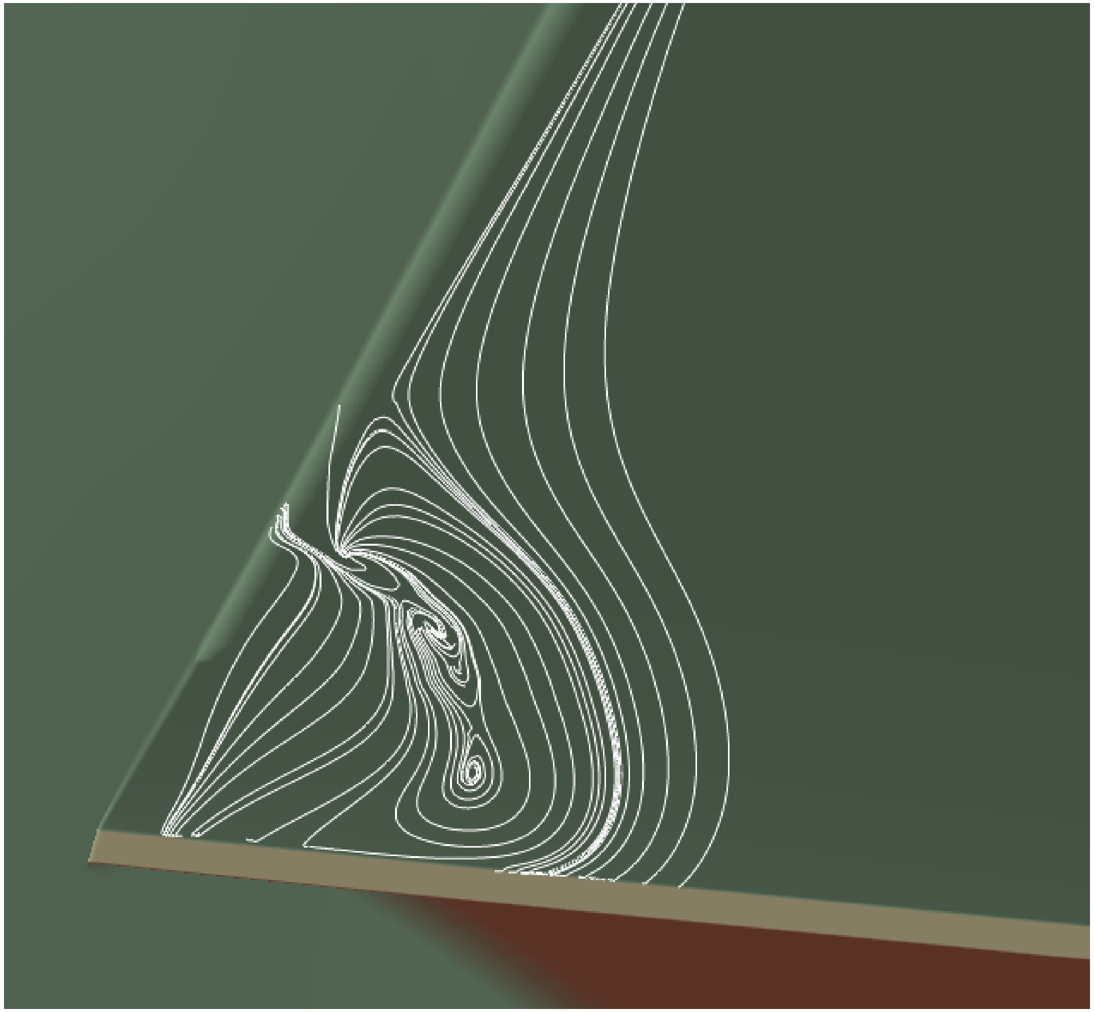


Case 6 : Juncture-Region
Wing Separation

Wing separation:

α=3.25°

q/E=0.334 x10^{-6}

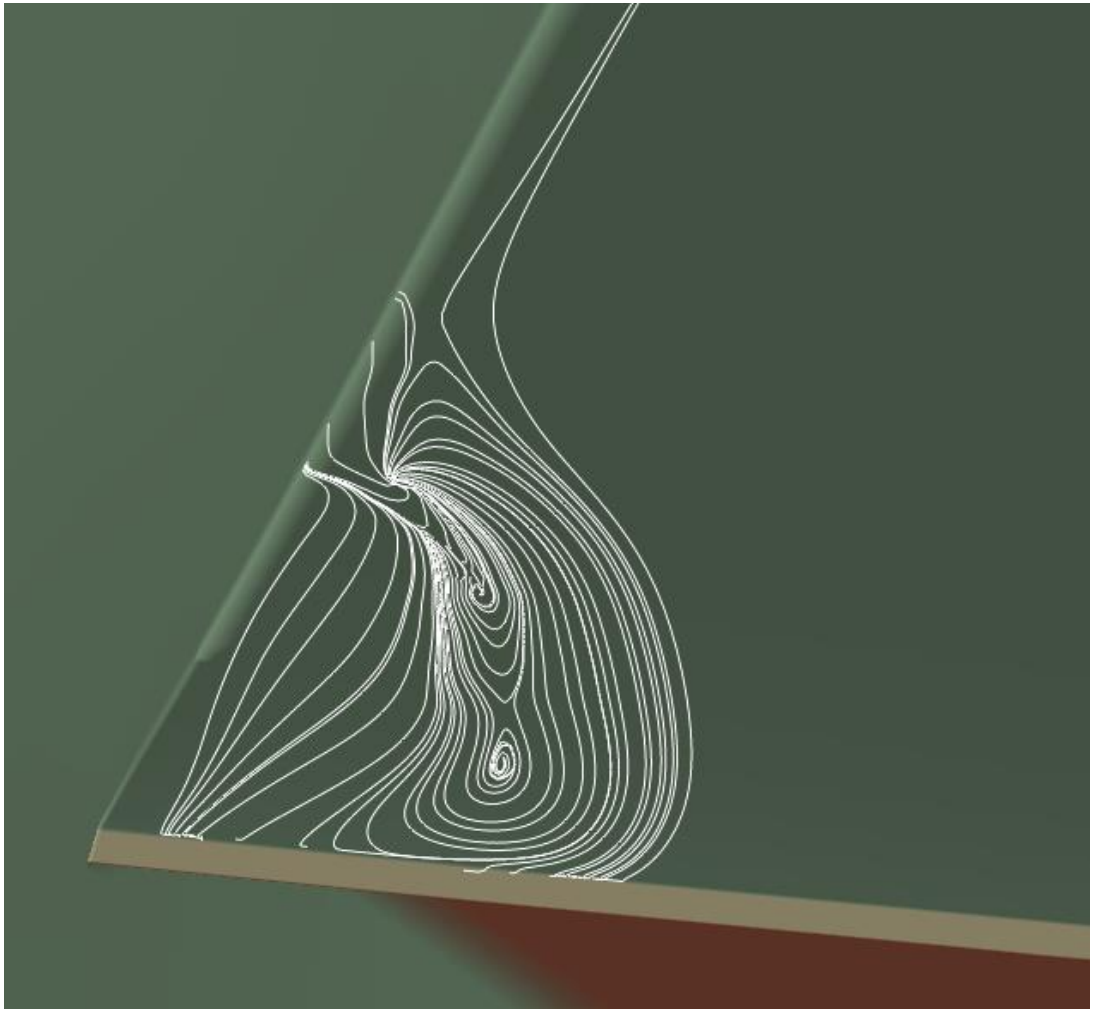


Case 6 : Juncture-Region
Wing Separation

Wing separation:

$\alpha=3.50^{\circ}$

$q/E=0.334 \times 10^{-6}$



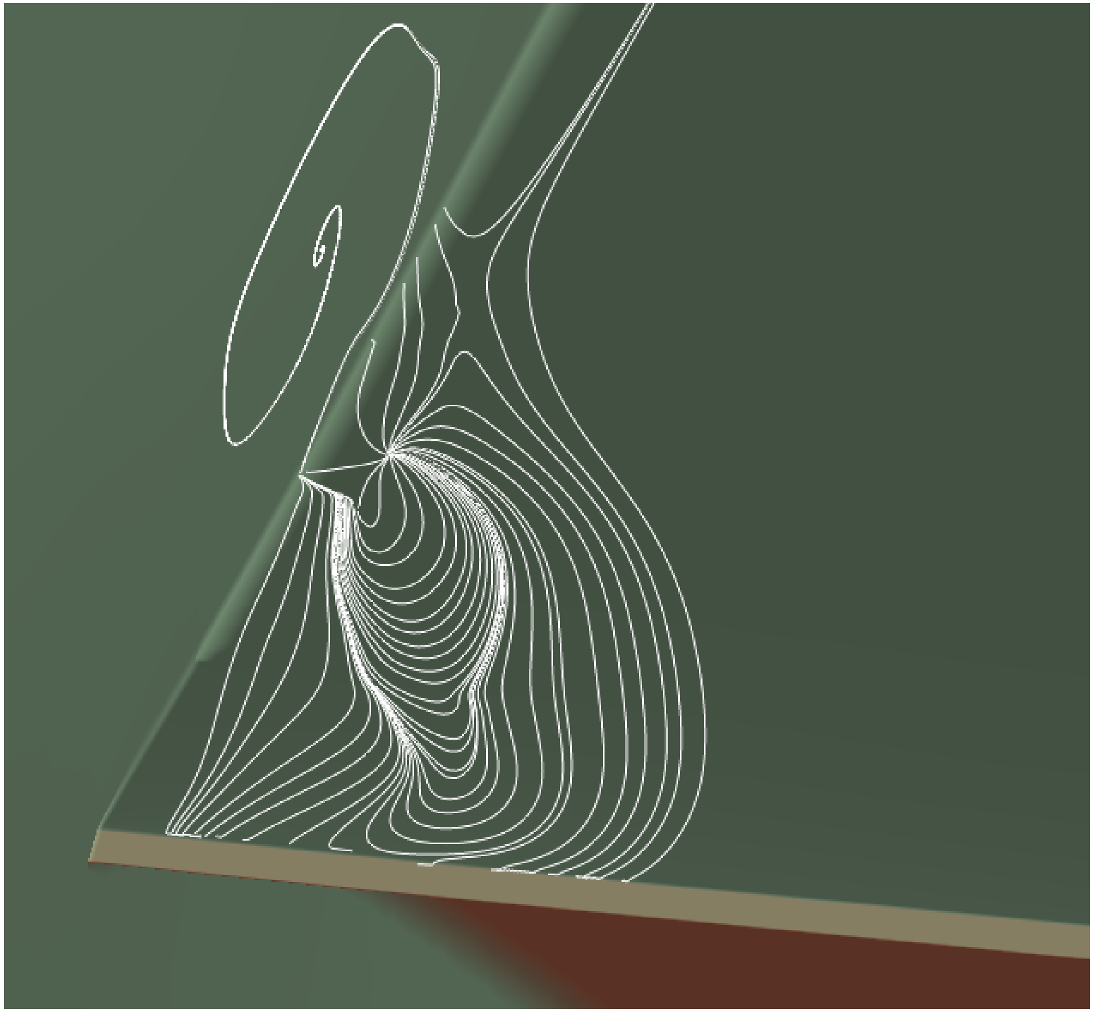
Case 6 : Juncture-Region

Wing Separation

Wing separation:

$\alpha=3.75^{\circ}$

$q/E=0.334 \times 10^{-6}$

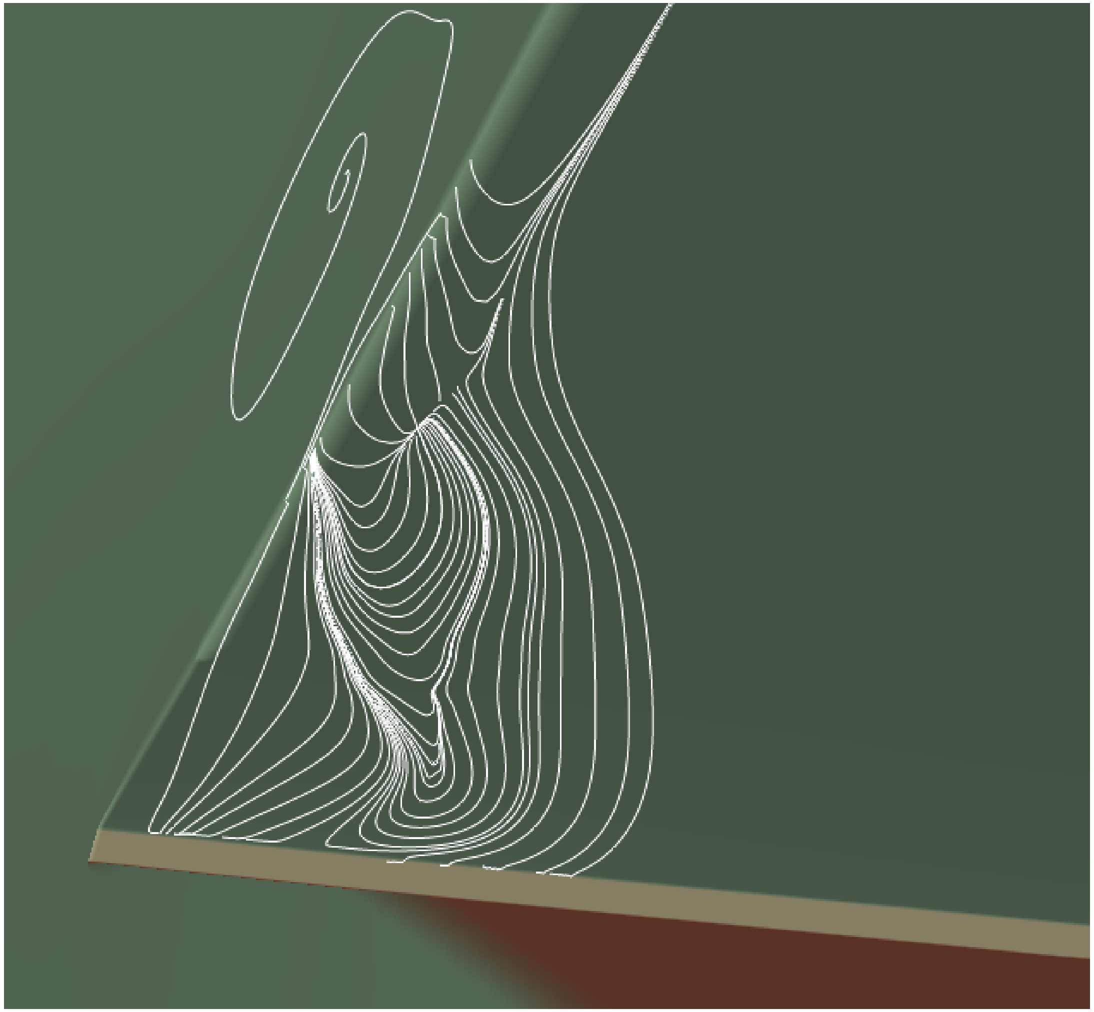


Case 6 : Juncture-Region
Wing Separation

Wing separation:

$\alpha=4.00^{\circ}$

$q/E=0.334 \times 10^{-6}$

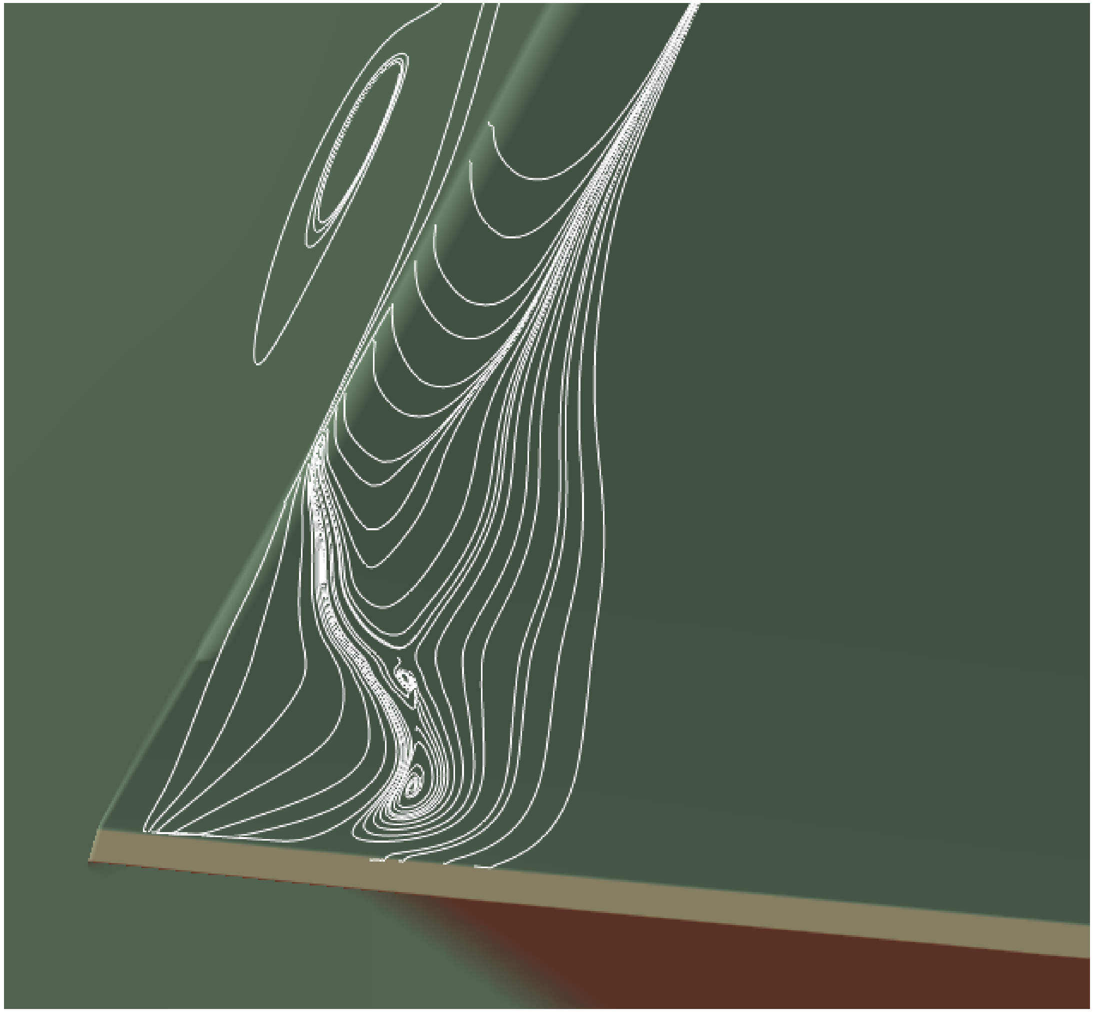


Case 6 : Juncture-Region
Wing Separation

Wing separation:

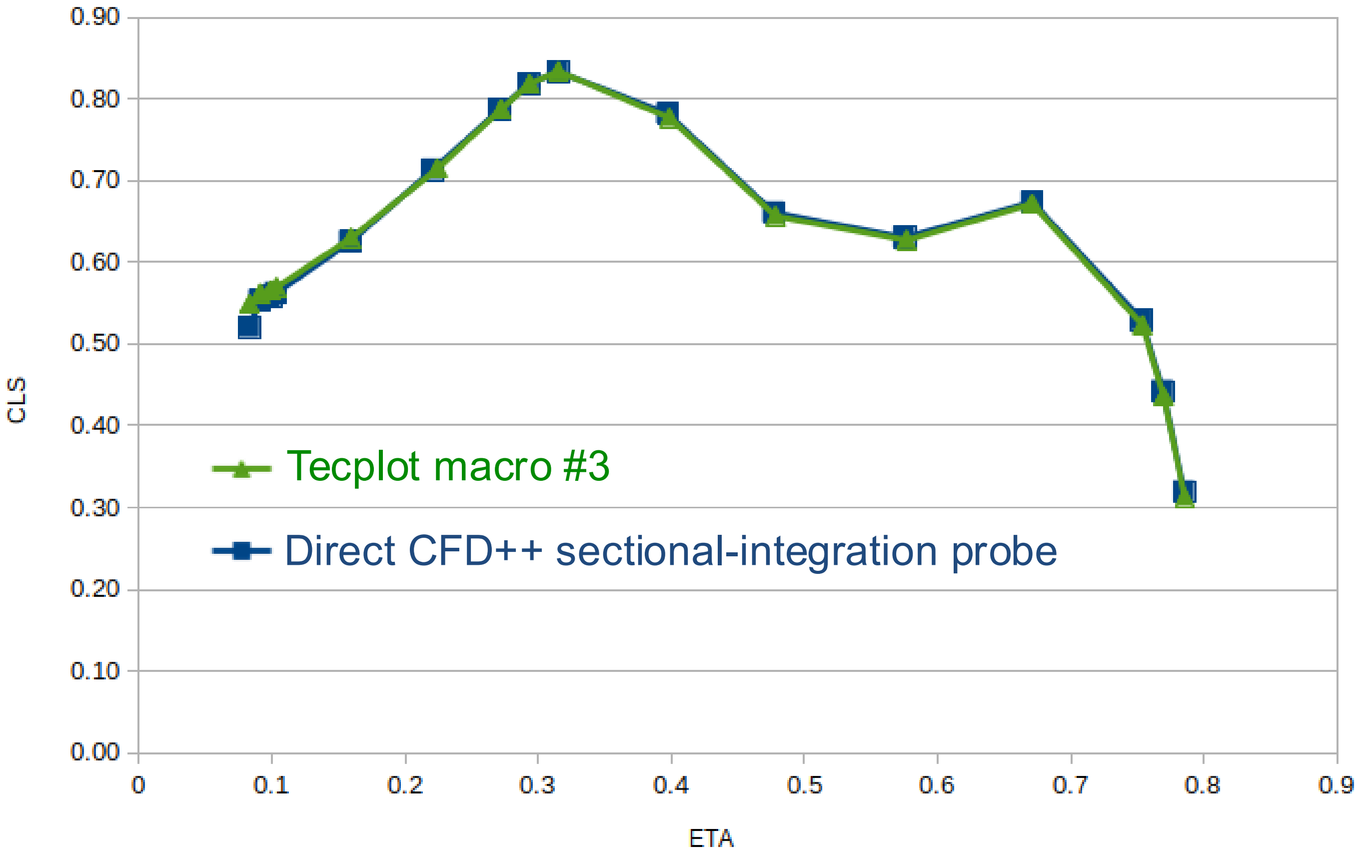
α=4.25°

q/E=0.334 x10^{-6}



Misc. Observations 2

#2: Confirmation of Sectional-Integration Macro



Latest version of Tecplot sectional-integration macro agrees with the built-in sectional integration tool in CFD++

Case 6 : Coupled Aero-Structural Simulation

- CFD++ is coupled with Metacomp's software suite designed for Fluid-Structure Interaction:
  - CSM++ : An in-house finite-element based structural mechanics and dynamics package
  - MetaFSI: A suite of tools designed to
    - ✓ **Transfer** loads from CFD++ to CSM++
    - ✓ **Morph** the CFD++ mesh based on structural displacements

FE Model: Eigenvalue Analysis

- Start with the FE model for wing/body/tail=0˚ configuration from NASA CRM website
- Create a wing/body configuration by removing all elements making up the horizontal tail
- Import NASTRAN model in to CSM++ and run modal analysis for both configurations
- Compare frequencies and mode shapes from CSM++ with Prof. Mavriplis' results (Abaqus)

Mode #	CSM++ (Wing/Body)	CSM++ (Wing/Body/Tail=0˚)	Prof. Mavriplis
1	38.157 Hz (-3.06%)	38.147 Hz (-3.08%)	39.360 Hz
2	39.561 Hz (-3.37 %)	39.535 Hz (-3.44 %)	40.942 Hz

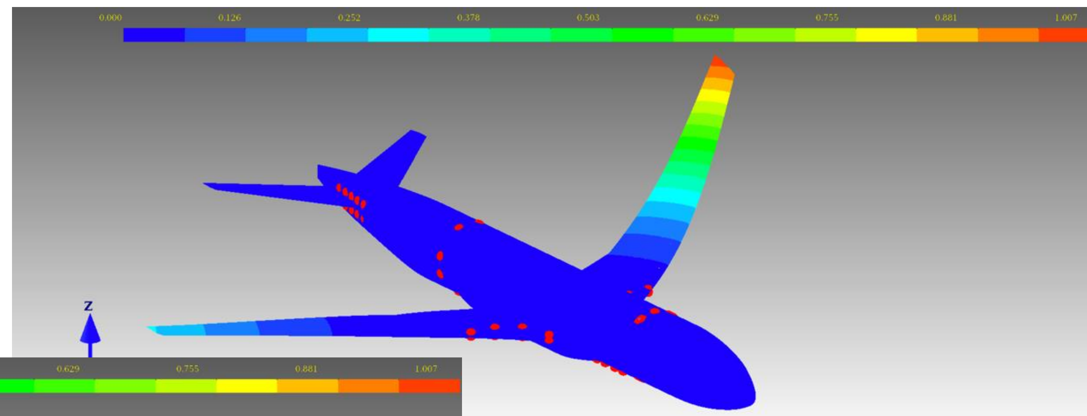
FE Model: Adjusted Eigenvalue Analysis

- Flow conditions: Mach 0.85, Re=20M, T_{total}=116° K
- Default value of Young's Modulus of the wing in FEM Model: E = 1.827×10^{11} N/m^2
- This resulted in a q/E of 0.351, higher than the intended q/E of 0.334!
- Young's Modulus adjusted to E = 1.918×10^{11} N/m^2 to match test case definition

Mode #	CSM++ (Wing/Body)	CSM++ (Wing/Body/Tail=0°)	Prof. Mavriplis
1	38.991 Hz (-0.94%)	38.979 Hz (-0.97%)	39.360 Hz
2	40.432 Hz (-1.25%)	39.535 Hz (-1.32%)	40.942 Hz

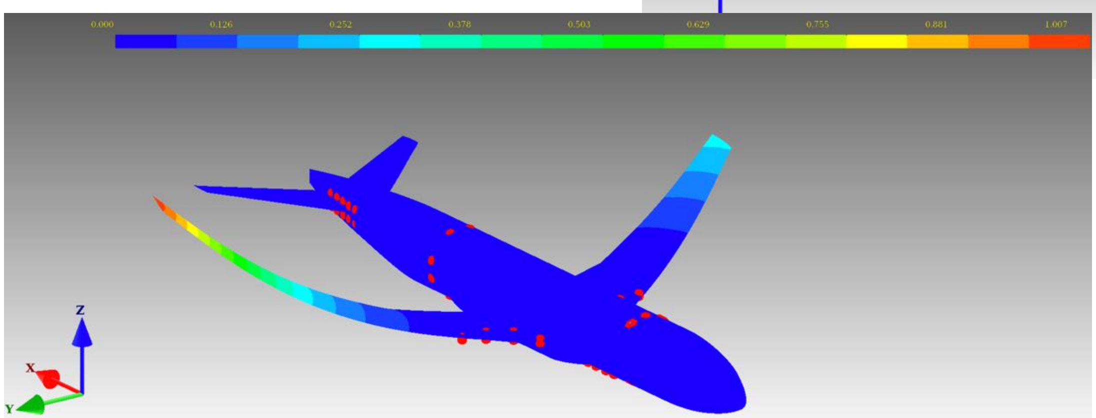
FE Model: Mode Shapes

Wing/Body/Tail=0˚



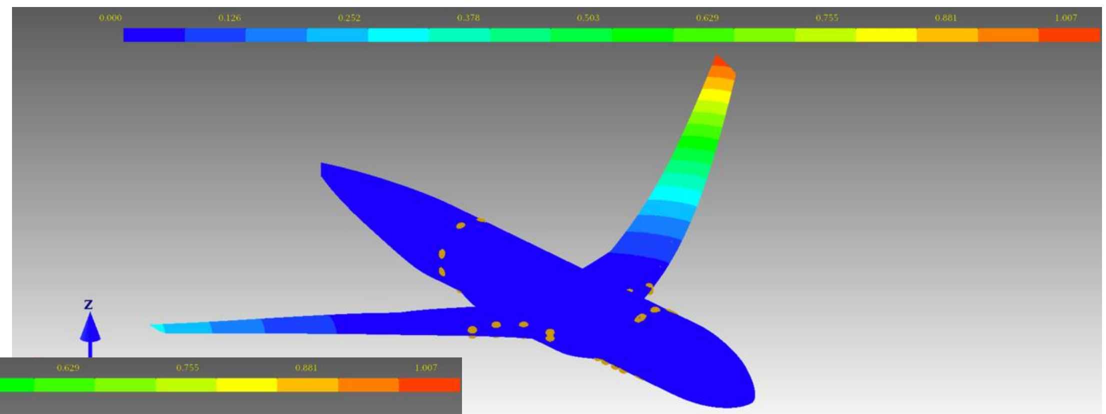
Mode 1: 38.979 Hz

Mode 2: 40.401 Hz



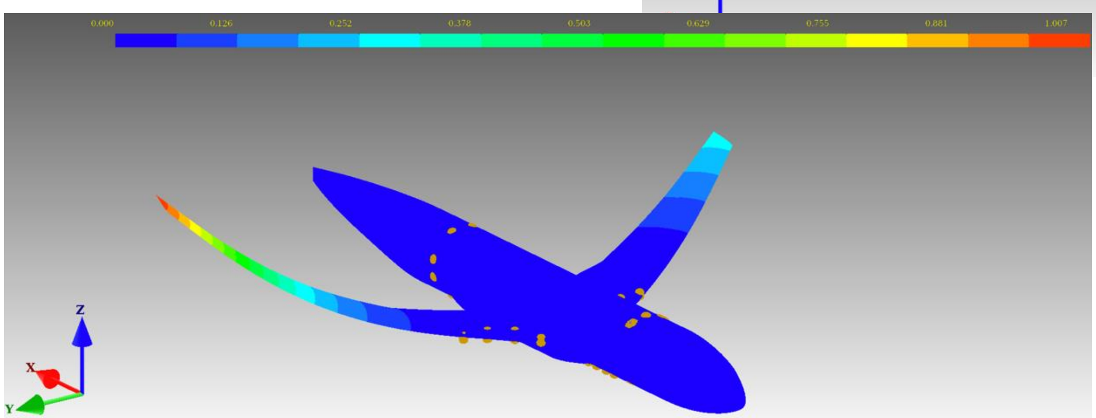
FE Model: Mode Shapes

Wing/Body



Mode 1: 38.991 Hz

Mode 2: 40.432 Hz

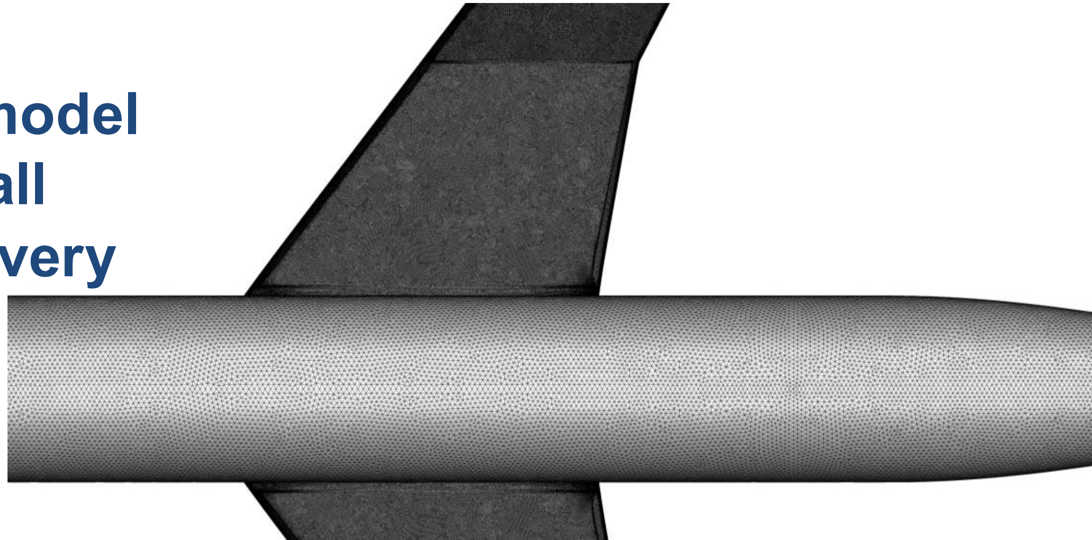


Simulation Strategy

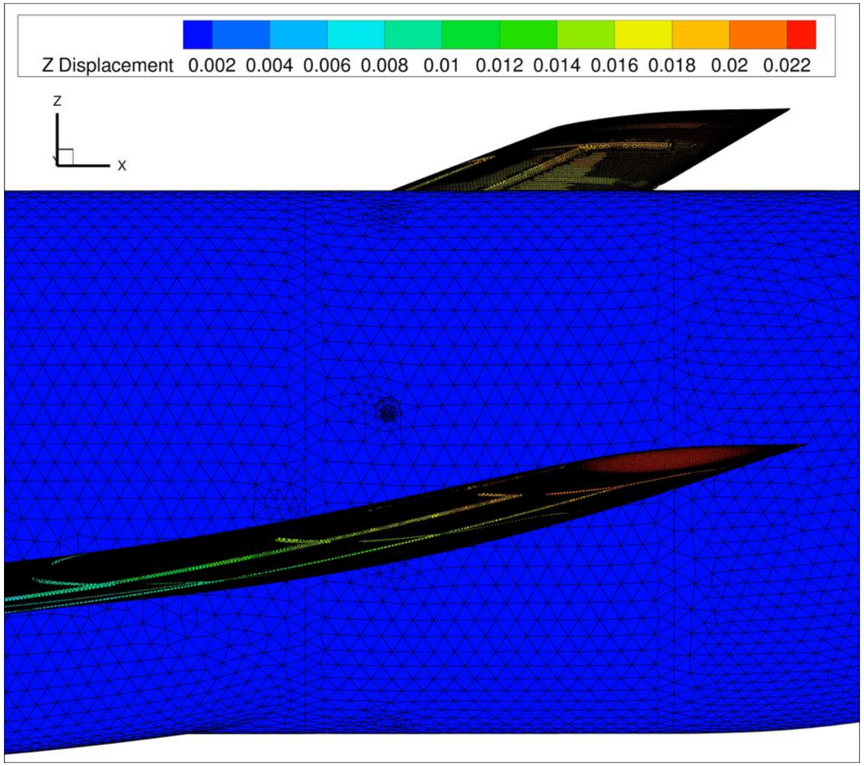
- *Full* aircraft model with ~ 4 million DoFs
  - Linear tetrahedral solid elements, bushing springs and kinematic rigid body elements
- *Linear* static analysis during FSI
- *Pressure* and *wall shear* from CFD++ transferred to CSM++ using nearest-neighbor interpolation
- Computed deformations sent back to MetaFSI for *mesh morphing*
- Repeat till displacements converge to within a tolerance of $1x10^{-6}$

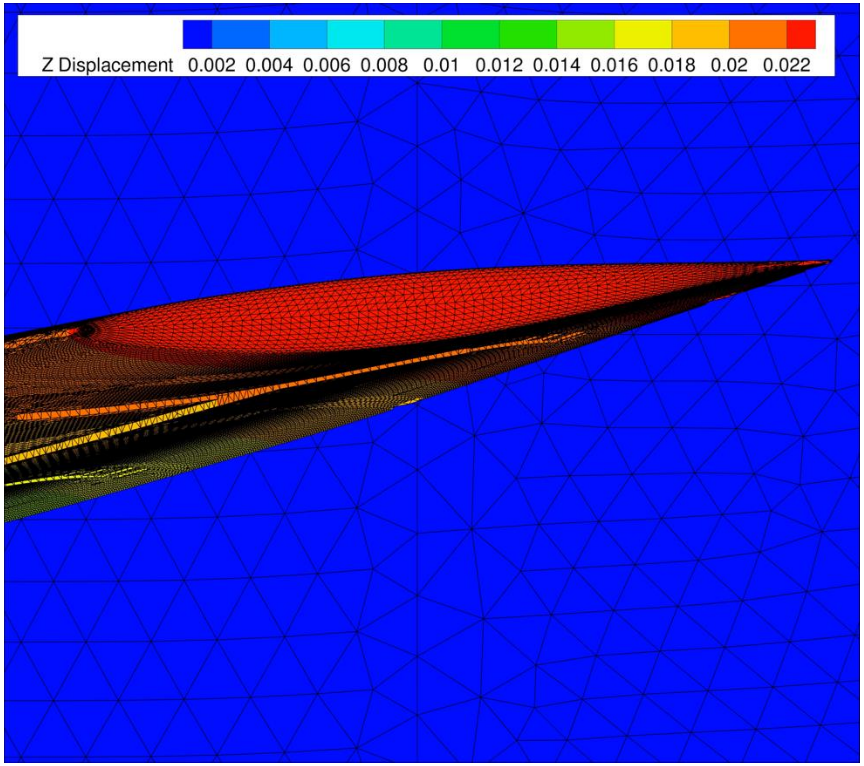
Simulation Strategy

- CFD++ used a *mirrored* Medium Baseline *NoQ* Re=30M grid
  - 164,065,758 x 2 = 328,131,516 cells
- Start with a steady-state “rigid” CFD++ run
- Restart to begin coupled aero-structural analysis
- Run CFD++ for 100 steps between each CFD-CSM coupling step
- SARC-QCR turbulence model requires recomputing wall distance function after every FSI iteration

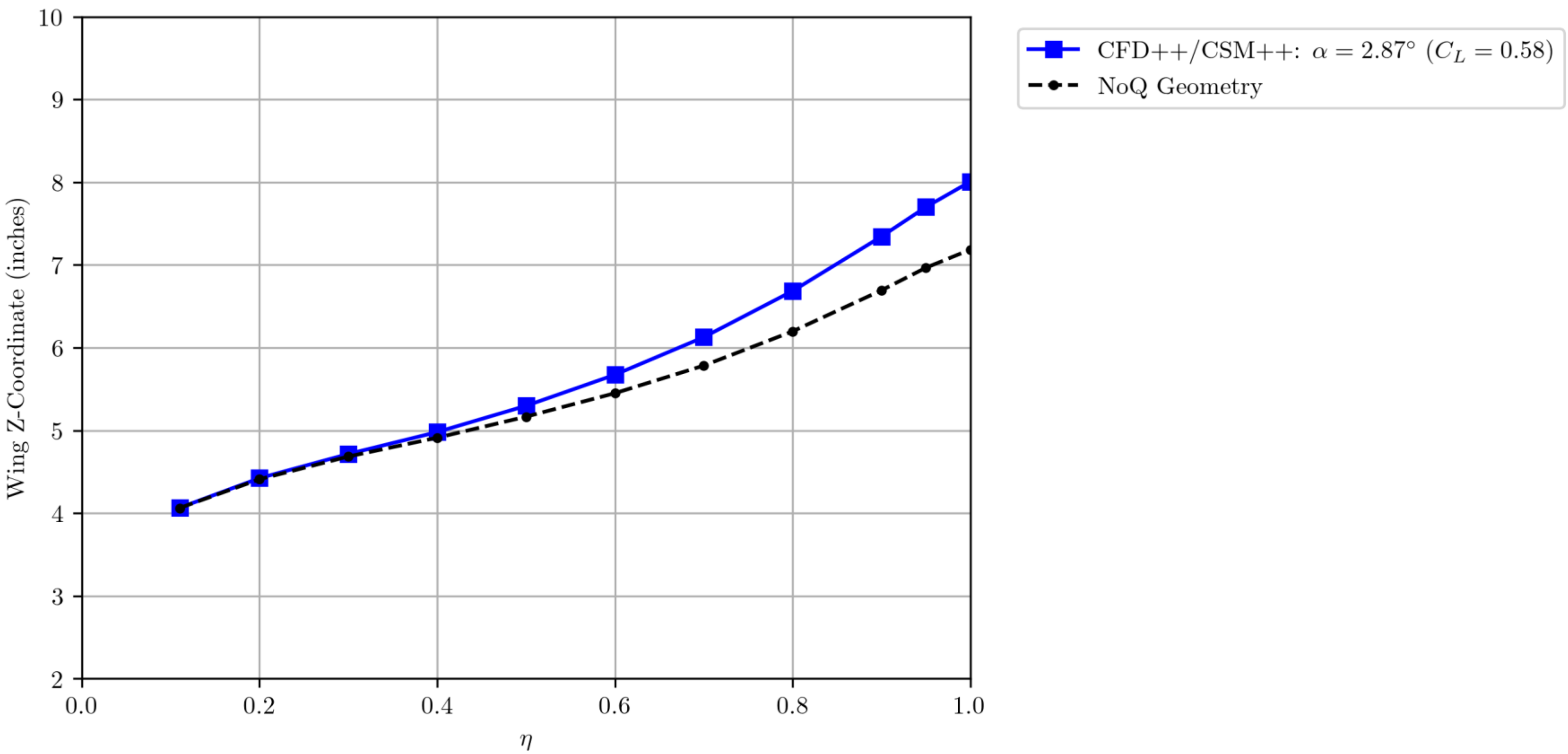


Converging to a solution…

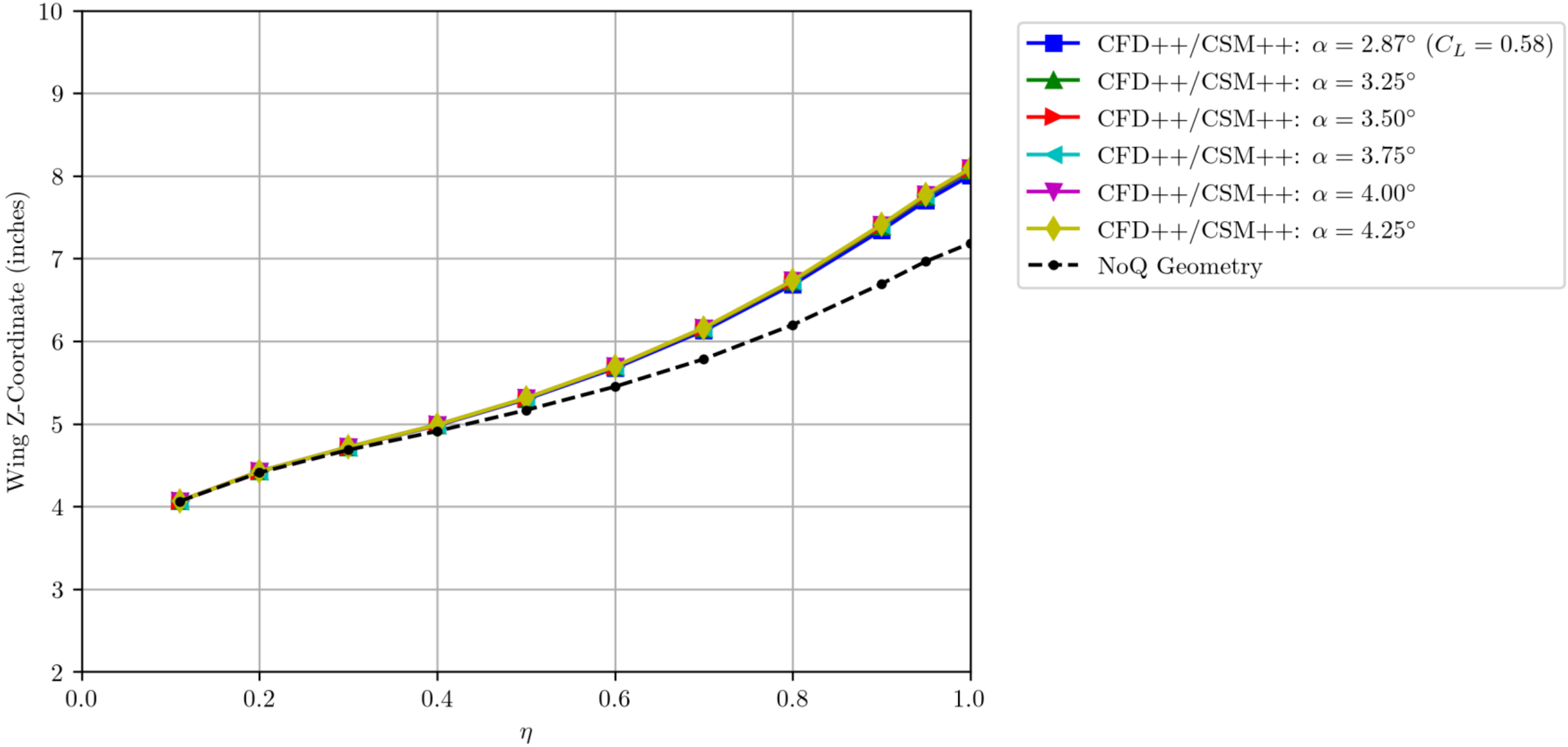




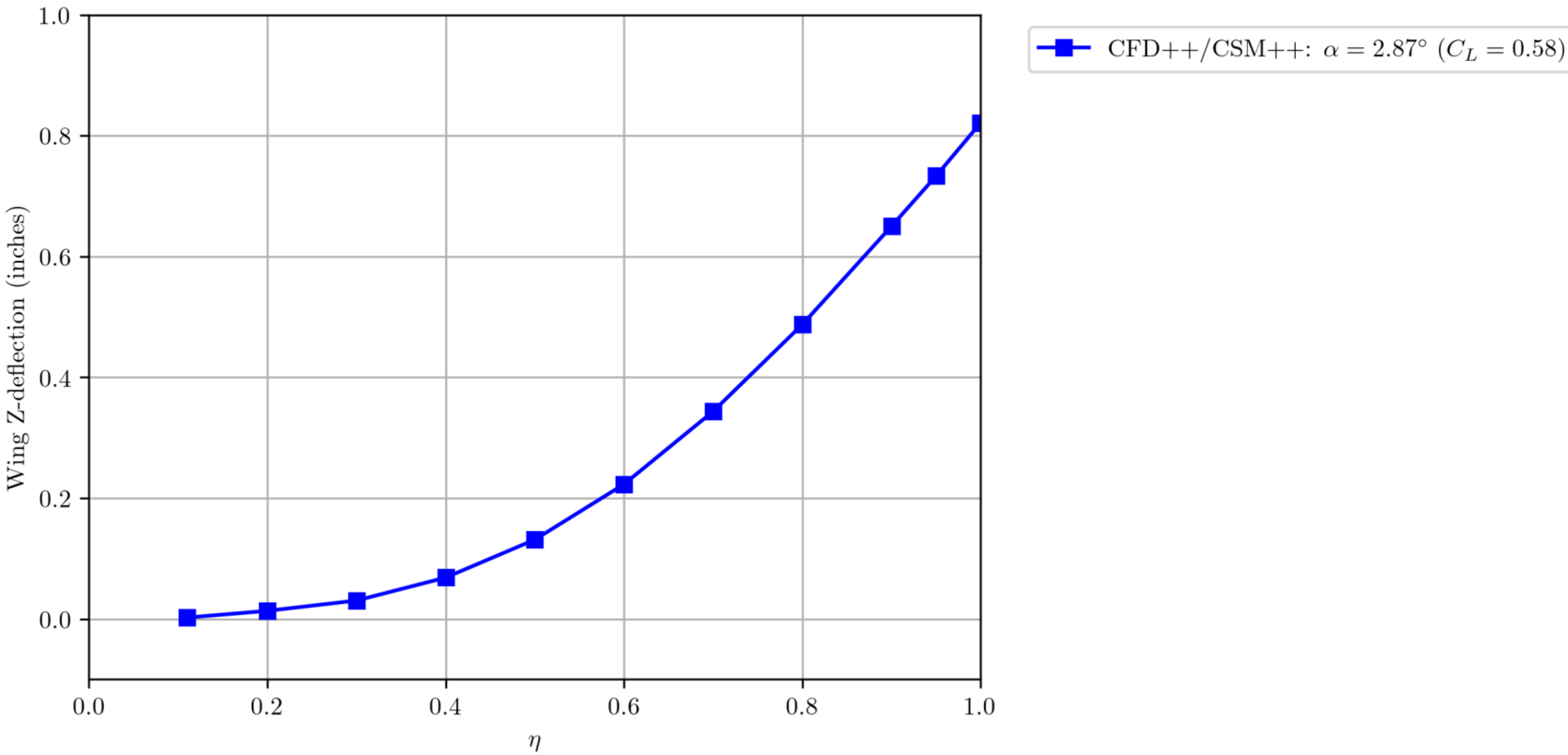
Results: Deflected 50%-chord line



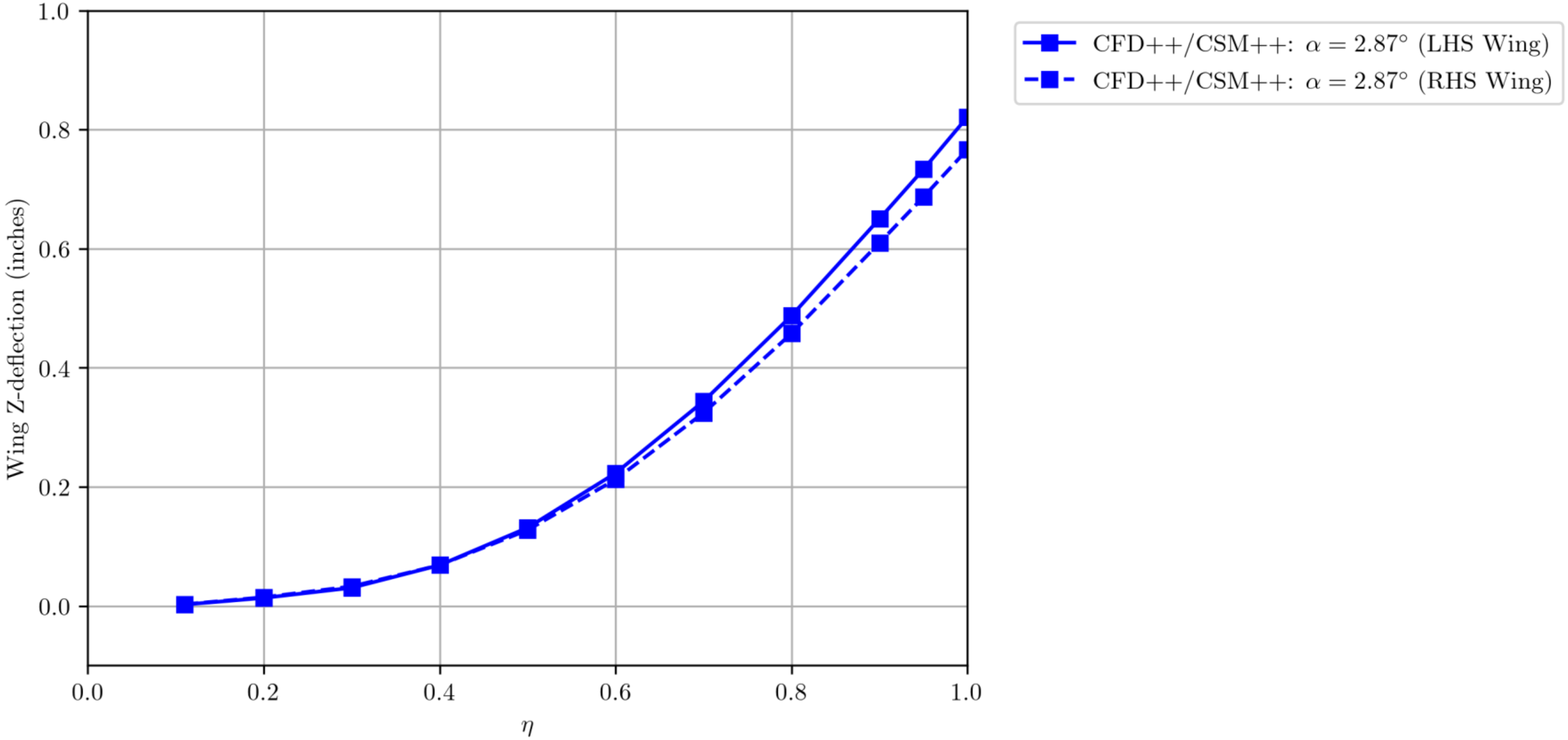
Results: Deflected 50%-chord line



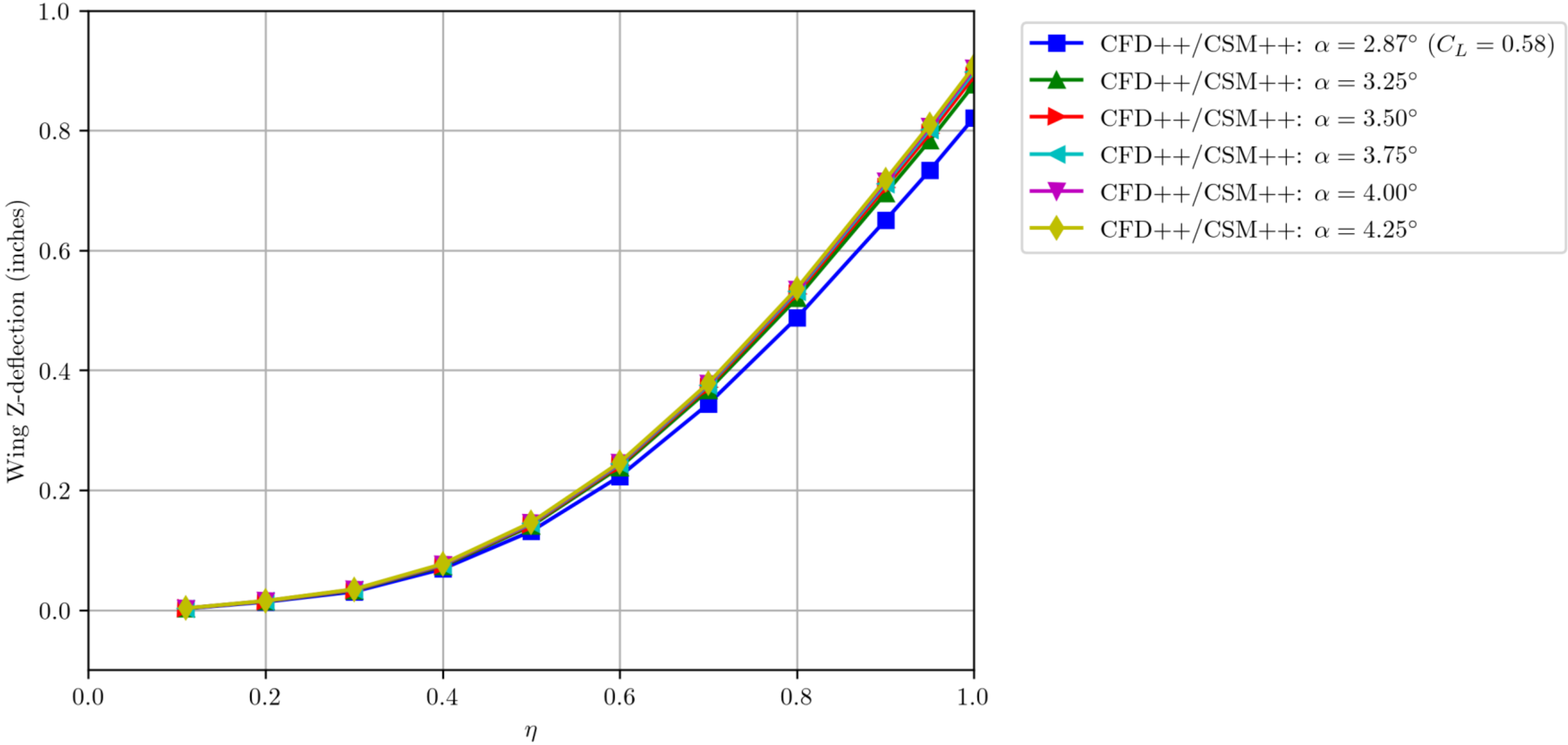
Results: Wing Bending Deformation



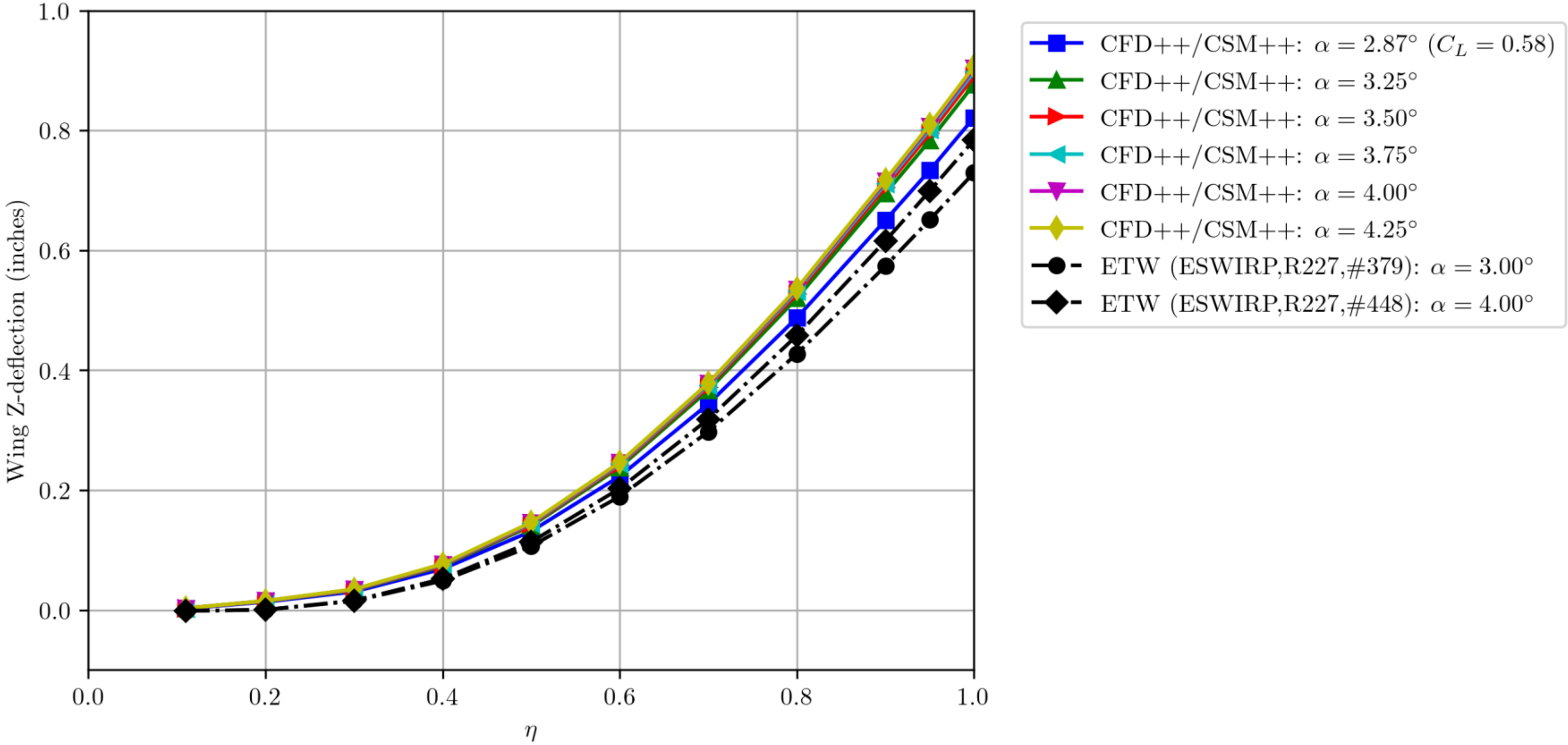
Results: Wing Bending Deformation



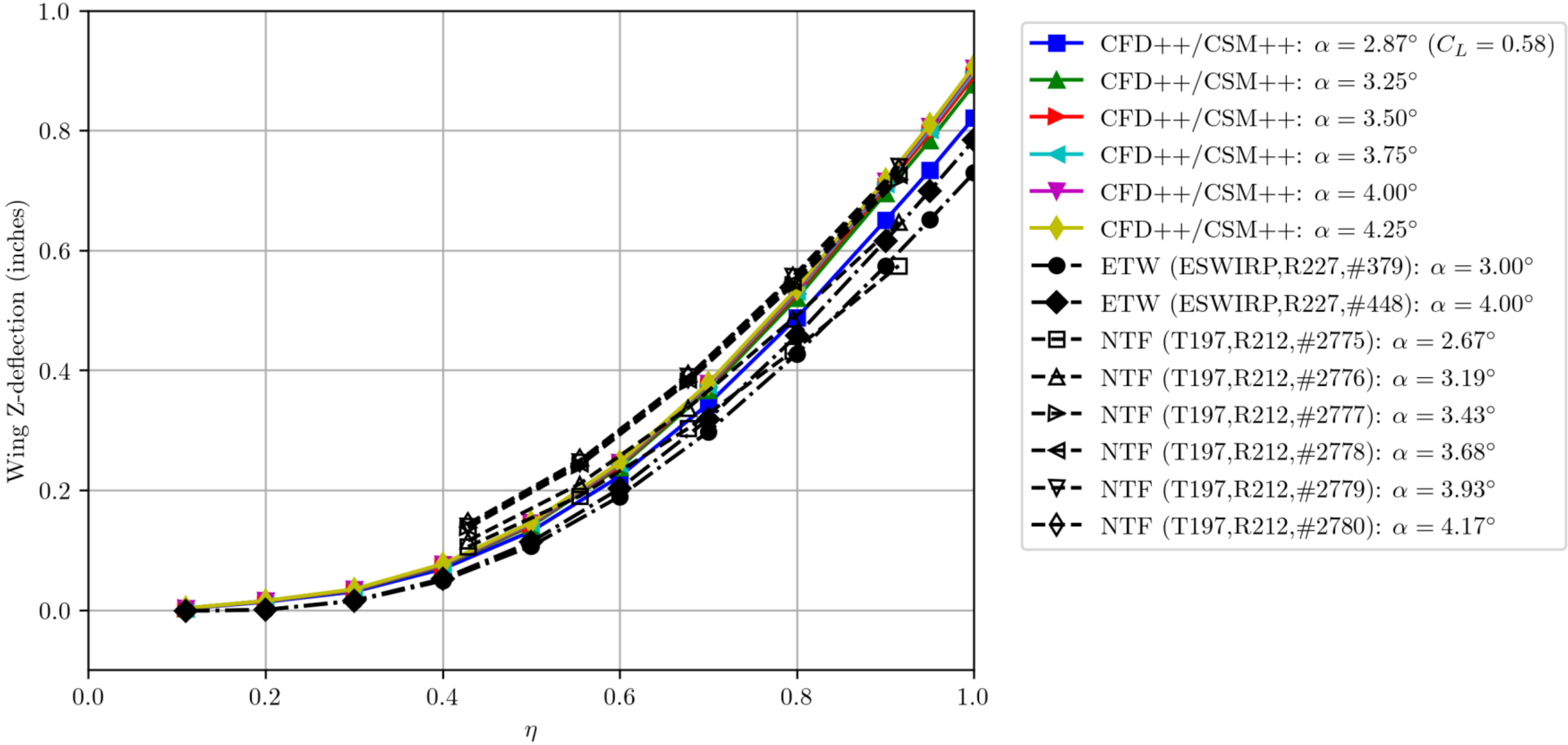
Results: Wing Bending Deformation



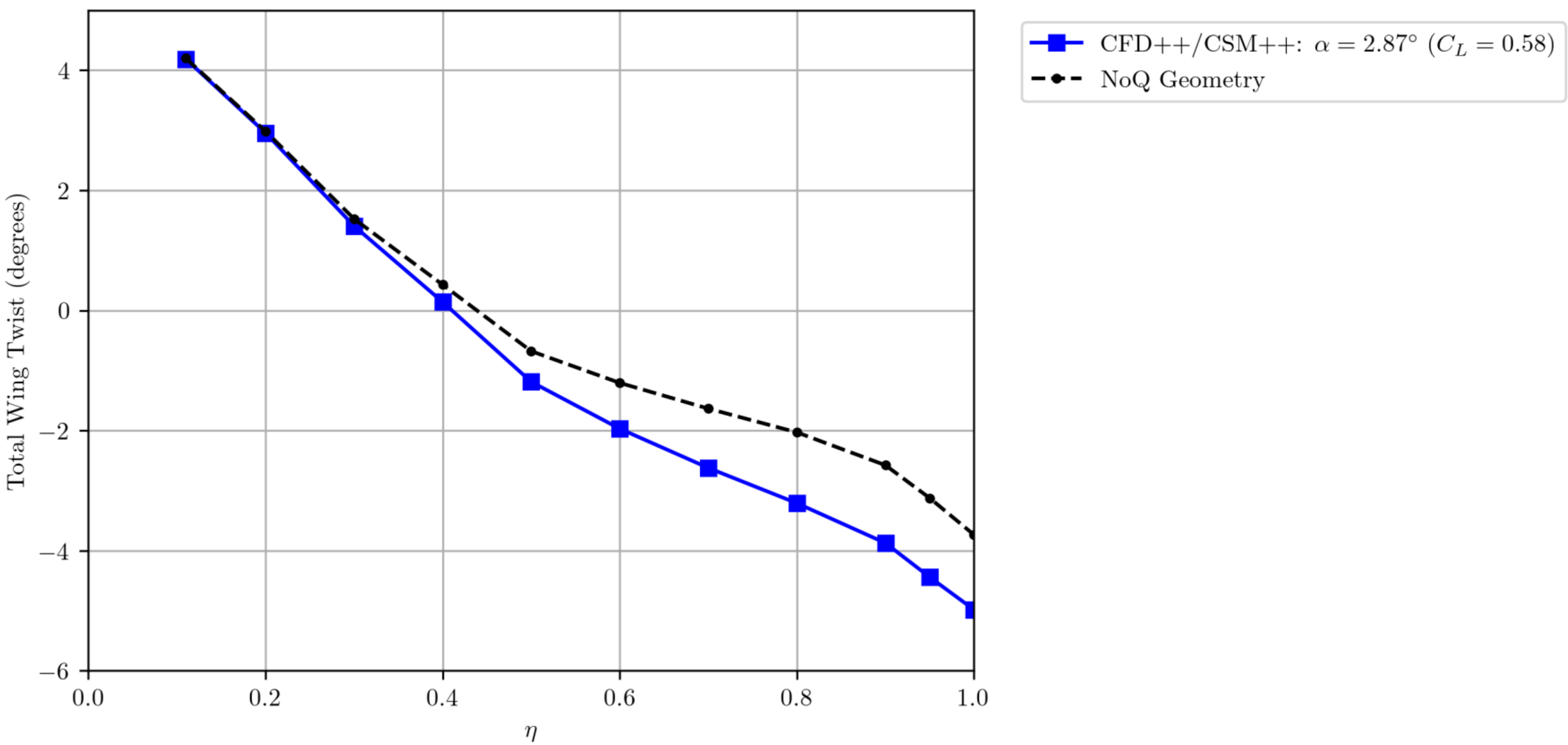
Results: Wing Bending Deformation



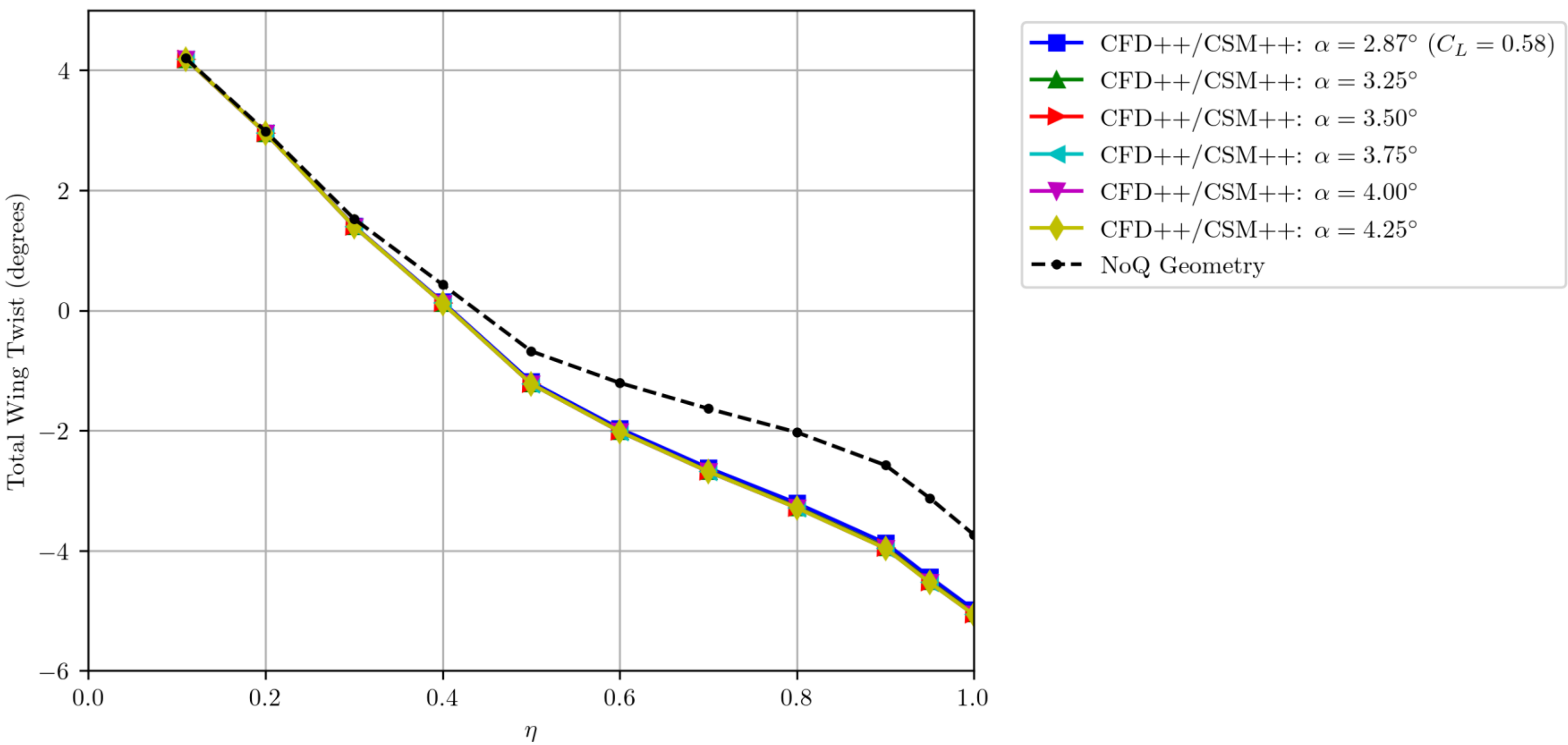
Results: Wing Bending Deformation



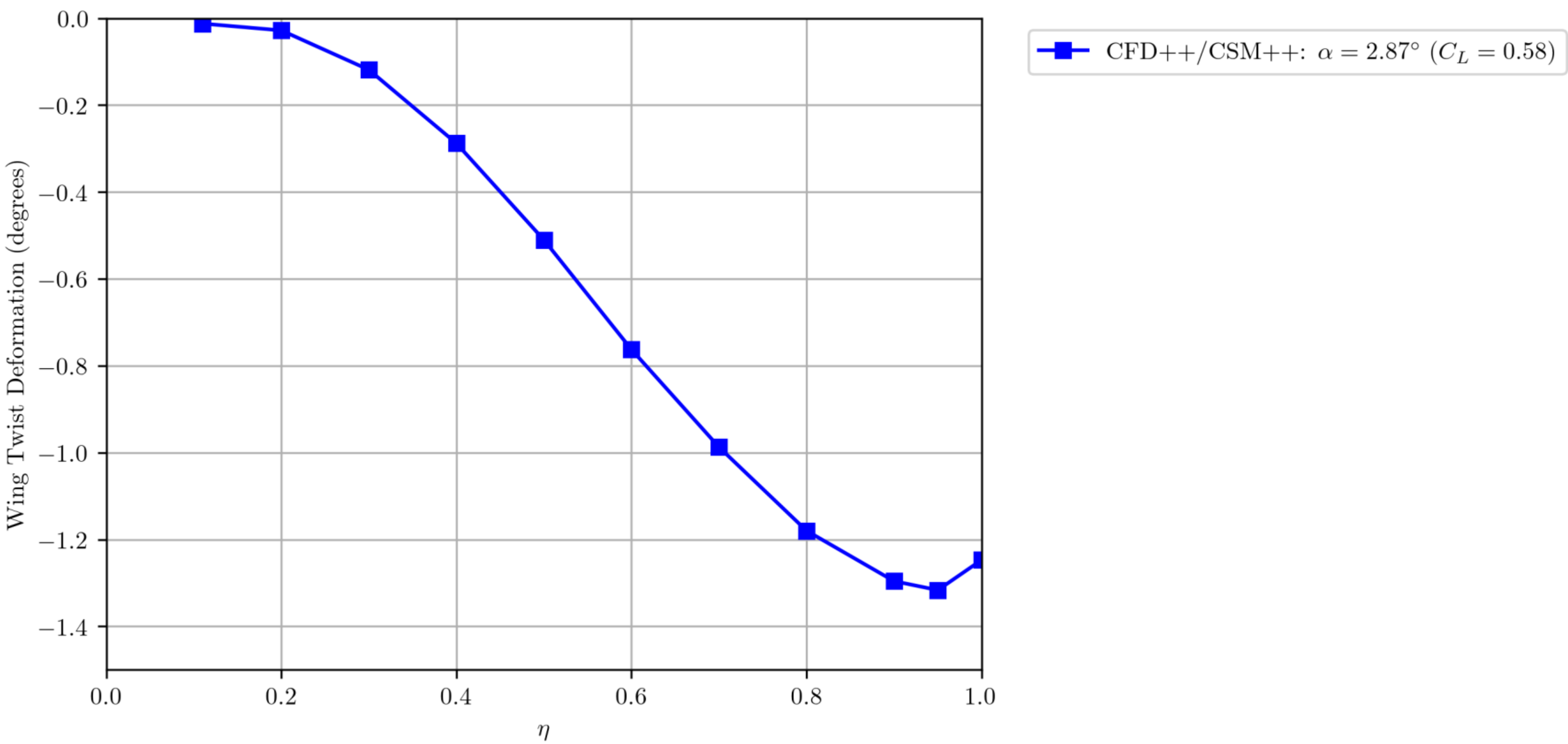
Results: Total Wing Twist



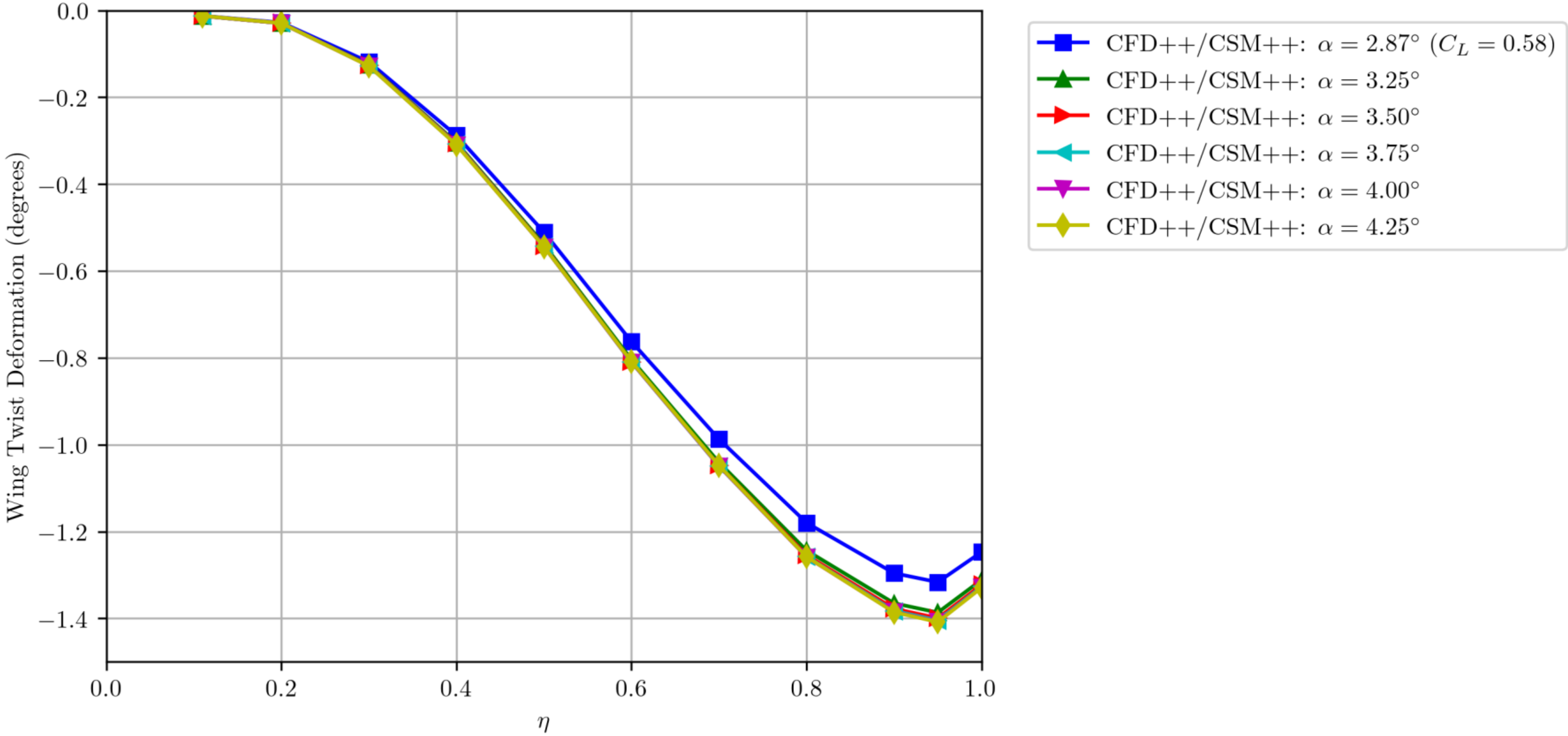
Results: Total Wing Twist



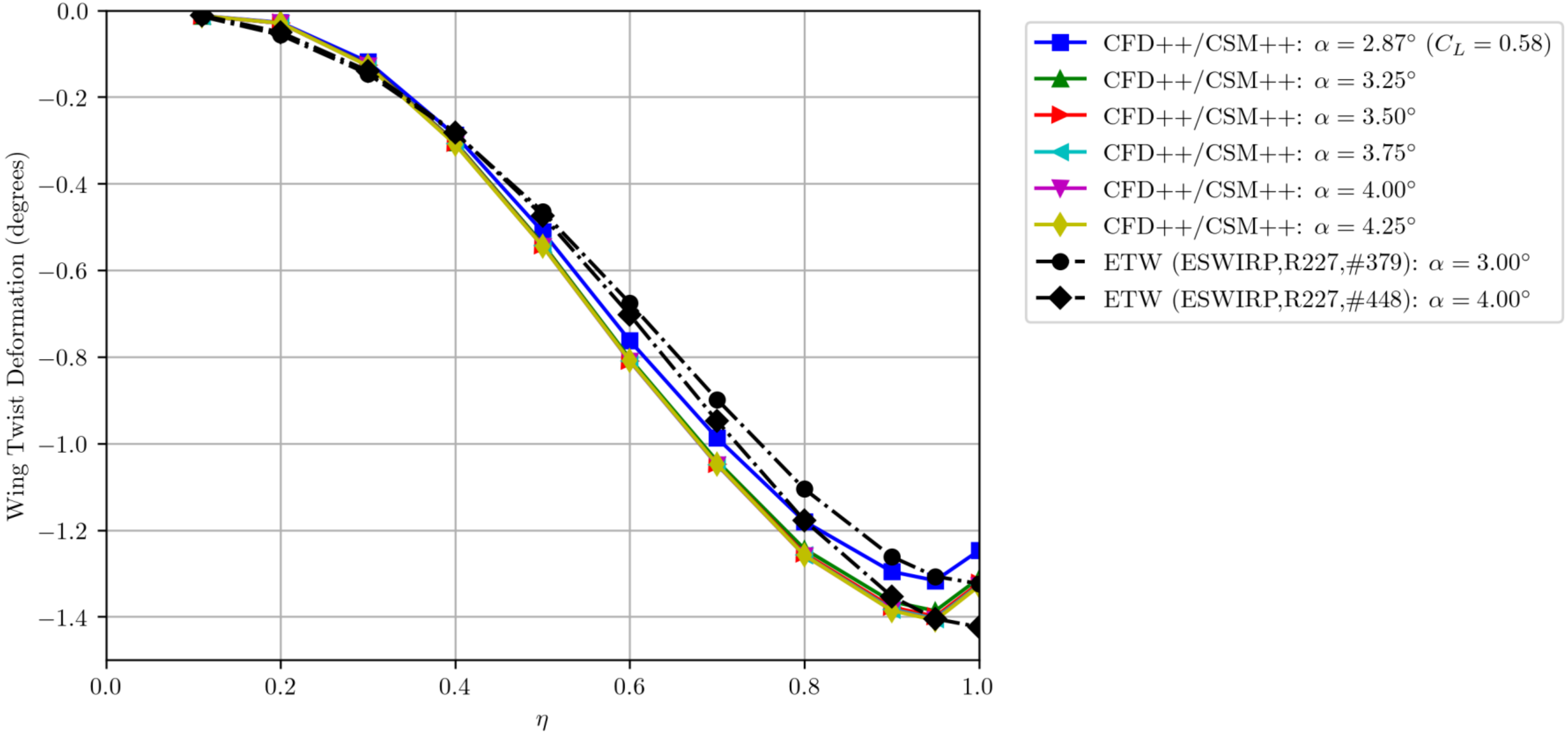
Results: Wing Twist Deformation



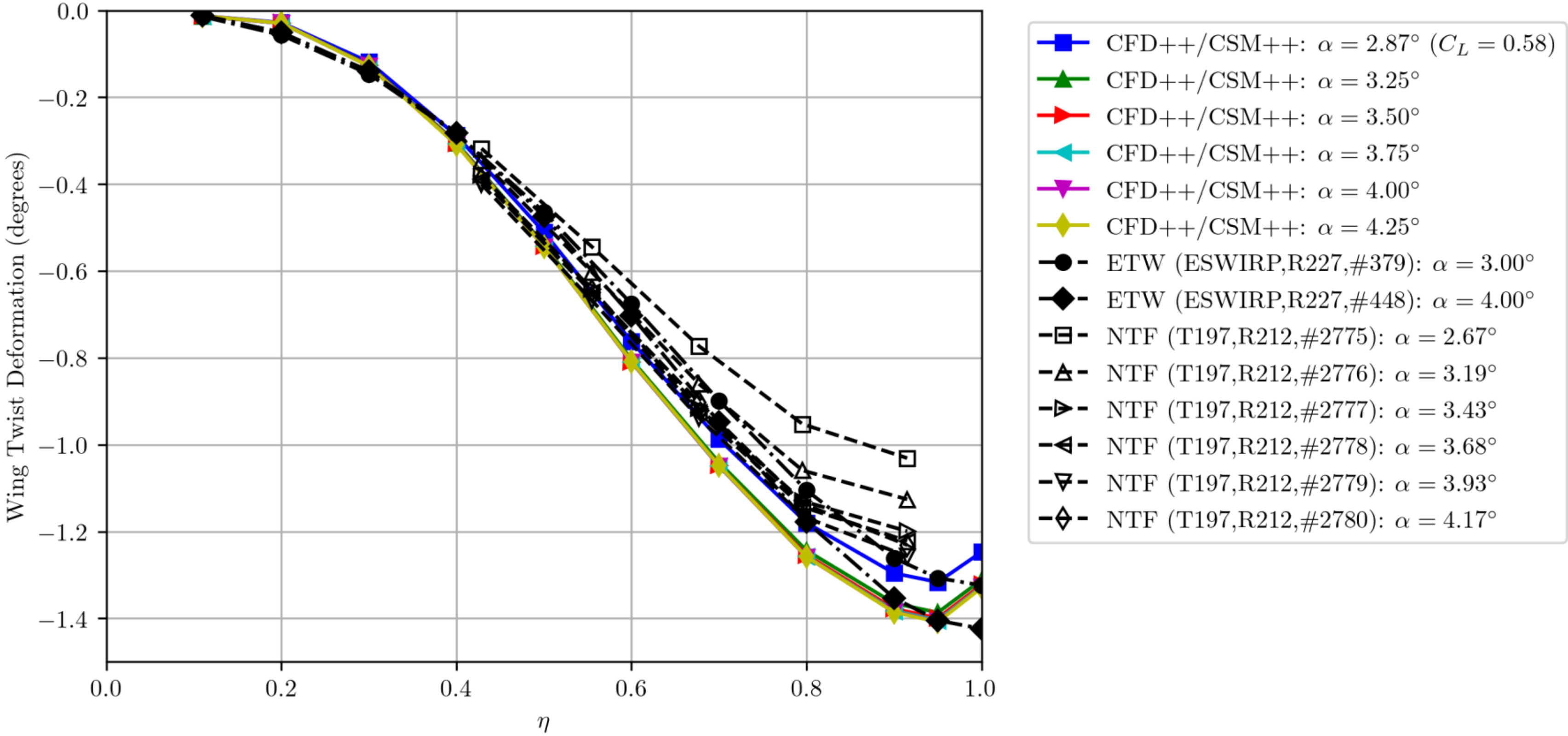
Results: Wing Twist Deformation



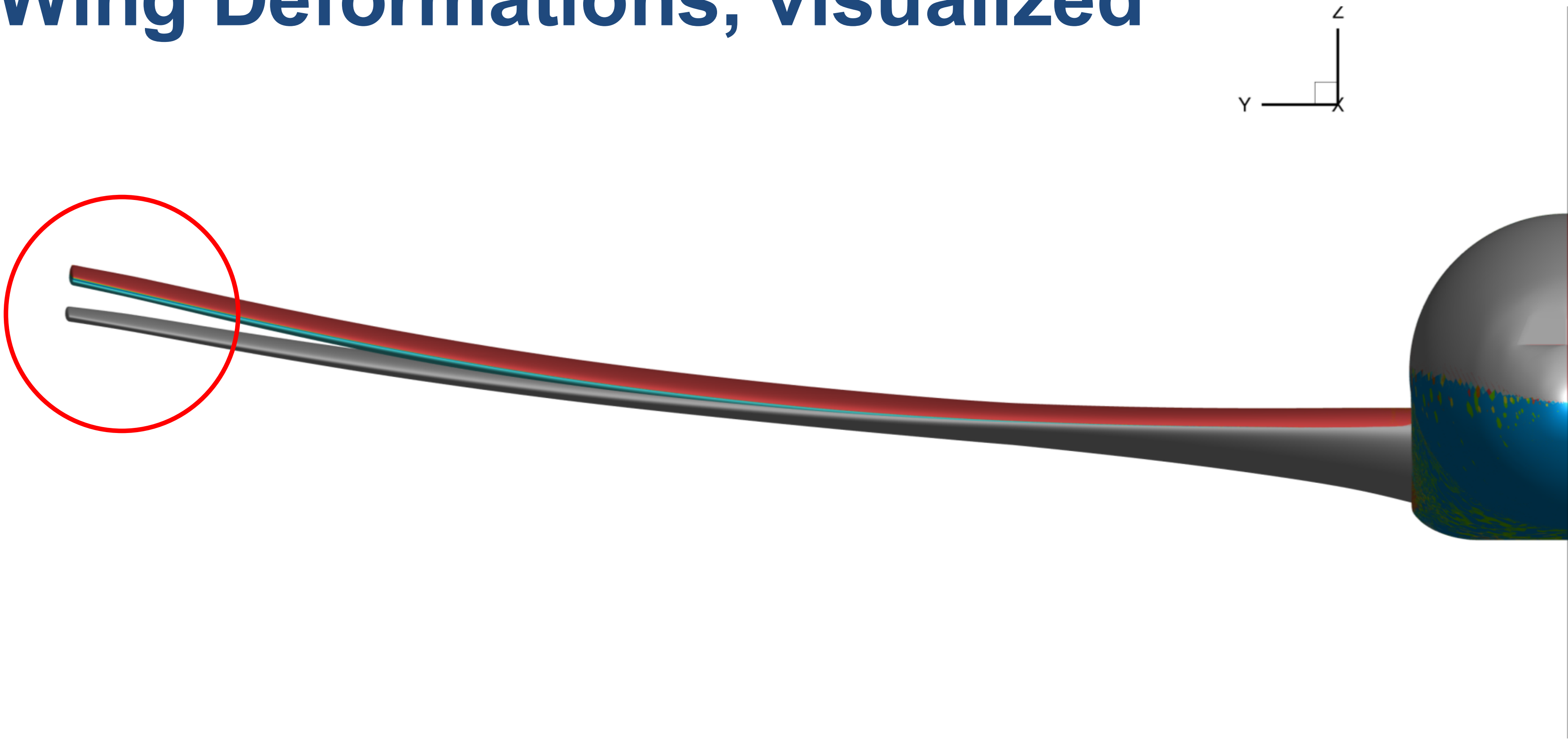
Results: Wing Twist Deformation



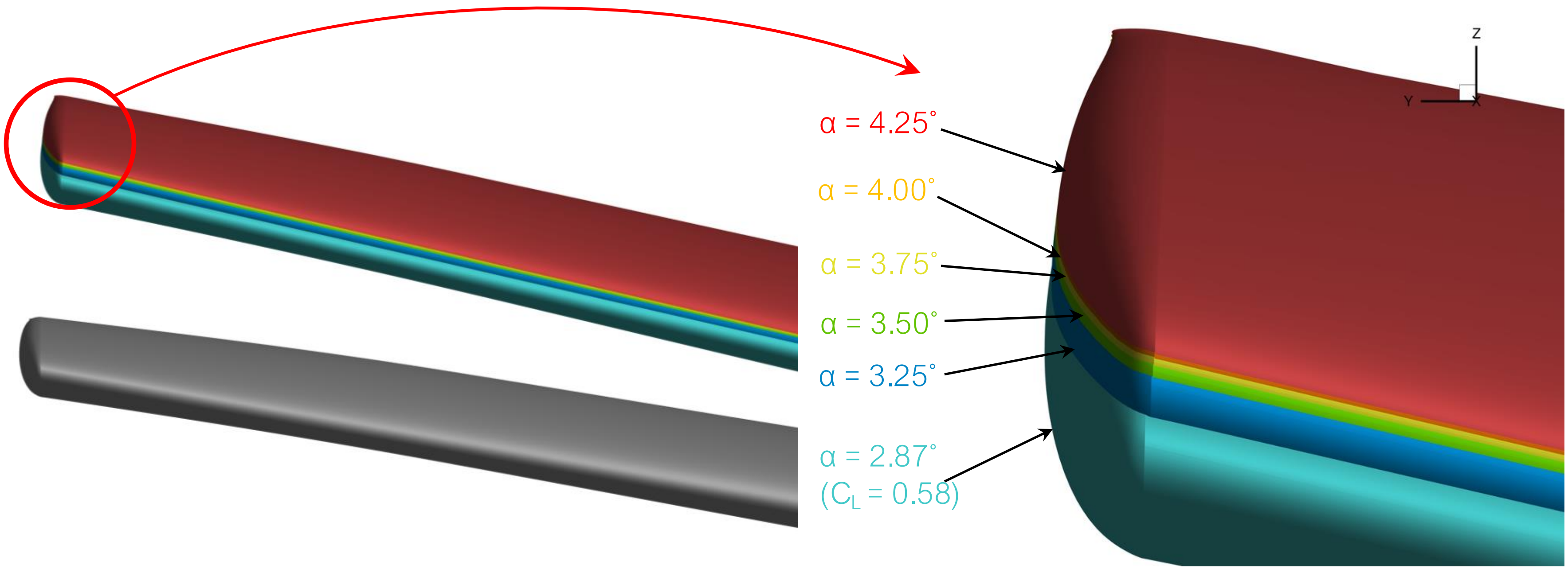
Results: Wing Twist Deformation



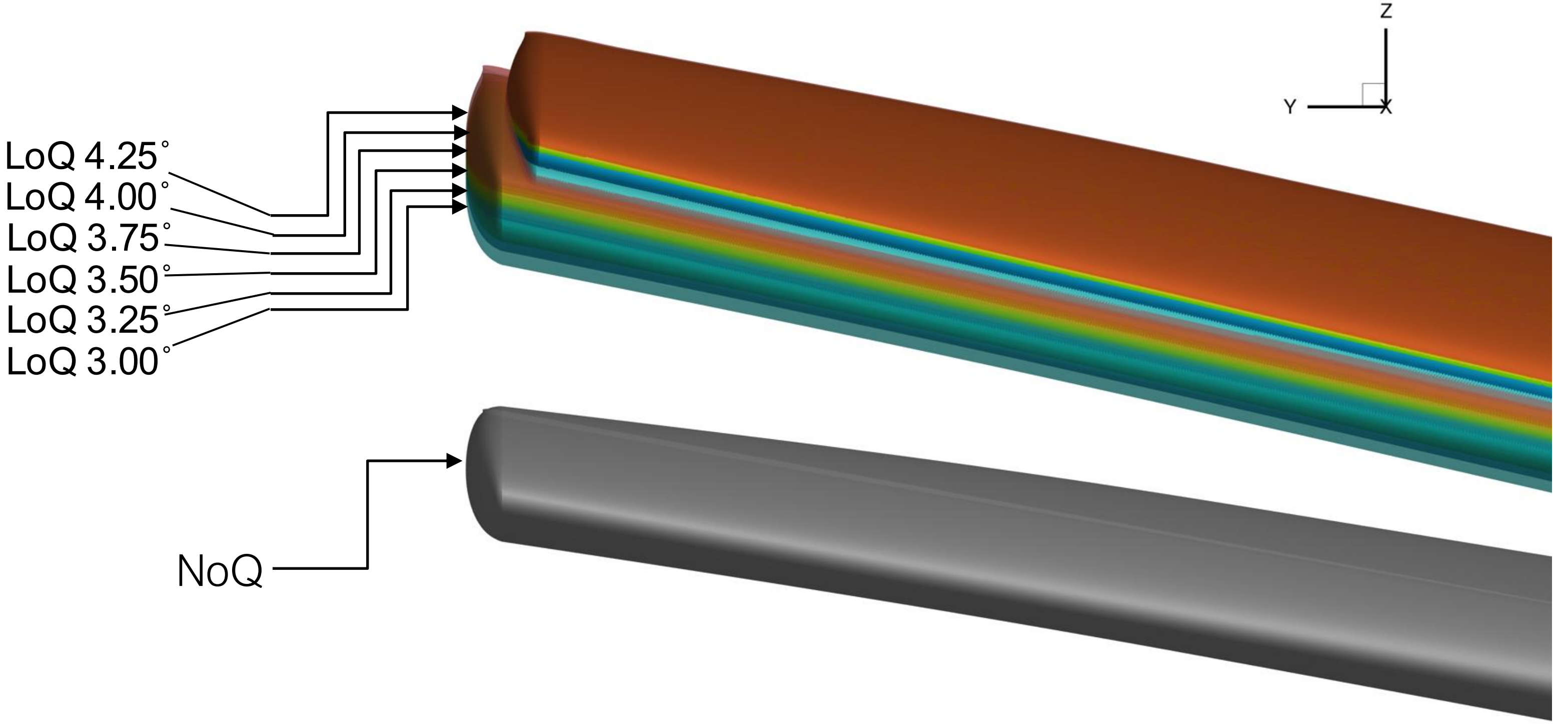
Wing Deformations, visualized



Wing Deformations, visualized



Comparison with “LoQ” grids



Summary

- ✓ **Good convergence for SARC+QCR, SST more problematic**
- ✓ **SARC+QCR captures experimentally-observed pitch-break**
  - SST showed bifurcating solution & larger juncture separation
- ✓ **Juncture-region separation pattern not mesh converged**
- ✓ **Shock-induced separation and body vortex footprint clear and unequivocal in all cases, but…**
  - Wing-vortex eye structure ambiguous in several runs
- ✓ **Coupled aero/structural model predicted deflections reasonably well (after matching q/E)**
  - Some discrepancies on length of deflected wings w.r.t. committee grids

Thank you ☺