# *Quantification of Grid Refinement Effects for NASA High Lift Trap Wing Using Error Transport Model*

P.A. Cavallo, G.M. Feldman
Combustion Research and Flow Technology, Inc. (CRAFT Tech)

30th AIAA Applied Aerodynamics Conference
New Orleans, LA
June 25, 2012

# *Presentation Overview*

- Analysis Objectives
  - Assess refinement effects as we approach stall
  - How well do our error prediction methods work?
  - How can we address/identify dissimilar refinement pairs?
- Error Quantification Method - ETE Solver
- Discussion of FUN3D results
  - 28 through 36 degrees angle of attack
  - Coarse/Medium/Fine grids
- Error Predictions Using ETE
  - *FUN3D* Grid Sequence
  - Cell-centered ETE on *USM3D* Solution
- New Approach for Assessment of Refinement Pairs
- Conclusions and Lessons Learned

# *Errors in CFD Analysis*

- Solution errors inherent to any CFD analysis
  - Discretization errors (grid size/spacings, time step)
  - Modeling errors (turbulence, transition, *etc*.)
  - Usage, iterative convergence, coding errors, *etc*.
- Discretization errors generally most dominant, but must be understood before tackling turbulence modeling issues
- How do we check our results? Verification & Validation (V&V)
  - Compare with test data (validation)
  - Perform grid refinement study (verification) – required workshop element!
  - Richardson extrapolation given 3 mesh sequence
- Our prior work at HLPW-1 examined refinement sequences at 13°, 28°
  - Error transport model seemed capable of predicting increments between coarse/fine and medium/fine solutions for these conditions
  - Current follow-on explores increments near stall, maximum $C_L$

# *Study Objectives*

- Explore mesh dependent effects as we approach stall
  - UT5 tetrahedral grid sequence employed
  - *FUN3D* solver, Spalart-Allmaras turbulence model
- Apply Error Transport Model to solution sequences
  - Evaluate method's ability to predict increments between solutions
  - If grid-induced errors can be predicted reliably, it potentially precludes need to run fine grid solution
  - In addition, reliable prediction could confirm confidence in results
- Investigate how to quantify dissimilar solution pairs
  - Such pairs cannot be considered in refinement sequence
  - ETE method cannot account for such disparities
  - Potential approach developed with preliminary results shown
- Identify shortcomings that remain to be addressed

# Error Prediction / Quantification

- 3D Error Transport Equation (ETE) Solver for steady state flows

$$\frac{\partial}{\partial t}\iiint\left(\vec{Q}-\vec{Q}^h\right)dV+\iint\left(\left(\vec{F}\left(\vec{Q}\right)-\vec{F}\left(\vec{Q}^h\right)\right)\cdot\hat{n}\right)dA=\iint\left(\left(\vec{G}\left(\vec{Q}\right)-\vec{G}\left(\vec{Q}^h\right)\right)\cdot\hat{n}\right)dA-\vec{R}$$

$$\boxed{\frac{\partial}{\partial t}\iiint\vec{\varepsilon}\,dV+\iint\left(\left(A\left(\vec{Q}^h\right)\vec{\varepsilon}\right)\cdot\hat{n}\right)dA=\iint\left(\vec{G}\left(\vec{\varepsilon}\right)\cdot\hat{n}\right)dA-\vec{R}_{INV}-\vec{R}_{TURB}}$$

  - Inviscid residual: upwind terms of Roe flux
  - Turbulent residual: accounts for effects of error in $\mu_t$ on mean flow
  - $k$–$\varepsilon$, $k$–$\omega$, Spalart-Allmaras models supported
  - Recently expanded to support cell-centered solvers and solve ETE using cell-centered or node-centered discretization*
- Error Function Library
  - Propagates predicted errors into derived variables of interest
  - PLOT3D functions, integrated functions, *etc.*

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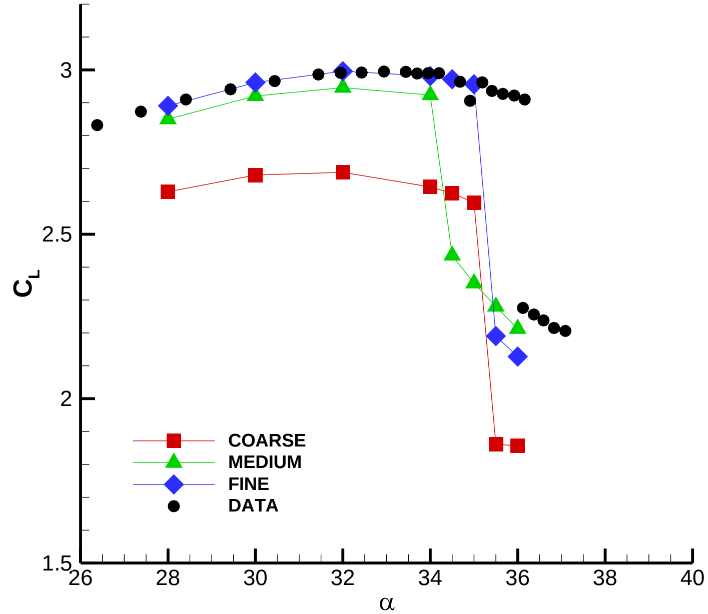
* Cavallo, P.A., O'Gara, M.R., Feldman, G.M., and Liu, Z., "Unified Error Transport Equation Solver for Solution Verification on Unstructured Grids," AIAA Paper 2012-3345, 42nd Fluid Dynamics Conference, New Orleans, LA, June 25-28, 2012.

# What Are We Looking For?

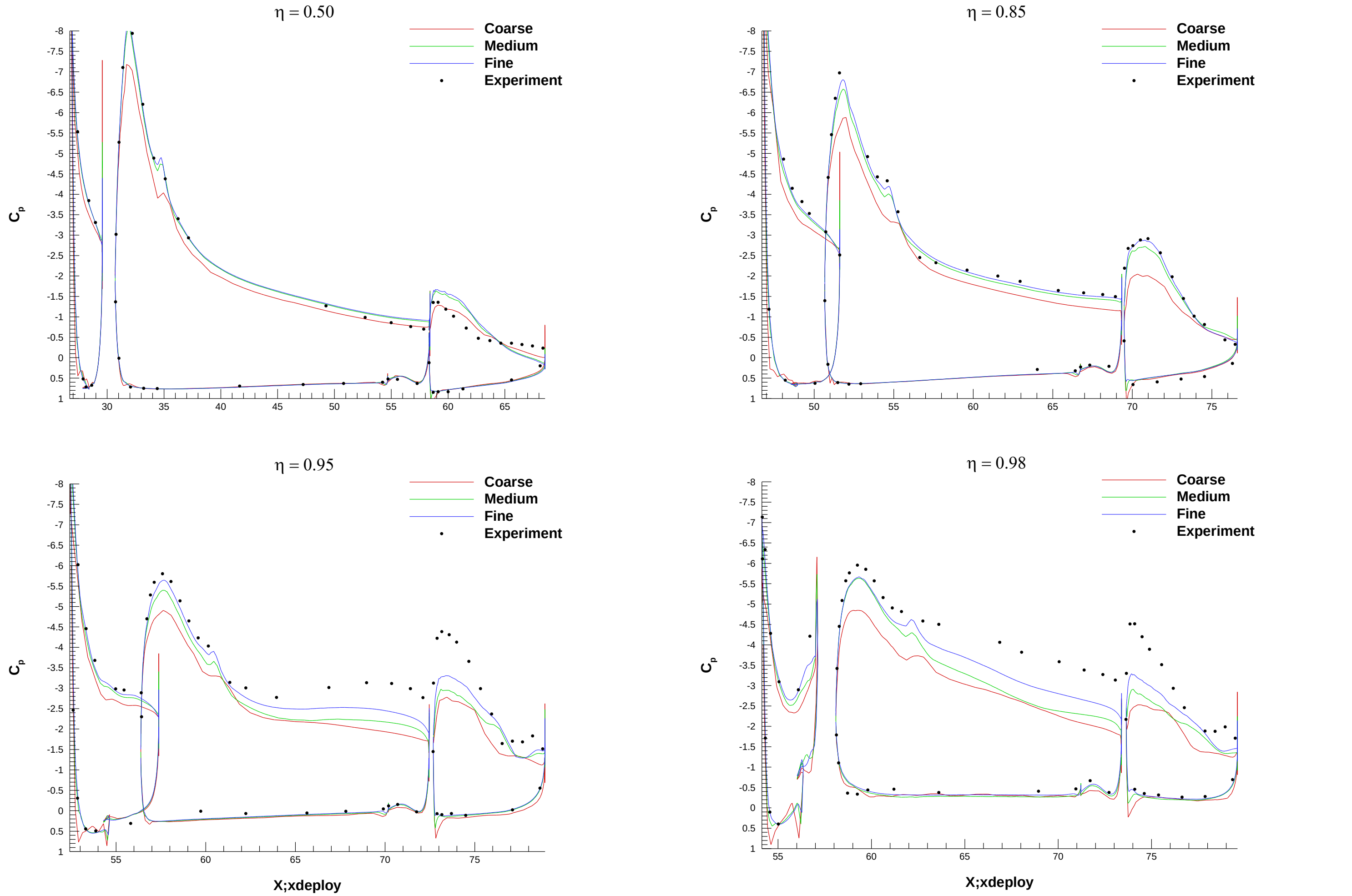
- Goal of Error Transport research is to establish alternative solution verification method
  - Provide reliable predictions of mesh-induced errors
  - Prediction of coarse-to-fine grid increments
  - Useful for quantifying local and integrated quantities
- Error bars predicted by ETE solution and Error Functions should:
  1) Contain fine grid results
  2) Contain results of Richardson extrapolation
  3) Decrease in magnitude with grid refinement
  4) Not be overly conservative as to be unusable
- If fine grid results fall outside predicted error bars, it potentially indicates new flow features result from grid refinement
- If test data falls outside predicted solution and error bars, it potentially indicates a deficiency in physical modeling

# *Lift Characteristics Near Stall*

- Maximum $C_L$ predicted to occur at 32 degrees for each grid
- Stall point is mesh dependent
  - Medium grid stalls first just beyond 34 degrees
  - Coarse and fine grids both stall at ~35 degrees
  - Separation patterns on coarse, fine grids are quite different



# FUN3D Results, α=28°



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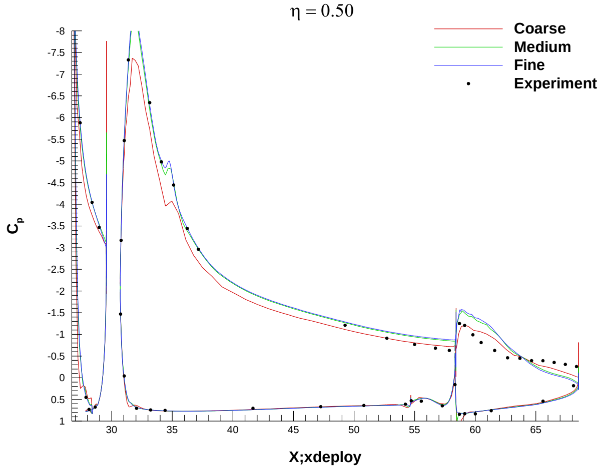
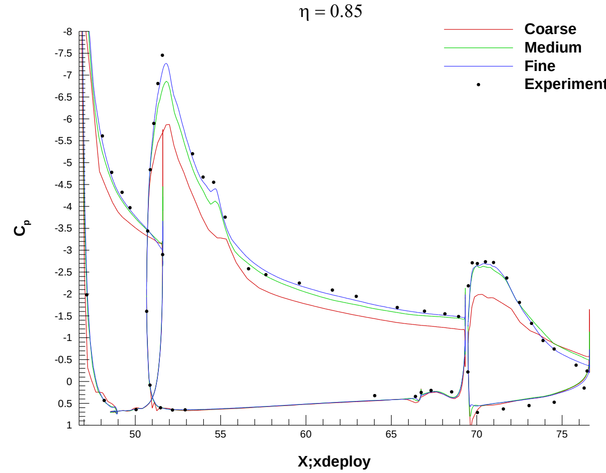
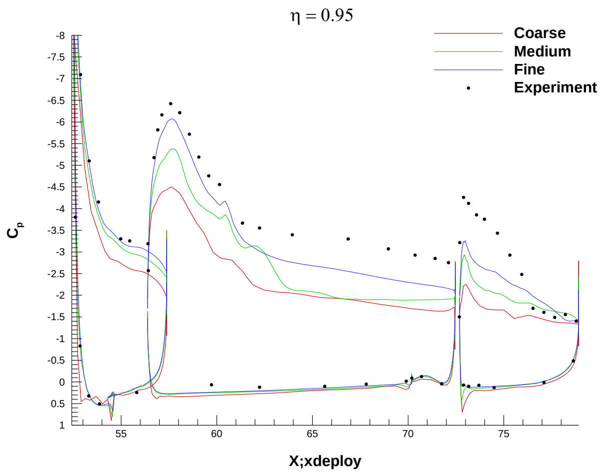
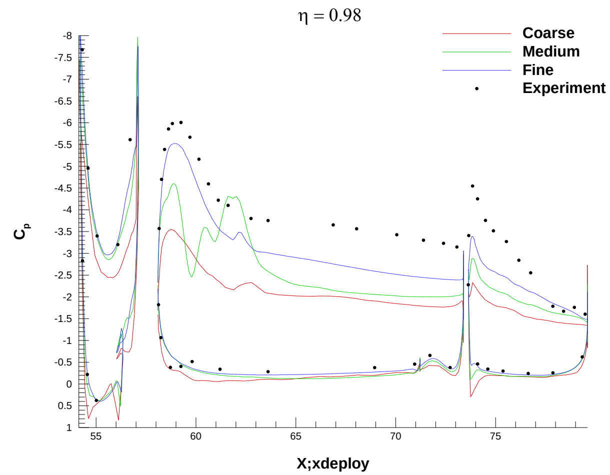
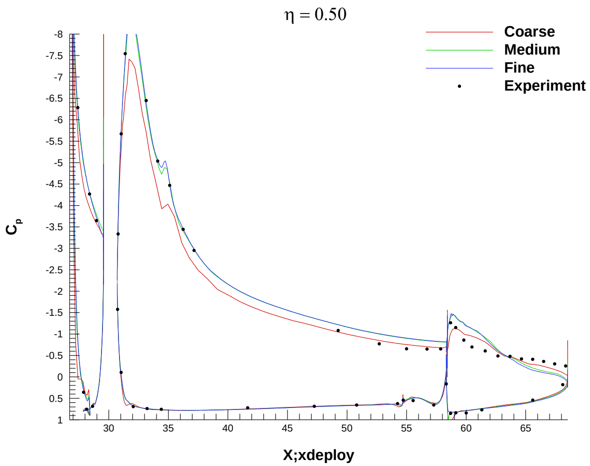


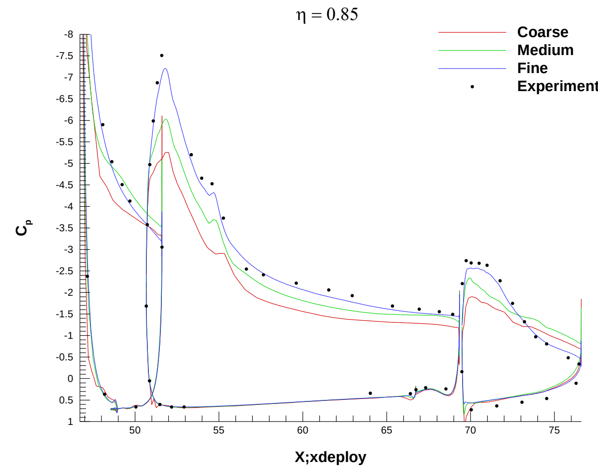



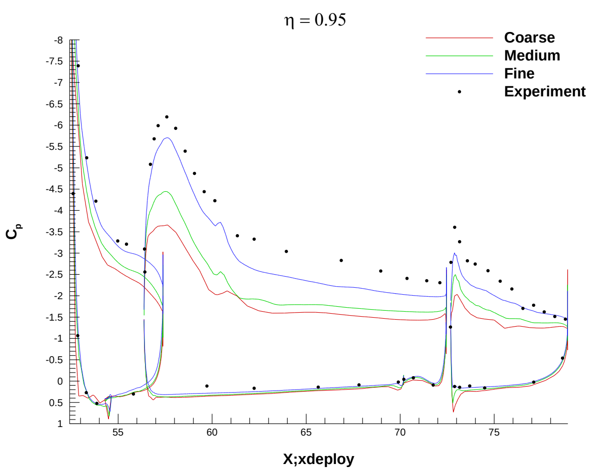



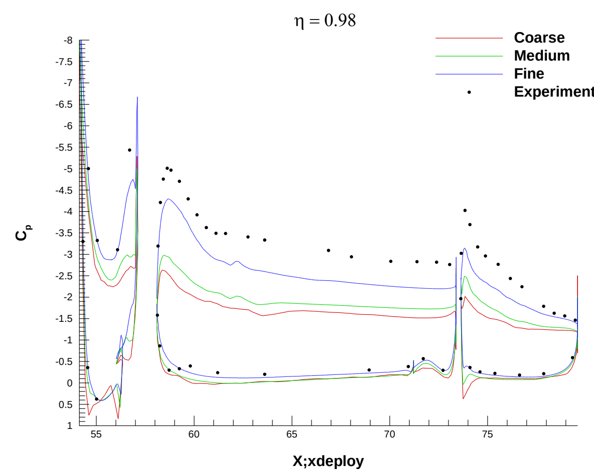



# *FUN3D Results, α=34°*



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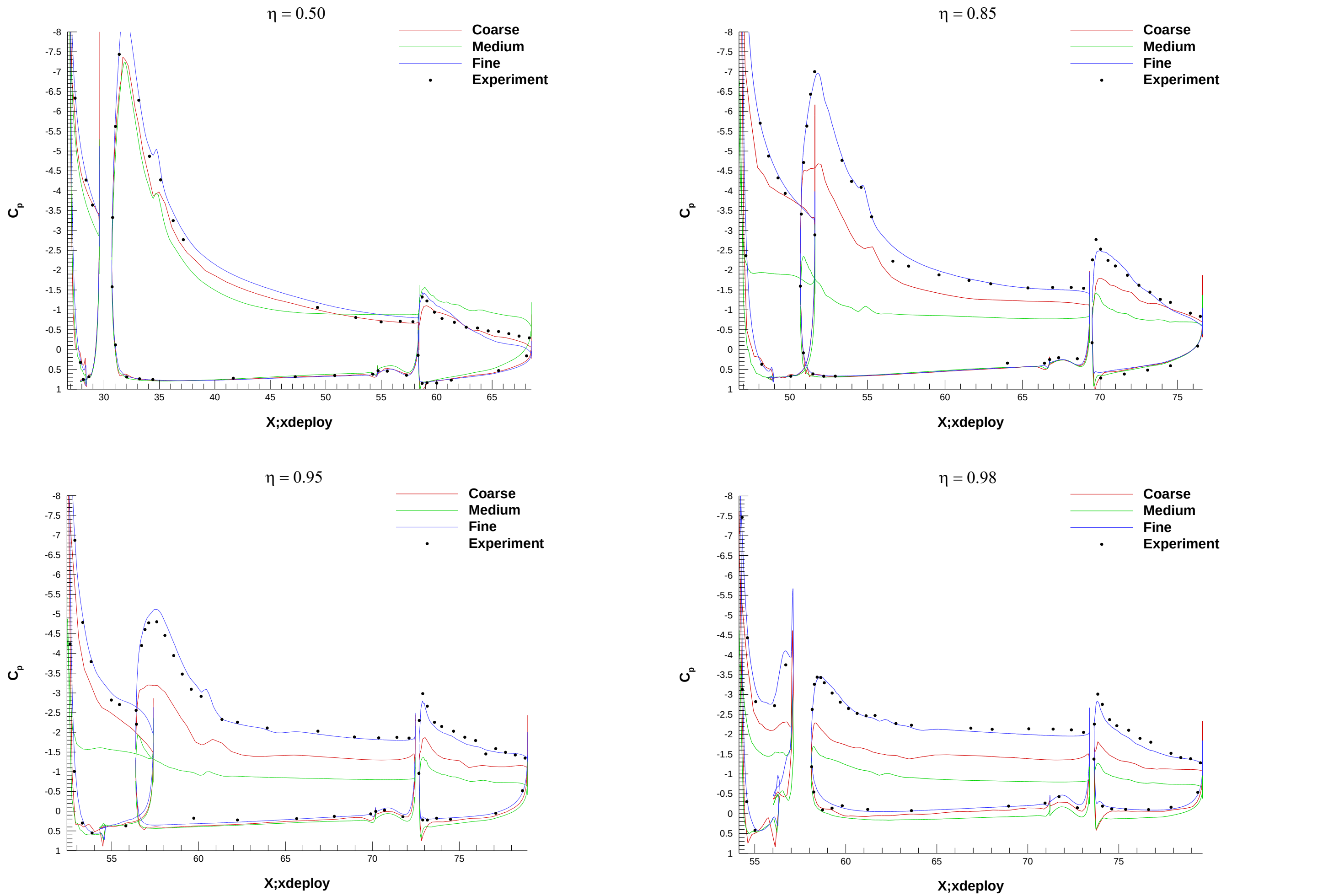
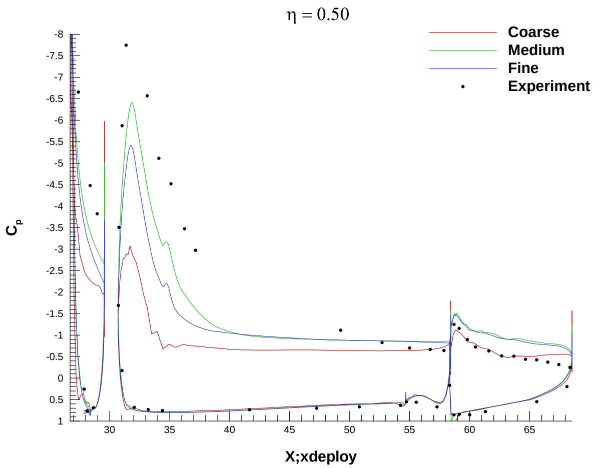
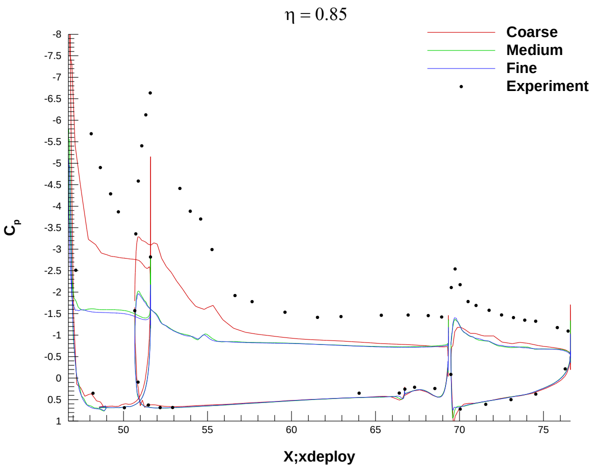
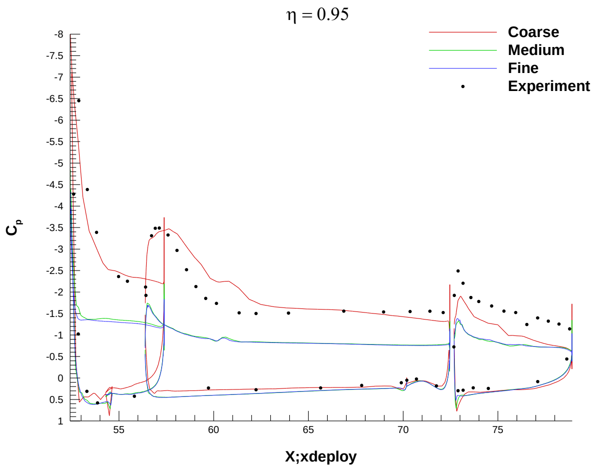
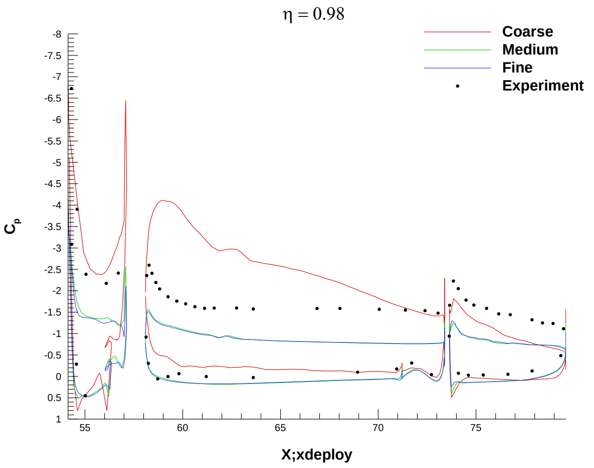


# *FUN3D Results, α=36°*

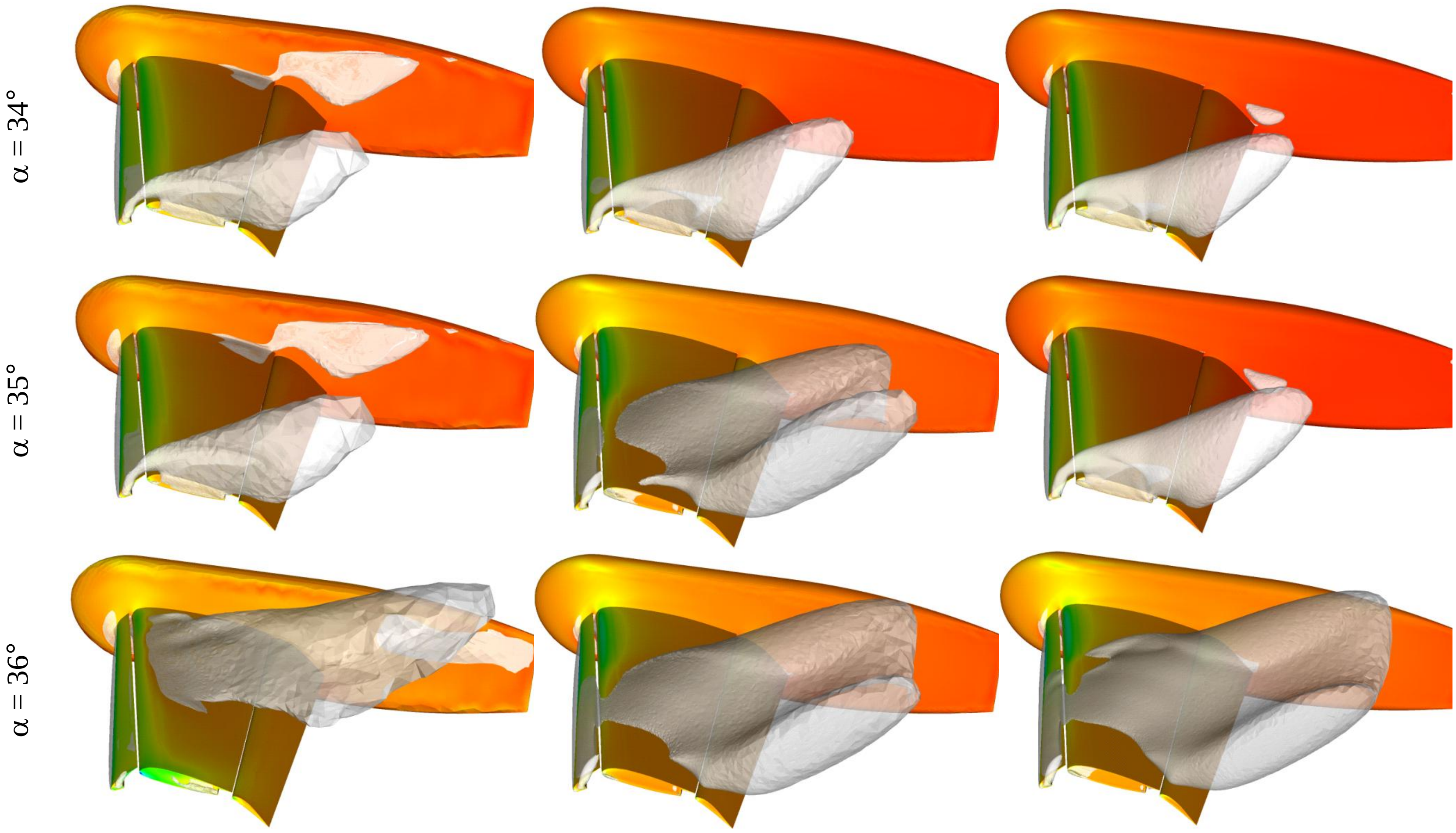


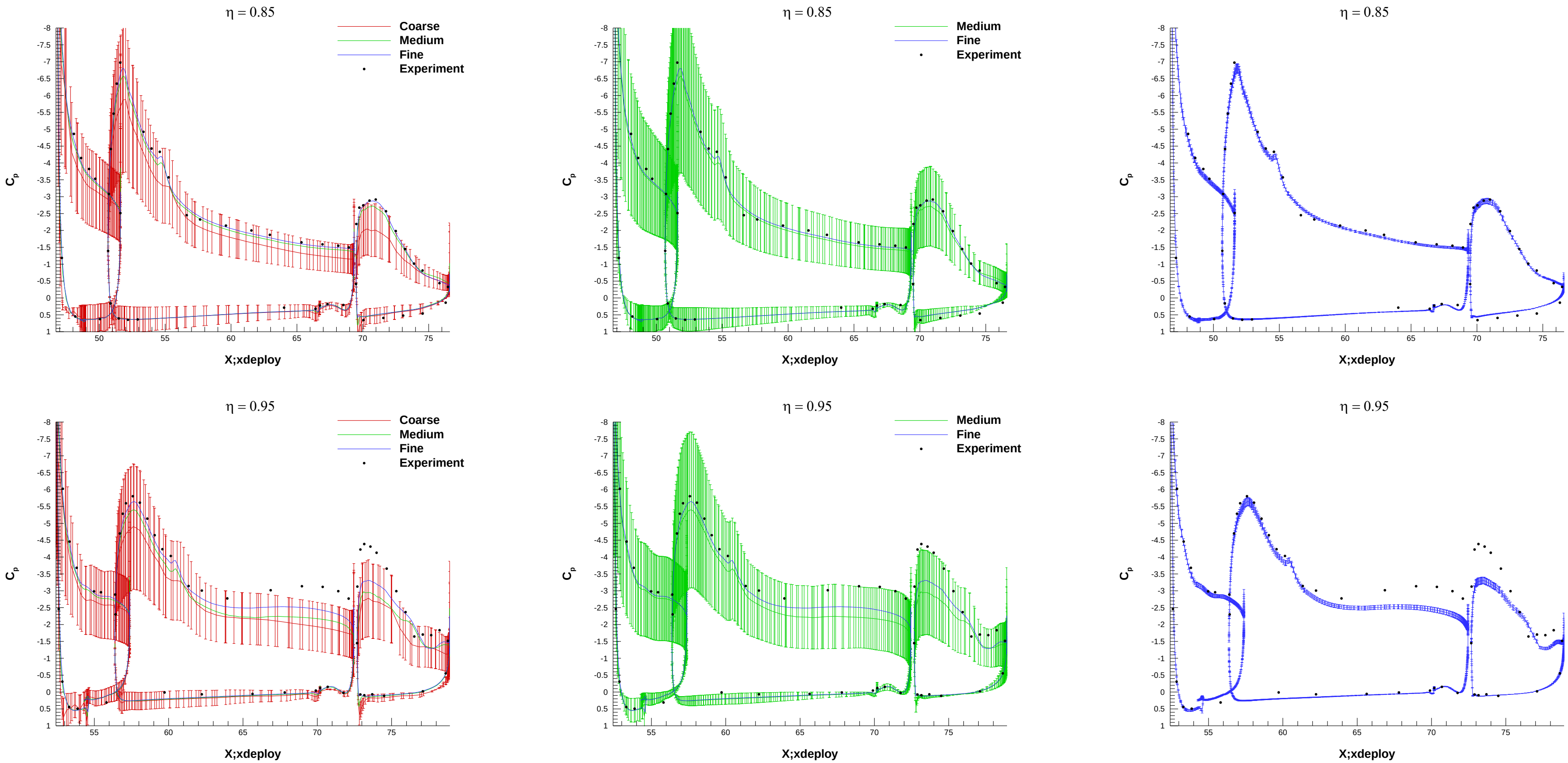



# *Stall Patterns*



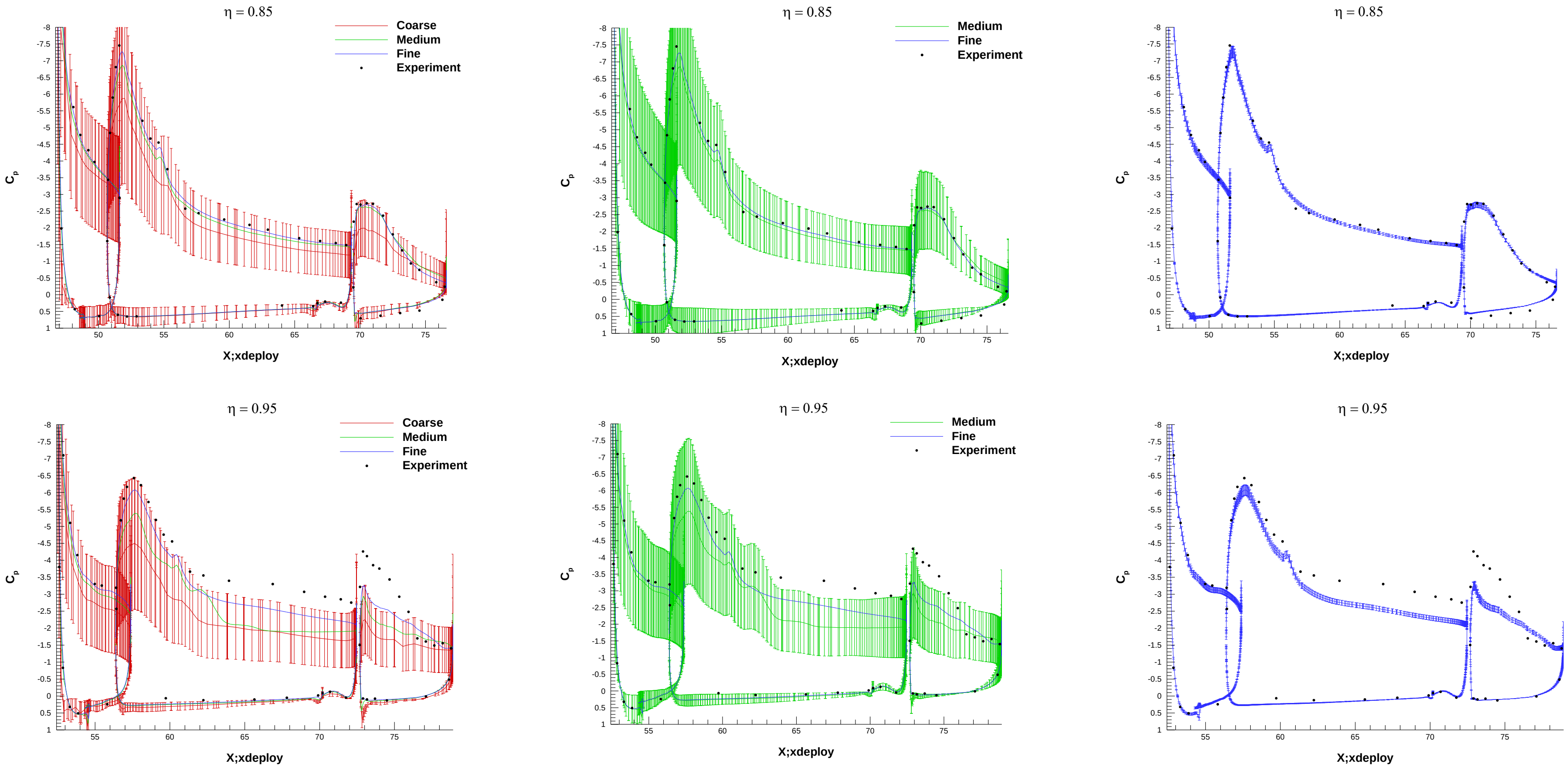

a) Coarse grid b) Medium grid c) Fine grid

# *ETE Results, α=28°*



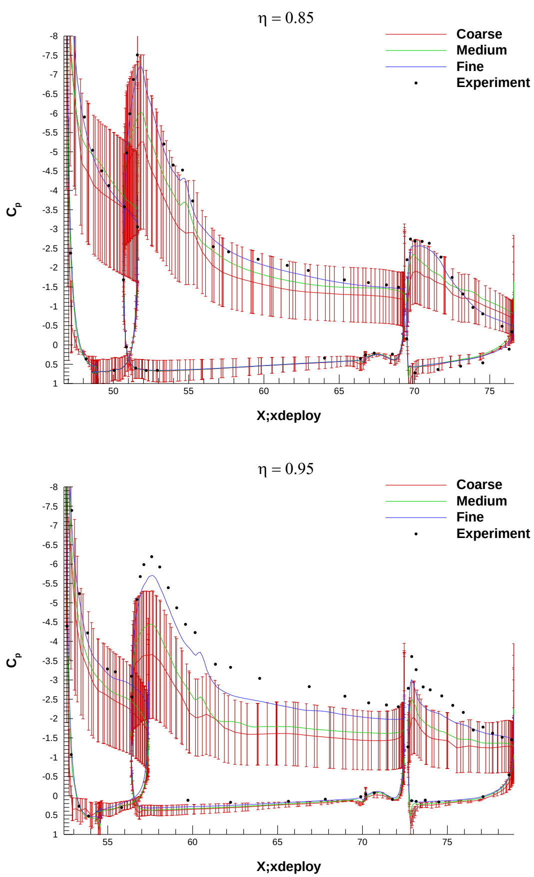

a) Coarse b) Medium c) Fine

# ETE Results, α=32°

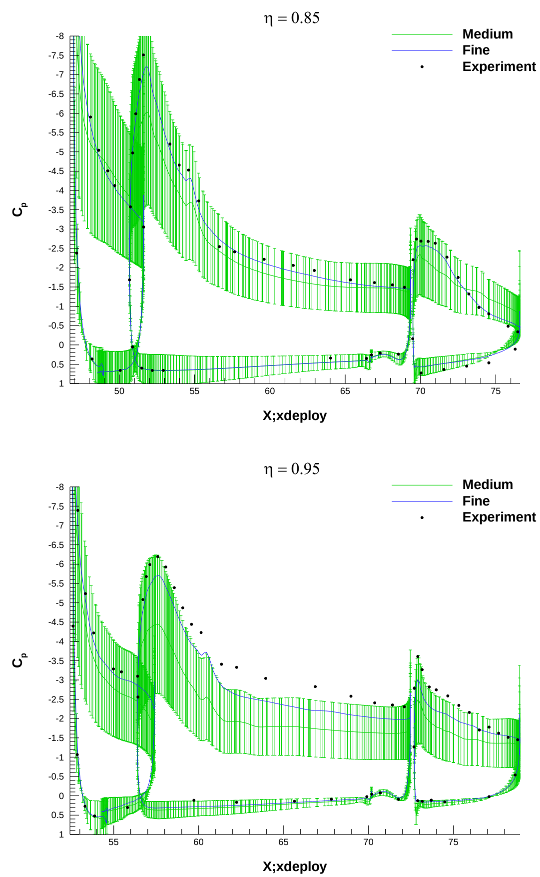



a) Coarse    b) Medium    c) Fine

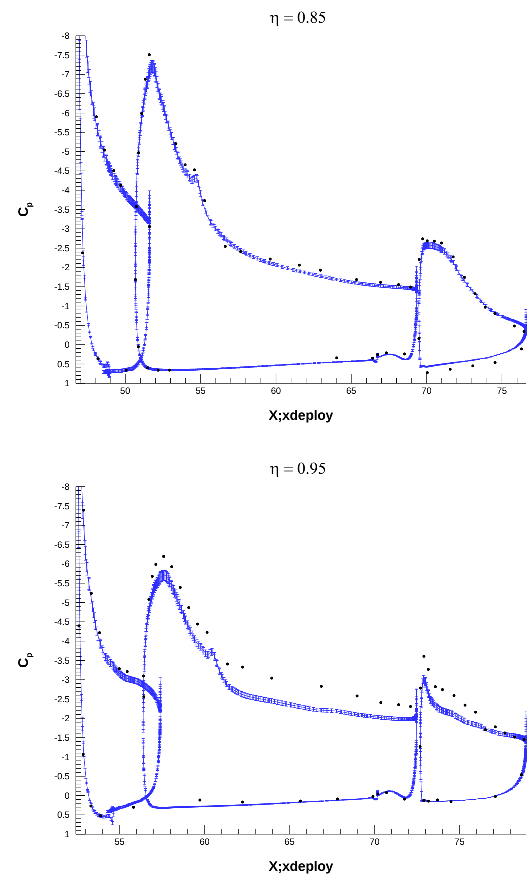
# ETE Results, α=34°




a) Coarse

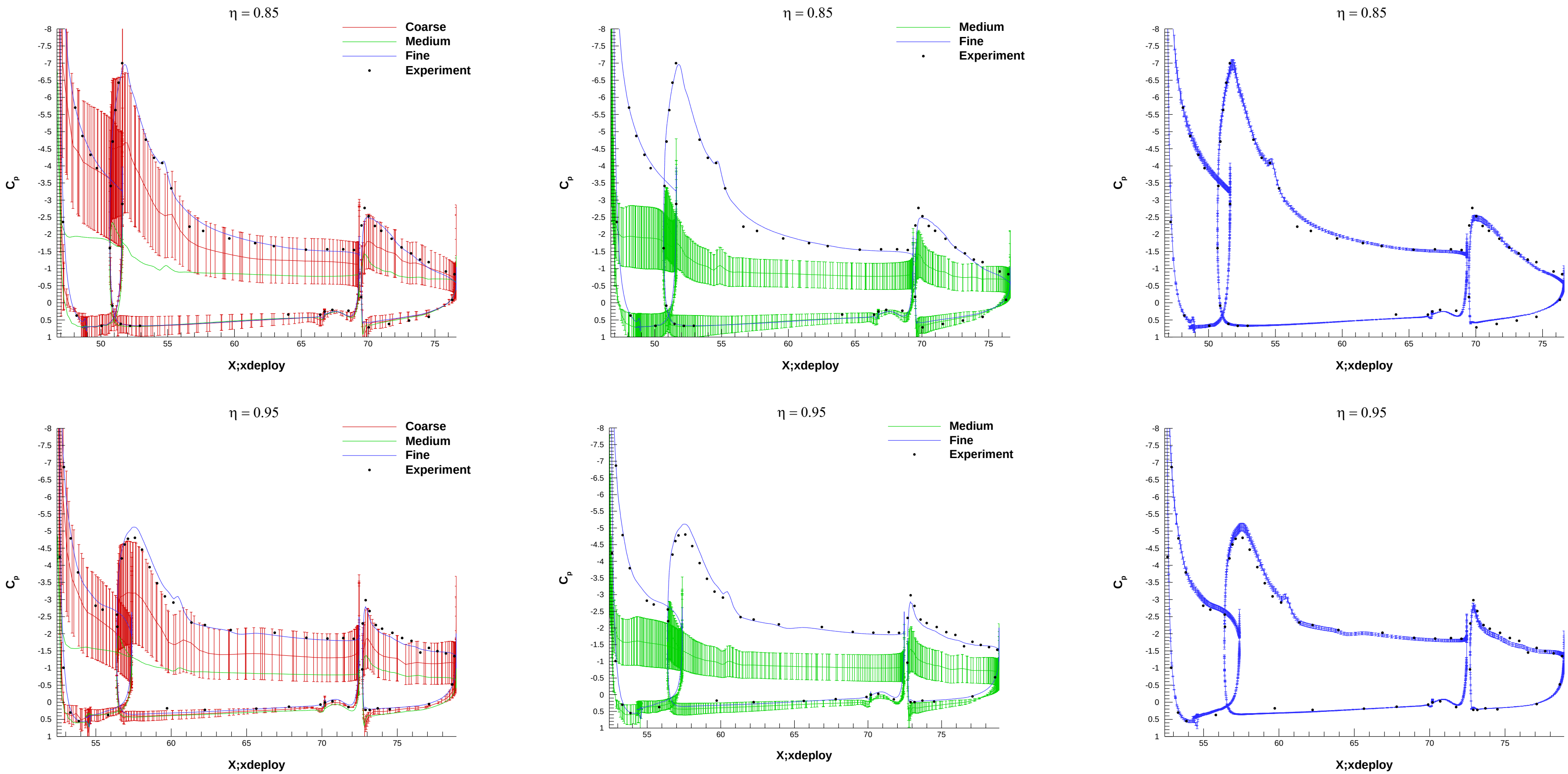



b) Medium



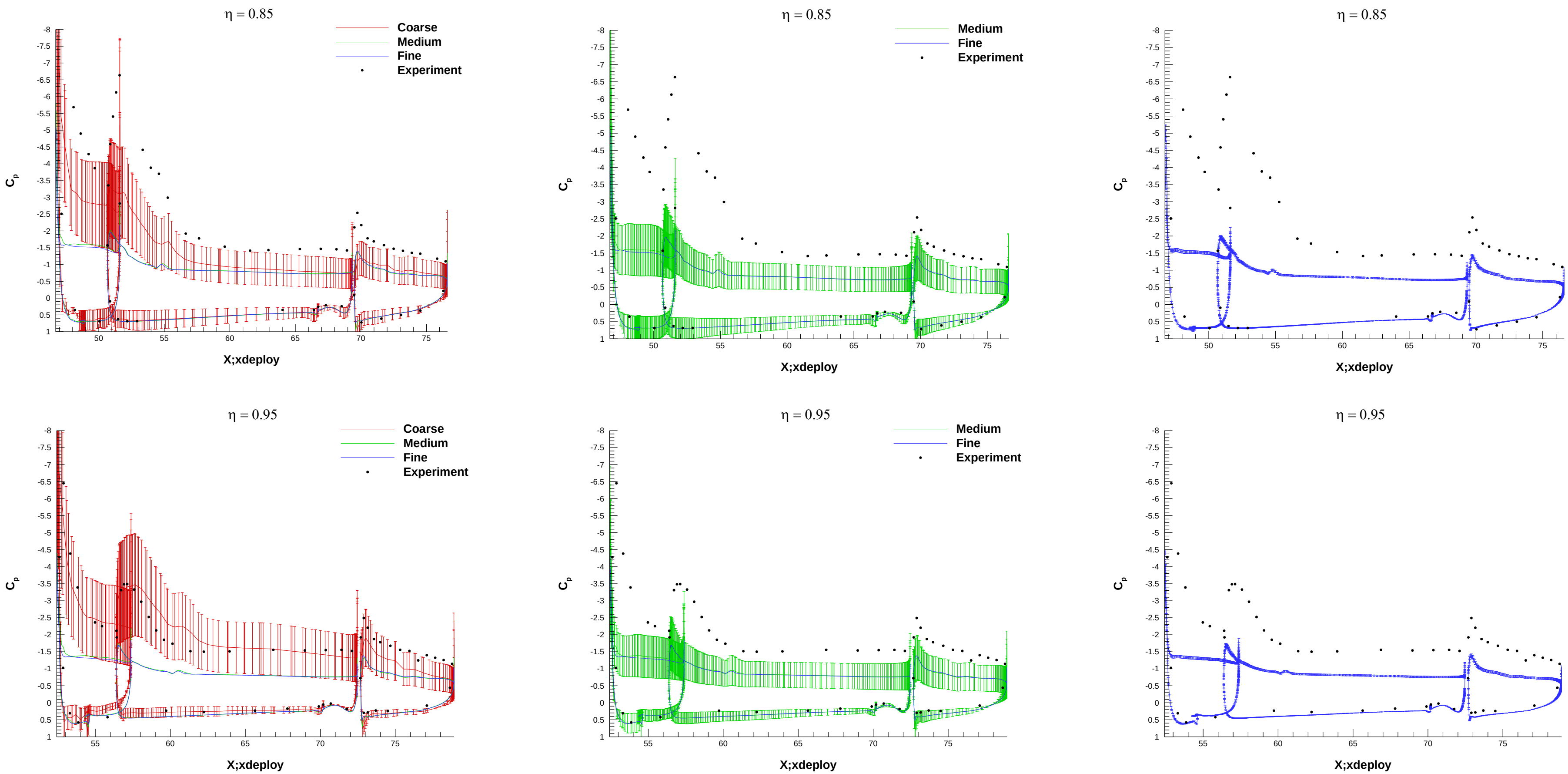

c) Fine

# *ETE Results, α=35°*




a) Coarse b) Medium c) Fine

# *ETE Results, α=36°*

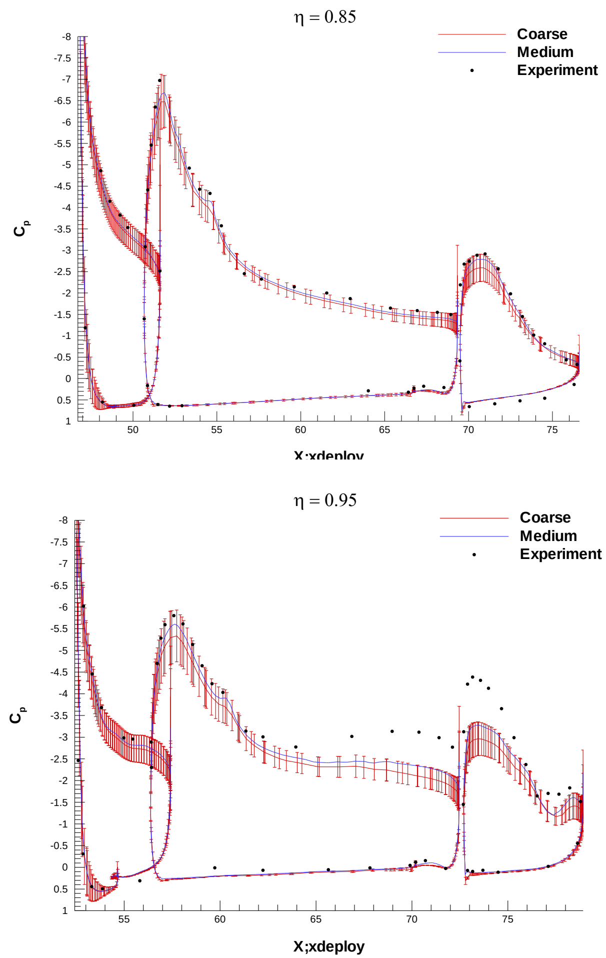



a) Coarse

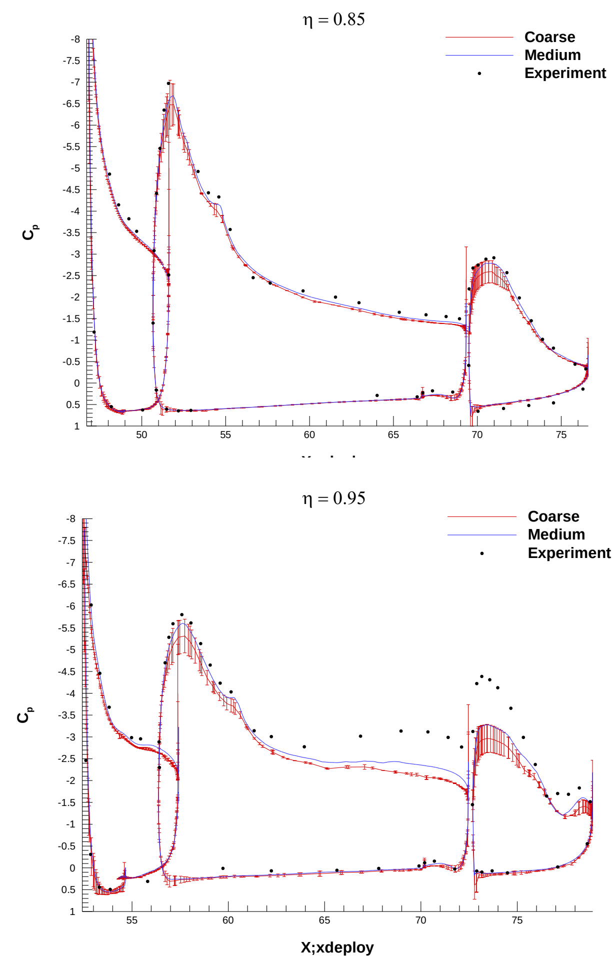
b) Medium

c) Fine

# *USM3D ETE Results, α=28°*



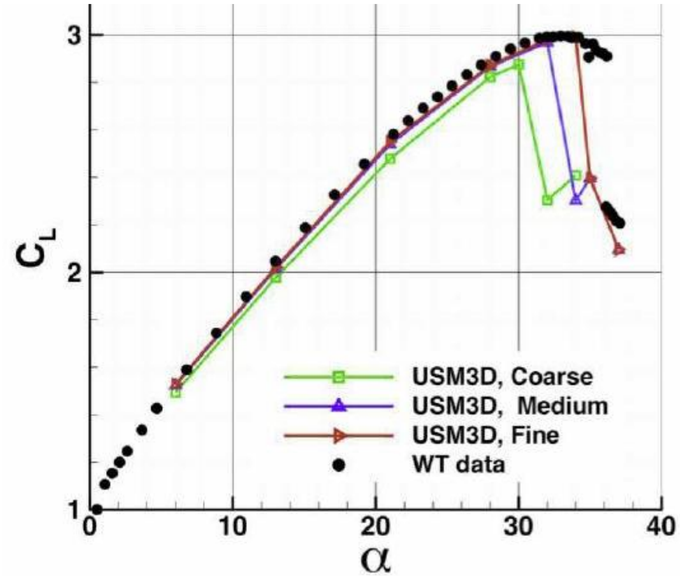

a) Node-centered ETE




b) Cell-centered ETE

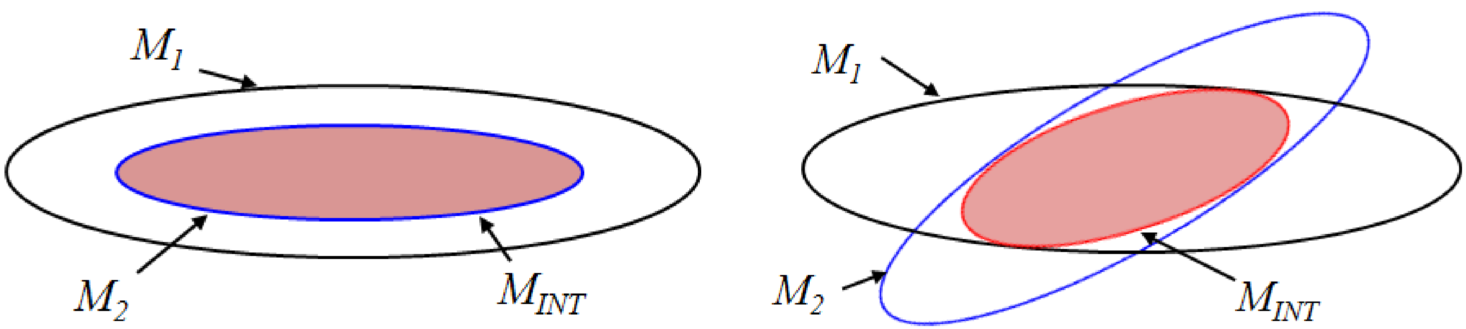
# *Assessing Solution Pairs*

- Error Transport model cannot account for absence or presence of a flow structure due to grid refinement
  - e.g., stall vs. no stall
- Means of quantifying similarly between solution pairs needed to assess if sequence is near monotonic range – otherwise Richardson extrapolation and ETE are not applicable
  - e.g., *USM3D* solution sequences beyond 30 degrees (*Pandya et al*., 2011)
- Approach explored based on intersection of metric ellipsoids
  - Metric formed using Hessian matrix of 2nd derivatives
  - Eigenanalysis extracts principal directions and length scales associated with flowfield



# *Metric Intersections*

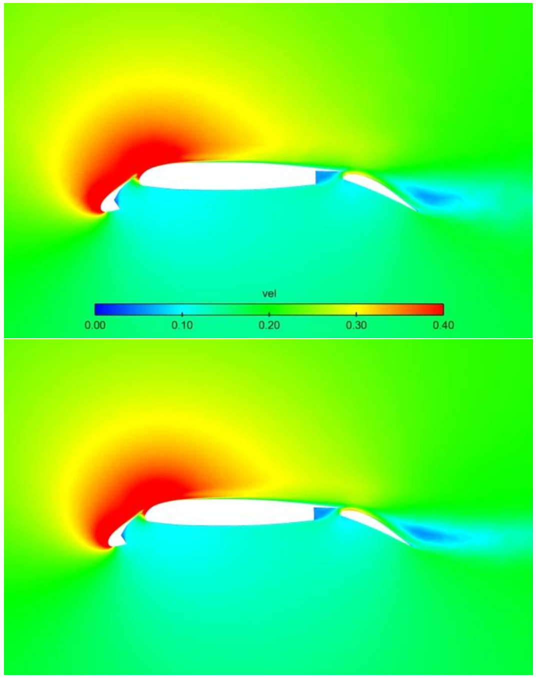
- Metric tensors represented as 3D ellipsoid
- Intersection of ellipsoids can indicate scaling and alignment
  - Consider M1 to be coarse solution metric, M2 fine solution metric
  - Solution should sharpen with mesh refinement:  principal directions are nearly aligned and length scales are merely scaled from coarse to fine grid
  - Misalignment between solution pairs would result in intersected volume that is less than volume of metric ellipsoid M2

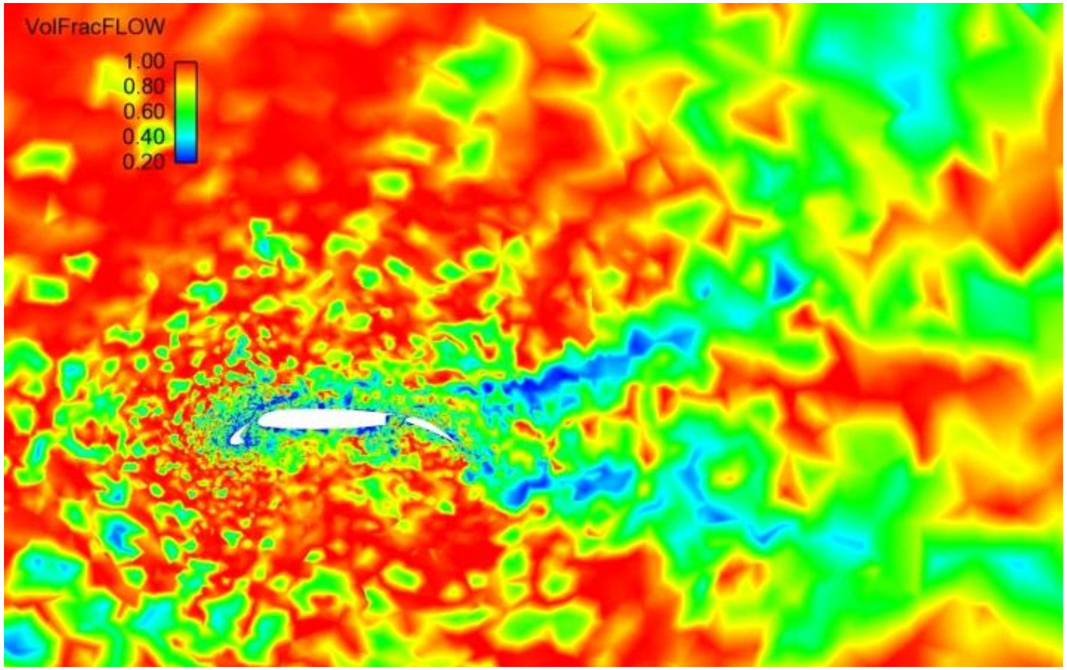



- Examine the volume fraction $\phi = V_{INT} / V_2$

# *Similar Solution Pair, α=28°*

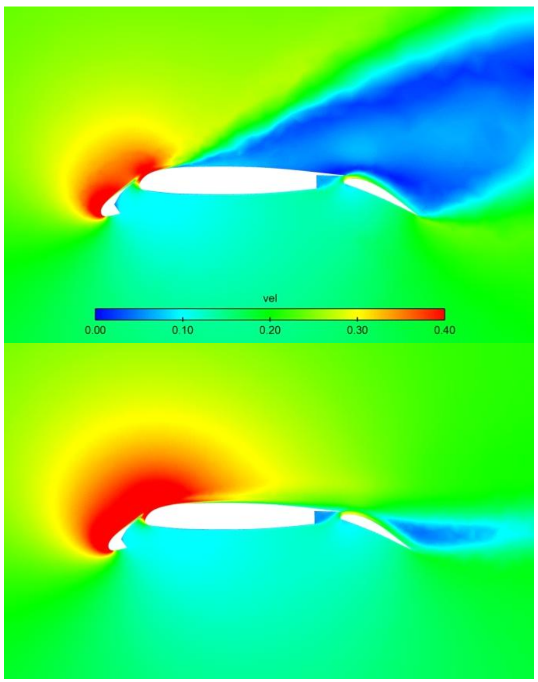
- Preliminary results comparing Coarse (top) and Medium (bottom) grid solutions from *USM3D*
- Solution pair is similar and volume fraction is consistent with this
- “Spottiness” of plot believed related to data transfer/interpolation

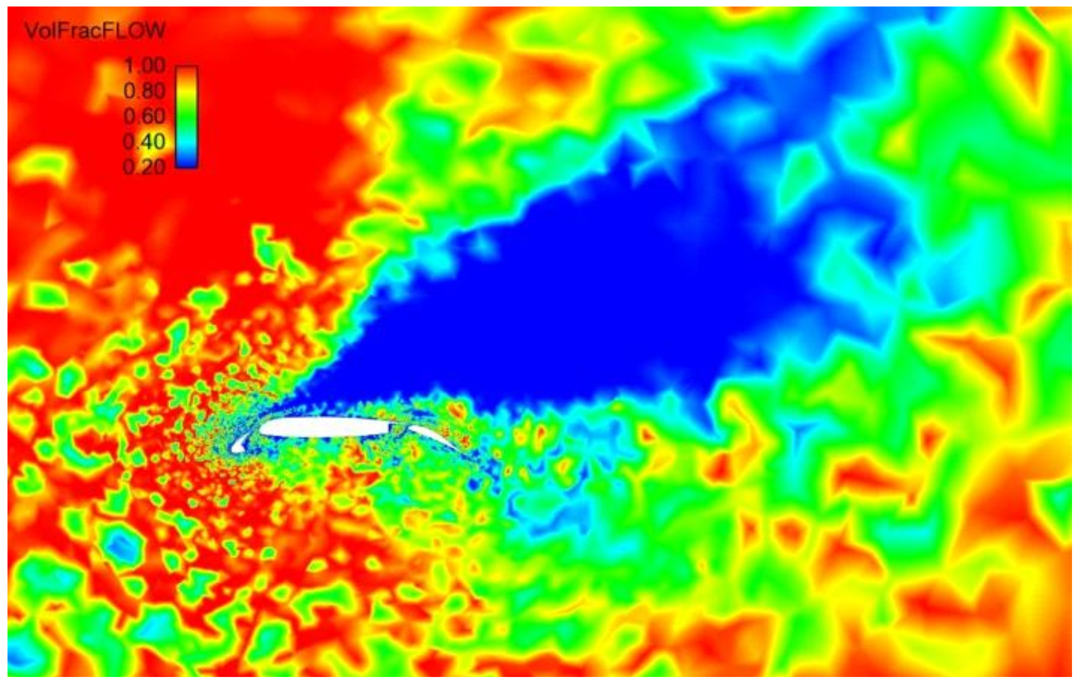


# *Dissimilar Solution Pair, α=32°*

- At 32 degrees, the Coarse *USM3D* solution predicts stall, while the Medium grid predicts attached flow
- Volume fraction from metric intersection comparing the solutions picks up this disparity well
- Still exploring how we can improve method and use this information



# *Conclusions and Lessons Learned*

- Investigated grid refinement effects up to and beyond maximum $C_L$
  - Angle of peak $C_L$ itself is grid-independent (~32 degrees)
  - Onset of stall, separated flow structures exhibit mesh dependent behavior
  - Inboard vs. outboard evolution of separation
- High alpha cases were a considerable challenge for Error Transport Model's ability to capture grid-induced increments
  - Generally, predicted errors in $C_p$ were quite large for all medium grid *FUN3D* solutions
  - Clearly, accuracy concerns must be revisited for these cases
  - Cell-centered ETE solution for *USM3D* shows promise
- Path towards quantifying solution similarity established
  - Method based on computing metric tensor intersections
  - Preliminary application on *USM3D* sequence
  - Method needs further development and testing

# Acknowledgment

- Research conducted under Phase II SBIR program sponsored by NASA Langley Research Center, Hampton, VA

- ***Questions?***

- Contact info:

Dr. Peter Cavallo, Senior Research Scientist
CRAFT Tech
6210 Keller's Church Road
Pipersville, PA 18947
(215)-766-1520
*cavallo@craft-tech.com*