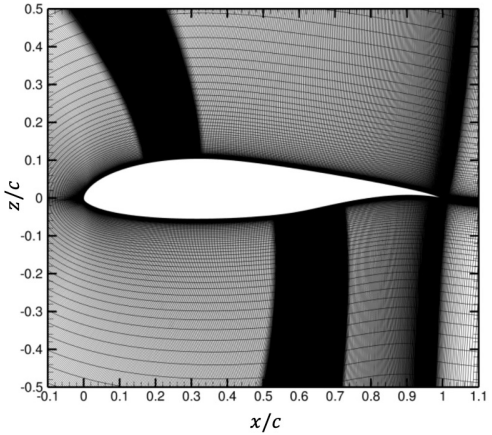
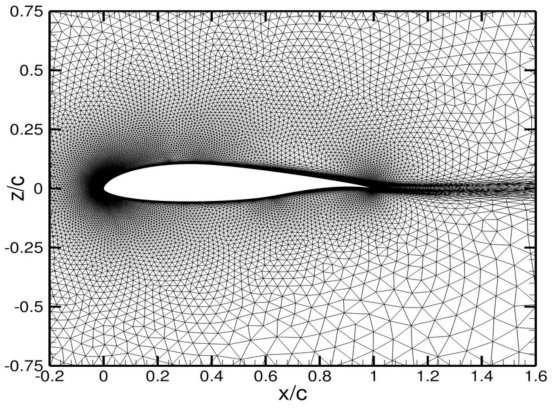
Grid Refinement Techniques for the γ-Re_{θ_t} Transition Model in FUN3D





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APA-72: Turbulence and Transition Modeling I
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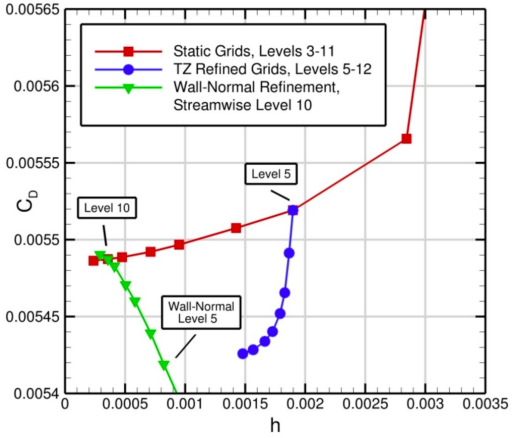
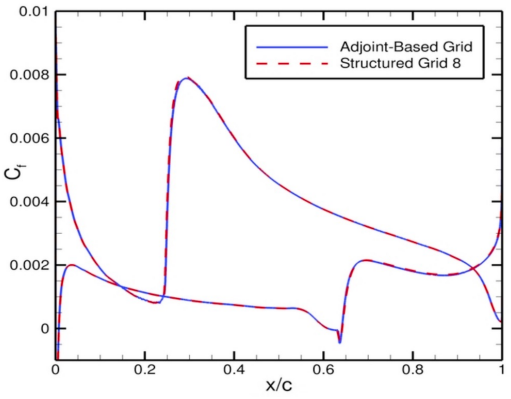
Orlando, Florida; January 12, 2024





Motivation

- Large scatter amongst results from RANS-based transition models for simple 2D flow configurations at recent workshops (flat plates, airfoils, etc.)
  - 1st AIAA CFD Transition Modeling and Prediction Workshop
  - AVT-313 Incompressible Laminar-to-Turbulent Transition Workshop

- To achieve grid converged results with FUN3D and OVERFLOW requires many cells/points
  - Schubauer and Skramstad flat plate: $N = 31$ million
  - NLF-0416 airfoil: $N = 17$ million
  - Venkatachari et al. (*Journal of Aircraft* 2023)

- Hard to verify RANS-based transition model implementations against these 2D results because of grid resolution requirements
  - More difficult for 3D flow configurations

- Explore different grid refinement techniques to reduce overall node count for convergence by at least an order of magnitude, gain insights on how to improve grid adaption (e.g., metrics, topology, near-wall constraints), and develop guidelines on how grids are to be crafted for RANS-based transition models

Outline

- Langtry-Menter γ-Re_{θ_t} transition model and FUN3D suite of codes
  - γ-Re_{θ_t} transition model is paired with the SST-2003 turbulence model and has 4 transport equations for the turbulent kinetic energy, dissipation, intermittency, and transition momentum-thickness Re
  - FUN3D is an implicit finite-volume node-centered upwind-biased flow solver that is 2^{nd}-order accurate for inviscid/viscous fluxes and 1^{st}-order accurate for convective terms

- Structured zonal streamwise refinement around transition to turbulence
  - Schubauer and Skramstad flat plate with natural transition
  - NLR-7301 transonic airfoil at $\alpha = -2.267°$ with separation-bubble-induced transition
  - Refer to conference paper for NLF-0416 airfoil

- Unstructured mesh refinement for the NLF-0416 airfoil with $\alpha = 5°$
  - Family of uniformly-refined grids
  - Metric-based refinement using the $refine$ library with FUN3D
  - Adjoint-based refinement with C_D objective function

- Verification study where grids and solutions will be posted on the NASA Turbulence Modeling Resource (TMR) – https://turbmodels.larc.nasa.gov/

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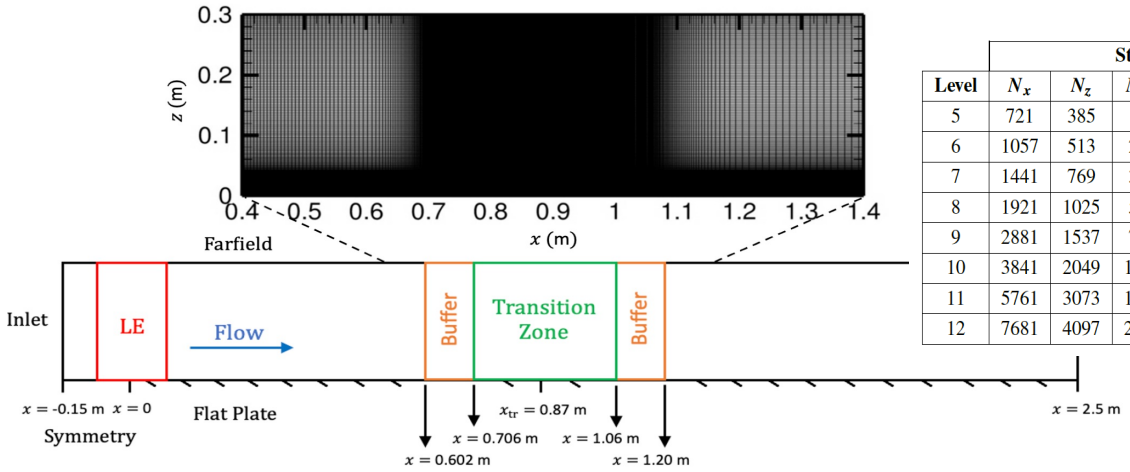
Schubauer and Skramstad Flat Plate Configuration

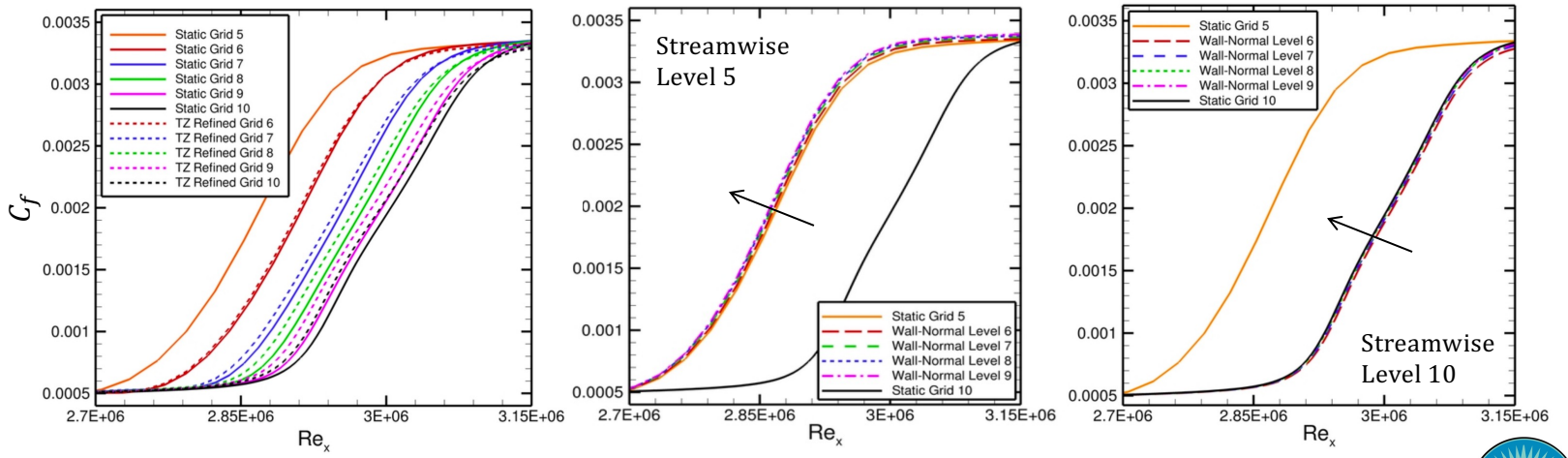
- $M = 0.147$, $\mathrm{Re}_\infty = 3.36\mathrm{e}6\ 1/\mathrm{m}$, $T = 288.17$ K, $\mathrm{Tu} = 0.1337\%$, and $\mu_t/\mu = 1$
- Local streamwise refinement (colored boxes) close to natural boundary-layer transition
  - Level 5 is the baseline grid with $\Delta y^+ \approx 0.25$
  - Insert next levels in transition zone
- Also examine the impact of global wall-normal refinement



	Static Grids					Locally Refined Transition Zone Grids						
Level	N_x	N_z	N_{LE}	N_{tot}	h	N_x	N_z	N_{LE}	N_{tot}	h	N_{TZ}	N_{buf}
5	721	385	193	0.27e6	19.0e-4	721	385	193	0.278e6	19.0e-4	-	-
6	1057	513	257	0.542e6	13.6e-4	746	385	193	0.287e6	18.6e-4	53	21
7	1441	769	385	1.11e6	9.5e-4	776	385	193	0.299e6	18.3e-4	79	23
8	1921	1025	513	1.97e6	7.1e-4	810	385	193	0.312e6	17.9e-4	105	27
9	2881	1537	769	4.43e6	4.8e-4	870	385	193	0.335e6	17.3e-4	157	31
10	3841	2049	1025	7.87e6	3.6e-4	938	385	193	0.361e6	16.6e-4	209	39
11	5761	3073	1537	17.7e6	2.4e-4	1058	385	193	0.407e6	15.7e-4	313	47
12	7681	4097	2049	31.5e6	1.8e-4	1186	385	193	0.457e6	14.8e-4	417	63

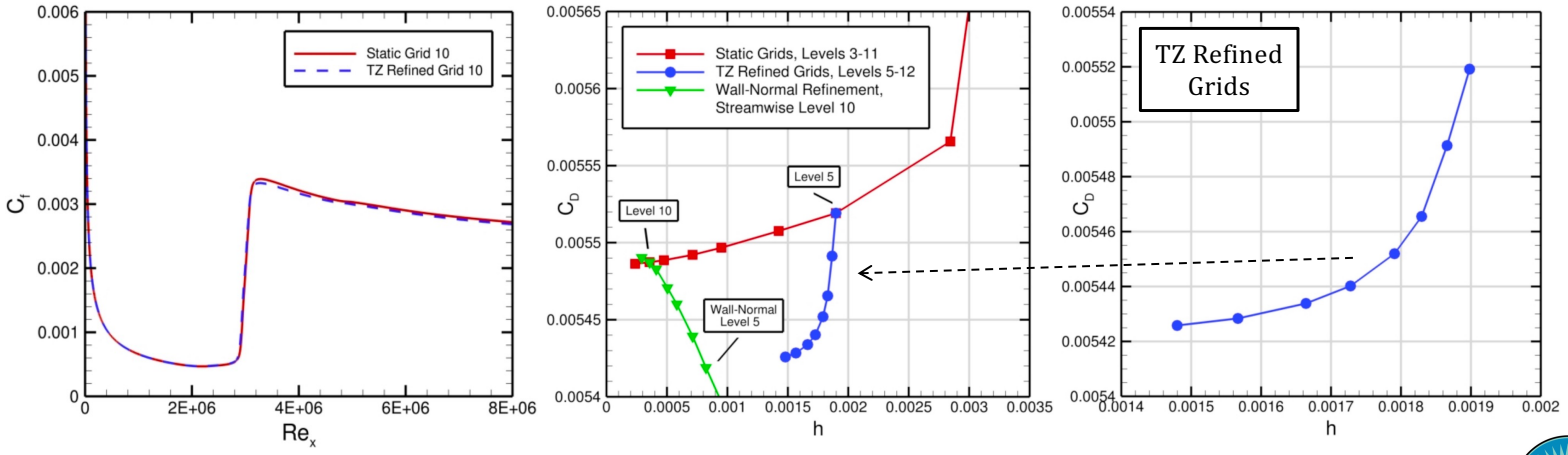
Local Streamwise and Global Wall-Normal Refinement Outcome

- Transition Zone (TZ) refined grid solutions yield similar locations of transition to turbulence as the corresponding static grid solutions with a very slight mismatch on the finest grids
- If the streamwise resolution is **not** fine enough, then adding more wall-normal resolution will result in an inaccurate converged solution
- Wall-normal resolution also impacts the value of turbulent skin friction



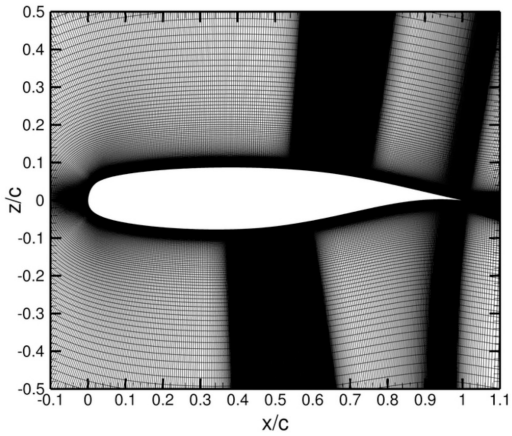
Grid Convergence of C_f and C_D for Flat Plate

- $h = \sqrt{N_{tot}} = \sqrt{N_x \times N_z}$ is the mesh spacing parameter
- Overall agreement between TZ refined and static grid solutions
  - C_f in turbulent region is lower due to wall-normal level five resolution
  - C_D is different by 6×10^{-5}, which is less than one drag count (10^{-4})
- Cost savings between level 12 grids would be $N_{\text{tot,static}}/N_{\text{tot,local}} = (31.5\times10^6)/(0.457\times10^6) \approx 69$

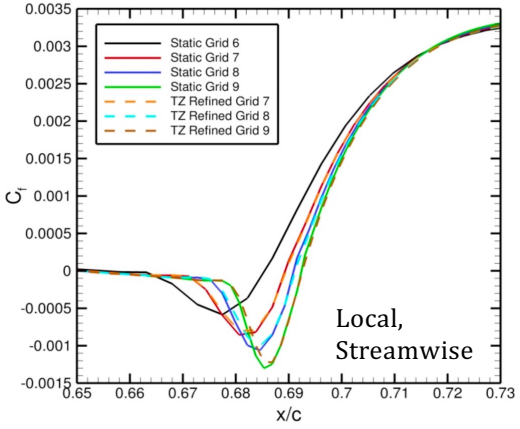


NLR-7301 Transonic Airfoil Configuration

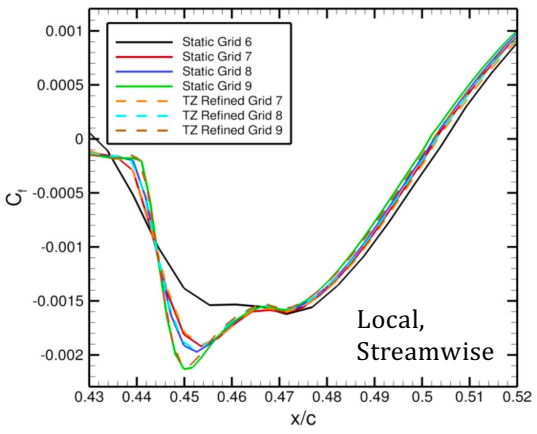
- $M = 0.748$, $\mathrm{Re}_c = 2.2\mathrm{e}6$, $T = 300$ K, $\alpha = -2.267°$, $\mathrm{Tu} = 0.158\%$, and $\mu_t/\mu = 1$
- Local streamwise TZ refinement around separation-bubble-induced transition on the upper and lower surfaces
- Good agreement, cost savings would be a factor of about 26



Upper Surface



Lower Surface



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Level	N_c	N_z	N_{wake}	N_{tot}	h	N_c	N_z	N_{wake}	N_{tot}	h	N_{TZ}	N_{buf}
2	265	105	33	0.03e6	57.7e-4	-	-	-	-	-	-	-
3	397	157	49	0.06e6	40.8e-4	-	-	-	-	-	-	-
4	529	209	65	0.11e6	30.2e-4	-	-	-	-	-	-	-
5	793	313	97	0.25e6	20.0e-4	-	-	-	-	-	-	-
6	1057	417	129	0.44e6	15.1e-4	1057	417	129	0.44e6	15.1e-4	-	-
7	1585	625	193	0.99e6	10.1e-4	1097	417	129	0.46e6	14.7e-4	61	19
8	2113	833	257	1.76e6	7.54e-4	1137	417	129	0.47e6	14.5e-4	81	21
9	3169	1249	385	3.96e6	5.03e-4	1217	417	129	0.51e6	14.0e-4	121	24
10	4225	1665	513	7.03e6	3.77e-4	1297	417	129	0.54e6	13.6e-4	161	27
11	6337	2497	769	15.8e6	2.52e-4	1457	417	129	0.61e6	12.8e-4	241	31

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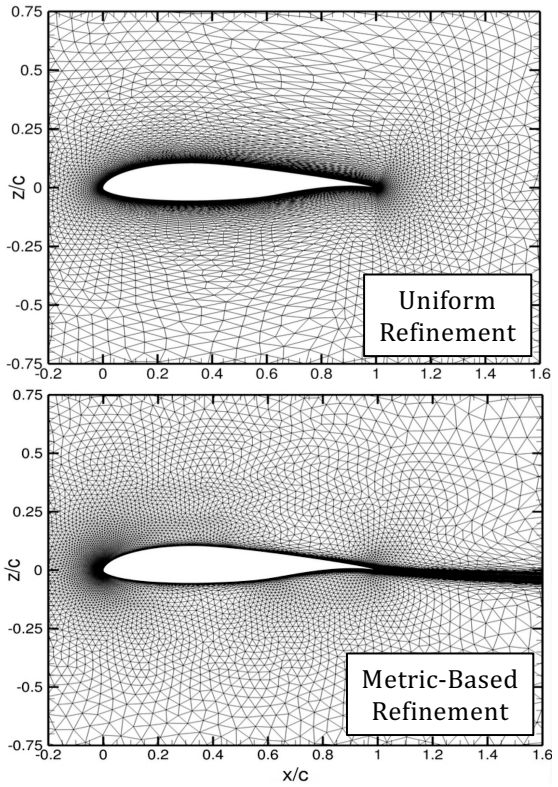
Uniformly-Refined and Metric-Based Unstructured Grids

- NLF-0416 airfoil with natural and separation-induced transition
  - $M = 0.1$, $\mathrm{Re}_c = 4e6, T = 300$ K, $\mathrm{Tu} = 0.15\%$, and $\mu_t/\mu = 1$
- Unstructured grids that are uniformly refined correspond to structured grid counterparts (same N_{tot} and Δz^+)

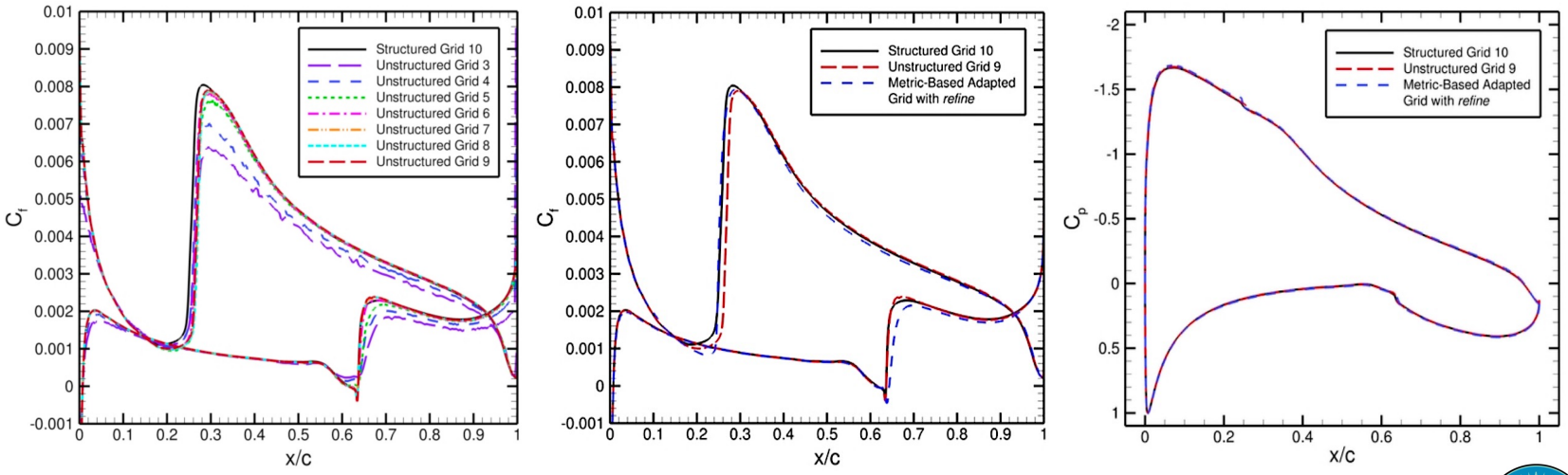
	Unstructured Static Grids						
Level	4	5	6	7	8	9	10
N_{tot}	0.130e6	0.268e6	0.650e6	1.30e6	2.57e6	4.10e6	10.2e6
h	27.7e-4	19.3e-4	12.4e-4	8.78e-4	6.24e-4	4.94e-4	3.13e-4
Δz^+	0.270	0.204	0.129	0.098	0.065	0.048	0.032

- Metric-Based grids range from $N_{\mathrm{tot}} = 5.34e3$ to 2.69e6 with coarse Δz^+ because of purely relying on the Hessian of the Mach number
- Generated with Sketch-to-Solution (Kleb 2019) and the *refine* library (Park 2008) with FUN3D
- Preliminary work on the metric-based grids are presented in Venkatachari et al. (2022) and Hildebrand et al. (2023) for the NLF-0416 airfoil at multiple angles of attack



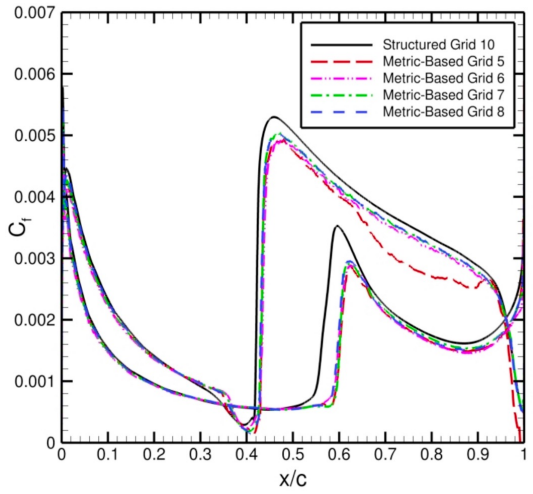
C_f and C_p Results for NLF-0416 Airfoil with $\alpha = 5°$

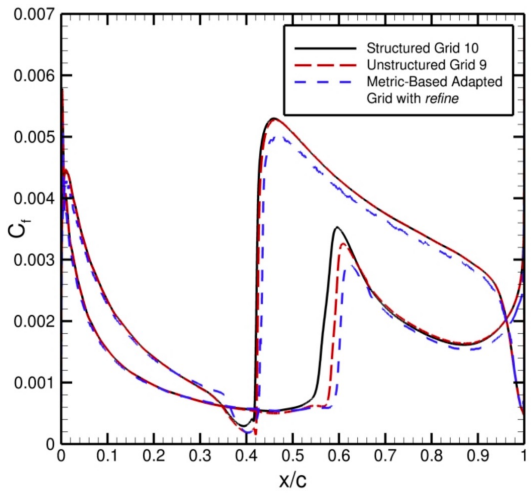
- Skin-friction distribution is oscillatory on coarse grids, but smooths out for the fine grids
- Good agreement in the pressure coefficient between the FUN3D solutions computed about the unstructured grid family, metric-based *refine* grids, and structured grid family
- Mismatch in the skin-friction distribution and transition locations due to poor grid convergence

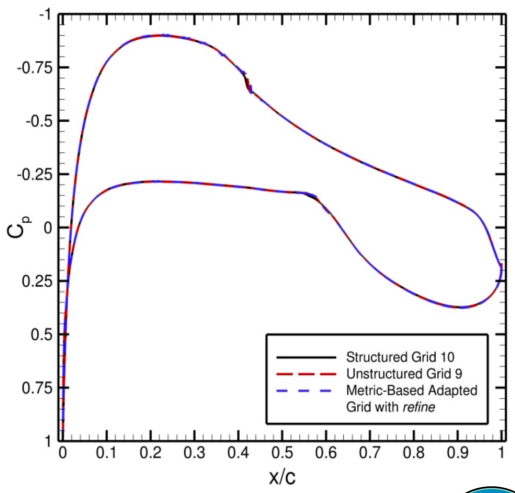


C_f and C_p Results for NLF-0416 Airfoil with $\alpha = 0°$

- Skin-friction distribution is oscillatory on coarse grids, but smooths out for the fine grids
- Good agreement in the pressure coefficient between the FUN3D solutions computed about the unstructured grid family, metric-based *refine* grids, and structured grid family
- Mismatch in the skin-friction distribution and transition locations due to poor grid convergence

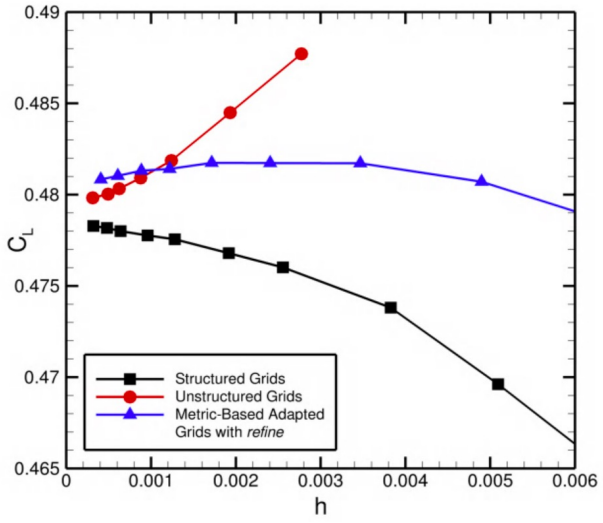


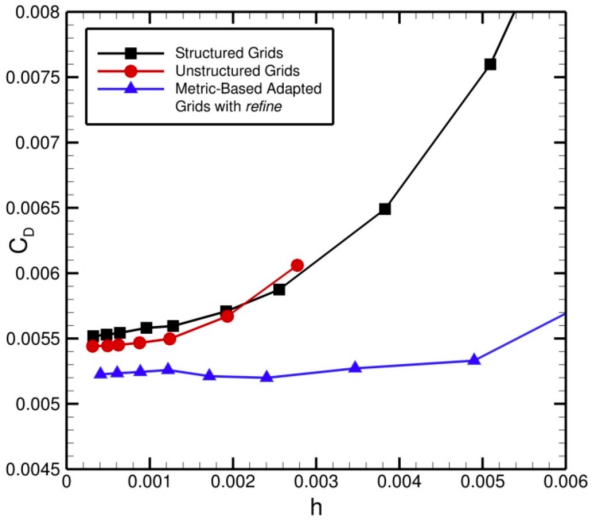




C_L and C_D Results for NLF-0416 Airfoil with $\alpha = 0°$

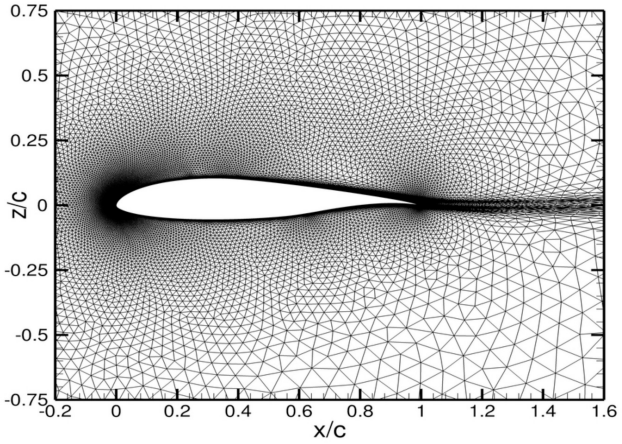
- Discrepancy in the lift and drag coefficients even for the finest grid resolutions
- Metric-based grid results converge faster than unstructured and structured uniform grid family results
- Need better resolution and quads near the airfoil surface

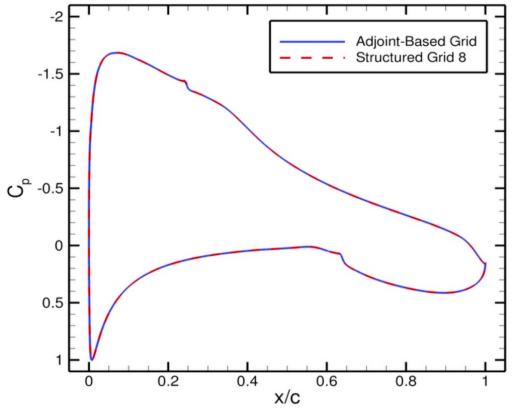


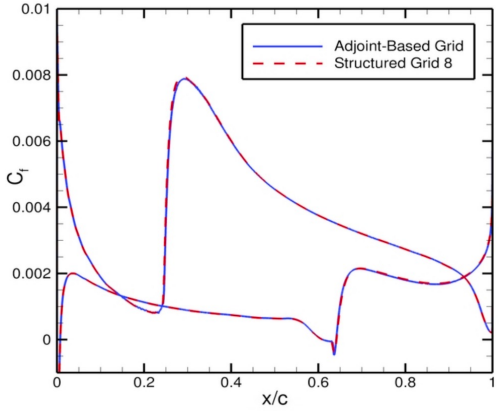


Adjoint-Based Unstructured Grids

- NLF-0416 airfoil with $\alpha = 5°$, Objective function is C_D
- SA turbulence model with imposed transition at $(x/c)_{\mathrm{tr}} = 0.24$ on the upper surface and the lower surface $(x/c)_{\mathrm{tr}} = 0.63$
- Grids range from $N_{\mathrm{tot}} = 1.15\mathrm{e}5$ to $N_{\mathrm{tot}} = 2.59\mathrm{e}6$ with the finest nondimensional viscous wall spacing of $\Delta z^+ = 0.071$
- Generated with Sketch-to-Solution and *refine*



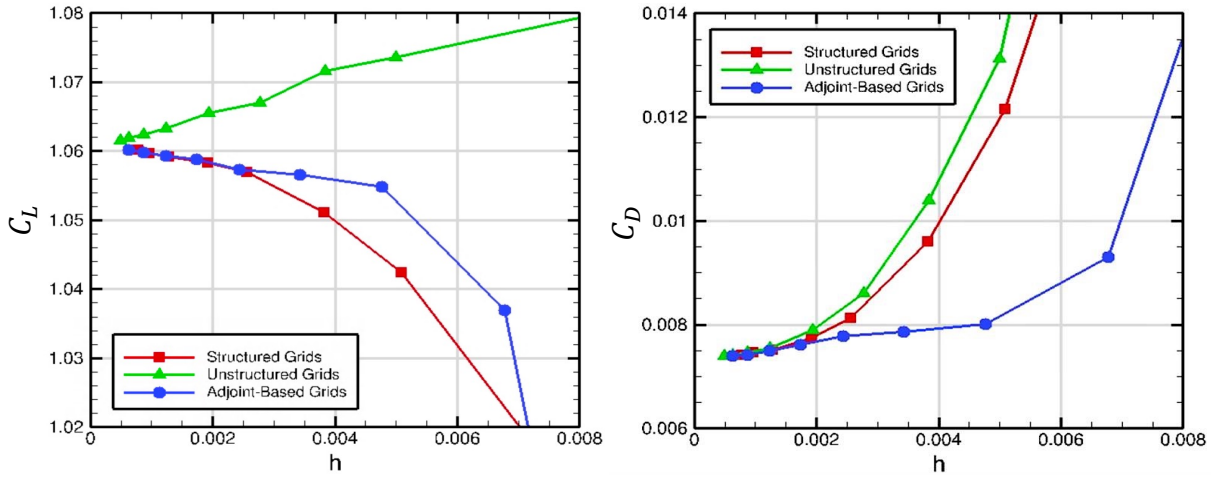




Good agreement between adjoint-based and structured grid results

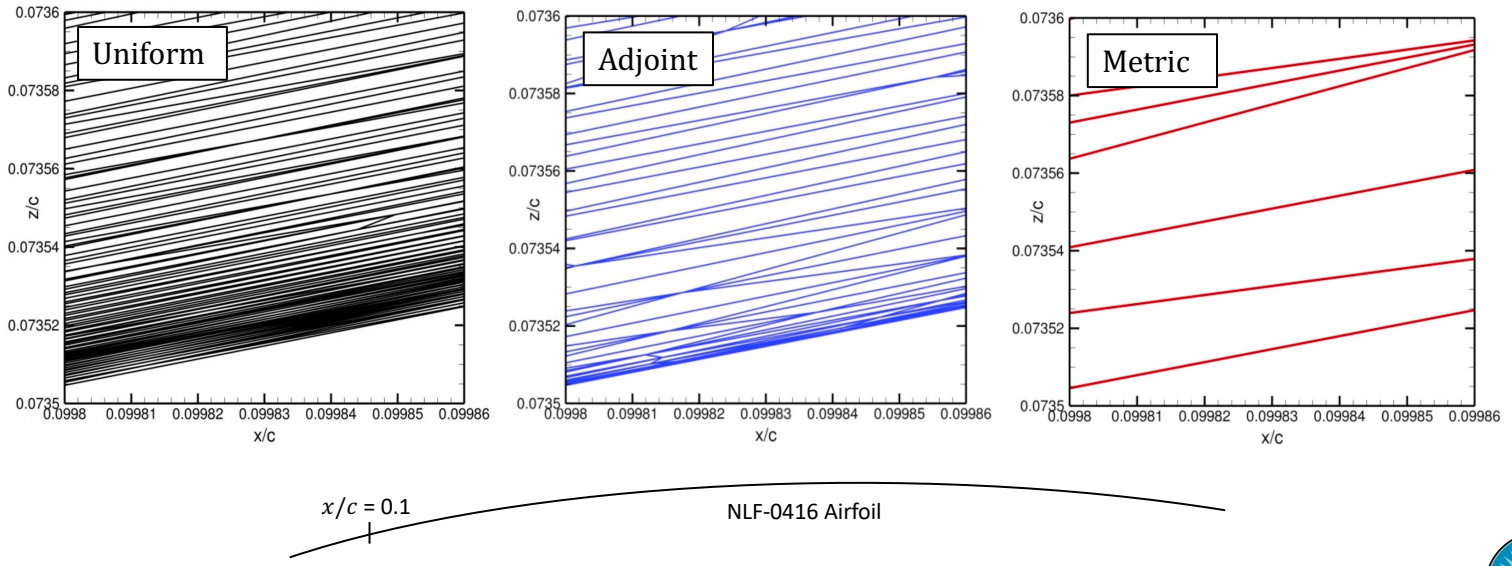
Adjoint-Based Grid Convergence of C_L and C_D

- SA turbulence model with imposed transition
- Good agreement between the structured, unstructured, and adjoint-based grid results in terms of C_L and C_D for the fine resolutions
- Adjoint-based grids yield more accurate results than structured grids and uniformly-refined unstructured grids for coarse resolutions



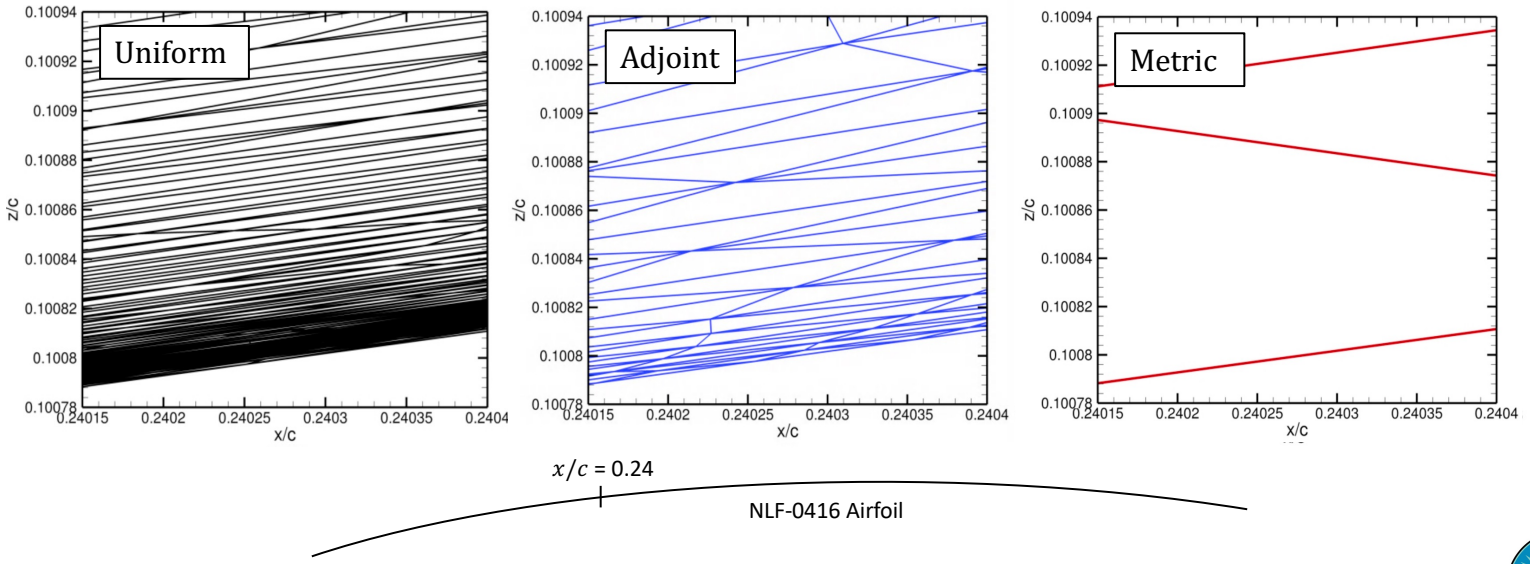
Near-wall Unstructured Grid Comparison – Laminar, Grid Level 8

- Unstructured grid family has the best near-wall resolution since it is based on the structured grid family
- Metric-based grid has poor near-wall resolution due to solely using Hessian of the Mach number
- Adjoint-based grid has very good near-wall resolution



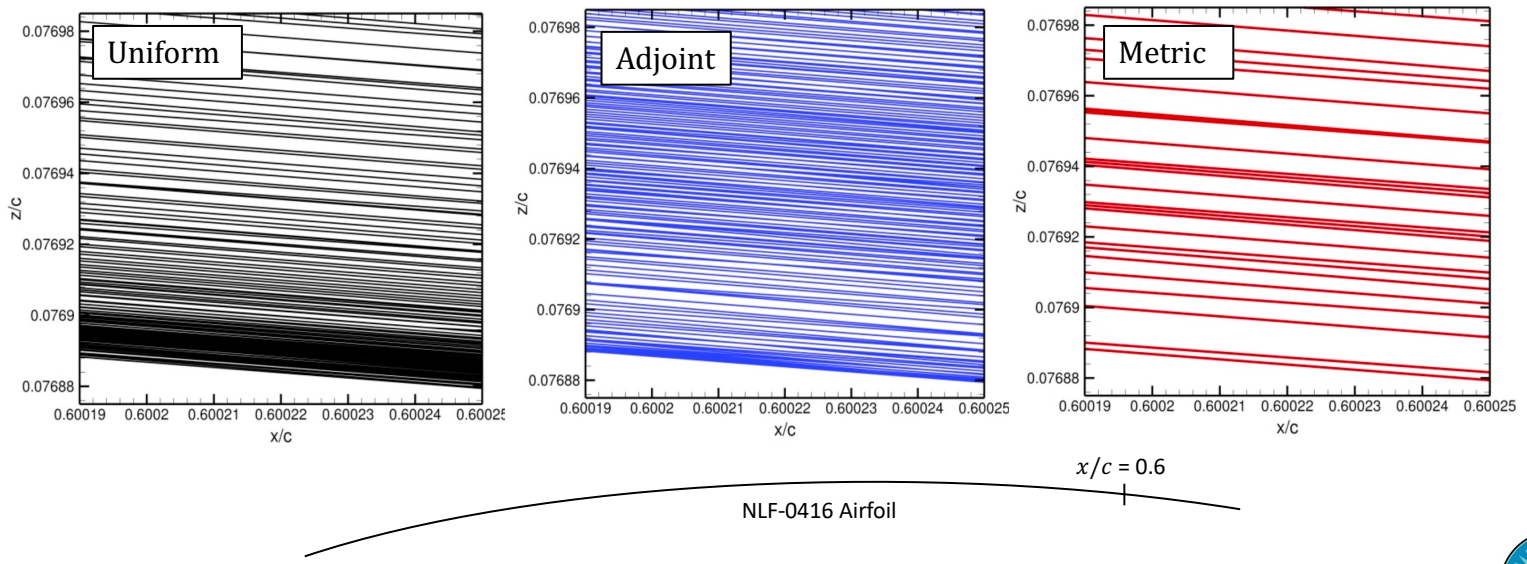
Near-wall Unstructured Grid Comparison – Transitional, Grid Level 8

- Unstructured grid family has the best near-wall resolution since it is based on the structured grid family
- Metric-based grid has poor near-wall resolution due to solely using Hessian of the Mach number
- Adjoint-based grid has very good near-wall resolution



Near-wall Unstructured Grid Comparison - Turbulent, Grid Level 8

- Unstructured grid family has the best near-wall resolution since it is based on the structured grid family
- Metric-based grid has poor near-wall resolution due to solely using Hessian of the Mach number
- Adjoint-based grid has very good near-wall resolution



Conclusions and Future Work

- Structured zonal streamwise refinement
  - Local streamwise refinement instead of global uniform refinement is enough to model natural transition for the Schubauer and Skramstad flat plate
    - Cost savings by a factor of 69
  - Local streamwise refinement instead of global uniform refinement is enough to model separation-bubble-induced transition for the NLR-7301 transonic airfoil
    - Cost saving by a factor of 26
  - Wall-normal resolution can have a strong impact on the turbulent skin-friction value
  - Explore local wall-normal refinement for the flat plate, NLF-0416, and NLR-7301 (also refinement near the leading/trailing edge or wake region)

- Unstructured grid adaptation
  - Uniformly-refined unstructured grid family lift and drag results do not converge faster than the structured grid family results; however, the adjoint-based grid adaptation converges much faster than both
  - Metric-based grid results plateau on relatively coarse grids, but can be inaccurate due to poor near-wall resolution
  - Two pathways forward:
    - Extend adjoint-based grid adaptation to Langtry-Menter γ-Re_{θ_t} transition model
    - In the *refine* library, add layers of quads and better resolution near the surfaces of interest

Acknowledgments

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