# Adaptive Mesh Refinement and Turbulence Modeling

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ICCFD11

# Introduction/Motivation

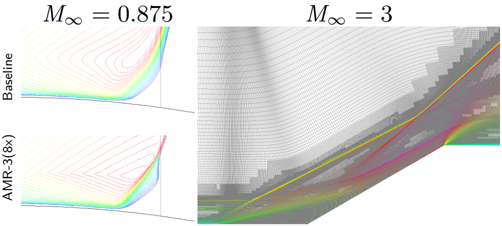




Turbulence modeling: Nonlinear PDE solved with discretization

How to deal with the problem of truncation error?

- Classic version:($\Delta x \mapsto \frac{1}{2}\Delta x$; $N_p \mapsto 4 \times N_p; \epsilon_n \mapsto \frac{1}{4} \times \epsilon$) Enormous fast!
- AMR computational efficiency (”Exact” solution/miniumum cost)
- AIAA-2016-3326: AMR Capability (Buning/Pulliam OVERFLOW)
- AIAA-2018-3858: Current methodology outlined




- AMR $\Longleftrightarrow$ Classic version
- Sub-,Trans-,Super-sonic
- Field variables converge last
- Shocks, BL edge: refine!

AMR ready for more complex turbulence models

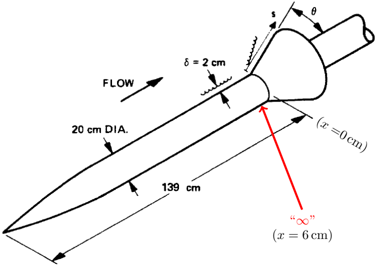
# Genesis

- Revisit AIAA-2005-101 "High Speed Turbulence" (defacto Lag-$\nu_T$ definition)
    - Flowfields of increasing complexity
    - Kussoy/Horstman $M = 7$ cylinder/flare
    - More complex models useful?
- Lag models:
    - Wilcox $k$-$\omega$(1988) at core
    - Eddy viscosity, $R_{ij}$, TTR(Transport $T_{ijk}$, and TAO(High Re) versions
    - Additional field equations (e.g. Lag-$\nu_T$):

$$\frac{D\nu_T}{Dt} = \omega\left(\nu_T - \nu_T^e\right)$$

    - No limiters
    - No wall distance
    - URANS: Grid and time converged solutions (Apollo, etc.)
    - RHS source terms based on exact equations
    - Most advanced (TAO) includes High Re anisotropy match
    - Simplest works more universally than alternative models

# Experiment Kussoy/Horstman TM-101075 (1989)




- $\theta = [20, 30, 32.5, 35°]$
  $\uparrow$ ... $\uparrow$
  attached ... separated
- Water cooled walls, long run time,
- Surface pressure, heat transfer
- Canonical high speed flow case

$$M_\infty = 7.04 \qquad u_\infty = 1127\,\frac{\mathrm{m}}{\mathrm{s}} \qquad T_w = 311\,\mathrm{K}$$

$$T_\infty = 81.2\,\mathrm{K} \qquad p_\infty = 576\,\mathrm{Pa} \qquad \tau_{w_\infty} = 25\,\mathrm{Pa}$$

$$\rho_\infty = 0.025\,22\,\mathrm{kg/m^3} \qquad Re = 5.8 \times 10^{-6}\,\frac{1}{\mathrm{m}} \qquad \dot{q}_{w_\infty} = 9300\,\mathrm{W/m^2}$$

# Computation: Solver/AMR usage

## Solver: Overflow 2.2k[modified/stock]

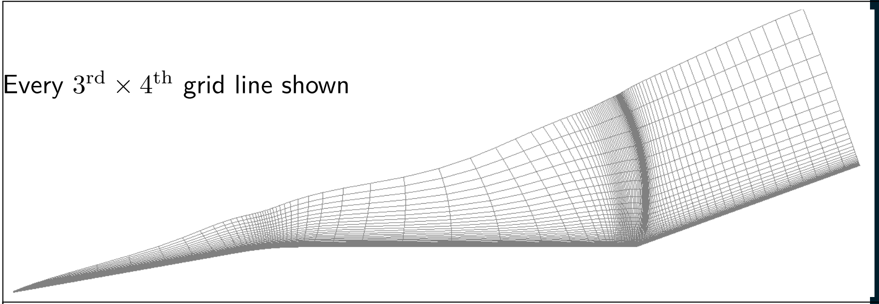
- Stock: verified SST, SA implementations
- Modified: Lag variants
- Cases steady (so far)
- Coarser starting grid (computational efficiency)
- General ethos:
  - Low dissipation
  - no multigrid
  - Well converged (solution)

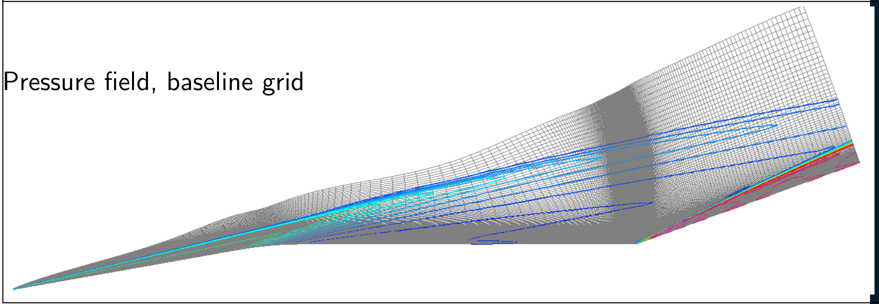
## AMR: "meta" algorithm

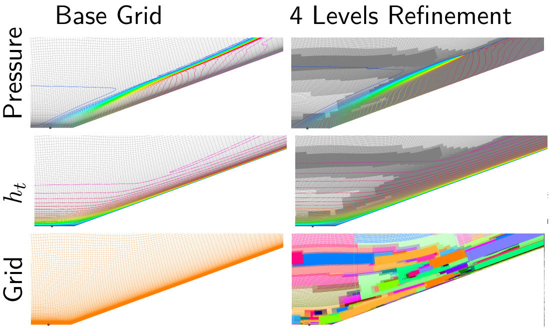
- Cauchy sequence? (grid convergence)
- Classic refinement comparison
- Where refinement? ("bespoke" grids)
- AMR sensor: linearity in $[\xi, \eta]$

$$S = \max_{i=j,k,l} \left\{ \max_{q=[\rho,\rho u,\dots]} \left[ \left( \frac{q_{i-1} - 2q_i + q_{i+1}}{2q_{ref}} \right)^2 \right] \right\}$$

# Baseline grid and solution domain






- Compression waves $\mapsto$ shock
- Boundary layer edge refined
- $\infty$ ($x = -6$ cm) visible

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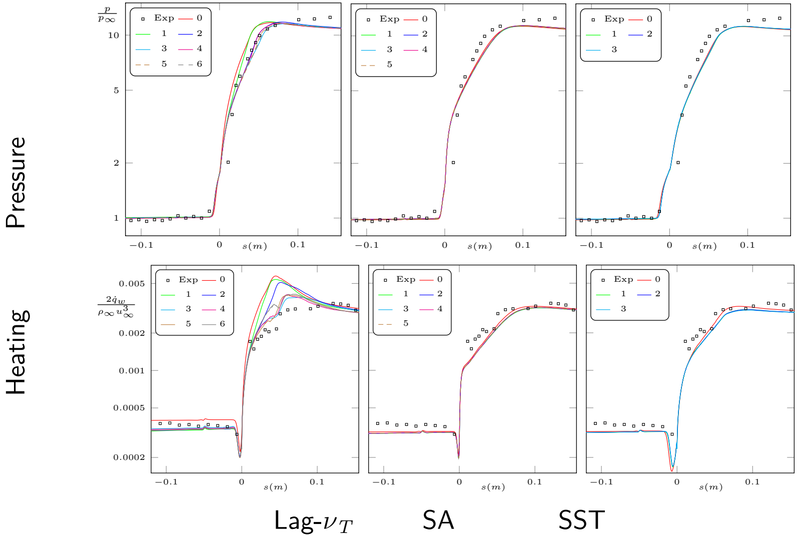
- Boundary layer edge habitually overlooked (important in hindsight)
- "proto-shock" region refinement focus
- Some regions remain unrefined (under proto-shock/boundary layer edge)
- Successive refinement informative

# Results: $\theta = 20$

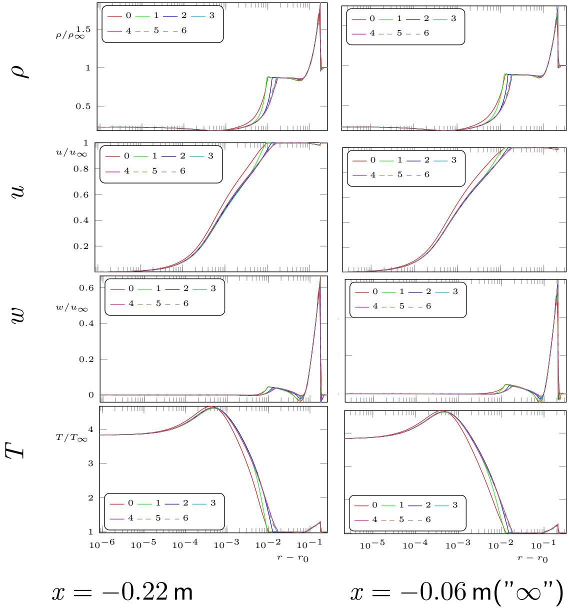


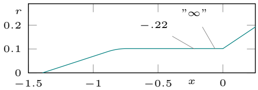



- Pressure results very consistent with 2005 results
- Heating results improved
- 6 levels $\mapsto$ 4096 grid increase

# Upstream Flowfield:($\infty$) $\theta = 20$

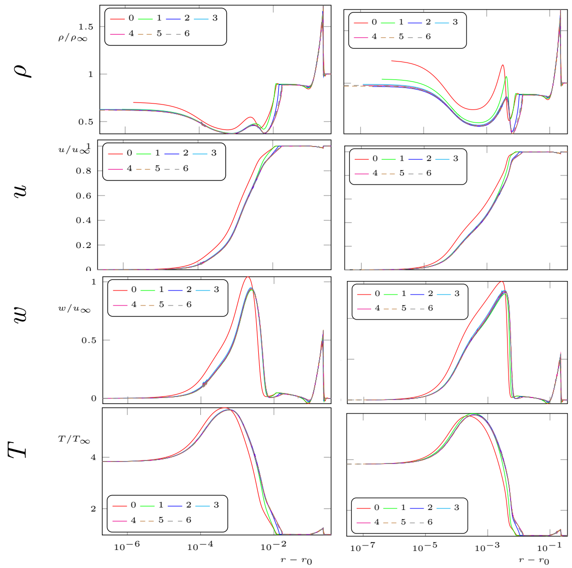




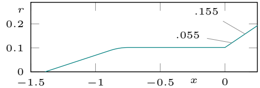




- 4th and higher refinements
- Boundary layer edge (and external shock) last to "grid converge"
- Surface quantities first to "grid converge"
- Consistent with 2018 findings

# Flare(Downstream) Flowfield: $\theta = 20$



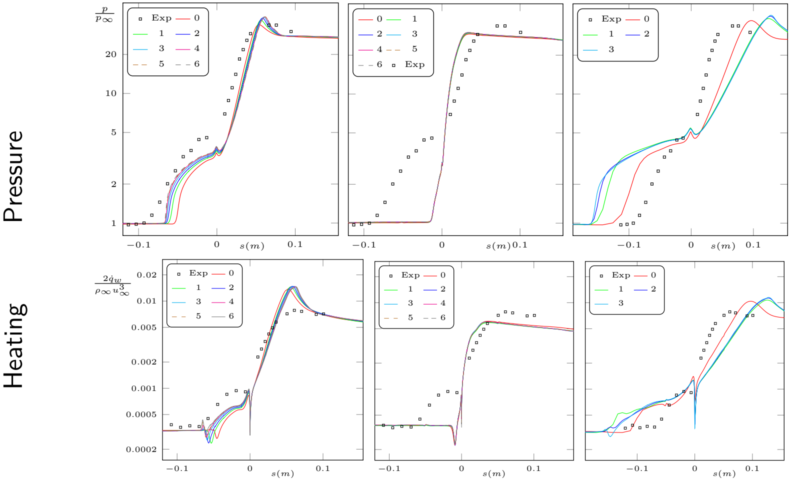

$x = 0.055\,\mathrm{m}$ $x = 0.155\,\mathrm{m}$




- Further downstream: more sensitive to refinement ($\rho$)
- Even surface changing at $x = 0.155\,\mathrm{m}$
- Fixed Wall $T$ is a boundary condition
- Larger differences than upstream

# Results: $\theta = 35$

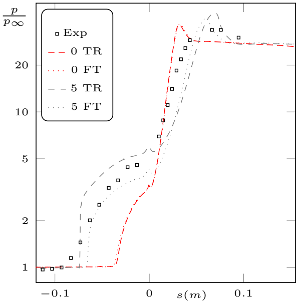




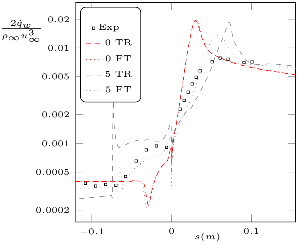

Lag-$\nu_T$ SA SST(extended)

- Pressure results much improved
- Heating results improved
- 6 levels $\mapsto 2^{12} = 4096$ grid size increase

Pressure




Heating




FT≡"Fully turbulent"
TR≡"Transitional"

- Baseline grid relatively transition insensitive
- Refined grid sensitive
- Other terms ($\sigma_k$) now matter
- Improved edge turbulent state of more advanced models(TTR)?
- Hindsight: Flowfield slatlike... (AMR allows accurate propagation)

# Conclusions, further work



AMR:

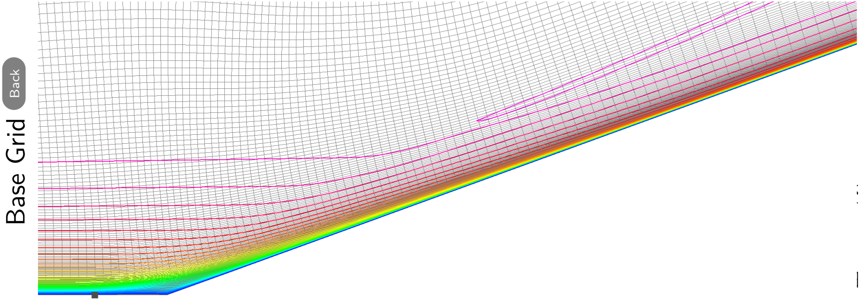
- Provided better predictions
- Allows accurate information propogation
- Showed inviscid/viscous interactions not seen on baseline (compression $\mapsto$ shock)
- Removes preconception bias (searching under the streetlamp)
- "cosmetic" choices now important and tunable

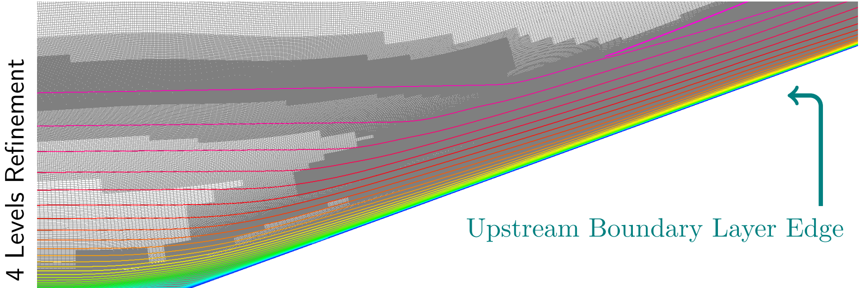
Forward:

- Even more refinement (levels, "errest")
- Assess the now important parameters, tune them
- More complex models (do they work, improve things, create craters?)
- 3D
- At higher refinement, unsteady?

# Interaction Region, $h_t$ $\theta = 20^\circ$ (attached)







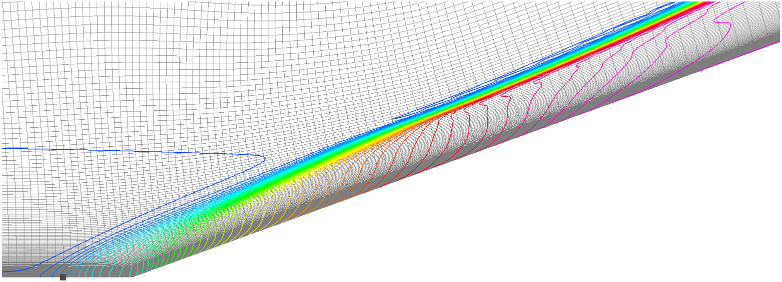

Back

# AMR and pressure details, Interaction region $\theta = 20^\circ$ (attached)

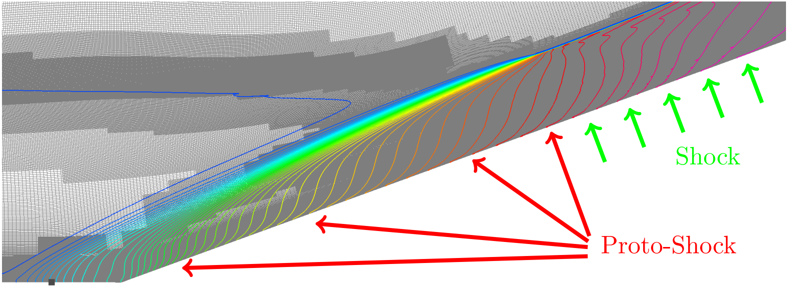


Back

Base Grid



4 Levels Refinement



# AMR Grid as abstract art $\theta = 20^\circ$ (attached)



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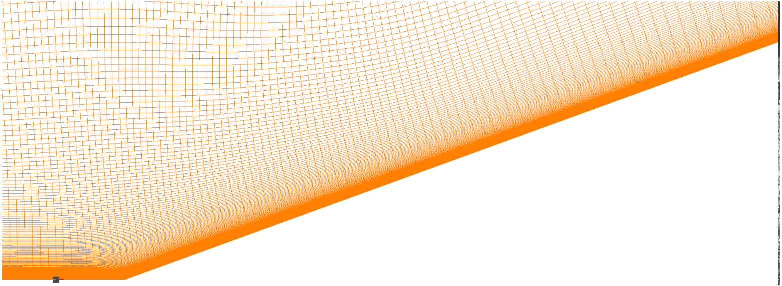
Base Grid



4 Levels Refinement