

Automatic Boundary-Layer Adaptation of Structured Grids in VULCAN-CFD

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Outline

- 1 Motivations
- 2 Problem Statement
- 3 Results
- 4 Summary and Concluding Remarks

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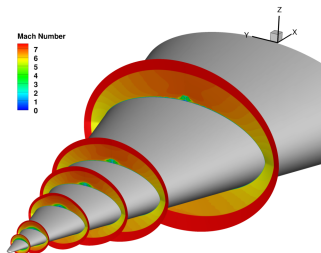
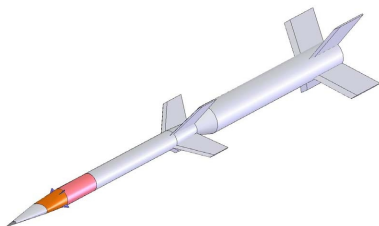
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Need for boundary-layer adaptation

- Save human and computational time while using VULCAN-CFD
- Allow the use of simpler initial grids
 - ▶ Can be automatically adapted to small changes in flow conditions
 - ▶ Do not have to account for complex flow features that alter the boundary layer in ways that are difficult to predict
 - ★ Vortical structures (HIFiRE-5)
 - ★ Streamwise streaks (BoLT)
 - ★ Separation regions (compression ramp)
 - ★ Reattachment shocks (cylinder-flare)
- Improve solution accuracy
 - ▶ Surface heating quantification
 - ▶ Transition prediction via linear stability analysis
 - ▶ Separation prediction

HIFiRE-5³

- 2:1 elliptic cone, $M_\infty = 7.8$, $Re_\infty = 9.0 \times 10^6/\text{m}$, $\alpha = -1.2^\circ$, $t = 514.83\text{s}$
- Complex vortical structure near the minor-axis symmetry plane at zero yaw angle
 - ▶ Shifts away from the symmetry plane at nonzero yaw angles
 - ▶ No a priori knowledge of its shape and trajectory, or about the secondary structures spawned on either side of the main structure
- HIFiRE-5 flight geometry ¹
- Mach number contours ²



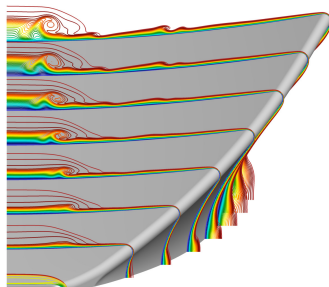
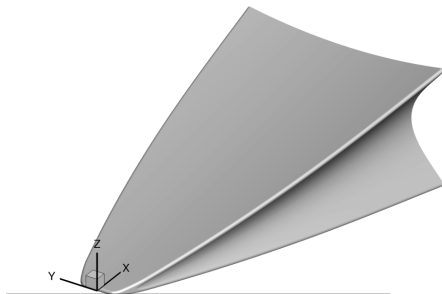
¹R. Kimmel et al. HIFiRE-5 flight vehicle design. AIAA Paper 2010-4985. 2010

²M. Choudhari et al. Transition Analysis for the HIFiRE-5 Vehicle. AIAA Paper 2009-4056. 2019

³M. Choudhari, F. Li, and P. Paredes. Streak instabilities on HIFiRE-5 elliptic cone. AIAA Paper 2020-0828. 2020. DOI: 10.2514/6.2020-0828

BoLT

- Subscale geometry at $M_\infty = 6$, $Re_\infty = 9.9 \times 10^6/m$
- Streaks leading to azimuthally inhomogeneous distribution of boundary-layer thickness ⁴
- Predictability issues if pitch or yaw angles are altered
- BoLT flight geometry ⁵
- Streamwise velocity contours ⁶

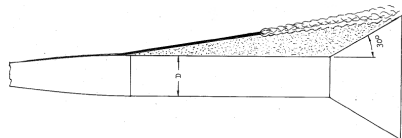


⁴F. Li, M. Choudhari, and P. Paredes. Streak instability analysis for BOLT configuration. *AIAA Paper 2020-3028*. 2020. doi: 10.2514/6.2020-3028

⁶B. Wheaton et al. Boundary Layer Transition (BOLT) Flight Experiment Overview. *AIAA Paper 2018-2892*. 2018

Compression ramps and corners

- Recirculation region, thickening of the boundary layer
- Easier to predict, but grid has to be adjusted to each flow condition
- Flat plate with wedge ⁷
- Ogive-cylinder-Flare ⁸



⁷D. Chapman, D. Kuehn, and H. Larson.

Investigation of separated flows in supersonic and subsonic streams with emphasis of the effect of transition. Tech. rep. TR 1356. NTRS number 19930092343. NACA, 1958

⁸J. Becker and P. Korycinsky.

Heat transfer and pressure distribution at a Mach number of 6.7 on bodies with conical flares and extensive flow separation. Tech. rep. RM L56F22. DTIC citation AD0274584. NACA, 1956

Outline

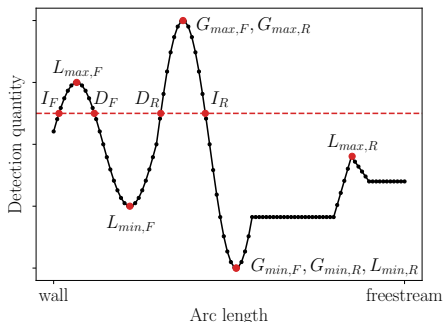
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Boundary-layer adaptation procedure

- Can already adapt the grid to the outermost shock and adapt the wall adjacent cell size
- Boundary-layer adaptation occurs last to overwrite part of the shock-adapted (or unadapted) grid until a junction location
- 3 step process (similar to shock adaptation)
 - ① Detection of the boundary-layer edge using user-defined parameters:
 - ★ Detection quantity: $\frac{h_t}{h_{t,\infty}}, \frac{u}{u_\infty}, \frac{S}{S_{total}}, \frac{M}{M_\infty}$
 - ★ Method: six options (see next viewgraph)
 - ★ Direction: surface to freestream or in reverse
 - ② Smoothing of the surface
 - ③ Adaptation of the grid to the surface

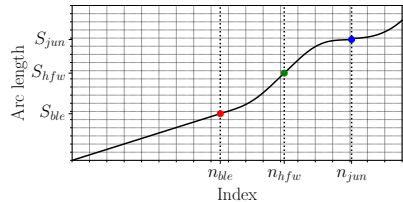
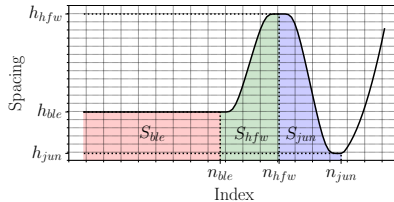
Boundary-layer edge detection

- Edge can be detected as the location where the detection quantity:
 - 1 Increases past a specified threshold (I)
 - 2 Decreases past a specified threshold (D)
 - 3 Reaches the global minimum (G_{min})
 - 4 Reaches the global maximum (G_{max})
 - 5 Reaches the first local minimum (L_{min})
 - 6 Reaches the first local maximum (L_{max})
- Either forward (F , wall $\rightarrow$ freestream) or reverse (R) scanning along wall-normal direction



Boundary-layer adaptation constraints

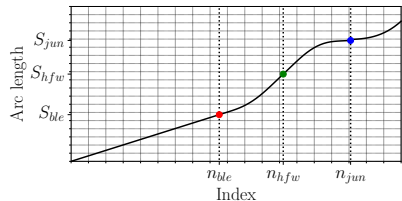
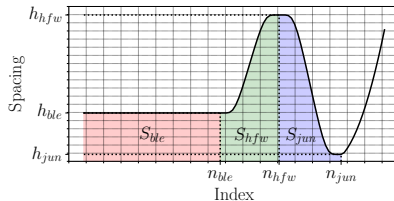
- Smoothly merge the new grid with the previous one to make gradual changes in grid distribution
- Define the grid using grid spacing between surface-tangent grid lines
 - ▶ Integral of grid spacing = arc length
 - ▶ Use this to guarantee the grid's extent to a junction location with the original grid
 - ▶ Grid spacing at the junction has to be matched
- Boundary-layer adapted grid consists of two regions:
 - ▶ Constant spacing boundary layer
 - ▶ Variable spacing junction region extending from BL edge up to junction



- Shaded areas below grid spacing line equal to arc length between matching indices

Boundary-layer adaptation constraints (cont.)

- Constant spacing boundary-layer points can be distributed once edge is detected and number of points calculated
- Junction region spacing requires four constraints to be satisfied:
 - ① Integral of the spacing function within the junction region has to equal the arc length between the boundary-layer edge and the junction location
 - ② Fixed number of points within the junction region
 - ③ Spacing at boundary-layer edge has to be smoothly matched
 - ④ Spacing at junction location has to be smoothly matched
- Use two smooth functions with known integral
- Connect both functions at index halfway between BL edge and the junction
 - Allows both to have enough resolution for coarser grids



Smoothed (C-infinity) Heaviside functions

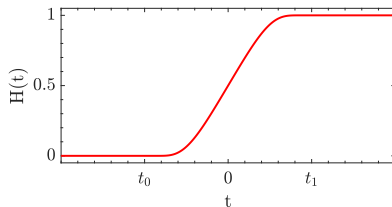
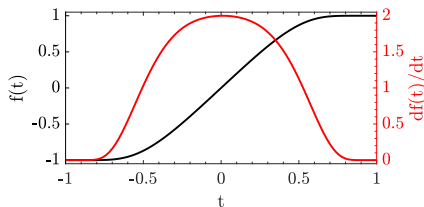
- Given the C-infinity function $f(t)$:

$$f(t) = \begin{cases} -1; & t \in (-\infty, -1], \\ \tanh(1/(1-t) - 1/(1+t)); & t \in (-1, 1), \\ 1; & t \in [1, \infty). \end{cases}$$

- Define $H(t; t_0, t_1)$, a C-infinity Heaviside function with smooth step between t_0 and t_1 , and with known analytical integral

$$H(t; t_0, t_1) = \frac{1}{2} \left(1 + f\left(\frac{2t - (t_1 + t_0)}{t_1 - t_0}\right) \right), \quad \int_{t_0}^{t_1} H(t; t_0, t_1) dt = \frac{t_1 - t_0}{2}$$

- Finite grid: accuracy of integral is crucial otherwise junction between previous and newly adapted grids will not be smooth



Parameters required

- Known parameters after boundary-layer edge detection and shock adaptation
 - ▶ n_{ble} , S_{ble} : number of points and boundary-layer edge location
 - ▶ n_{jun} , h_{jun} , S_{jun} : index, grid spacing, and junction location
- Calculate constant spacing within boundary layer and index of halfway location connecting both C-infinity functions
 - ▶ $h_{ble} = \frac{S_{ble}}{n_{ble}}$
 - ▶ $n_{hfw} = \frac{n_{ble} + n_{jun}}{2}$
- Last parameter: grid spacing at halfway location (h_{hfw})
 - ▶ $S_{hfw} = S_{ble} + h_{ble}(n_{hfw} - n_{ble}) + \frac{h_{hfw} - h_{ble}}{2}(n_{hfw} - n_{ble})$
 - ▶ $S_{jun} = S_{hfw} + h_{hfw}(n_{jun} - n_{hfw}) + \frac{h_{jun} - h_{hfw}}{2}(n_{jun} - n_{hfw})$
- Set both equations equal to S_{hfw} and solve for h_{hfw}
 - ▶ $h_{hfw} = \frac{2}{n_{jun} - n_{ble}} \left(S_{jun} - S_{ble} - \frac{h_{ble}}{2}(n_{hfw} - n_{ble}) - \frac{h_{jun}}{2}(n_{jun} - n_{hfw}) \right)$

Grid spacing and point distribution

- With all parameters defined, the spacing at each grid point:

$$h(n) = \begin{cases} h_{ble}; & n = 1, n_{ble}, \\ h_{ble} + (h_{hfw} - h_{ble}) \cdot H(n; n_{ble}, n_{hfw}); & n = n_{ble} + 1, n_{hfw}, \\ h_{hfw} + (h_{hfw} - h_{ble}) \cdot H(n; n_{hfw}, n_{jun}); & n = n_{hfw} + 1, n_{jun}. \end{cases}$$

- Location for each point along the grid line given by numerical integration:

$$S(n) = \begin{cases} 0; & n = 1, \\ S(n-1) + h(n-1); & n = 2, n_{ble}, \\ S(n-1) + h(n-1) + \frac{h(n)-h(n-1)}{2}; & n = n_{ble} + 1, n_{jun}. \end{cases}$$

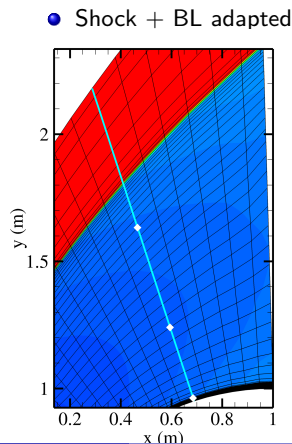
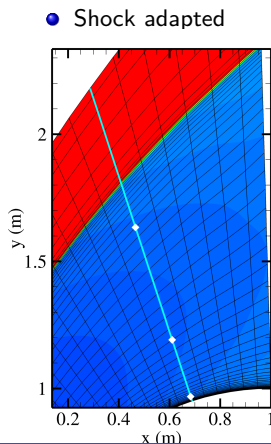
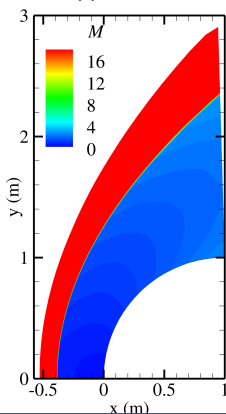
- Trapezoidal integration used for the variable grid spacing to ensure smooth connection to the previous grid

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2D cylinder

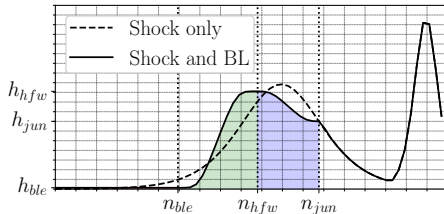
- $r = 1$ m cylinder, $M_\infty = 17.6$, with grid: 61×65 points
- BL edge defined at $h_t/h_{t,\infty} = 0.9$
- White diamonds correspond to the indices n_{ble} , n_{hfw} , and n_{jun} .
- Spacing and grid line distribution of light blue lines shown next slide.



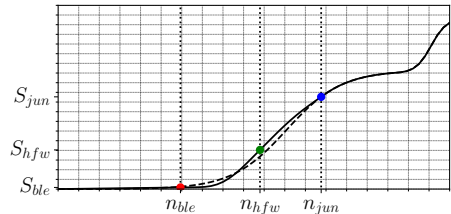
2D cylinder - grid distribution

- Original grid already resolves the boundary layer well
- Slight increase in number of points inside boundary layer
- Spacing remains continuous across junction

- Grid spacing



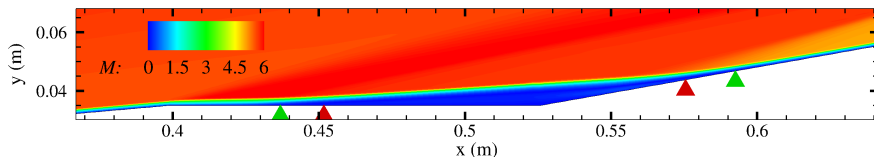
- Arc length



- Shaded areas below grid spacing line equal to arc length between matching indices

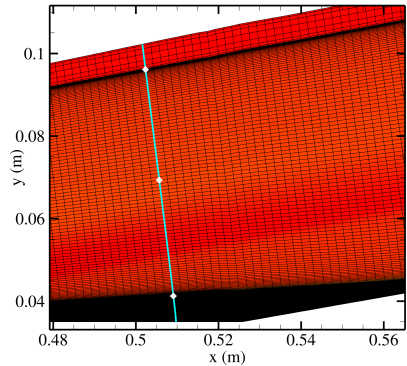
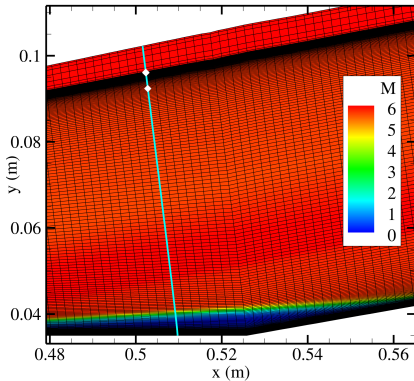
Axisymmetric cone-cylinder-flare

- $r_n = 0.1$ mm, 5° half-angle cone, 12.6 cm long cylinder, 10° half-angle flare
- $M_\infty = 6$, with grid: 601×301 points
- BL edge defined at $h_t/h_{t,\infty} = 0.95$
- Grid split to run across 40 processors
- Mach contours of the shock and boundary-layer adapted flow shown below
- Separation region given by triangles for the **shock** and **shock + BL** adapted grids



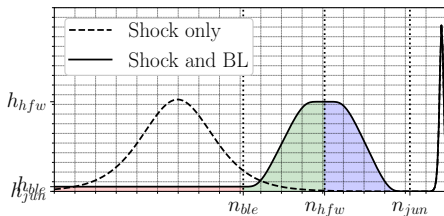
Axisymmetric cone-cylinder-flare - comparison

- Points taken from the shock and moved closer to the surface (see white diamonds)
- Shock itself did not change position
- Shock adapted
- Shock + BL adapted



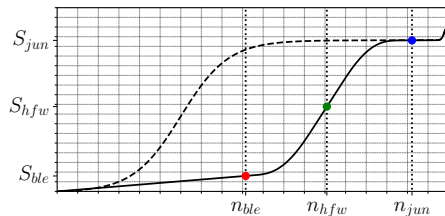
Axisymmetric cone-cylinder-flare - grid distribution

- Points redistributed closer to the wall to satisfy number of points within BL
- Maximum grid spacing between BL edge and shock is not increased
- Shock resolution is not lowered
- Grid spacing



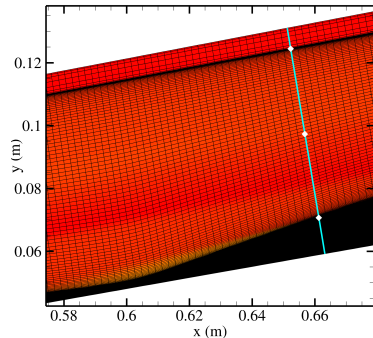
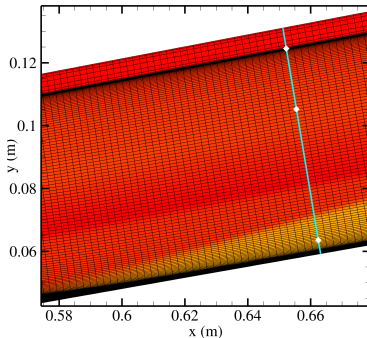
- Shaded areas below grid spacing line equal to arc length between matching indices

- Arc length



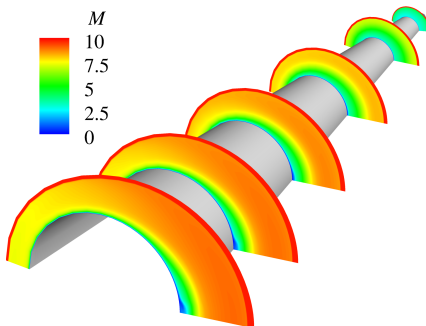
Axisymmetric cone-cylinder-flare - Enthalpy vs Mach number based edge detection

- Reattachment shock fit improved by Mach number adaptation
 - Boundary layer may not be resolved well enough
 - Grid distribution similar to previous comparison with unadapted grid
 - Future improvements include a rework of the distribution within the boundary layer
-
- $h_t/h_{t,\infty} = 0.95$
 - $M/M_\infty = 0.85$



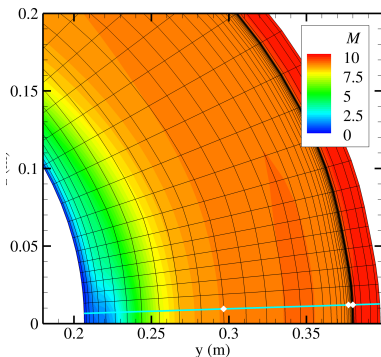
3D cone

- $r_n = 9.525$ mm, 7° half-angle, 1.5 m long cone
- $M_\infty = 9.79$, AoA = 5°
- BL edge defined at $h_t/h_{t,\infty} = 0.95$
- Initial two block grid of $9 \times 17 \times 45$ and $105 \times 33 \times 45$ points is split in both the surface tangent and azimuthal direction to avoid the boundary layer edge crossing a block boundary
- Mach contours on streamwise-normal slices over the BL + shock adapted solution

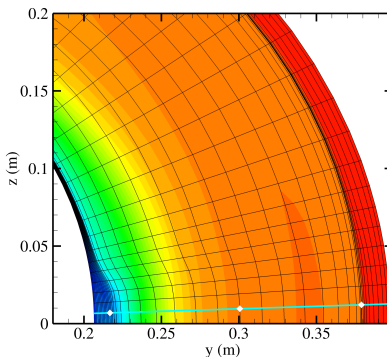


3D cone - comparison

- Significantly fewer points inside the BL with only shock adaptation
- Leeward vortex shape differs
 - ▶ A finer grid or one that is split could have helped, but the grid would still not be fit to the vortex
- Although not shown, convergence history improved even with the very coarse grid used
- Shock adapted

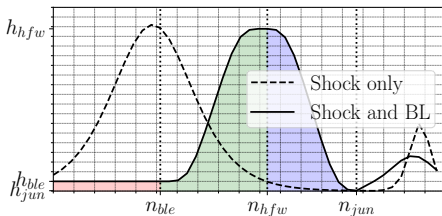


- Shock + BL adapted



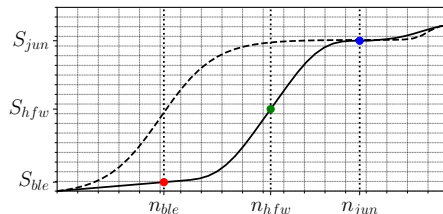
3D cone - grid distribution

- Points redistributed closer to the wall
- Maximum grid spacing not increased
- Points within shock also altered as the 3 adaptation cycles change the solution
- Grid spacing



- Shaded areas below grid spacing line equal to arc length between matching indices

- Arc length



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Concluding Remarks

- Preliminary implementation of automatic boundary-layer adaptation in VULCAN-CFD
- Details of the algorithm are presented
 - ▶ Smooth transition between boundary-layer and outer grid
- Adaptation demonstrated with three high-speed configurations with laminar boundary layers:
 - ▶ Two-dimensional flow over a cylinder at Mach 17.6
 - ▶ Axisymmetric flow over a cone-cylinder-flare at Mach 6
 - ▶ Three-dimensional flow over a blunt circular cone at a nonzero angle of attack at Mach 9.79
- Future work:
 - ▶ Evaluation and improvements of the adaptation for flows with laminar, transitional, and fully turbulent regions
 - ▶ Additional criteria for boundary-layer edge detection
 - ▶ User-defined junction location
 - ▶ Detection and adaptation of interior features (separated boundary layers, reattachment shock)
 - ▶ Eliminate block and partition boundaries as adaptation obstacles

Thank You for Your Attention

- Acknowledgments

- ▶ This research was sponsored in part by the U. S. Office of Naval Research (ONR) under award number N00014-20-1-2261 with P.O. Eric Marineau and by the NASA Hypersonic Technology Project (HTP) under the Aeronautics Research Mission Directorate (ARMD).
- ▶ Resources supporting this work were provided by the DoD High Performance Computing Modernization Program, the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at the Ames Research Center and the NASA K-Midrange Cluster at the Langley Research Center.

