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

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Abstract: Well-resolved boundary layers in supersonic and hypersonic flows are critical for quantifying surface heating, transition prediction, and performing stability analysis. However, the design of grids to ensure a well resolved boundary layer presents a challenging task, especially for hypersonic flows. An automatic grid adaptation process offers significant improvement in computational time and solution quality as opposed to a manual one. The VULCAN-CFD solver already includes proven automatic adaptation of structured grids to the bow shock. The current effort focuses on the implementation of the boundary-layer adaptation capability in VULCAN-CFD to allow the automatic, simultaneous adaptation of structured grids to both the bow shock and the boundary layer. This document presents a proof of concept by using an initial, shock-adapted, solution over a blunt, circular cone at angle of attack in a Mach 10 flow. The grid is adapted to the boundary layer and the flow solution is converged again. Significant improvement is observed in the resolution of the the complex vortical structures over the leeward side of the cone.

Keywords: Boundary Layer Stability, Grid Adaptation.

1 Problem Statement

Well-resolved boundary layers are paramount to capture the fine details of the boundary layer profile for the purposes of stability analysis. An automatic grid adaptation process built into the VULCAN-CFD solver [1] can allow for initial grids with generic shapes to provide accurate final flow fields. Furthermore, a priori design of grids to resolve the boundary layer over complex geometries is extremely challenging, particularly when vortical structures form, which can lead to large variations in the boundary layer thickness. Because of this, the number of wall normal points is usually oversized leading to inefficient calculations.

For example, the HIFiRE-5 geometry, consisting of a 2:1 elliptic cone, was designed to study transition due to multiple instability mechanisms. At zero yaw angle, a complex vortical structure forms near the minor-axis symmetry plane, but this structure shifts away from the symmetry plane at nonzero yaw angles and it is not possible to make advanced predictions of the trajectory and the shape of this structure, as well as of the adjacent secondary structures that may form in the neighborhood of the primary structure [2]. Thus, several iterations of grid refinement and adaptation, involving computational and human-in-the-loop time, are required to properly resolve the boundary layer.

To illustrate the strong vortical structures present in hypersonic boundary layers and the benefits of boundary-layer adaptation, laminar flow solutions are computed for a circular cone at angle of attack. A 1.5 m long, 9.525 mm nosetip radius, and 7-degree half-angle cone was run at 5 degrees angle of attack and a freestream unit Reynolds number of 17.1 million per meter to match conditions of the experiments conducted at Mach 10 in the Arnold Engineering Development Complex (AEDC) Hypervelocity Wind Tunnel 9 [3]. Figure 1 shows the Mach number contours of the converged solution with the unadapted and adapted boundary layer grids, respectively. The redistribution of wall-normal points better resolves the vortical structure on the leeward side of the cone. The boundary-layer adaptation used the boundary-layer thickness defined as the wall-normal location where the total enthalpy ratio $h_t/h_{t,\infty} = 0.995$, and total enthalpy defined as $h_t = c_pT + 0.5|\mathbf{u}|^2$, where c_p is the specific heat capacity, T denotes the static temperature, and $\mathbf{u}$ is the velocity vector. This grid adaptation procedure allows for a better control and refinement over the boundary-layer region, thus providing more accurate solutions.

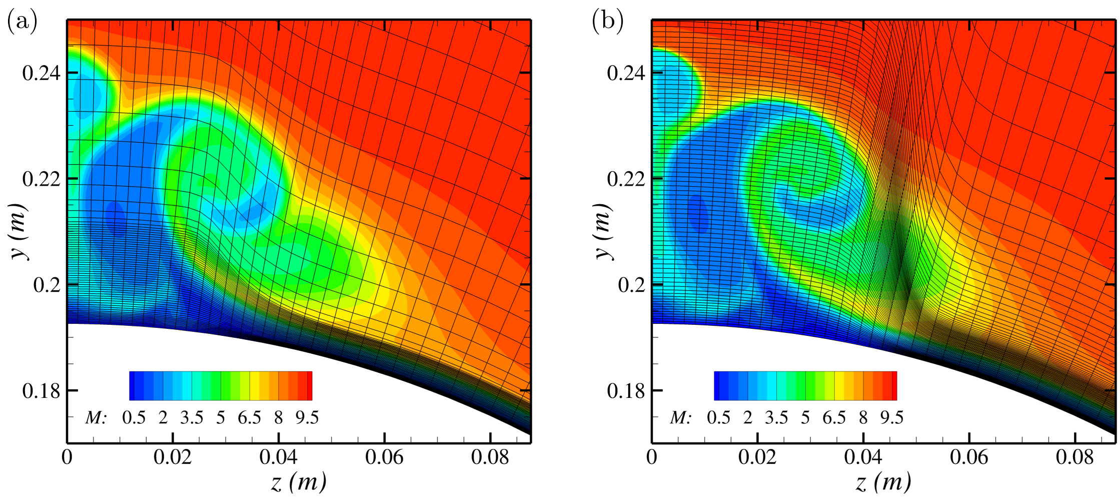

Figure 1: Grid lines overlaid onto Mach contours for the (a) initial grid and the (b) boundary-layer adapted grid. Only one fourth of the grid lines in each direction are shown.

The final paper will include more details on the boundary layer adaptation algorithm, as well as additional applications demonstrating its use.

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