A Structured Grid Based Solution-adaptive Technique for Complex Separated Flows

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ABSTRACT

The objective of this work has been to enhance the predictive capability of widely used CFD codes through the use of solution adaptive gridding. Most problems of engineering interest involve multi-block grids and widely disparate length scales. Hence, it is desirable that the adaptive grid feature detection algorithm be developed to recognize flow structures of different type as well as differing intensity, and adequately address scaling and normalization across blocks. In order to study the accuracy and efficiency improvements due to the grid adaptation, it is necessary to quantify grid size and distribution requirements as well as computational times of non-adapted solutions. Flowfields about launch vehicles of practical interest often involve supersonic freestream conditions at angle of attack exhibiting large scale separated vortical flow, vortex–vortex and vortex–surface interactions, separated shear layers and multiple shocks of different intensity. In this work a weight function and an associated mesh redistribution procedure is presented which detects and resolves these features without user intervention. Particular emphasis has been placed upon accurate resolution of expansion regions and boundary layers.

Flow past a wedge at Mach = 2.0 is used to illustrate the enhanced detection capabilities of this newly developed weight function. Figure 1 presents weight functions evaluated using the previous procedure, lower half plane, as well as the current procedure, upper half plane.

It can be observed that both weight functions clearly detected the primary shock. It can also be seen
that the expansion fan, boundary layer, and the reflected shocks are much more clearly represented in the current weight function. Adapted grids using both weight function formulations are presented in Fig. 2. The high gradient regions of the expansion region are only reflected in the adapted grid using the new weight function. The reflected shock is also much sharper. Figure 3 compares the solution obtained using the current adaption procedure with that obtained using the original grid. The enhanced resolution is clearly evident.

Supersonic flow at Mach=1.45 and 14 degree angle of attack has been simulated around a tangent-ogive cylinder. The grid and associated flow solution constructed after two adaption cycles using hybrid differencing of the grid equations and the current weight functions is presented in Figure 4.

Figure 5 presents the grid constructed using the previous weight function and the same flow conditions and number of adaptation cycles. Figures 5 and 6 present streamwise cuts of the two grids shown in Figs 4 and 5 at X/D = 5.5 and 7.5 respectively.
Figure 8 present the flow solution obtained using the NPARC [NASA 1993] flow solver, the KE turbulence model option and two adaptation cycles. Figure 9 presents the associated weight function.

Examples will presented to demonstrate the capability for solution–adaptive regridding of multi-block launch vehicle simulations.

References


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OBJECTIVES

Improved resolution of complex flows through the use of solution adaptive gridding

1. Develop a weight function suitable for use with a solution adaptive grid redistribution procedure for complex flows, including viscous dominated separation.

2. Minimum user inputs.

3. Appropriate feature detection for a wide range of flow features (Vortices, Shear layers, Shocks).

4. Robust redistribution procedure for use with weight function.
GOVERNING EQUATIONS FOR GRID MOVEMENT

1. Inverted form:

\[
\sum_{i=1}^{3} \sum_{j=1}^{3} g^{ij} \vec{r}_{\xi_j \xi_i} + \sum_{k=1}^{3} g^{kk} P_k \vec{r}_{\xi_k} = 0
\]

Where:
- \( \vec{r}_{ij} \): Position vector,
- \( g^{ij} \): Contravariant metric tensor,
- \( \xi^i \): Curvilinear coordinate, and
- \( P_k \): Control Function.

2. Control of distribution and characteristics of grid system can be achieved by varying control Functions \( P_k \).
\[ P_i = (P_{\text{initial geometry}})_i + c_i (P_{\text{wt}}) \quad (i = 1, 2, 3) \]

where \( (P_{\text{initial geometry}})_i \) : control function based on initial grid geometry

\( P_{\text{wt}} \) : control function based on gradient of flow parameter

\( c_i \) : constant weight factors

\[ P_i^{(n)} = P_i^{(n-1)} + c_i (P_{\text{wt}})^{(n-1)} \quad (i = 1, 2, 3) \]

\[ P_i^{(1)} = (P_{\text{initial geometry}})_i + c_i (P_{\text{wt}})^{(0)} \quad (i = 1, 2, 3) \]
EVALUATION OF FORCING FUNCTIONS

1. Smoothness.
2. Near orthogonality.
3. Equidistribution of 'error' or weight function.
4. One-dimensional equidistribution law
   \[ W X_{\xi} = \text{constant, where } W \text{ is a weight factor.} \]
5. Poisson equation form, (Anderson, Thompson), obtained by differentiating equidistribution law.
   \[ W X_{\xi\xi} + W_{\xi} X_{\xi} = 0, \]
   \[ X_{\xi\xi} + PX_{\xi} = 0, \]
   i.e. \( P = W_{\xi}/W \)
6. For Multiple dimensions:
   \( P_k = W_{\xi}^{k}/W, \quad k = 1,2,3 \)
CHARACTERISTICS OF WEIGHT FUNCTIONS

1. Weight functions approximately equidistributed over solution domain.

2. Determine grid spacing and characteristics.

3. Approximation to local truncation error.
   - Use lower order derivatives to approximate high order truncation error terms.
   - Detect structures of disparate strength.
   - Minimum variation of coefficients.
EVALUATION OF WEIGHT FUNCTIONS

1. Density or pressure is not sufficient for viscous flows.
2. Boolean sums used to eliminate 'multiplying' effect.
3. Relative derivatives are necessary to detect features of varying intensity.
5. Nearly uniform flowfields require minimum normalization value.
WEIGHT FUNCTIONS

\[
W = \frac{W^1}{\max(W^1, W^2, W^3)} \oplus \frac{W^2}{\max(W^1, W^2, W^3)} \oplus \frac{W^3}{\max(W^1, W^2, W^3)}
\]

Where,

\[
W^k = 1 + \frac{|q_{\ell k}|}{|q|+\epsilon} \oplus \frac{|q_{u\ell k}|}{|q_u|+\epsilon} \oplus \frac{|q_{v\ell k}|}{|q_v|+\epsilon} \oplus \frac{|q_{w\ell k}|}{|q_w|+\epsilon}
\]

for \( k=1,2,3 \), and

The symbol \( \oplus \) represents the Boolean sum. Note that the directional weight functions are scaled using a common maximum in order to maintain the relative strength.
OVERALL SOLUTION PROCEDURE

1. Obtain initial flow solution.
2. Adapt grid.
3. Interpolate solution onto adapted grid.
4. Restart flow solution.
5. Repeat steps 2–4 until satisfactory result.
ADAPTIVE GRID PROCEDURE

1. Read PLOT3D grid and solution files.
2. Evaluate weight function,
   (no input parameters).
3. Evaluate and smooth $P_k$.
4. Integrate grid.
5. Interpolate $P_k$ onto current adapted grid.
6. Repeat steps 4 and 5 until convergence.
7. Output adapted grid.
SOLUTION OF GRID EQUATIONS

1. Solution difficulties transferred form flow equations to grid equations.
2. Accuracy not as important for postulated law.
3. Adaptive Central/Upwind differencing scheme, based upon forcing function gradients.
4. Integrated in time using CSIP.
5. Non-linear terms are quasi-linearized.
7. Precise geometry definition is critical.
Adapted Grid Central Difference NPARC Sol. Case 3 Cycle
BOUNDARY POINT MOVEMENT

1. Very important.
   - Orthogonality.
   - Skewness.

2. Non Uniform Rational B-Spline (NURBS) representation of arbitrary surface (Yu).

3. Boundary surface redistribution based on specified region of surface.
   - Explicit.
   - Local iteration for desired distribution.
   - Can be used to keep sharp corners, and to transfer information between blocks.
Figure 1. Comparison of Weight Functions.

Figure 2. Comparison of Adapted Grids.
Figure 3. Comparison of Solutions Using Adapted Grid.
Case 1 NPARC Sol Grid 7 KE Model
Case 1 NPARC Grid 7 a2 KE Model
Gimble Nozzle, Left UBIFLOW Density, Right Weight Function
Gimble Nozzle, Left UBIFLOW Density, Right Marked Cells
Gimble Nozzle, Left UBIFLOW Density, Right Marked Cells
SUMMARY

1. Developed Weight function which requires no user input.
2. Implemented adaptive upwind/central difference scheme.
3. Demonstrated enhanced grid resolution.
   - Thinner shocks.
   - Stronger circular vortices.
   - Lower values of artificial dissipation may be used.
   - Larger time steps may be used.
   - Improved convergence behaviour.
   - More closely resembles experimental data.
ONGOING WORK

1. Multiblock problems.
   - Global scaling across blocks.
   - Block interface or block point movement.

2. Local refinement (Solver of Koomullil)

3. Coupling with flow solver.

4. Coding efficiency.

5. Reacting flow.
   - Include temperature in weight function.

6. Unsteady flow problems.
   - $P_k$, viewed as velocities in temporally parabolized grid equations.
Scramjet Inlet NPARC Solution (lower), Weight Func (upper)