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

by

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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.

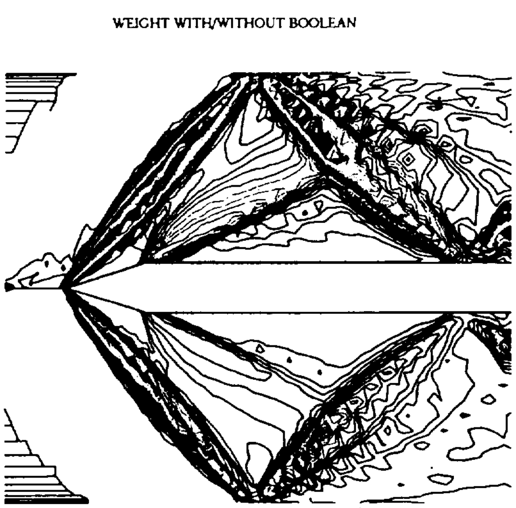

Figure 1. Comparison of Weight Functions.

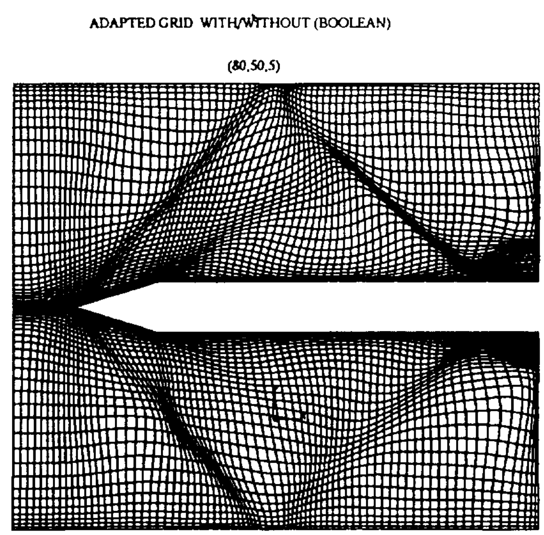

Figure 2. Comparison of Adapted Grids.

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.

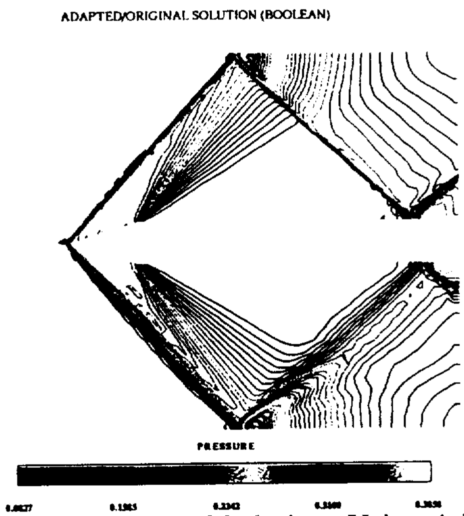

Figure 3. Comparison of Solutions Using Adapted Grid.

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 is presented in Figure 4.

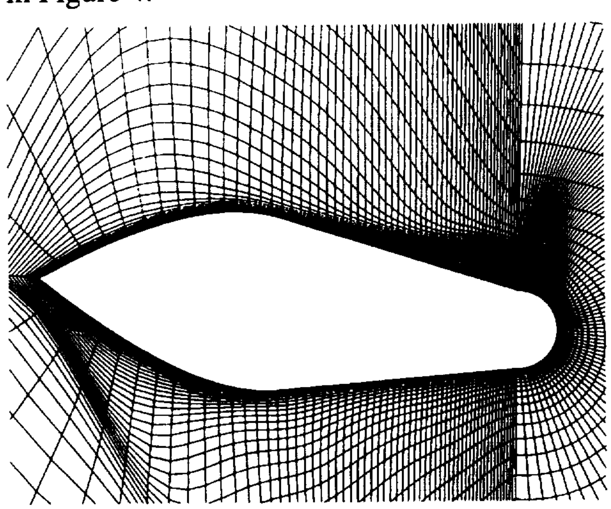

Figure 4. Adapted grid after two cycles.

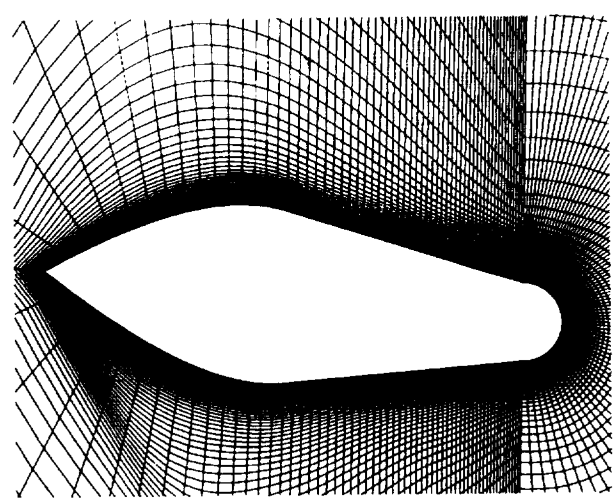

Figure 5. Adapted grid after two cycles.

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

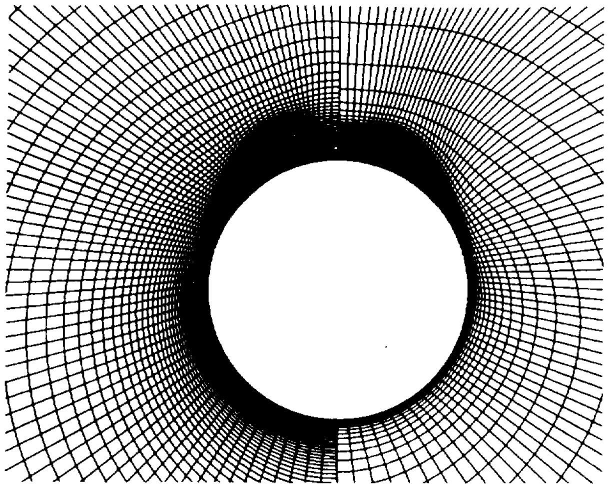

Figure 6. X/D = 5.5

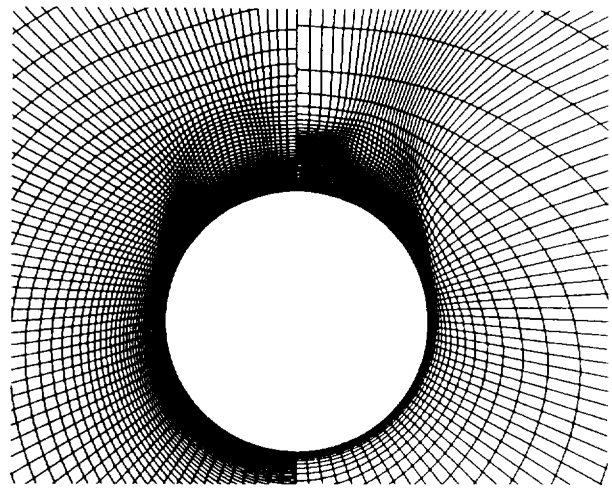

Figure 7. X/D = 8.5.

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.

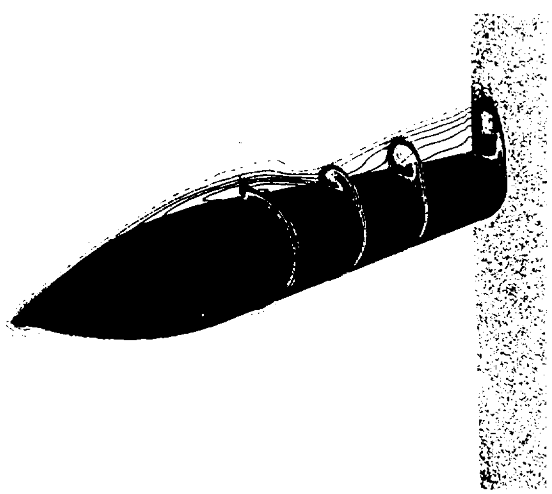

Figure 8 Normalized Stagnation Pressure.

Figure 9. Weight Function.

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

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ENGINEERING RESEARCH CENTER FOR
COMPUTATIONAL FIELD SIMULATION
COMPLEX GEOMETRY / COMPLEX PHYSICS

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 (Vorticies, Shear layers, Shocks).
4. Robust redistribution procedure for use with weight function.

GOVERNING EQUATIONS FOR GRID MOVEMENT

1. Inverted form:

$$\sum_{i=1}^{3}\sum_{j=1}^{3} g^{ij}\,\vec{r}_{\xi^i\xi^j} + \sum_{k=1}^{3} g^{kk}\,P_k\,\vec{r}_{\xi^k} = 0$$

Where:

$\bar{r}_{ij}$: Position vector,
g^{ij} : Contravariant metric tensor,
ξ^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.

$$P_i = (P_{\substack{\text{initial}\\\text{geometry}}})_i + c_i\,(P_{wt}) \qquad (i = 1,2,3)$$

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

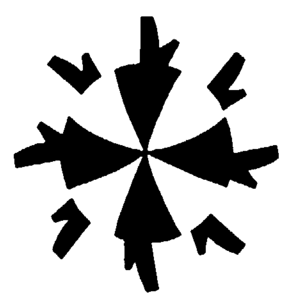
P_{wt} : control function based on gradient of flow parameter

c_i : constant weight factors

$$P_i^{(n)} = P_i^{(n-1)} + c_i\,(P_{wt})^{(n-1)} \qquad (i = 1,2,3)$$

where

$$P_i^{(1)} = (P_{\substack{\text{initial}\\\text{geometry}}})_i^{(0)} + c_i\,(P_{wt})^{(0)} \qquad (i = 1,2,3)$$



EVALUATION OF FORCING FUNCTIONS

1. Smoothnes.
2. Near orthogonality.
3. Equidistribution of 'error' or weight function.
4. One–dimensional equidistribution law

   $W X_{\xi} =$ constant, where W is a weight factor.
5. Poisson equation form, (Anderson, Thompson), obtained by differentiating equidistribution law.

   $W X_{\xi\xi} + W_{\xi} X_{\xi} = 0,$

   $X_{\xi\xi} + P X_{\xi} = 0,$

   i.e. $P = W_{\xi}/W$
6. For Multiple dimensions:

   $P_k = W_{\xi}{}^{k}/W, \; k = 1,2,3$

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.
4. Regions of zero flow variables require special treatment.
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, $k=1,2,3,$ *and*

$$W^k = 1 + \frac{\frac{|\varrho_{\xi^k}|}{|\varrho| + \varepsilon}}{\left(\frac{|\varrho_{\xi^k}|}{|\varrho| + \varepsilon}\right)_{\max}} \oplus \frac{\frac{|(\varrho u)_{\xi^k}|}{|(\varrho u)| + \varepsilon}}{\left(\frac{|(\varrho u)_{\xi^k}|}{|(\varrho u)| + \varepsilon}\right)_{\max}} \oplus \frac{\frac{|(\varrho v)_{\xi^k}|}{|(\varrho v)| + \varepsilon}}{\left(\frac{|(\varrho v)_{\xi^k}|}{|(\varrho v)| + \varepsilon}\right)_{\max}} \oplus \frac{\frac{|(\varrho w)_{\xi^k}|}{|(\varrho w)| + \varepsilon}}{\left(\frac{|(\varrho w)_{\xi^k}|}{|(\varrho w)| + \varepsilon}\right)_{\max}}$$

$$\oplus \frac{\frac{|\varrho_{\xi^k\xi^k}|}{|\varrho| + \varepsilon}}{\left(\frac{|\varrho_{\xi^k\xi^k}|}{|\varrho| + \varepsilon}\right)_{\max}} \oplus \frac{\frac{|(\varrho u)_{\xi^k\xi^k}|}{|(\varrho u)| + \varepsilon}}{\left(\frac{|(\varrho u)_{\xi^k\xi^k}|}{|(\varrho u)| + \varepsilon}\right)_{\max}} \oplus \frac{\frac{|(\varrho v)_{\xi^k\xi^k}|}{|(\varrho v)| + \varepsilon}}{\left(\frac{|(\varrho v)_{\xi^k\xi^k}|}{|(\varrho v)| + \varepsilon}\right)_{\max}} \oplus \frac{\frac{|(\varrho w)_{\xi^k\xi^k}|}{|(\varrho w)| + \varepsilon}}{\left(\frac{|(\varrho w)_{\xi^k\xi^k}|}{|(\varrho w)| + \varepsilon}\right)_{\max}}$$

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

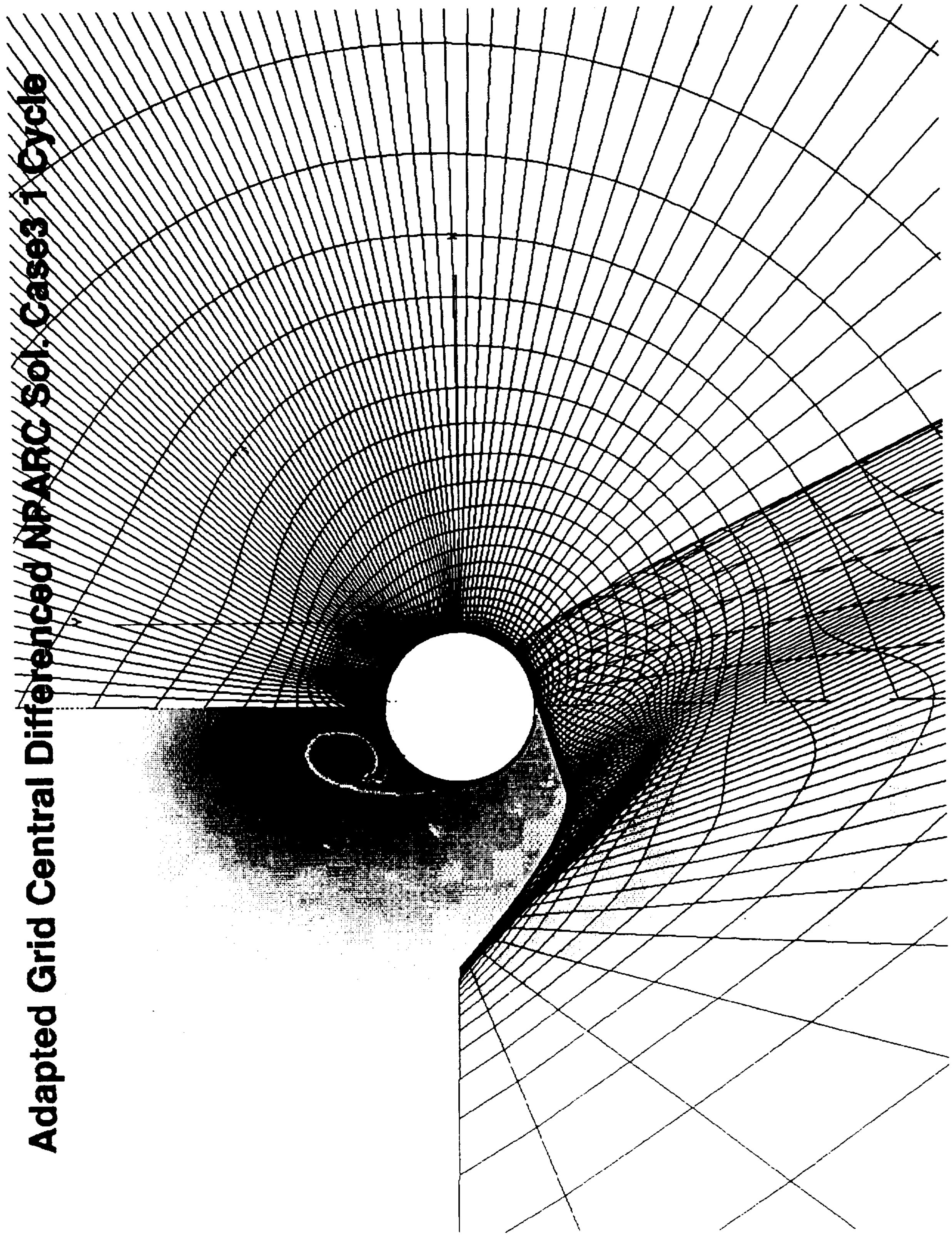
1. Obtain initial flow solution.
2. Adapt grid.
3. Interpolate solution onto adapted grid.
4. Restart flow solution.
5. Repeat steps 2–4 until satisfactory result.

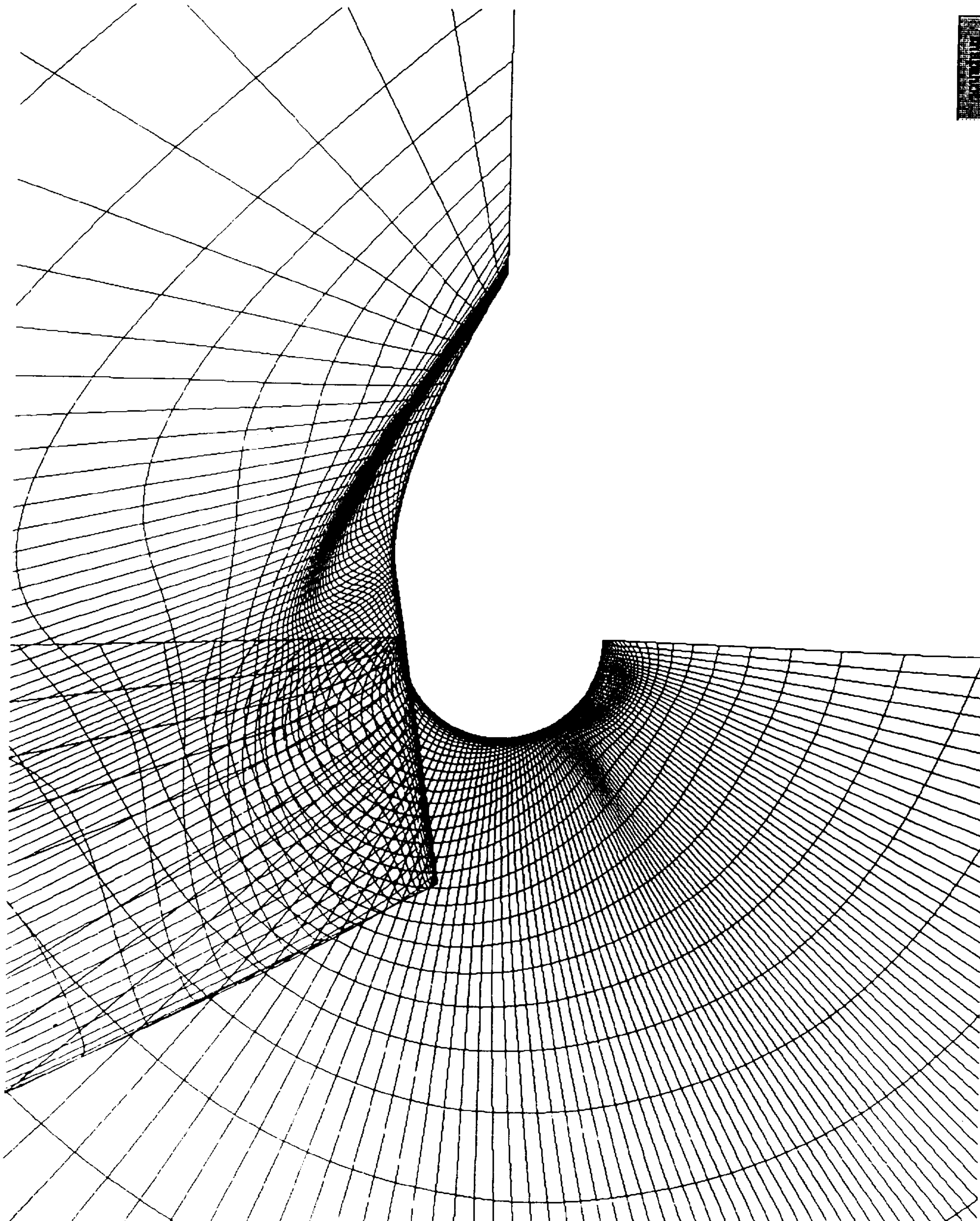
ADAPTIVE GRID PROCEDURE

1. Read PLOT3D grid and solution files.
2. Evaluate weight function,
   (no input pararmeters).
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. Ouput adapted grid.

SOLUTION OF GRID EQUATIONS

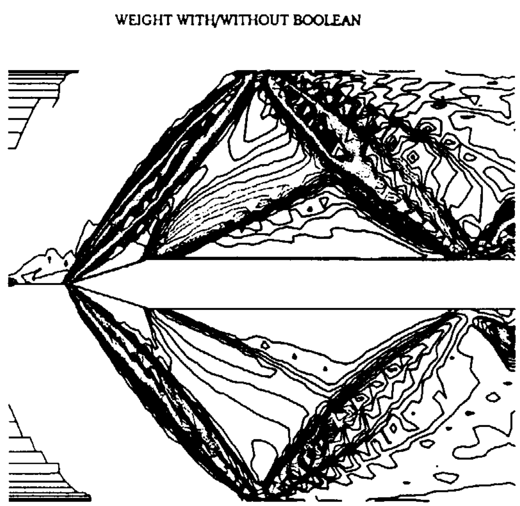
1. Solution difficulties transferred form flow equations to grid equations.
2. Accuracy not as important for postulated law.
3. Adaptive Central/Upwind differencing scheme, based upon forcing function gradients.
4. Integrated in time using CSIP.
5. Non–linear terms are quasi–linearized.
6. Explicit boundary point movement.
7. Precise geometry definition is critical.


Adapted Grid Central Differenced NPARC Sol. Case3 1 Cycle



BOUNDARY POINT MOVEMENT

1. Very important.
   - Orthogonality.
   - Skewness.
2. Non Uniform Rational B–Spline (NURBS) representaion 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.



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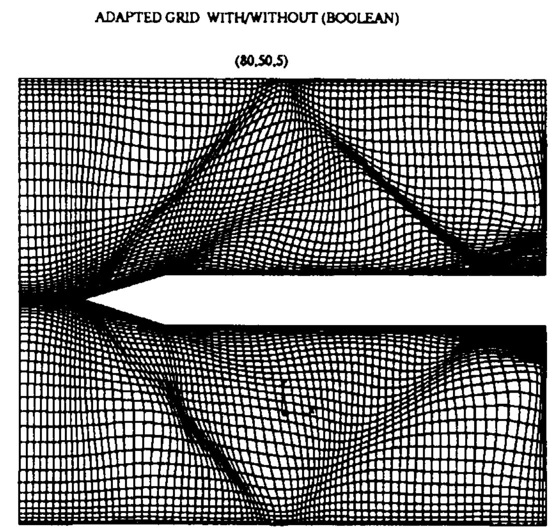


Figure 2. Comparison of Adapted Grids.

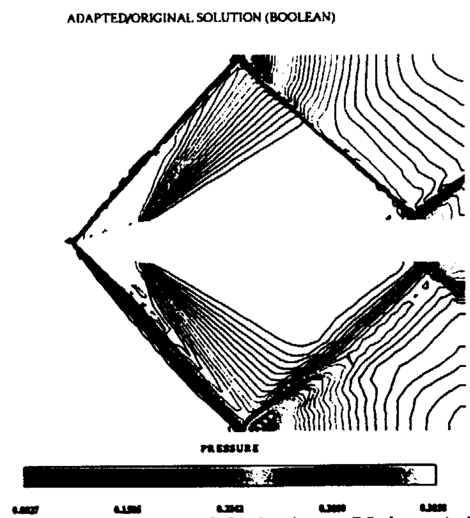
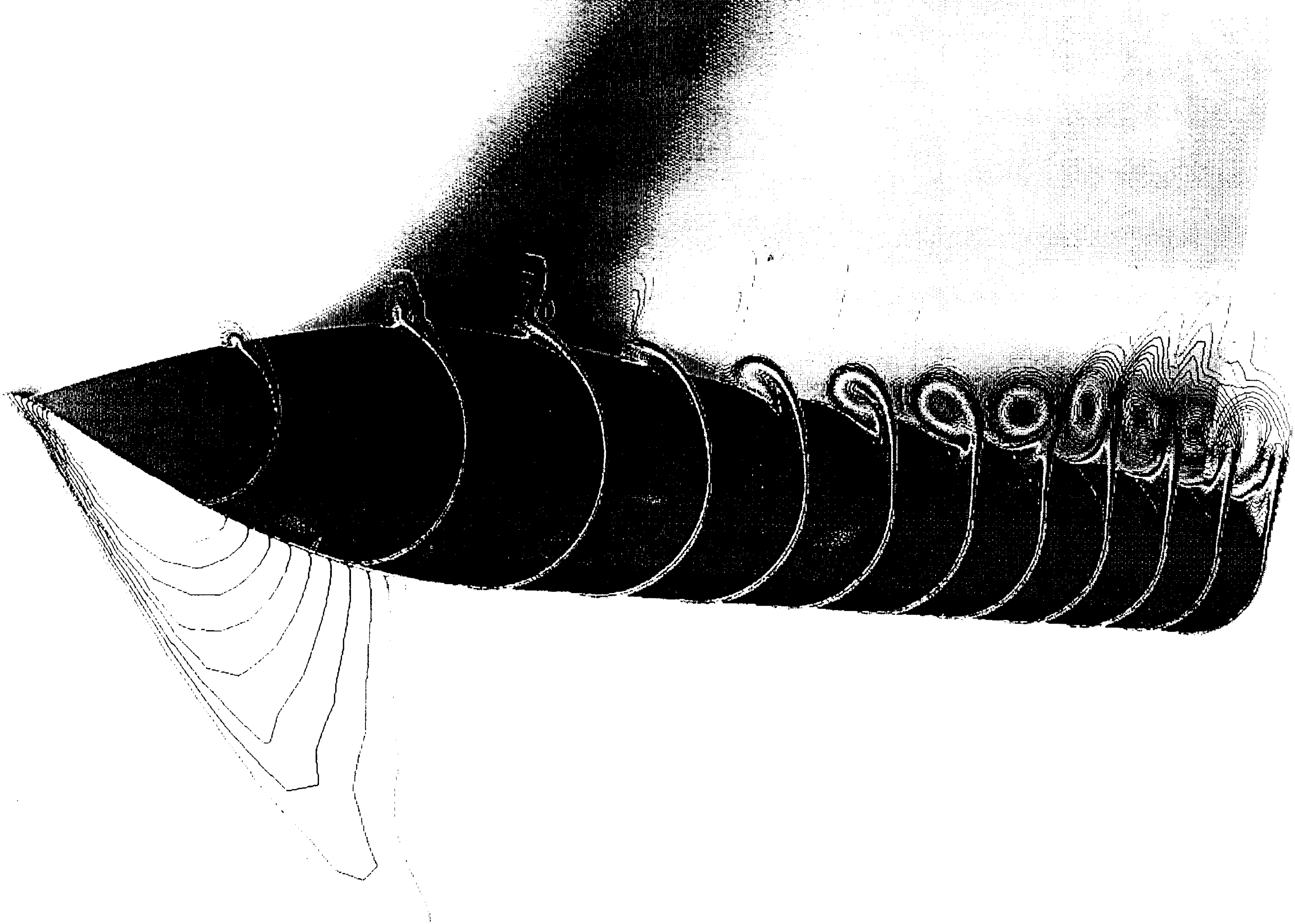
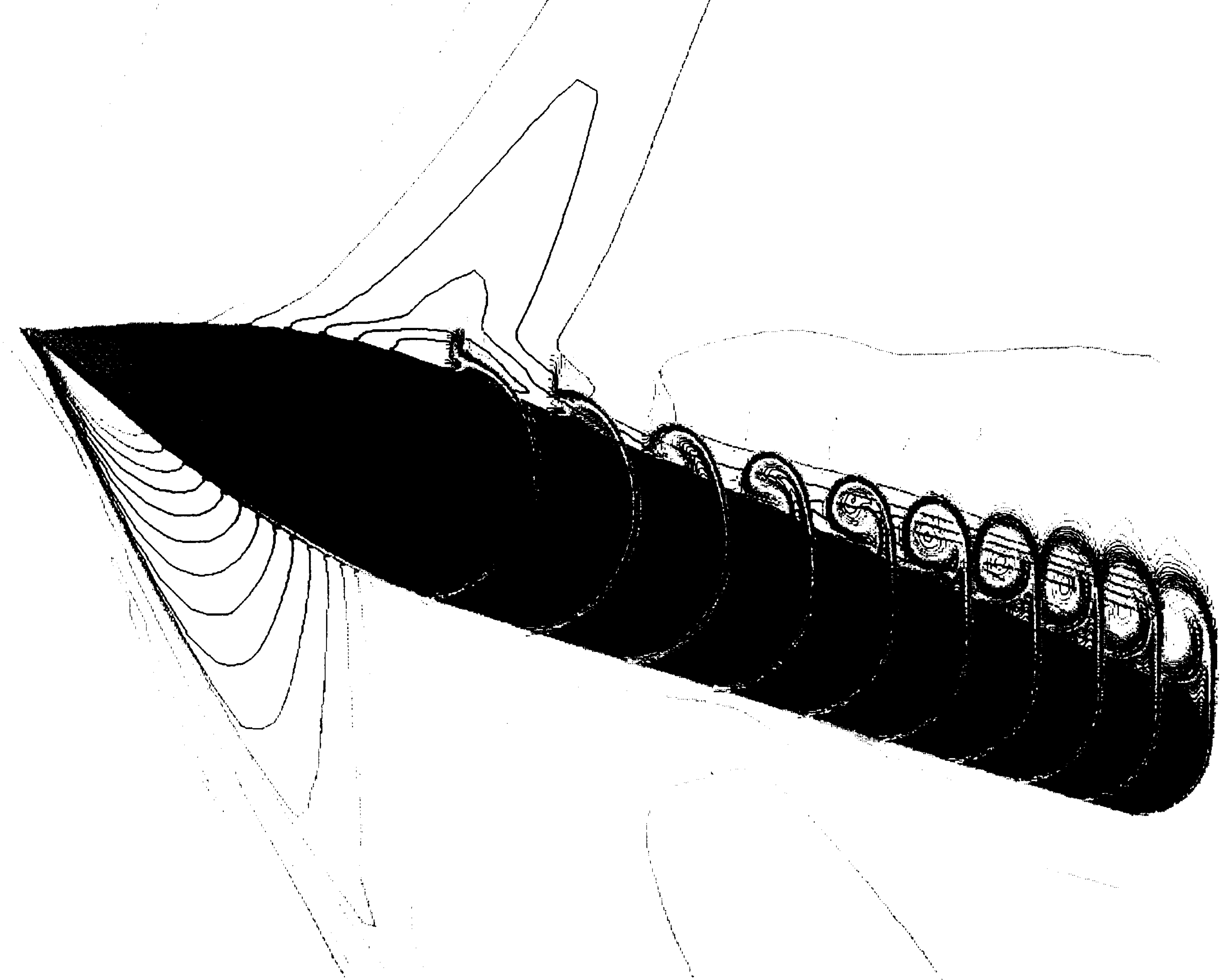


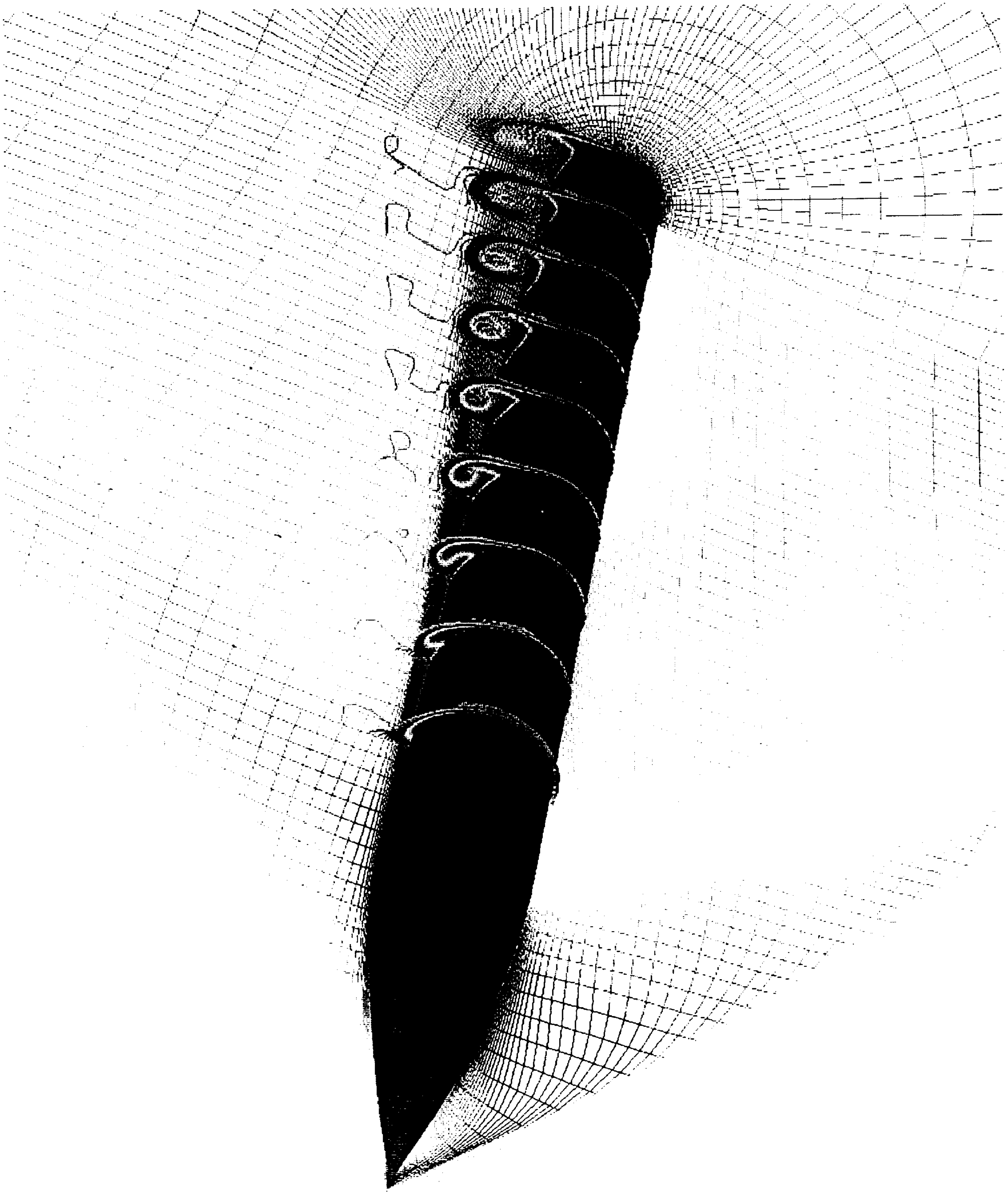
Figure 3. Comparison of Solutions Using Adapted Grid.

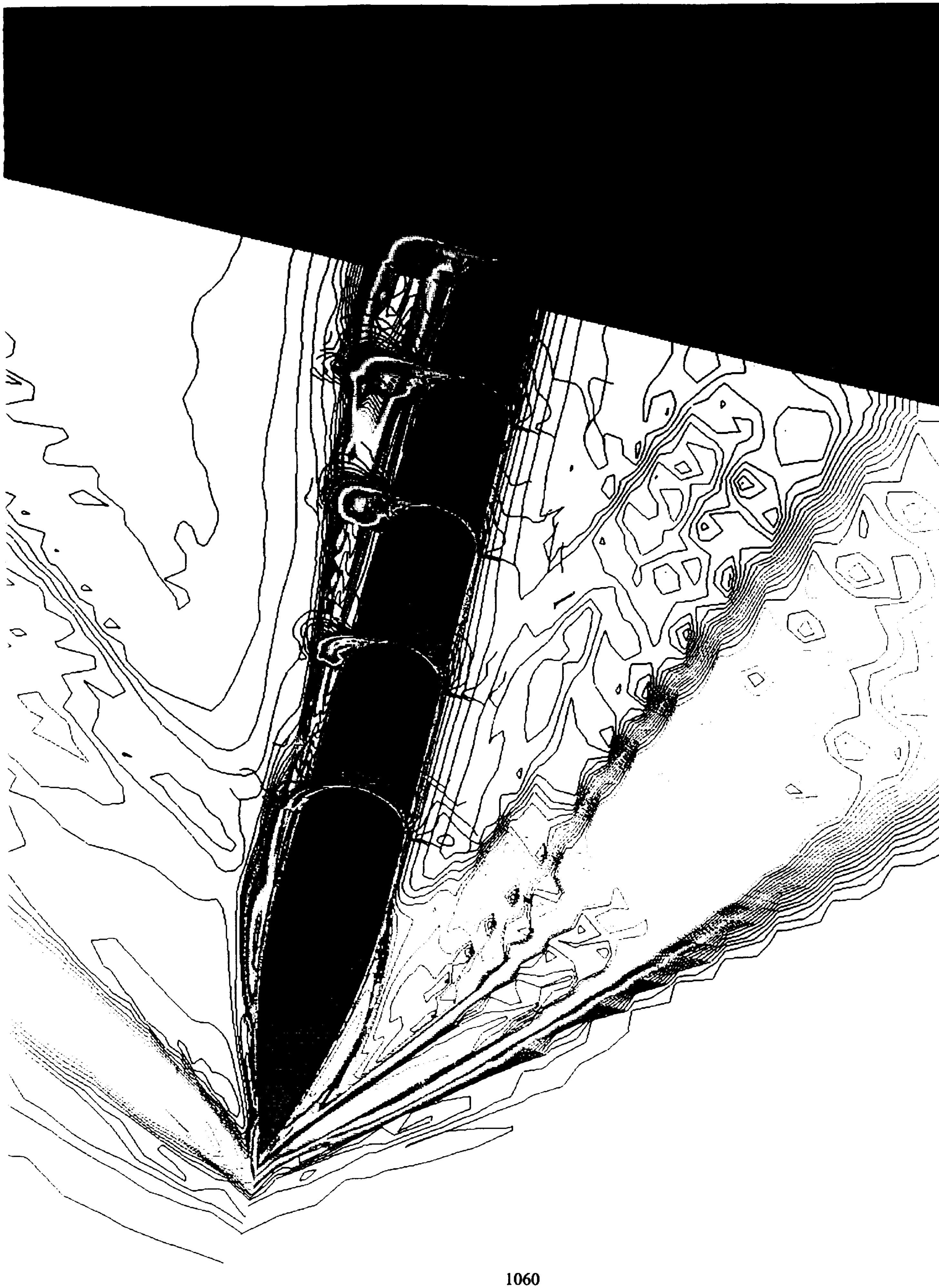
Case 1 NPARC Sol Grid 7 KE Model



Case 1 NPARC Grid 7 a2 KE Model







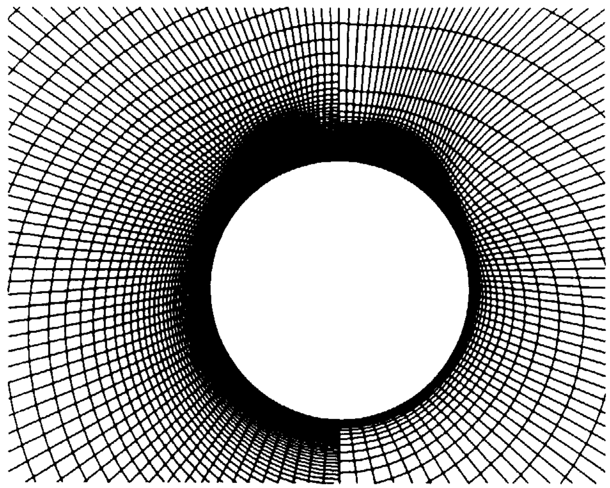


Figure 6. X/D = 5.5

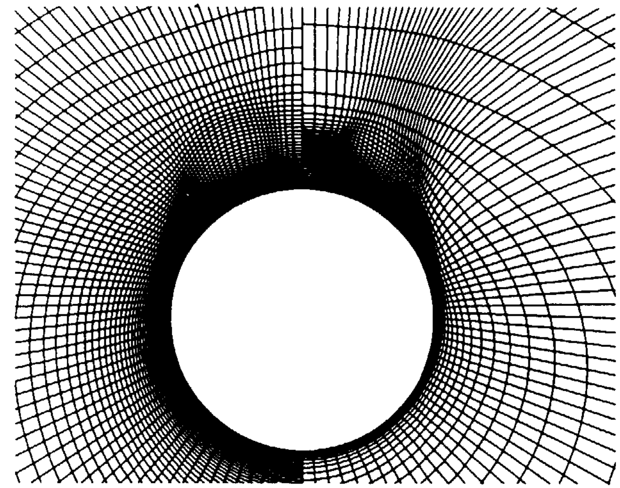
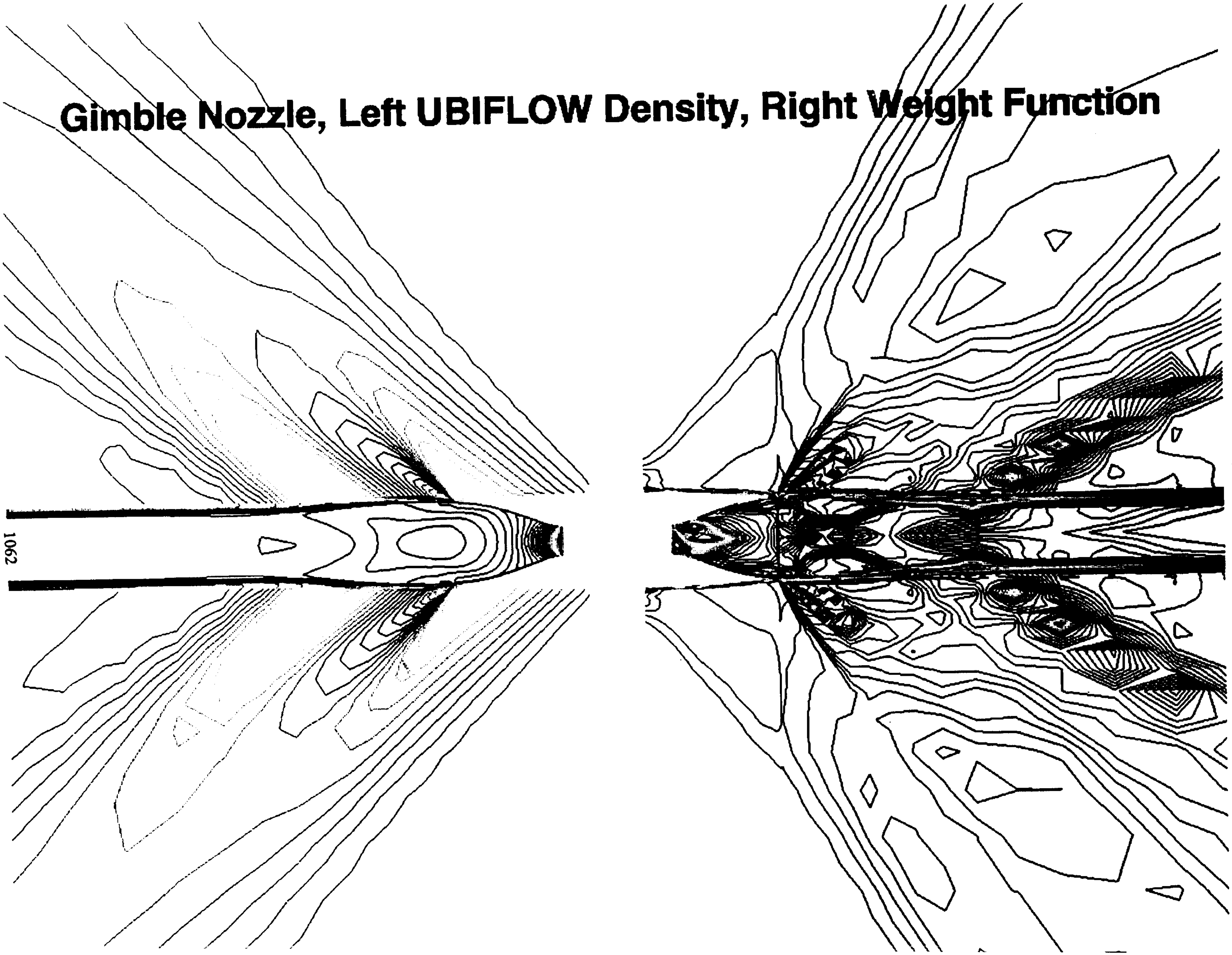
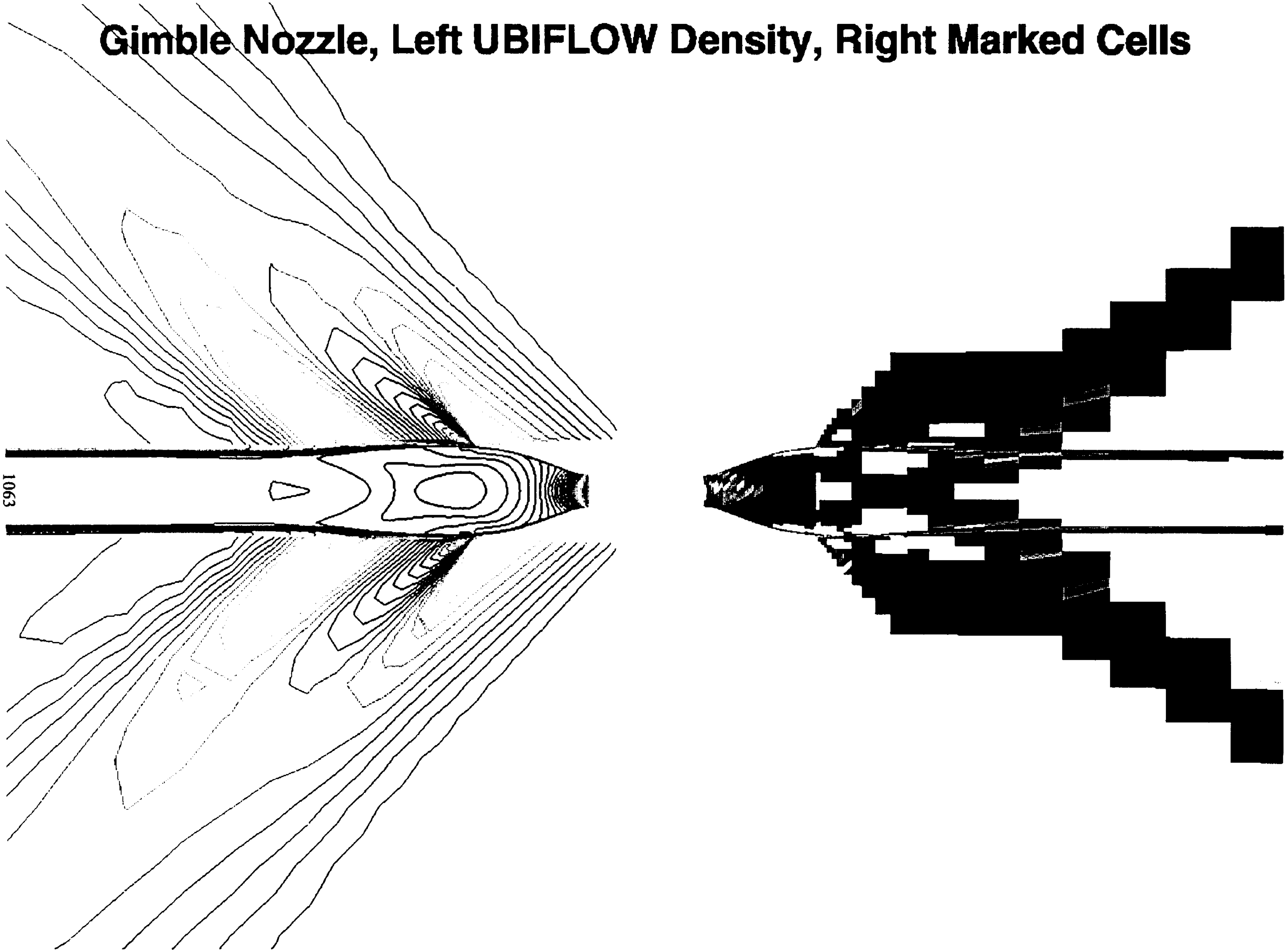


Figure 7. X/D = 8.5.

Gimble Nozzle, Left UBIFLOW Density, Right Weight Function



Gimble Nozzle, Left UBIFLOW Density, Right Marked Cells



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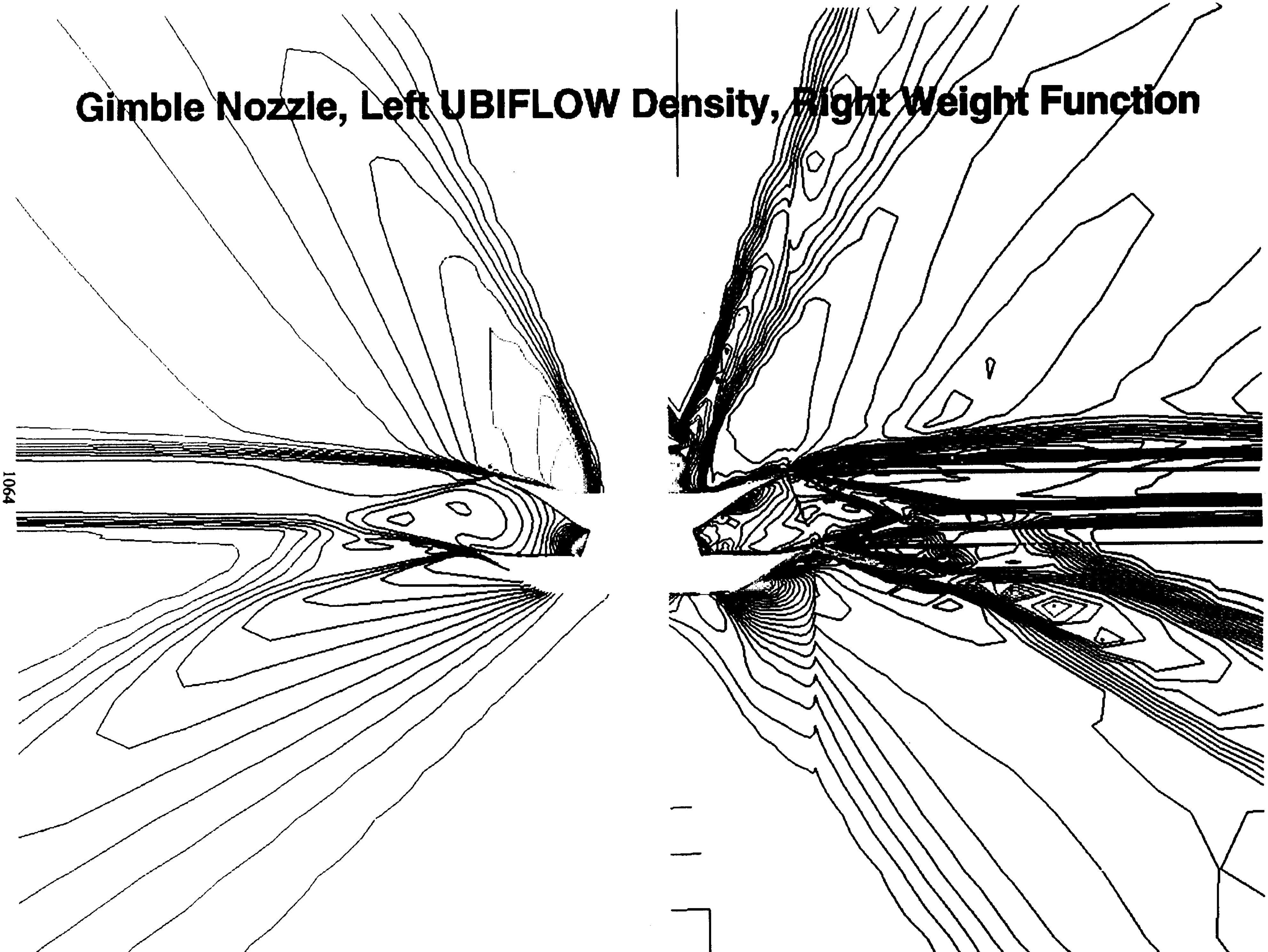
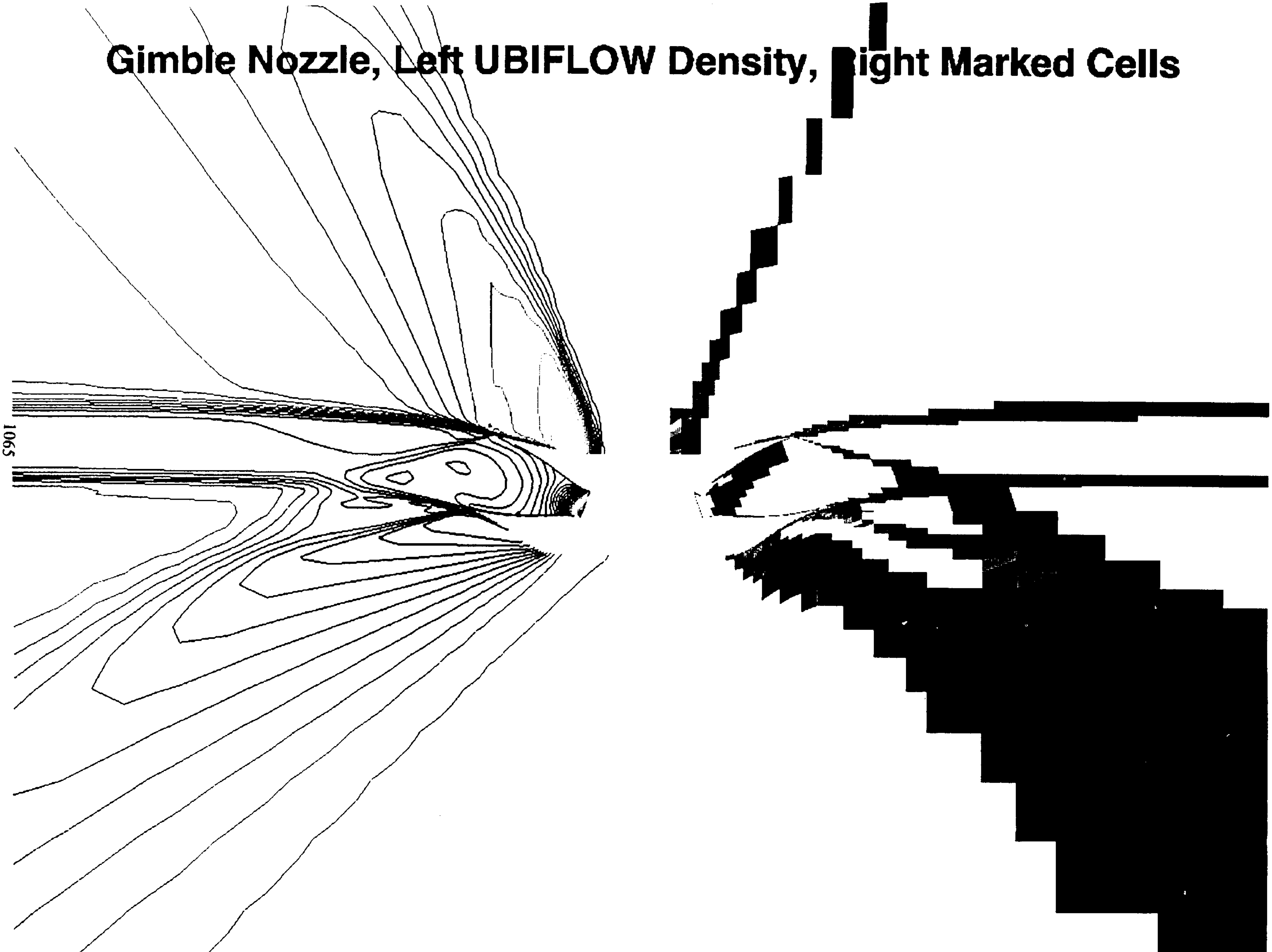


Gimble Nozzle, Left UBIFLOW Density, Right Marked Cells



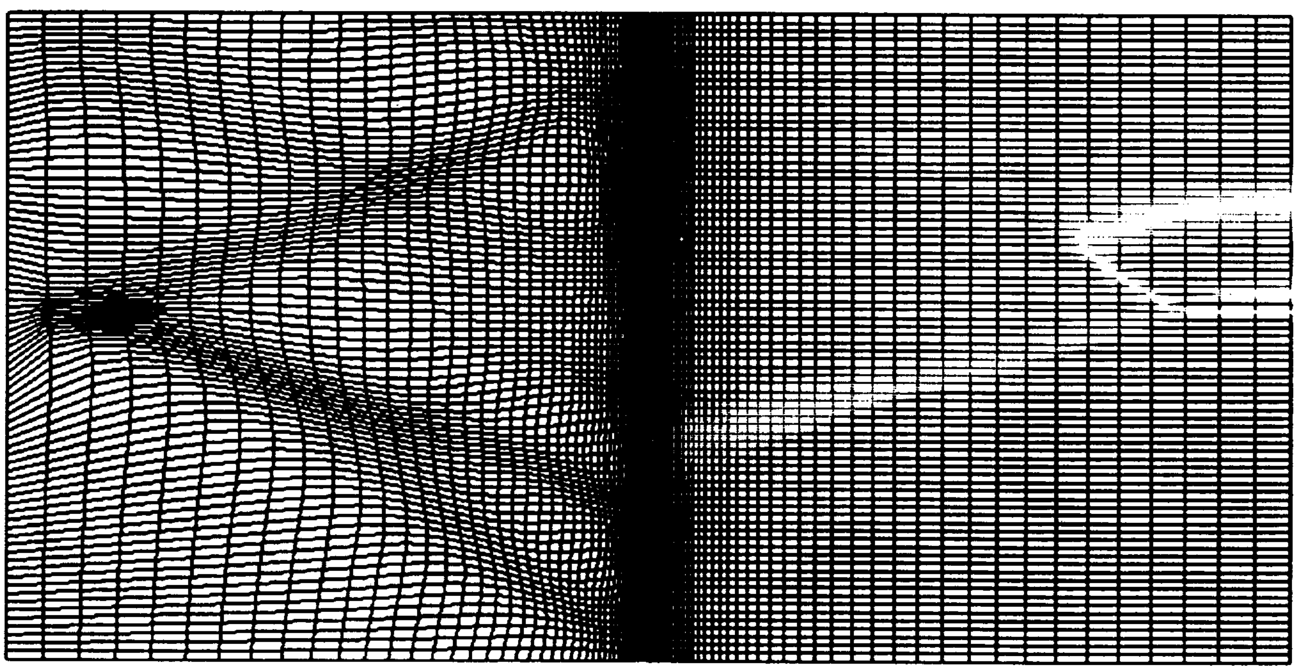
SUMMARY

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 vorticies.
   - Lower values of artificial dissipation may be used.
   - Larger time steps may be used.
   - Improved convergence behaviour.
   - More closely resembles experimental data.

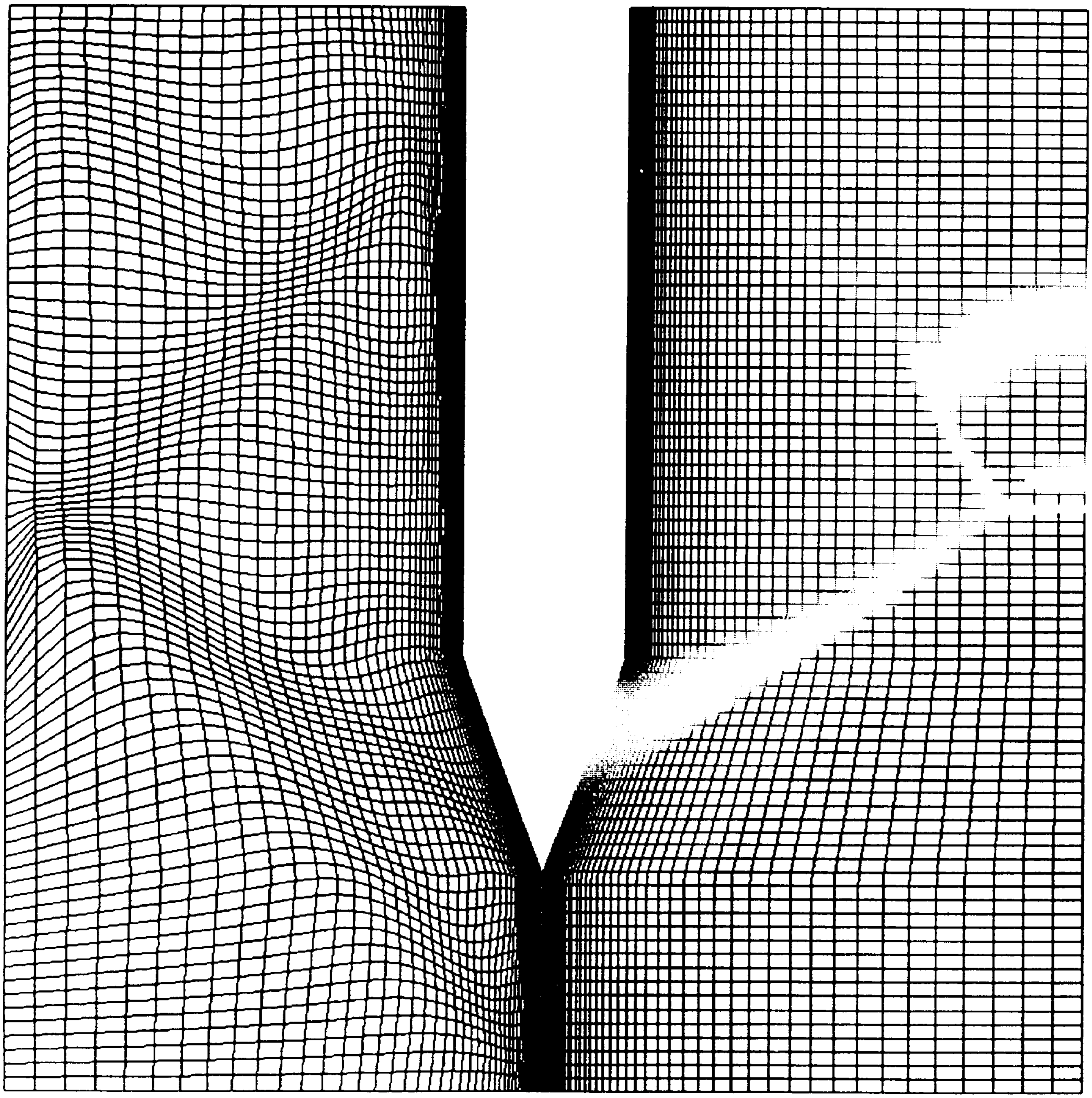
ONGOING WORK

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.

ADAPTED DISTRIBUTION MESH



ADAPTED GRID



Scramjet Inlet NPARC Solution (lower), Weight Func (upper)