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INVISCID AND VISCOUS FLOW CALCULATIONS FOR THE F16XL CONFIGURATION

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This presentation is a report on the ongoing activity at NASA LaRC in support of Supersonic Laminar Flow Control (SLFC) research. Details of the computation involved in obtaining the meanflow around bodies in high-speed flow and interfacing the results to a stability analysis will be presented. Particular attention is given to the F16XL configuration, which is the test-bed for the supersonic LFC experiment.

Meanflow solution for two geometries will be discussed. The first one is for the F16XL wing, with emphasis on the flow near the attachment line and the upper surface. Calculations have been done with and without suction. The results have been processed using an interface program and fed into a stability analysis program.

The second geometry is a scale model of a swept wing leading edge at M=3.5. Experimental measurements on transition on this model are planned at NASA LaRC. The computations are in support of this effort.

Computational Study of LFC

for Supersonic Fuselages and Swept Wings

Cases Under Study:

(1) F16XL Wing LFC Experiment

$M=1.6\text{-}2.0$, $\alpha=0\text{-}2$ deg., $\Lambda=70$ deg, Suction On/Off

(2) Supersonic Swept Leading Edge

Closer Study of L.E. region B-L stability

$M=3.5$, $\Lambda=77.1$ deg., α, Re variable

A number of programs, all developed at NASA LaRC have been used to address the problem of supersonic boundary-layer stability. The codes CFL3D and GASP are upwind-differenced, finite volume N-S solvers that have been applied to a wide variety of flows. For simpler geometries, 3D boundary-layer solvers can be applied, which uses the boundary layer-edge pressure boundary condition from an Euler calculation. Two such programs, one implicit and the other explicit are available.

The boundary layer stability program COSAL has been modified to interface with any of the above programs.

COMPUTATIONAL TOOLS

MEAN-FLOW

N-S/EULER SOLVERS

CFL3D (TLNS)
GASP (PNS)

3-D B-L SOLVERS

$O(\Delta Z^2)$ and $O(\Delta Z^4)$ Programs

B-L STABILITY

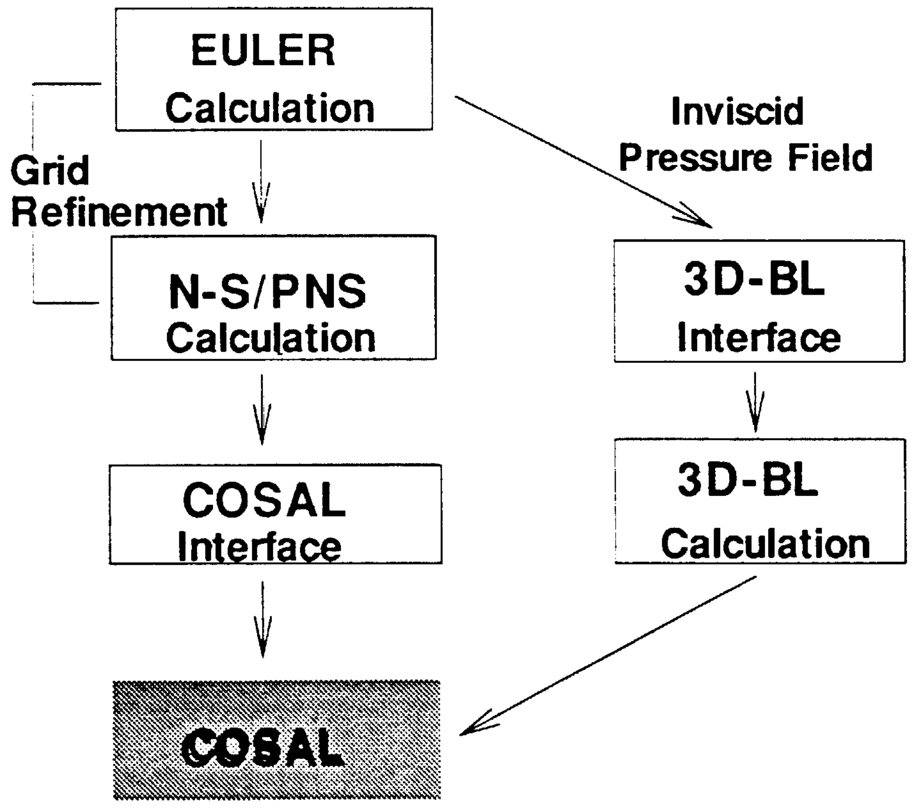
COSAL Modified for 3D Compr. Flows

Depending on the complexity of the geometry, one of the two routes could be followed. For simpler (conical or infinite swept wing type) geometries, a cost-effective way is to run a 3D boundary-layer calculation and feed it directly to the COSAL linear stability analysis.

For more complex bodies such as the F16XL wing, a TLNS calculation is necessary. Grid refinement based on solution on coarse meshes may be required. Once a grid-converged N-S solution is obtained, an interface program is required to process the solution and output it into boundary-layer oriented coordinates suitable for the linear stability analysis.

PRESENT APPROACH

for B-L Stability Analysis



EULER Calculation

Grid Refinement

N-S/PNS Calculation

COSAL Interface

COSAL

Inviscid Pressure Field

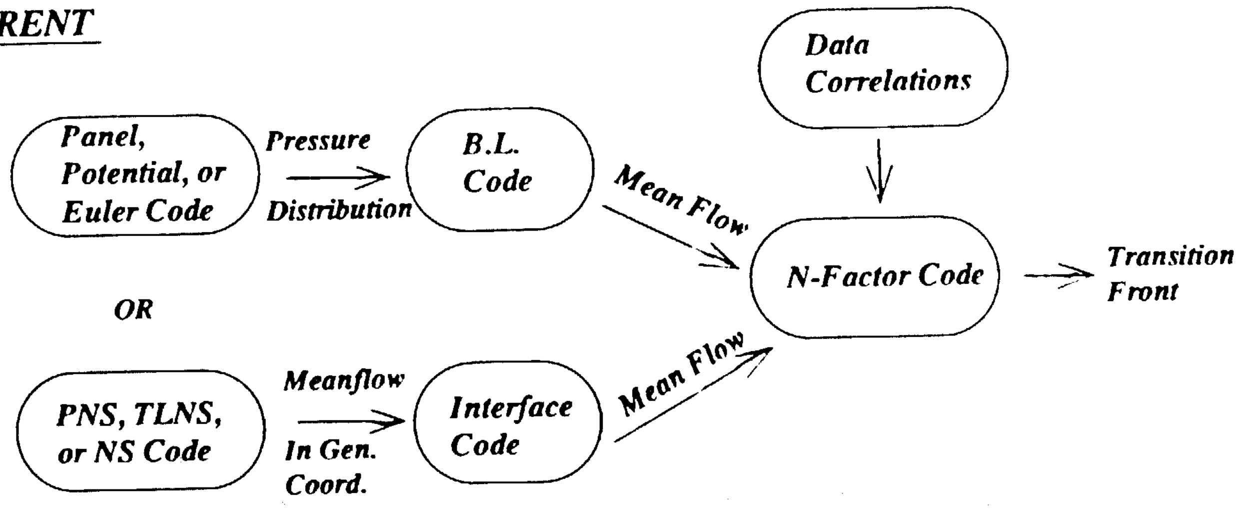
3D-BL Interface

3D-BL Calculation

In order to improve the transition prediction procedure, a future methodology would be to include modeling of the far-field disturbances and receptivity mechanisms and use a more general analysis such as the non-linear Parabolised Stability Equations (PSE). The inputs from the mean-flow solution remain the same in present and future methods. This talk will focus on the meanflow issue.

LAMINAR FLOW CONTROL METHODOLOGY

CURRENT



Panel, Potential, or Euler Code

Pressure Distribution

B.L. Code

Mean Flow

Data Correlations

N-Factor Code

Transition Front

OR

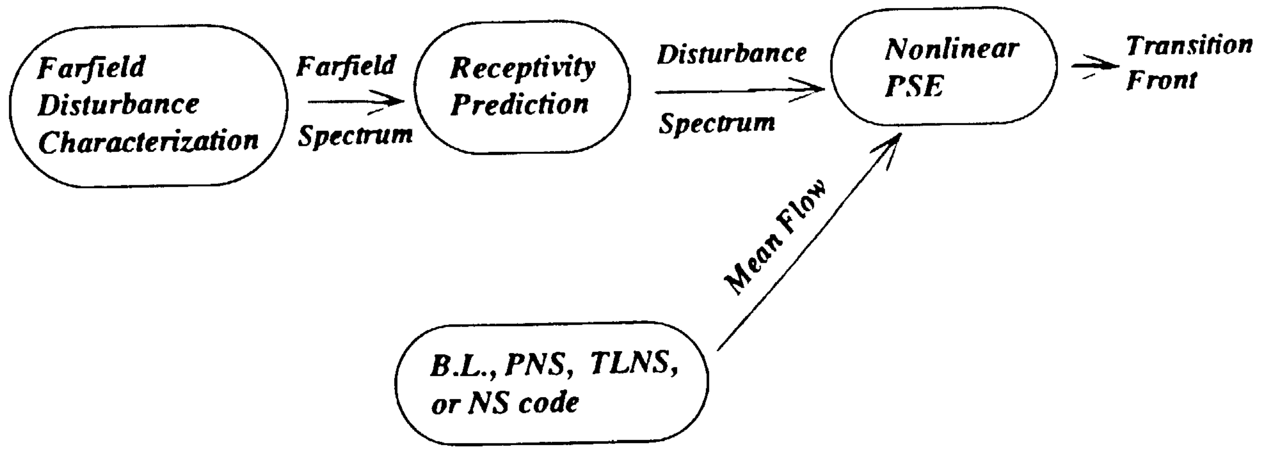
PNS, TLNS, or NS Code

Meanflow In Gen. Coord.

Interface Code

Mean Flow

FUTURE



Farfield Disturbance Characterization

Farfield Spectrum

Receptivity Prediction

Disturbance Spectrum

Nonlinear PSE

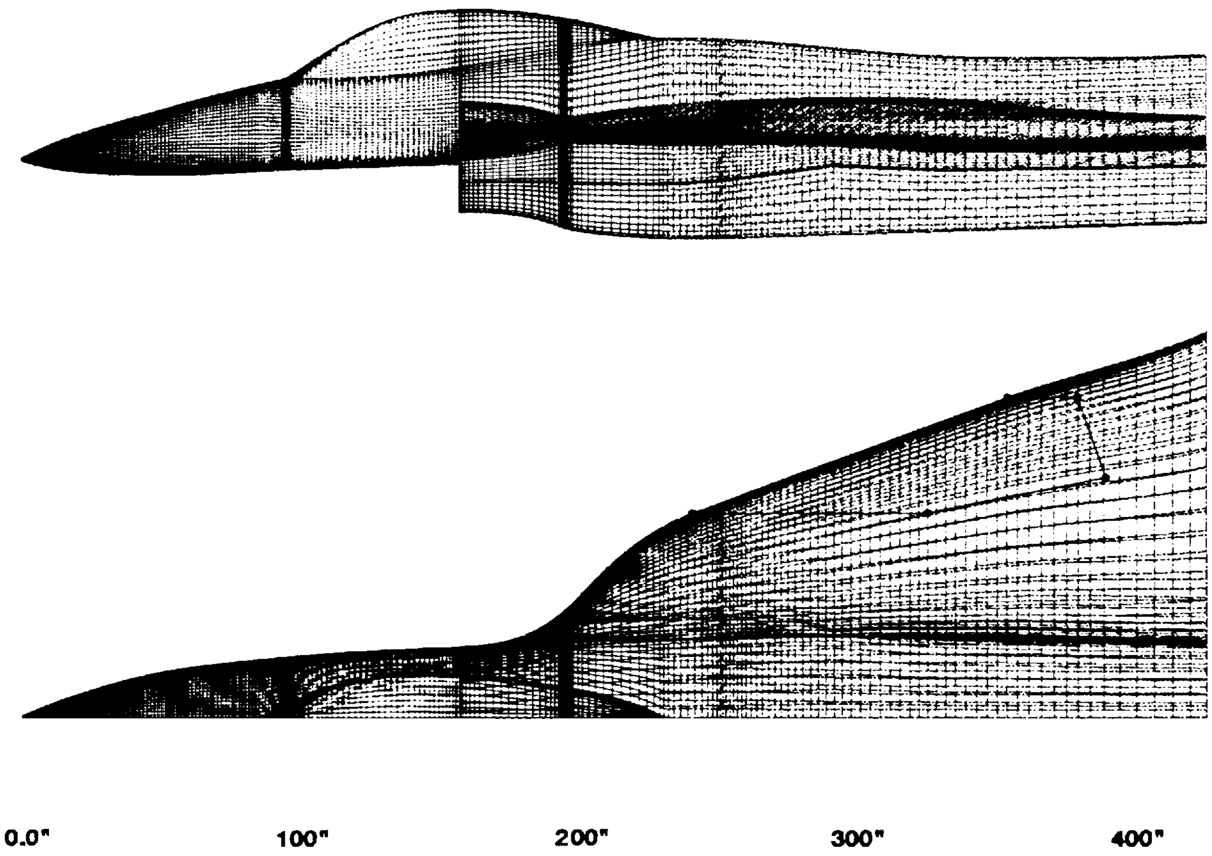
Transition Front

B.L., PNS, TLNS, or NS code

Mean Flow

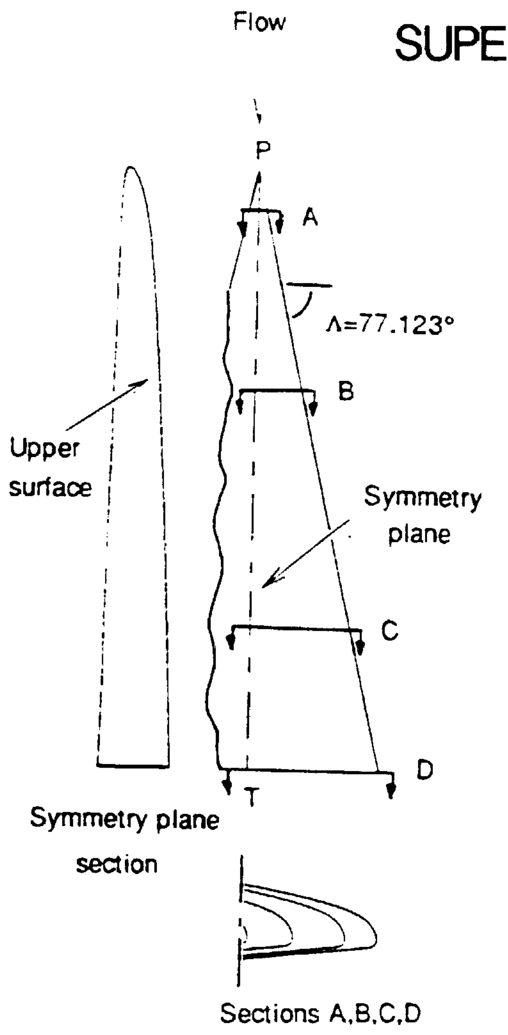
The first case discussed is the flow calculation on the F16XL wing. The figure shows the surface grid description of the body comprising of about 20,000 points. The glove location on the wing is also shown. Velocity and temperature profiles in the wing upper region are of interest from boundary-layer stability point of view.

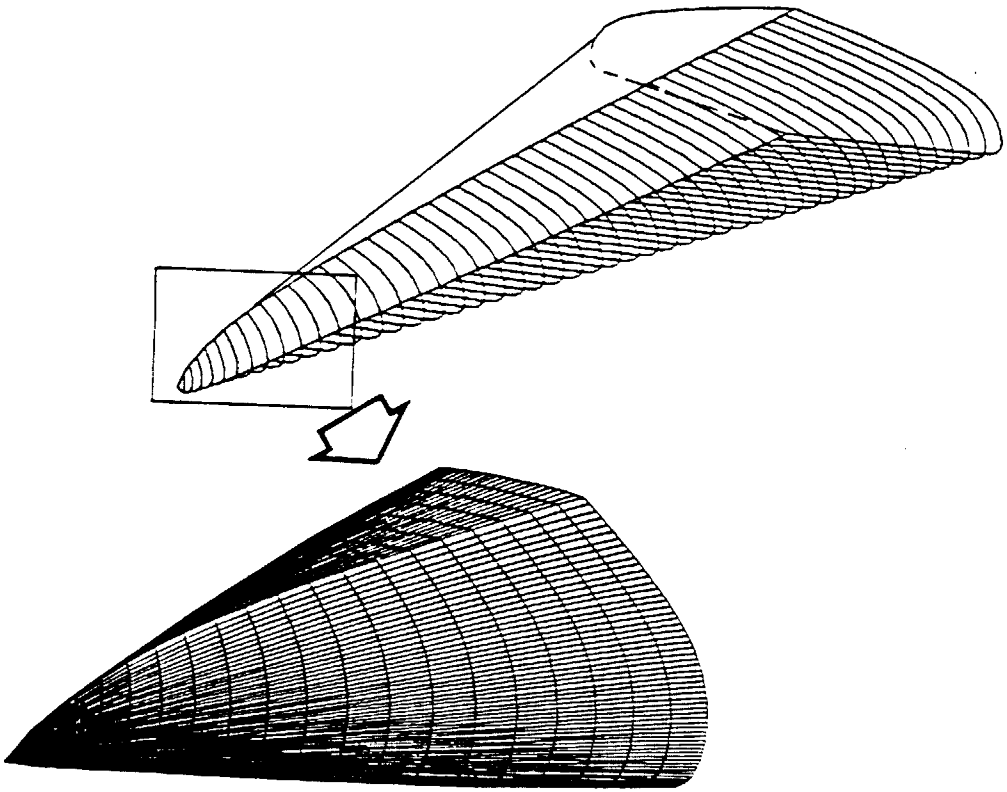
F16XL SURFACE GRID AND LFC GLOVE LOCATION



The second case is a wind-tunnel model of a swept wing leading edge region, planned to be tested under low free-stream turbulence conditions. This is a 15″ long symmetric model at a higher sweep angle and Mach number compared to the F16XL leading edge.

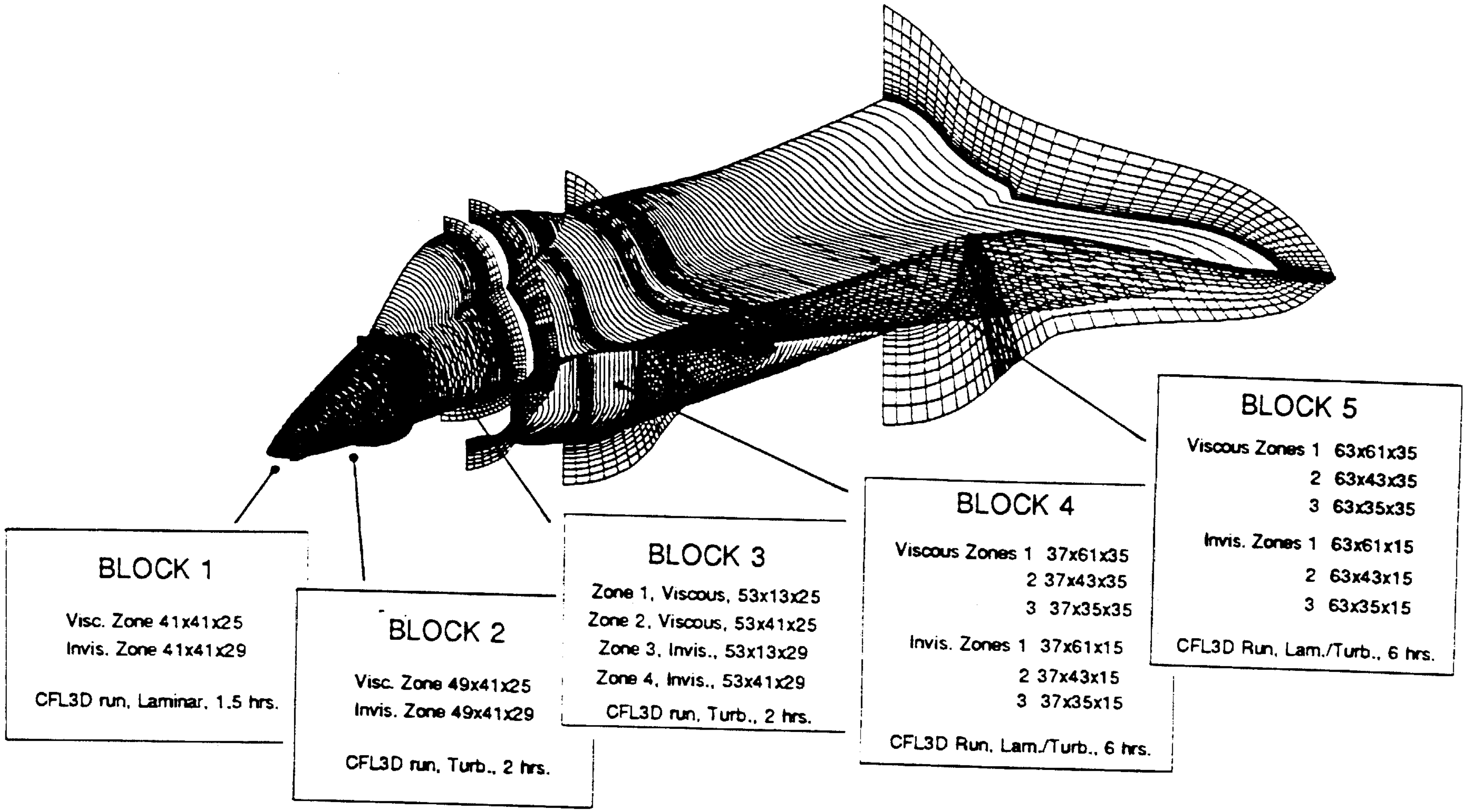
SUPERSONIC SWEPT LEADING EDGE WING





Reference length = Distance PT = 15 "

In order to compute the entire F16XL configuration, and at the same time to keep computer job sizes at reasonable levels, computation is performed in blocks. Within each block, a globally-iterated computation is performed using the program CFL3D. Between blocks, information is passed from upstream to downstream, which is correct for supersonic flow. A complete run on a grid of 1 million points takes up about 15 hours on the CRAY Y-MP. Some blocks can be run together, towards the end of convergence, in order to avoid interpolation errors between blocks.



BLOCK 1

Visc. Zone 41x41x25
Invis. Zone 41x41x29

CFL3D run, Laminar, 1.5 hrs.

BLOCK 2

Visc. Zone 49x41x25
Invis. Zone 49x41x29

CFL3D run, Turb., 2 hrs.

BLOCK 3

Zone 1, Viscous, 53x13x25
Zone 2, Viscous, 53x41x25
Zone 3, Invis., 53x13x29
Zone 4, Invis., 53x41x29
CFL3D run, Turb., 2 hrs.

BLOCK 4

Viscous Zones 1 37x61x35
2 37x43x35
3 37x35x35
Invis. Zones 1 37x61x15
2 37x43x15
3 37x35x15

CFL3D Run, Lam./Turb., 6 hrs.

BLOCK 5

Viscous Zones 1 63x61x35
2 63x43x35
3 63x35x35
Invis. Zones 1 63x61x15
2 63x43x15
3 63x35x15

CFL3D Run, Lam./Turb., 6 hrs.

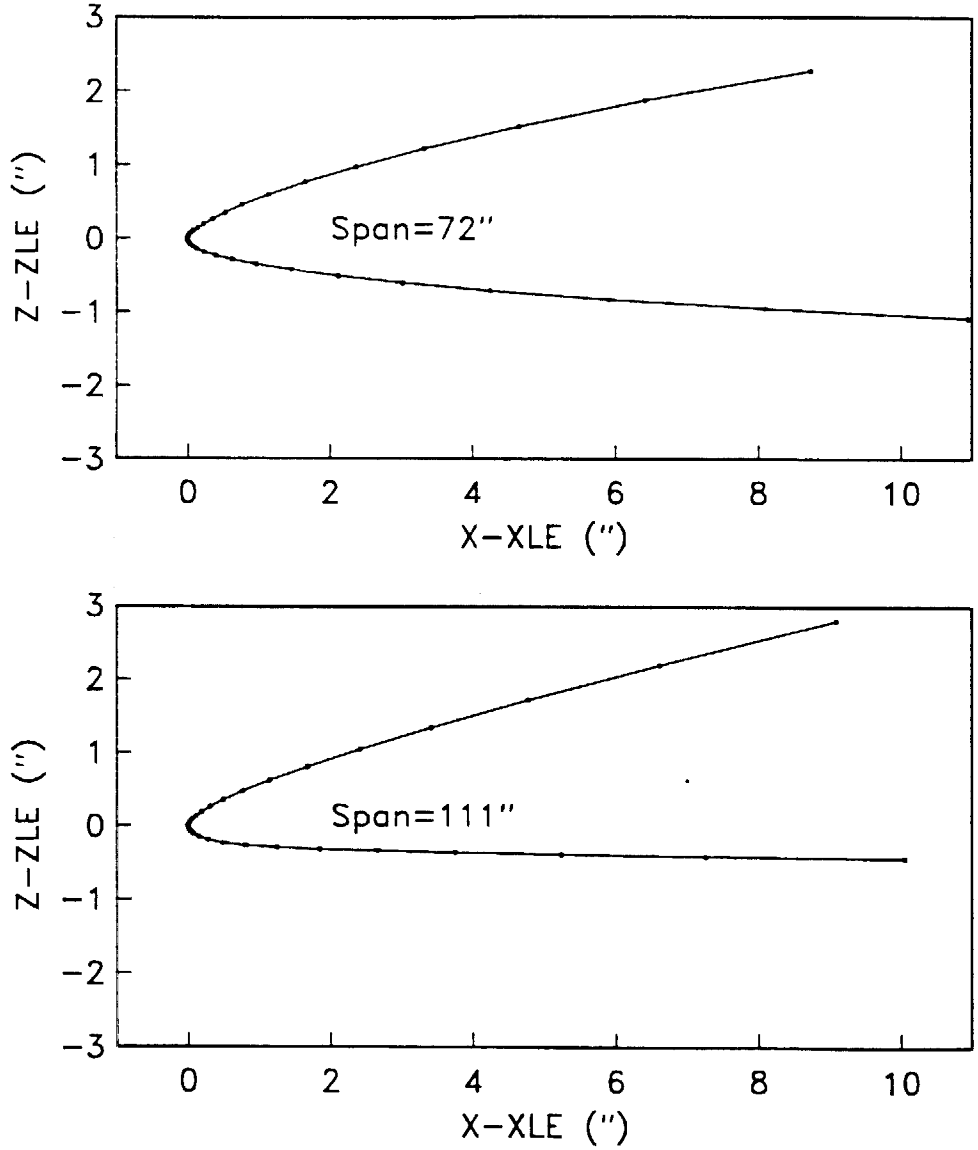
NAVIER-STOKES SOLUTION FOR F16XL GEOMETRY

Conditions: $M_\infty = 1.6$, $\alpha = 2^\circ$, Altitude= 44,000 ft.
No suction, adiabatic wall, laminar flow for y >40" spanwise

Summary: 1 million grid points, 20,000 surface points
15 to 20 hrs. Cray Y-MP computation time

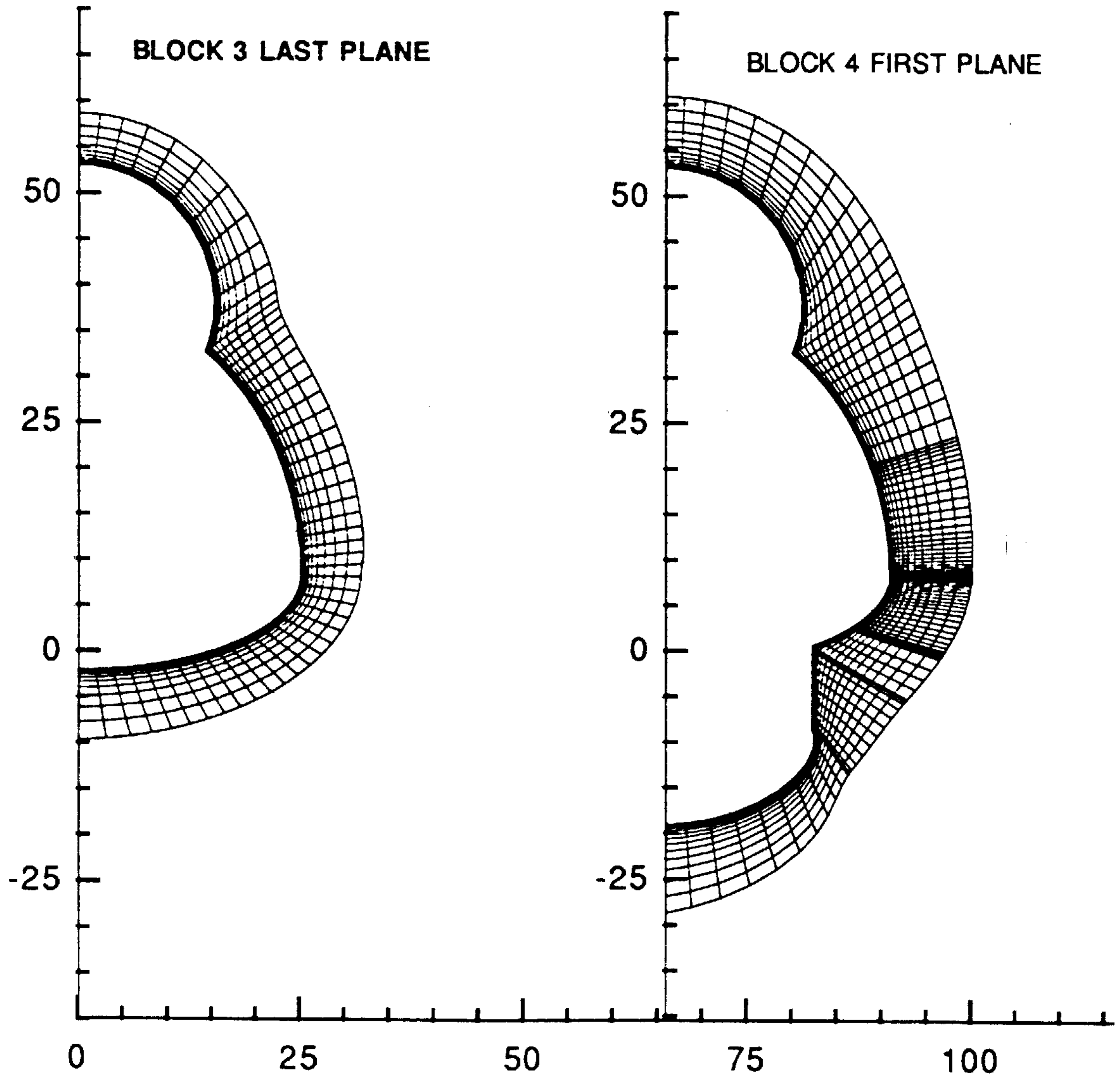
The region of interest is the boundary layer over the wing. This figure shows cross-sections of the wing parallel to the fuselage axis. Good resolution is required near the leading edge.

LFC Glove Cross-sections, Inboard & Outboard



This figure shows the viscous zones in the Block 3 — Block 4 interface. The grid clustering in Block 4 is changed to allow enough grid lines to cover the wing area. Solution in Block 3 is interpolated to the Block 4 plane. This assumes that the engine inlet is flow-through type and there is no upstream influence.

BLOCK INTERFACE AT F16XL ENGINE INLET



A list of runs for the F16XL configuration is given here. The conditions correspond to a few selected experimental flight conditions. Euler and Navier-Stokes runs have been made and the results have been applied to the stability analysis code to calculate the n-factors with and without boundary-layer suction.

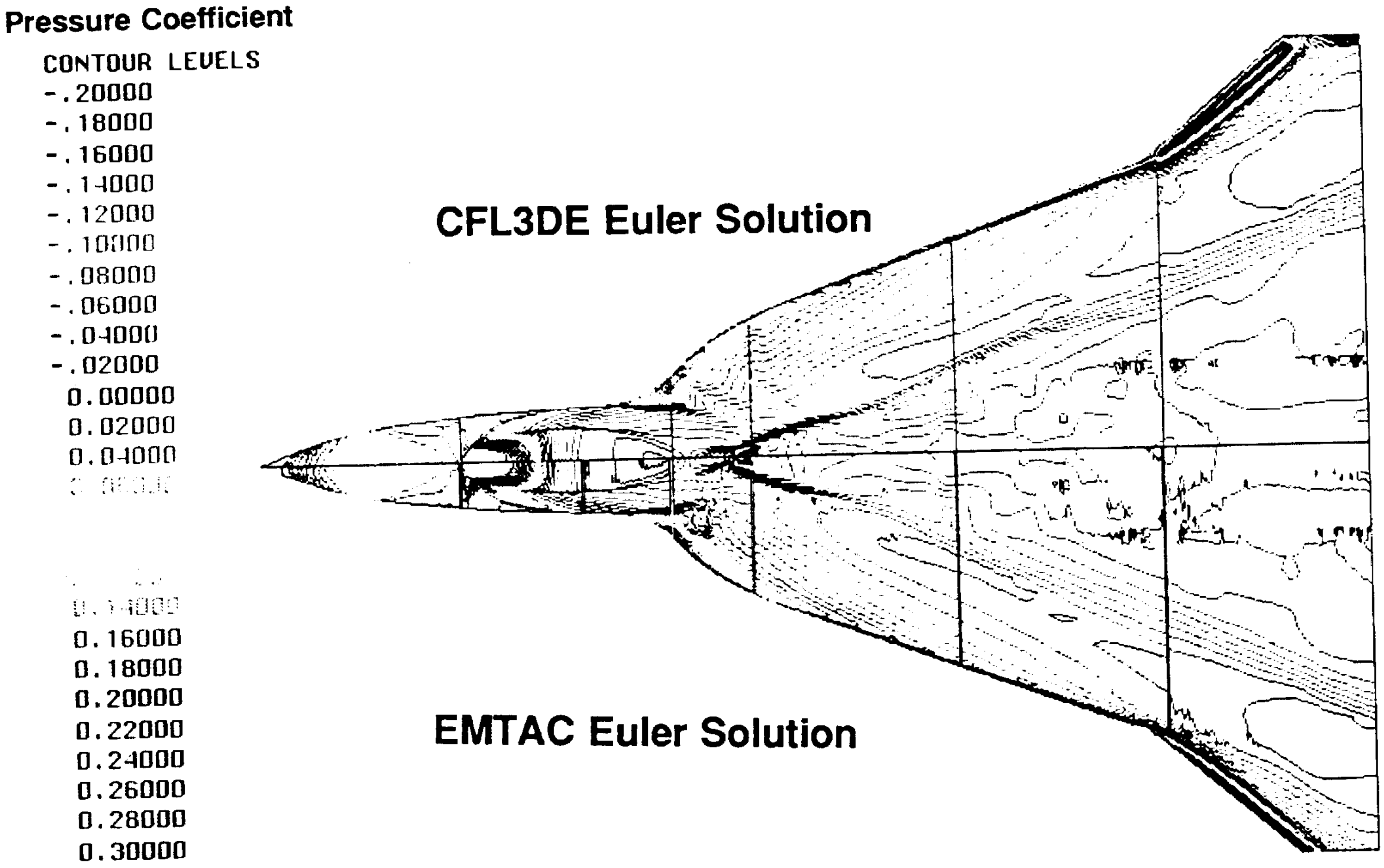
F16XL CALCULATIONS

- Space Marching Euler (CFL3DE)
  - **M=2, α=4°**
  - **M=1.58, α=2.019° (M=1.6, α=2 case)**
- N-S (CFL3D)
  - **M=1.58, α=2.019, Alt=43,735 ft., without suction**
  - **M=1.58, α=2.019, Alt=43,735 ft., with suction**
  - **M=1.702, α=2.268, Alt=35,033 ft., turbulent**
- B-L STABILITY (COSAL)
  - **M=1.58, α=2.019, Alt=43,735 ft., without suction**
  - **M=1.58, α=2.019, Alt=43,735 ft., with suction**

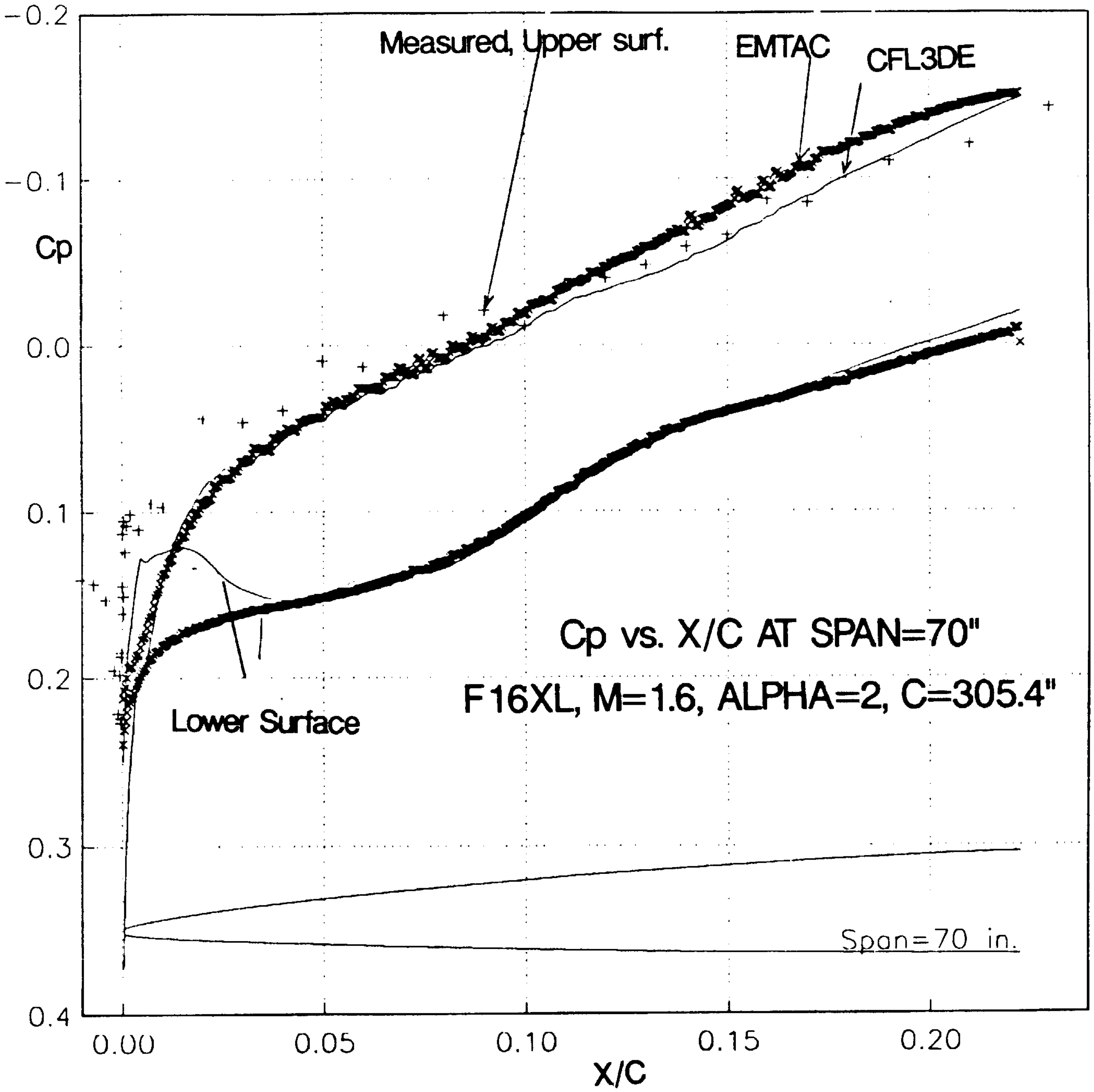
This figure shows the pressure coefficient contours on the F16XL upper surface. Euler solution from two space-marching codes are shown. Good agreement has been obtained. This figure also shows the location at which the canopy trailing edge shock will interact with wing boundary layer.

C-4.

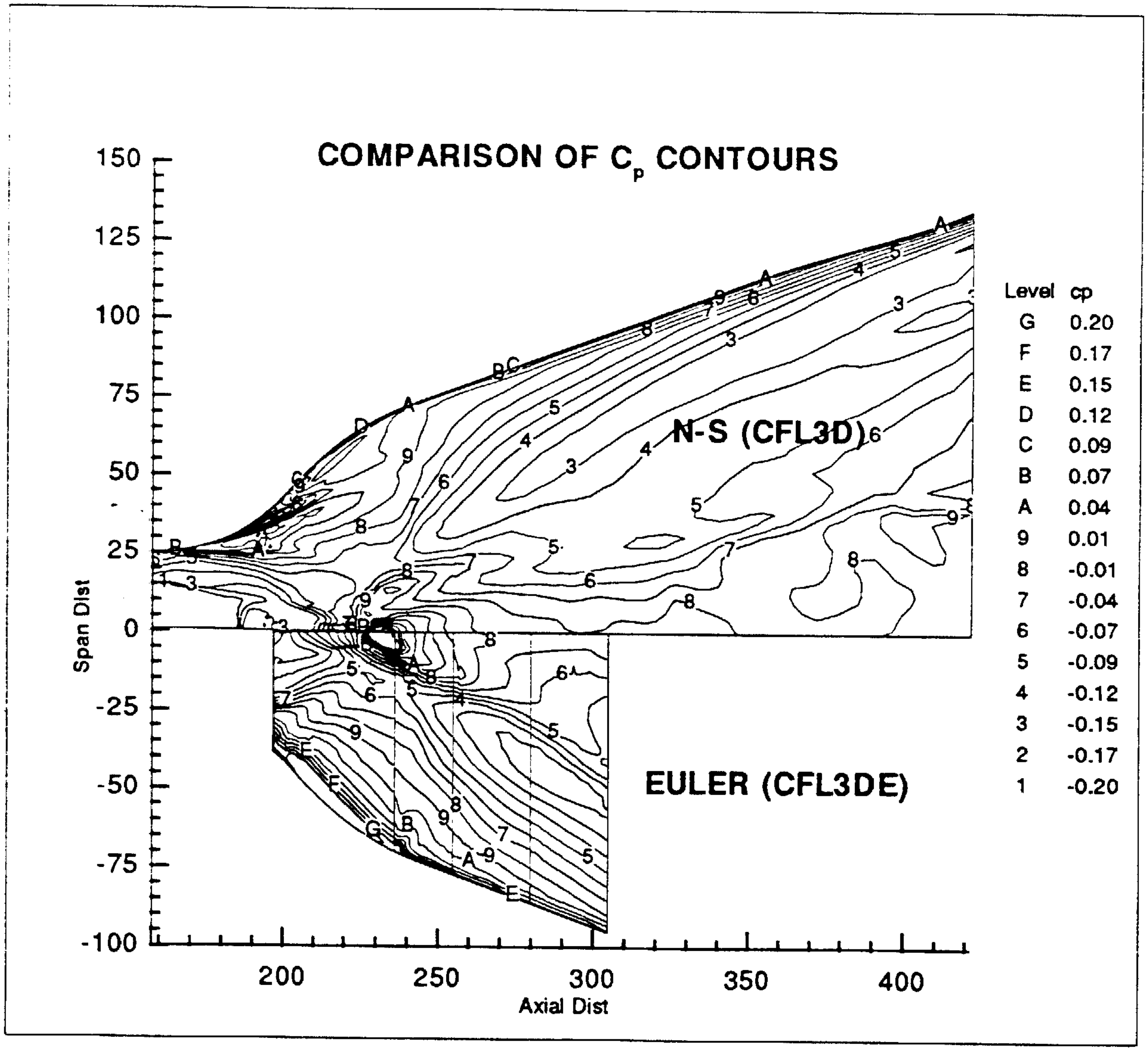
F16XL WING UPPER SURFACE, M_∞=2.0, α=4°



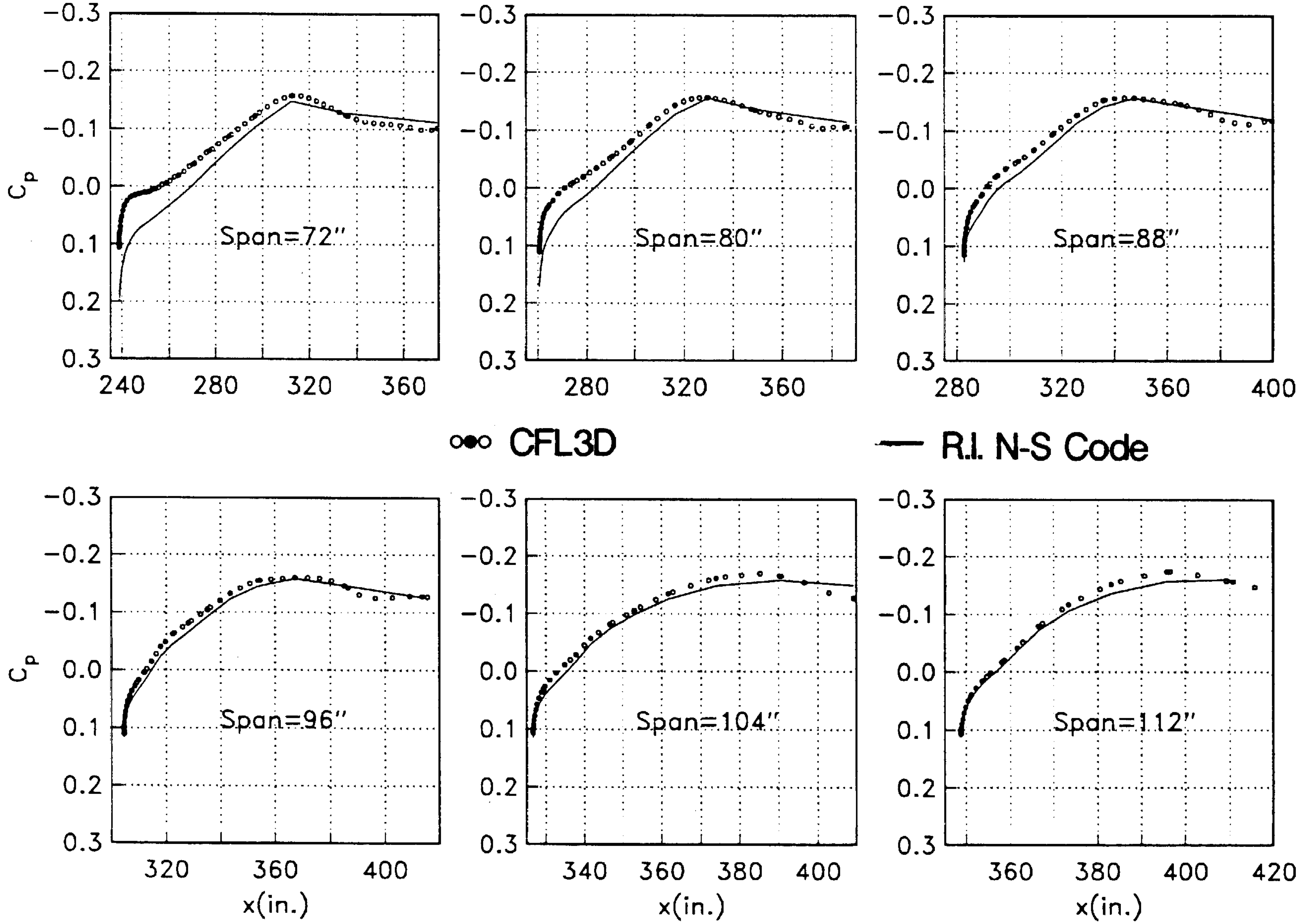
Comparison of C_p values at span of 70″ corresponding to the two calculations is shown here. Except for some differences very close to the attachment line, the two results compare well with the measured values which are also shown.


Measured, Upper surf.
EMTAC
CFL3DE
Cp vs. X/C AT SPAN=70"
F16XL, M=1.6, ALPHA=2, C=305.4"
Lower Surface
Span=70 in.
Cp
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
0.00
0.05
0.10
0.15
0.20
X/C

This is a comparison of the surface C_p contours from the Navier-Stokes and Euler calculations. The trends are quite similar, except that the shock off the canopy trailing edge is more diffused in the N-S calculation. The Navier-Stokes calculation also predicts lower values of C_p, or larger acceleration in the leading edge region.


COMPARISON OF C_p CONTOURS
N-S (CFL3D)
EULER (CFL3DE)
Span Dist
150
125
100
75
50
25
0
-25
-50
-75
-100
Axial Dist
200
250
300
350
400
Level cp
G 0.20
F 0.17
E 0.15
D 0.12
C 0.09
B 0.07
A 0.04
9 0.01
8 -0.01
7 -0.04
6 -0.07
5 -0.09
4 -0.12
3 -0.15
2 -0.17
1 -0.20

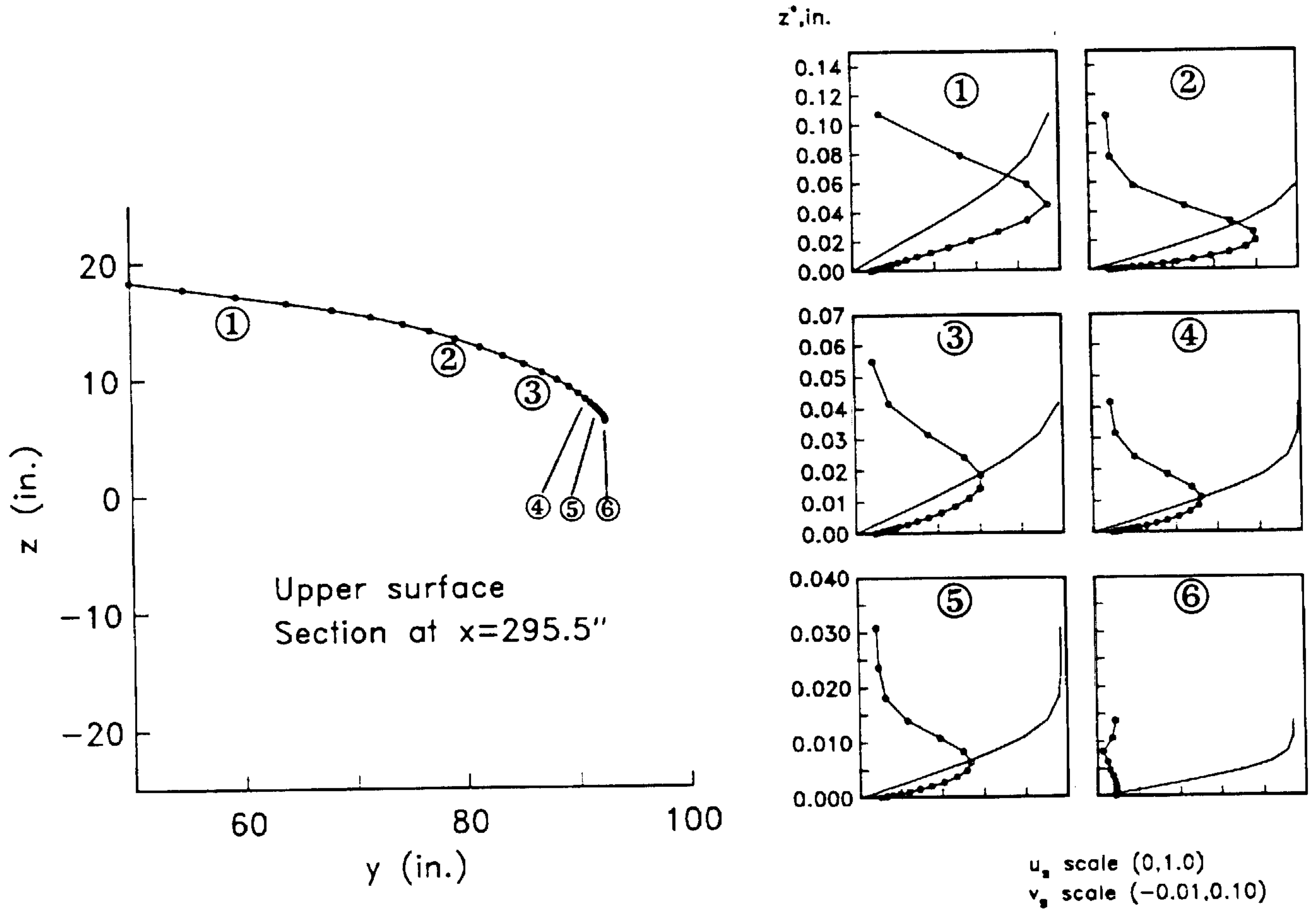
This is a comparison of the surface C_p variation in the chord direction at several span locations on the wing. The symbols correspond to the CFL3D calculation and the solid lines are the results from computation done at Rockwell Int'l. The inboard stations show some differences in the C_p variation near the leading edge. This is presumably resulting from the flow conditions existing in the forward part (fillet area) of the wing. Turbulent flow is assumed in this area of the wing close to the fuselage.



Chordwise Cp Variation, F16XL Upper Surface, M=1.6, Alpha=2°

This figure shows the streamwise and crossflow velocity profiles at a lateral section of the wing at mid-glove location. Station 6 is close to attachment point, showing near-zero crossflow. The crossflow rapidly increases away from this point. A maximum crossflow of about 8% occurs on the glove area, for this section.

F16XL LFC GLOVE MID-SECTION PROFILES



The eventual application of the meanflow solution is in B-L stability analysis. An interface program handles the conversion of the N-S solution to B-L oriented contravariant velocities along surface normals required by the linear stability program.

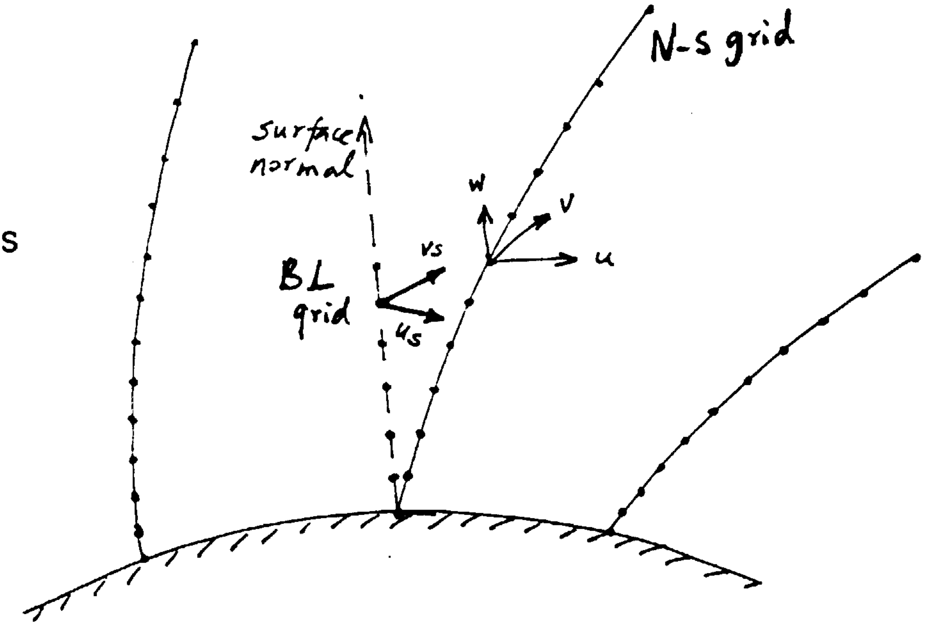
INTERFACE BETWEEN N-S and BL STABILITY PROGRAMS

N-S Solution

- u,v,w Cartesian velocities at N-S grid cell centers

B-L Stability Program

- requires contravariant velocity profiles along surface normals.



Since the N-S grid is highly clustered within the boundary-layer, certain approximations can be made in the interface program regarding local normals and normal distances. In this program, the boundary layer edge is located by looking at the absolute velocity and its gradient. The Cartesian velocities are then projected in edge streamline direction and an orthogonal crossflow direction.

INTERFACE BETWEEN N-S and BL STABILITY PROGRAMS (Cont'd.)

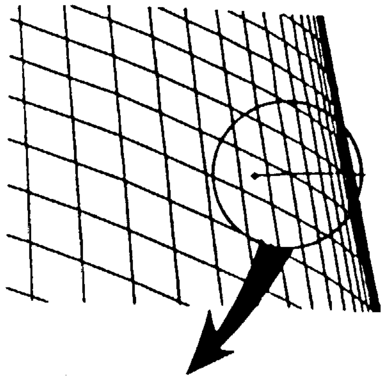
Approximation

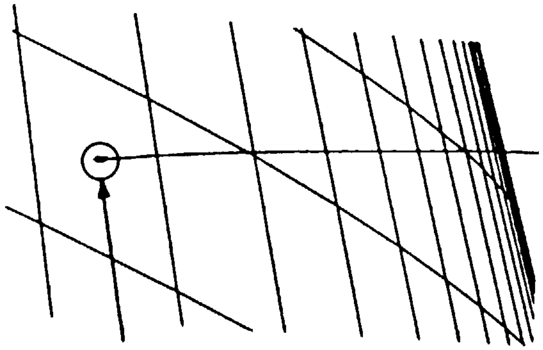
- Viscous solution along a cell center ζ line assumed to be along surface normal, at corresponding normal distances.
- Projection of cell-center points in the viscous layer stays within the corresponding grid cell.

Implementation -

- Calculate normal distances based on cell-center surface normals.
- Locate B-L edge by a criterion such as, $u_{abs}>0.9$ *AND* $\delta u_{abs}/\delta\zeta <0.01$ of maximum in profile.
- Convert (u,v,w) Cartesian velocities to (u_s,v_s) on a body-oriented or edge-streamline-oriented grid.
- Also calculate BL/Transition global quantites such as δ^*, $\delta_{0.99}$, $Re_{C\text{-}F}$, Re_θ, % crossflow.

A typical N-S surface grid with a ζ grid line from cell center

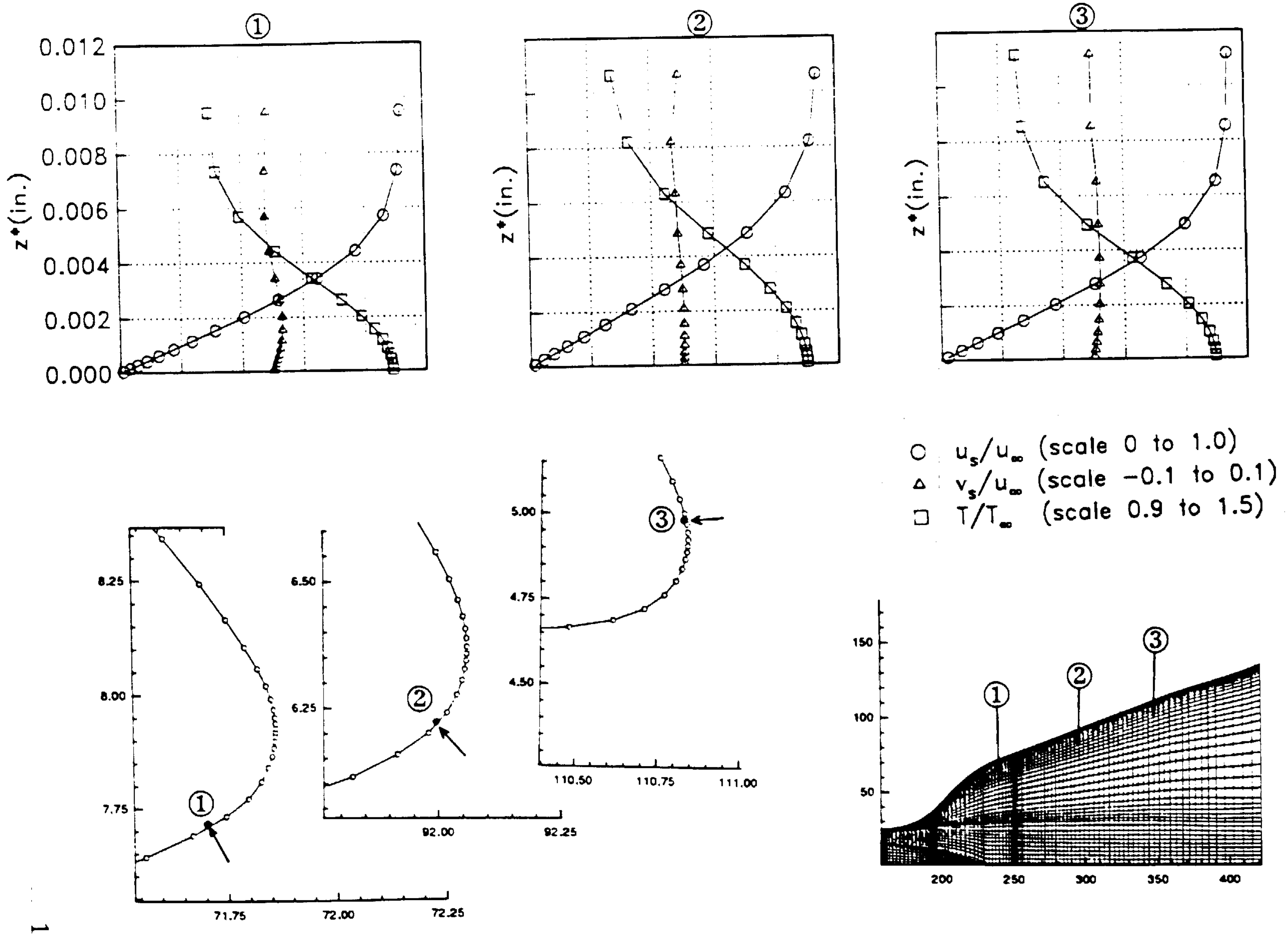




First 20 points off the surface enclosing the boundary layer

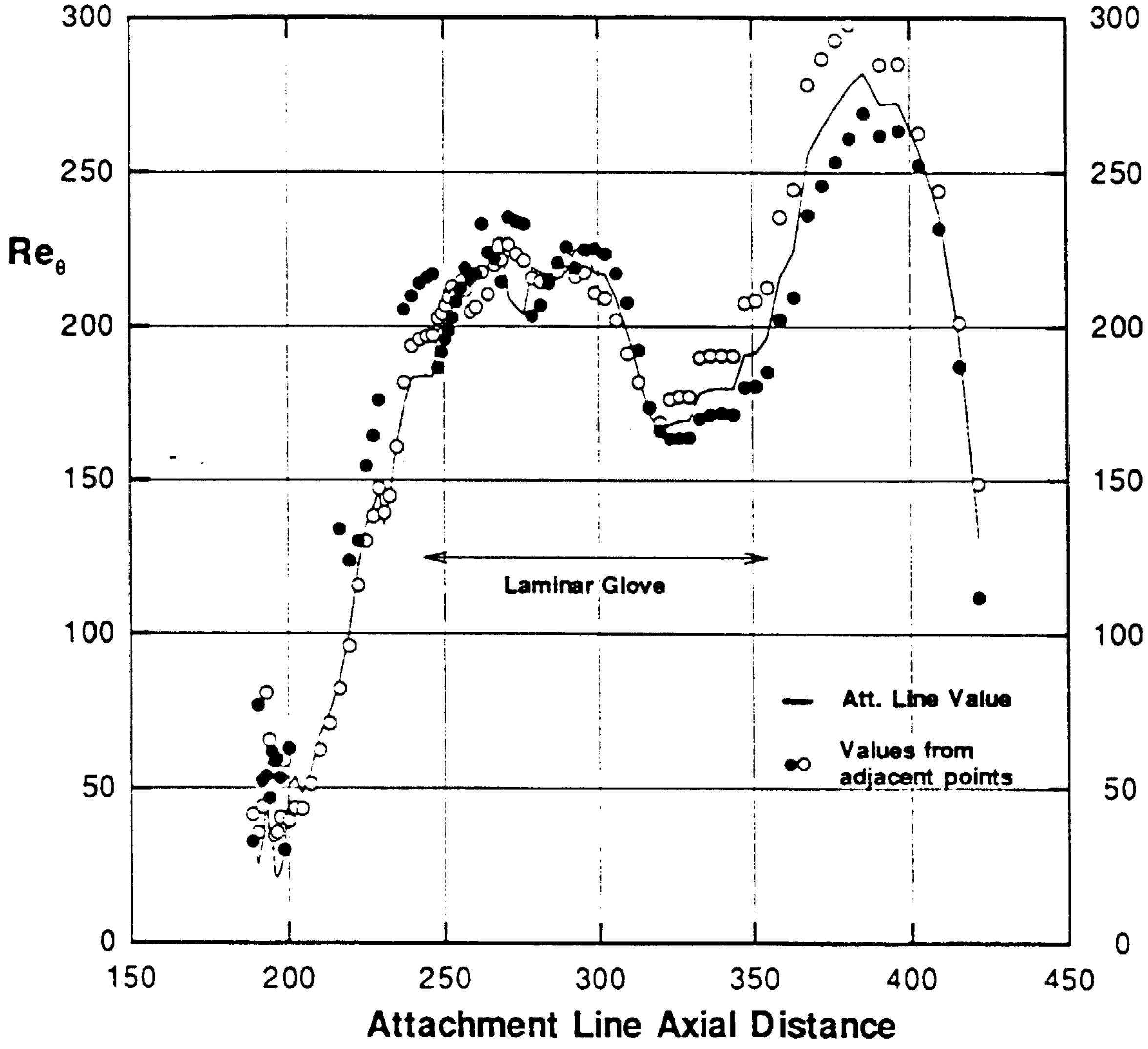
The interface program is useful in looking at boundary-layer type of profiles on the wing. This figure shows the location of the attachment line and the velocity and temperature profiles on the attachment line at three lateral sections of the wing.

F16XL ATTACHMENT LINE PROFILES FROM N-S/COSAL INTERFACE

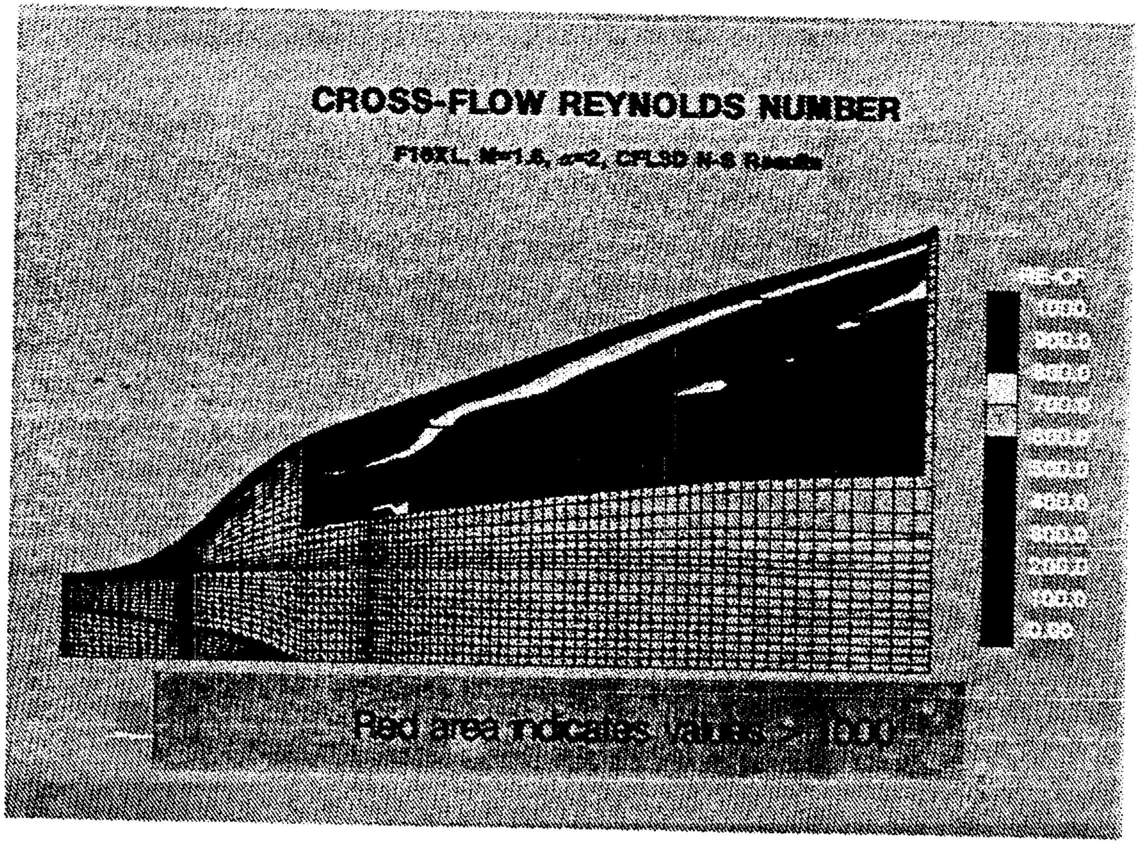


On the issue of attachment line stability, the momentum thickness Reynolds number is an important parameter. This figure shows the variation of Re_θ along the attachment line. There is a correlation of this value with the location of the attachment point relative to the leading edge.

F16XL ATTACHMENT LINE Re_θ VALUES, M=1.6,α=2,h=44,000 ft.



The crossflow Reynolds number based on the maximum crossflow and a length scale based on the crossflow profile is an important indication of crossflow instability. This can calculated from the interface program. The figure shows contours of Re_{CF} on the upper surface of the wing ($M=1.6$, $\alpha=2°$ case) with no suction. Based on a correlation, Re_{CF} of 300 represents the transition location for given freestream conditions.

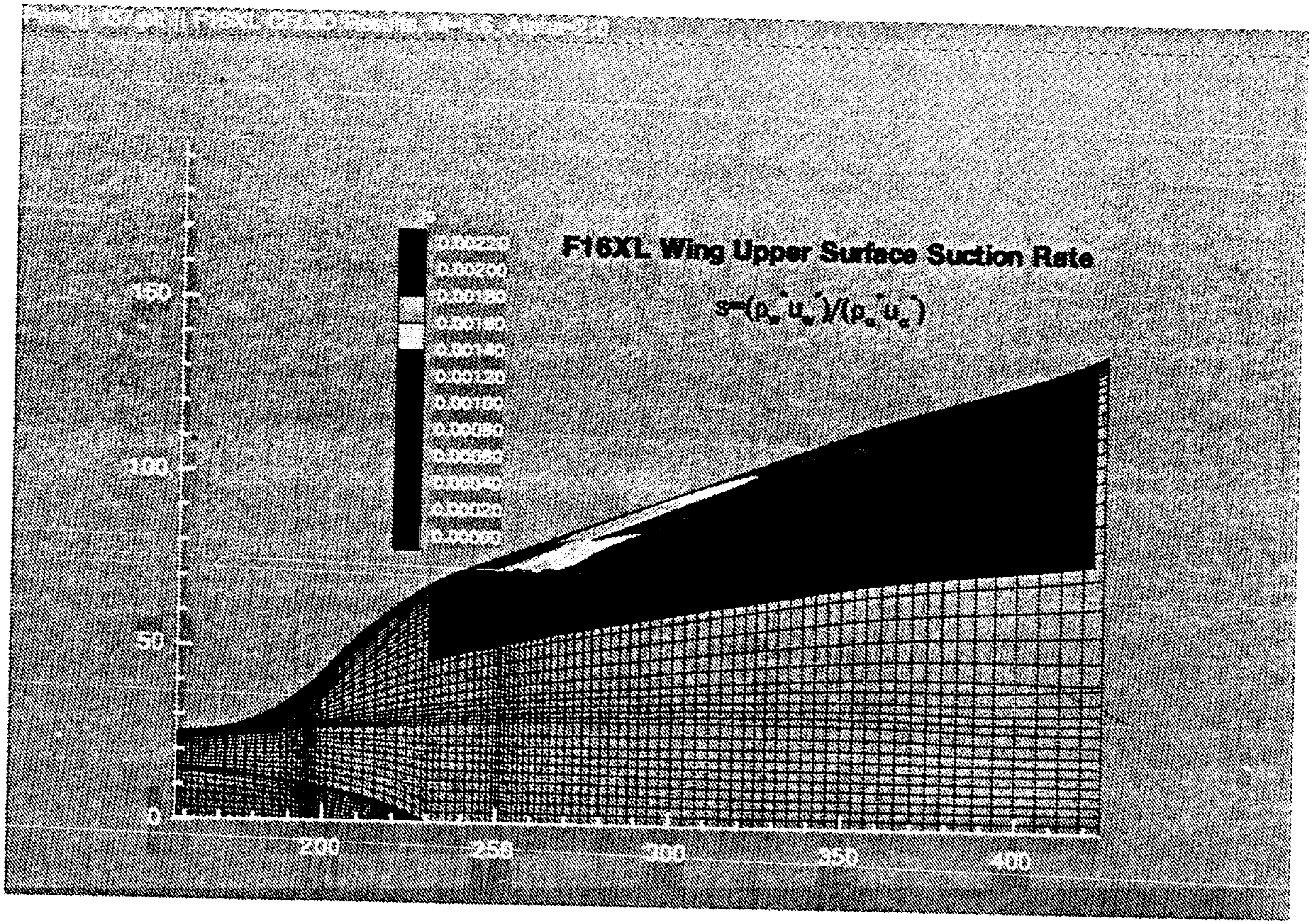


CROSS-FLOW REYNOLDS NUMBER

F16XL, M=1.8, α=2, CFL3D N-S Results

Red area indicates values > 1000

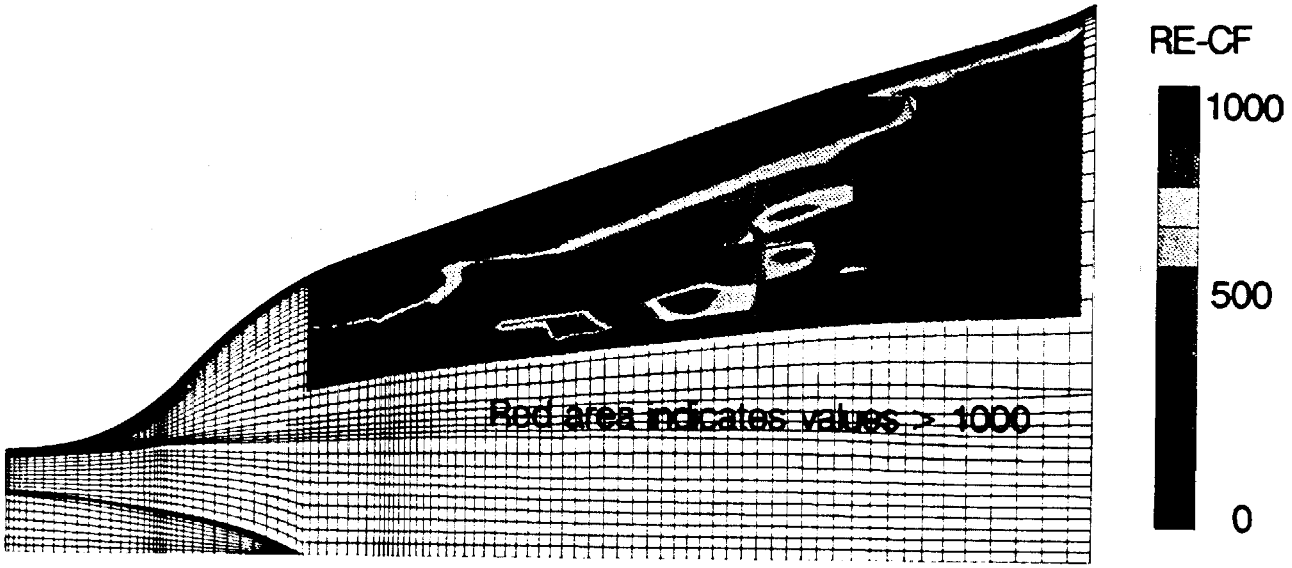
A subsequent calculation was made with suction on the upper surface of the wing. This figure shows the suction rates assumed for the calculation.


F16XL CFL3D Results, M=1.6, Alpha=2.0
F16XL Wing Upper Surface Suction Rate
s=(ρ_w*u_w*)/(ρ_e*u_e*)
s
0.00220
0.00200
0.00180
0.00160
0.00140
0.00120
0.00100
0.00080
0.00060
0.00040
0.00020
0.00000
0
50
100
150
200
250
300
350
400

The crossflow Reynolds numbers resulting from applying suction are shown here. It can be seen that the transition location based on the Re_{CF} correlation is now further downstream. This indicates that stable laminar flow over a larger area of the LFC glove can be achieved with suction. Optimization of suction rates under different flight conditions and validation with flight measurements are ongoing activities.

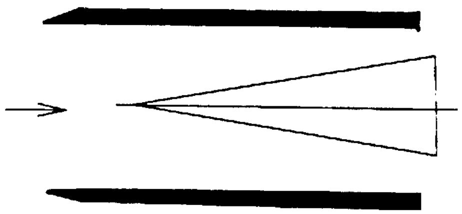
CROSS-FLOW REYNOLDS NUMBER WITH SUCTION ON LFC GLOVE

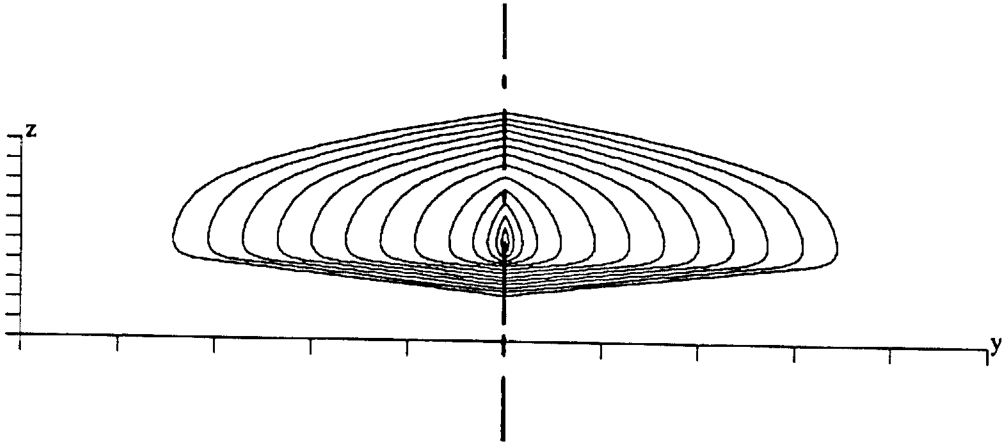
F16XL, M=1.6, α=2, CFL3D N-S Results



The second case corresponds to the flow solution past a highly swept leading edge. Tests are planned in the supersonic low-disturbance tunnel at NASA LaRC at M=3.5 and different freestream conditions. This figure shows lateral sections of this model viewed from upstream.

77.123 deg. Swept LE MODEL
SS LDPT, M=3.5





This is a list of the Euler/N-S calculations on this geometry. More runs will be done during the course of the experiment for validation.

SUPERSONIC SWEPT L.E. CALCULATIONS

Conditions

M = 3.5
p = 39.33 psf
T = 162.3 °R
Re = 2.37 million/ft.

Runs

At α=0.145°:

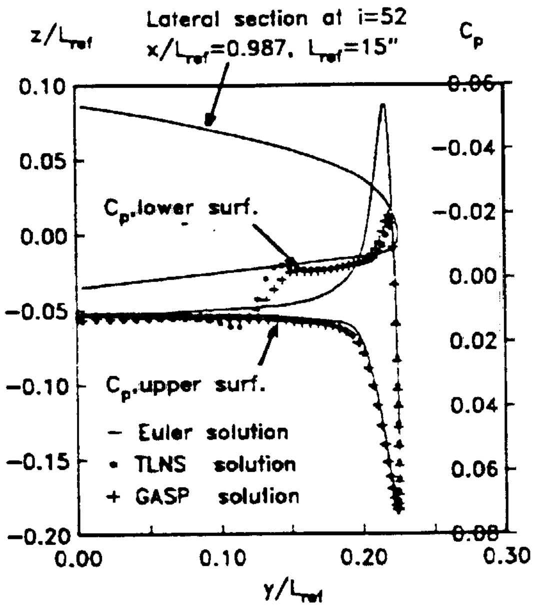
CFL3D Euler Coarse Grid (69x49x37)
TLNS3D Euler Coarse Grid
CFL3D Euler Fine Grid (69x97x37)
CFL3D N-S (69x97x61 grid)
GASP N-S
CFL3D N-S with optimised grid
3D-BL Attachment line Region with Euler Cp

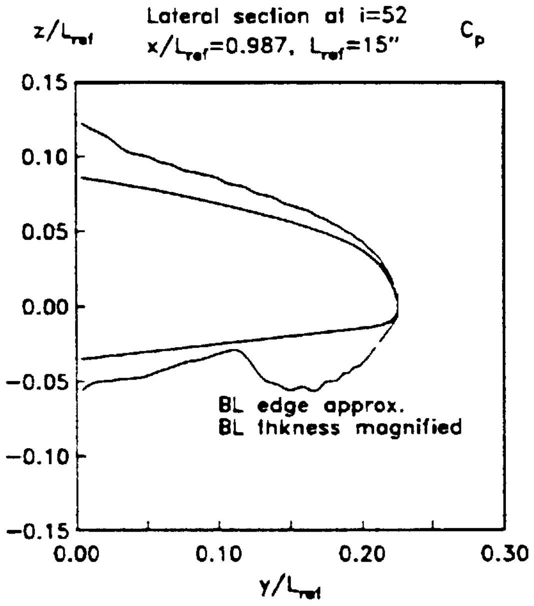
At α=3.0°:

CFL3D N-S

This shows a comparison of the C_p variation between Euler and N-S calculation for α=0.145°. The location is the near the last axial section of the computational grid. The upper surface C_p compares well, however, the lower surface C_p has a smaller peak in the N-S calculation. This has identified as due to cross-flow separation on the lower surface, resulting in larger boundary layer thickness values on the lower surface as shown.

SWEPT WING L.E., Euler/N-S Cp Comparison

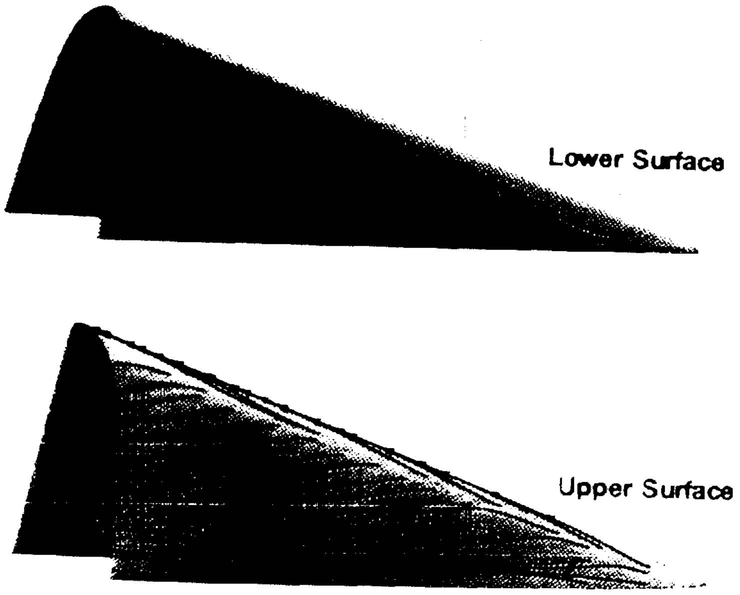




This figure shows limiting streamlines on the upper and lower surfaces of the swept leading edge, showing clearly the reversed crossflow on the lower surface.

Swept Leading Edge (F16XL) Limiting Streamlines

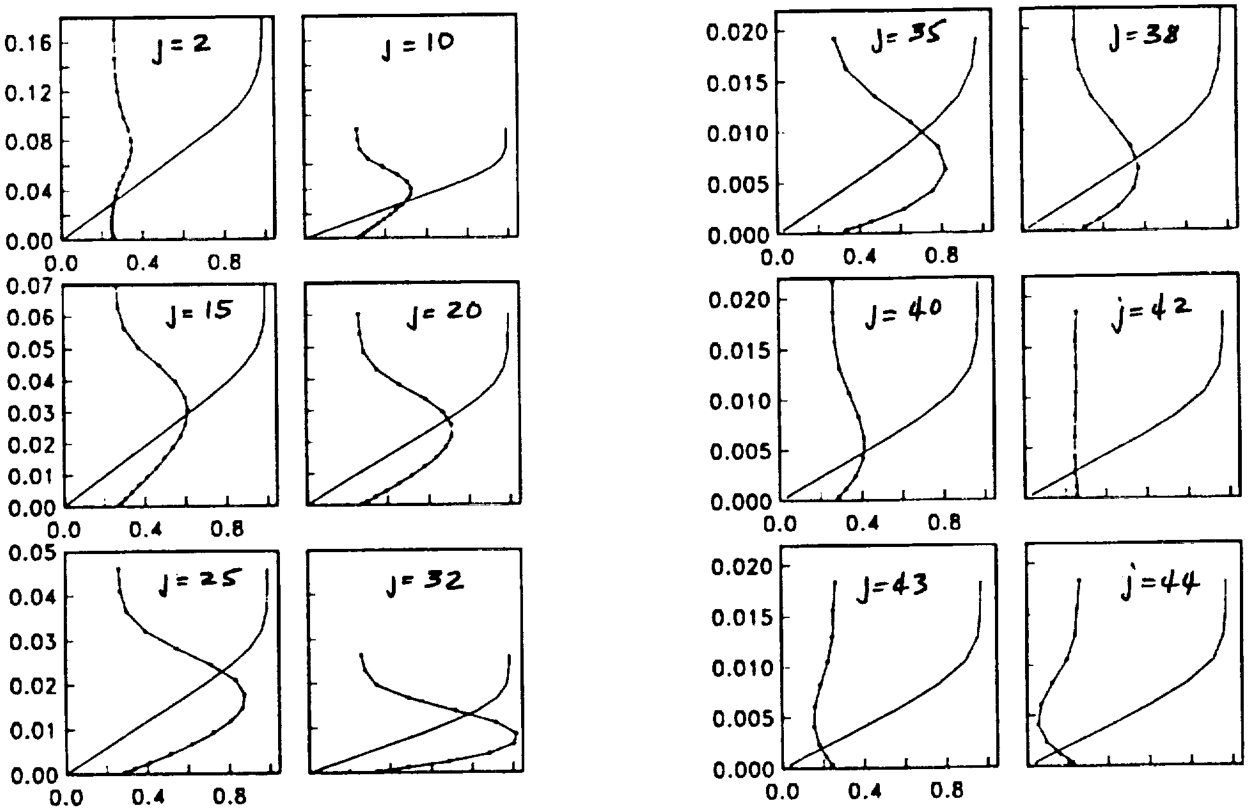
M=3.5, α=0.145, Λ=77.1 deg, TLNS (CFL3D) Results



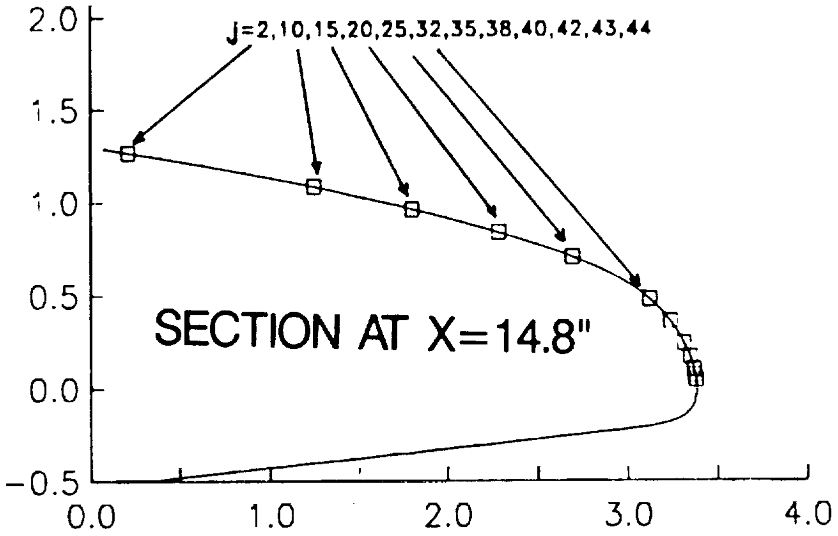
As seen before, the interface program can be used to look at profiles on the body, in streamline oriented coordinates. Shown are the streamwise and crossflow profiles at several locations on the upper surface

The attachment line is at the j=42 location, where the crossflow is nearly zero. Maximum crossflow location is at j=32. However, there are not points within the boundary-layer at all the profile locations, so a grid refinement was done, subsequent to this calculation

Streamwise and Crossflow Profiles

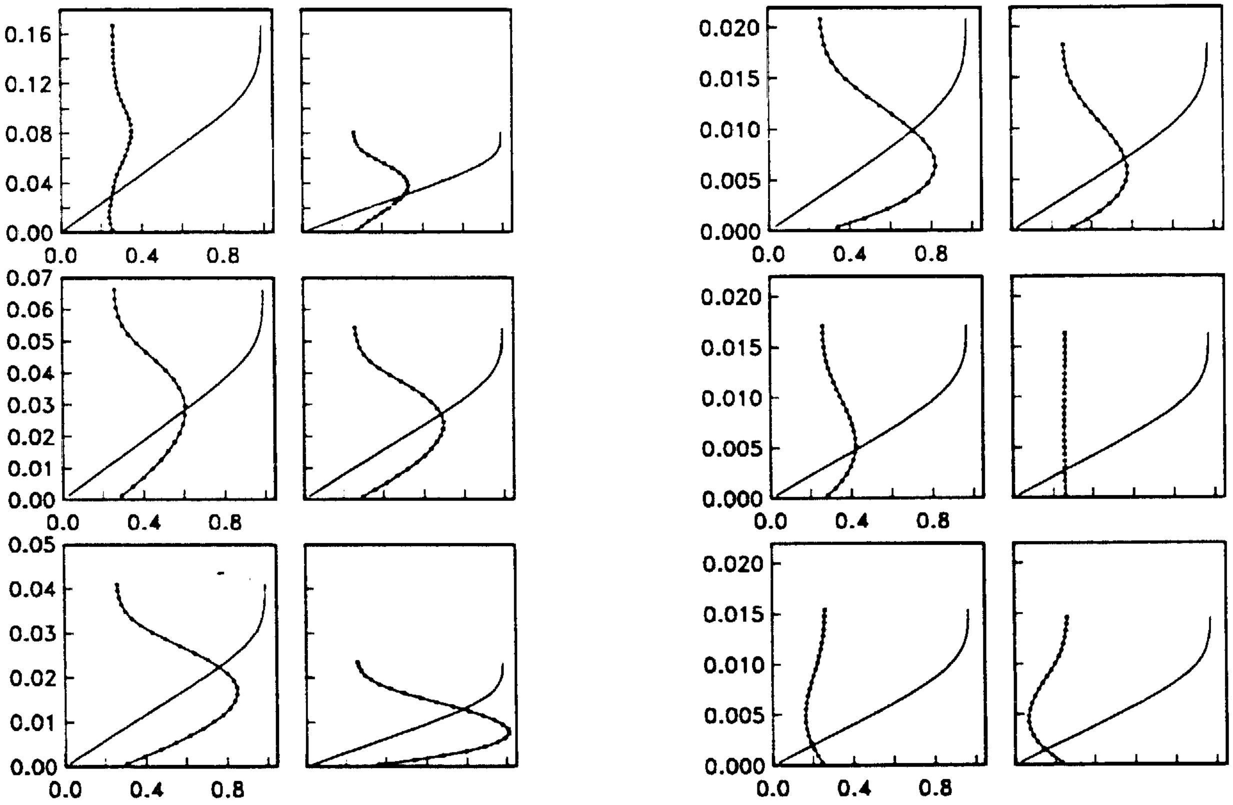


Scales: Us (0.0,1.05) Vs (-0.03,0.09)



Grid refinement was done to have at least 30 points within the boundary layer, a minimum number required for stability analysis. The resulting profiles are much smoother are can be used directly in the stability analysis.

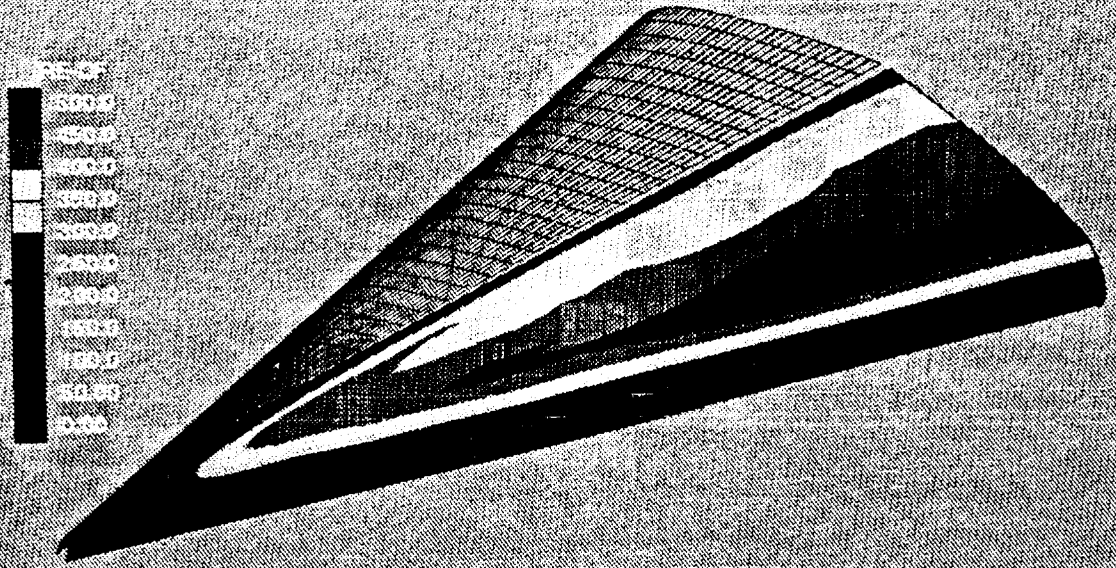
Streamwise and Crossflow Profiles (fine grid)



This figure shows the crossflow Reynolds number on the upper surface for M=3.5 α=0.145° case. Correlation indicates that Re_{CF} of 500 is the limit for crossflow instability. This means that, with experimental conditions in the given range, varying conditions of boundary layer stability can be realized in the experiment.

CROSS-FLOW REYNOLDS NUMBER

Swept L.E. Wing, M=3.5, Alpha=0.145, CFL3D N-S Results



A set of procedures are now in place to obtain accurate meanflow solutions for supersonic boundary-layer stability analysis. Further validation with experimental measurements are planned.

CONCLUDING REMARKS

- Set of procedures now in place to numerically address the issue of transition in supersonic swept wings.

- Coupling of N-S results to linear stability analysis has been done. If grid resolution in B-L is adequate, accurate profiles for stability analysis can be generated.

- For simpler geometries (cone, ellipsoid, Inf. swept wing), 3D-BL solution is a cheaper alternative and has been implemented.

- Future work:

(1) Cross-check mean-flow solution with other codes for F16XL flow (TLNS3D, GASP).

(2) Analysis of stability calculation sensitivity to quality of meanflow solution.

(3) Validation with experiments for different flight conditions.

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