College of Engineering
Kevin T. Crofton Department of Aerospace and Ocean Engineering
Virginia Tech

AOE 4144: Applied CFD

A series of 12 lectures by Prof. Raj (course co-instructor)

Reflections on the Effectiveness of Applied Computational Aerodynamics for Aircraft Design

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Lecture 7

Topic 5: Evolution of Applied Computational Aerodynamics (Part 3 of 5)

List of Topics

Effectiveness Codified: *1980-81*

Miranda, L.R., "Application of computational aerodynamics to airplane design," *AIAA 82-0018,* Jan 1982
(later published in AIAA Journal of Aircraft, 21(6), 1984)

Luis R. Miranda

Manager
Computational Aerodynamics
Lockheed-California Co.

Effectiveness = quality x acceptance

- ***Quality* factor**: accuracy and realism of numerical flow simulation
- ***Acceptance* factor**: applicability, usability, and affordability of selected computational method

"Although this expression [of effectiveness] has no actual quantitative value it serves to emphasize an often overlooked axiom: The impact that a given process has on the activity for which it is intended depends not only on how good the process itself is but also on how widely used or accepted it is."

"Effectiveness of computational aerodynamics in a design environment will depend on the nature of the elements that constitute the computer codes used in a numerical flow simulation."

"If increasing the accuracy of a computational procedure will detract from its ease and economy of use, the implied tradeoff between quality and acceptance should be considered carefully to determine if its effectiveness will actually be enhanced by the increase in accuracy."

Source: Ref. 5.2.1

Lockheed ACA Capability Development

Late 1970s and Early 1980s

- **QUADPAN (Quadrilateral Panel) Linear Potential Method** *(Youngren, Coopersmith, Bouchard and Miranda)*
  - ***Low-order Formulation:*** *As accurate as high-order for subsonic flows at greatly reduced cost*
  - ***Source/doublet Singularities with Dirichlet BC:*** *Essential for robustness*
  - ***Pressure Formula Consistent with Linear Theory:*** *Accurate force calculations*
  - ***Modified Kutta Condition****: For trailing edges with large included angles*

"The Quad Squad"

1. Guppy Youngren **2. Bob Coopersmith**
3. Gene Bouchard **4. Luis Miranda**

- **FLO 22.5: More Effective Nonlinear Full Potential Method** *(Raj & Reaser)*
  - ***More Accurate Geometry Modeling****: Planform-conforming grid for tapered wings*
  - ***Faster Turnaround****: Multi-grid acceleration*
  - ***Simulation Realism****: Fuselage effects; Viscous effects (interactive boundary layer coupling)*
  - ***Supercritical Wing Design****: Garabedian-McFadden wing design technique*
  - ***Documentation:*** *LR 29759; AIAA 83-0262; also Journal of Aircraft, 21(2), 1984*

Key Driver: *Effectiveness (= quality x acceptance)*

Source: Refs. 5.1.22, 5.1.40 to 5.1.42

1981: *A Pivotal Year for Lockheed*

- **December 7, 1981**
  - Lockheed discontinues L-1011 *(after $2.5B loss in 13 years!)*
    - ✓ Concentrate instead on defense opportunities expected under Reagan military buildup

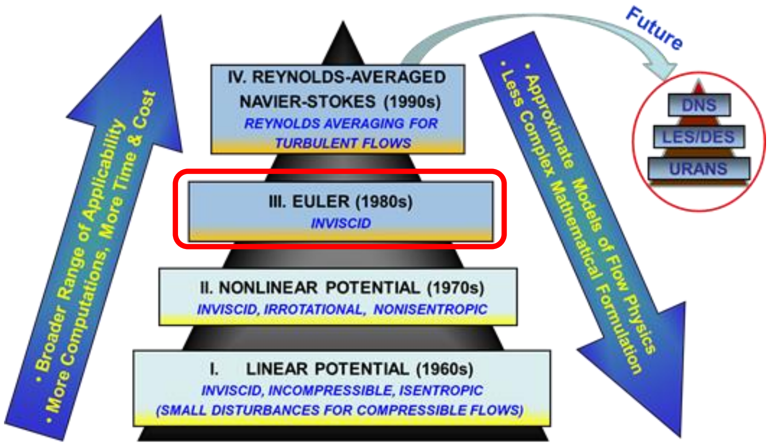
- **November 1981**
  - Department of Defense approves Milestone 0 for **Advanced Tactical Fighter (ATF)**—*a new air superiority fighter* (to replace F-15)
  - **Fighter aerodynamics dominated by <u>strong shocks</u> and <u>free-vortex flows</u>**

Computational simulation of flows with strong shocks and free vortices falls outside the range of validity of linear and nonlinear potential methods

ATF Provides Impetus for Exploring Euler Methods

Image Source: Internet

Level III
Euler Methods
1980s - present



Flow Model

- **Inviscid,** ~~Irrotational, Isentropic~~

$$Q_t + F_x + G_y + H_z = 0$$

$$Q = (\rho, \rho u, \rho v, \rho w, \rho E)$$

✓ System of nonlinear 1st order PDEs with appropriate boundary conditions

Applicability

- All Mach numbers and attitude angles
- Flow may have shocks and free vortices as long as it's not dominated by boundary-layer separation

Euler Solver:

One of the Four Major Developments of the Eighties

VIDEO CASSETTE RECORDER

COMPACT DISK PLAYER

EULER SOLVER

гла́сность

Source: Bram van Leer presentation at one of the AIAA Aerospace Sciences Meeting in Reno, NV, in the late 1980s

Bram van Leer

Professor Emeritus
University of Michigan
Major contributions to CFD, Fluid Dynamics and Numerical Analysis

1980s: 'Golden Era' of Euler Methods

Image Source: Internet

A *Small* Sample of Euler Solvers: *1980s*

- **Rizzi and Eriksson (1981): *Pioneering Solutions for External Flows***
  - *Grid generation*: Transfinite interpolation for 3-D boundary–conforming structured grids on wings or wing-bodies; O-O and C-O topologies most efficient
  - *Euler solver*: Finite-volume formulation; explicit pseudo time-marching scheme; nonreflecting boundary conditions; damping filter to improve convergence—***AIAA Paper 81-0999***
  - Shocks and wakes automatically “captured”; no explicit imposition of Kutta condition as long as the trailing edge was sharp
- **Jameson, Schmidt, and Turkel (1981): *Efficient Euler Solver***
  - *Strategy:* Finite-volume formulation decouples solver and grid; structured C and O meshes
  - *Features:* Cell-centered spatial discretization; a blend of second- and fourth-differences for numerical dissipation with pressure gradient sensor; convergence acceleration to steady state using multi-stage pseudo-time stepping procedure—***AIAA Paper 81-1259***
- **Usab and Murman (1983): *Framework for Complex Geometries***
  - Embedded mesh solutions on airfoils using a multiple-grid method—***AIAA Paper 83-1946***
- **Benek, Buning and Steger (1985): *Solutions on Complex Configurations***
  - A 3-D Chimera grid embedding scheme [hexahedral grids]—***AIAA Paper 85-1523***
- **Löhner, Morgan, Peraire and Zienkiewicz (1985): *Unstructured Grids***
  - Finite-element methods for high speed flows [tetrahedral grids]—***AIAA Paper 85-1531***
- **Jameson, Baker and Weatherill (1986): *Transonic Flow Over B747-200***
  - Inviscid Transonic Flow over a Complete Aircraft [tetrahedral grids]—***AIAA Paper 86-0103***
- **Mavriplis (1988): *Accurate & Efficient Flow Simulations***
  - Accurate multigrid solutions on unstructured and adaptive meshes—***NASA CR 181679***

Source: Refs. 5.2.2 – 5.2.9

Lockheed Focus in the 1980s:

Develop Full Aircraft Euler Analysis to Meet ATF Needs

1981

- Jameson creates **FLO 57** code for swept wings (using JST scheme in AIAA 81-1259)
- Finite volume formulation decouples solver and grid
- ***Shocks and wakes "automatically captured"*** without explicit imposition of Kutta condition as long as the trailing edge is sharp

1982

- Lockheed initiates **FLO 57GWB** development *(PI: Raj)* by extending FLO-57 swept wing code to generalized wing-body configurations *[FLO 57 source code courtesy of R.M. Hicks, NASA-Ames]*
- **Alan Brown**, F-117A Program Manager and Chief Engineer, recommends research in free-vortex interaction with vertical tails!

1984

- Lockheed wins USAF Wright Research & Development Center (WRDC) solicitation for
  Three-dimensional Euler Aerodynamic Method (TEAM)
- **Antony Jameson** visits Lockheed! *A fascinating individual with singular intellect!*

1987

- USAF amends contract scope and extends period of performance
  Three-dimensional Euler/Navier-Stokes Aerodynamic Method (TEAM)

1989

- ***USAF contract successfully completed; work documented in three USAF reports***

Source: Refs. 5.2.10 – 5.2.15

USAF/Lockheed TEAM Code

Full Aircraft Computational Aerodynamic Simulation Capability (1984-1989)

Contract Requirements

- *Geometries:* Aerodynamic analysis of fighter, transport, and flight research configurations with multiple lifting surfaces and flow-through or powered nacelles
- *Flow Conditions:* Symmetric or asymmetric flights at subsonic through hypersonic speeds for wide range of attitude angles
- *Output:* Forces, moments, surface and off-body pressures, velocities, etc.
- *Validation*: Demonstration of predictive capability using 10 test cases

Lockheed Team

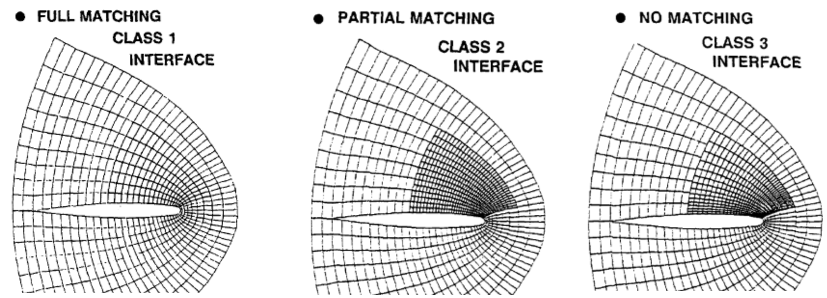
- Raj (Principal Investigator) with Brennan, Keen, Long, Mani, Olling, Sikora, and Singer contributing over five years under Miranda's leadership and supervision

USAF WRDC* Monitors

- Jobe, Sirbaugh, Jochum, Witzeman, Sedlock, Kinsey

Strategy for Effectiveness

- **Modular Computational System:** (i) Pre-processor; (ii) Grid Generator; (iii) Euler Solver; and (iv) Post-processor—*easier to incorporate technology advances*
- **Patched Zonal Hexahedral Grids:** multiple topologies, grid generator of user's choice—*facilitates analysis of complex configurations*



- **Spatial Discretization:** FLO-57 finite-volume formulation, cell-centered scheme with
  - JST adaptive dissipation—*balanced accuracy and robustness*
  - Characteristics-based—*increased robustness for hypersonic flows*
- **Time Discretization:** multistage pseudo-time stepping to steady state—*faster turnaround*

USAF WRDC & Lockheed Lead the Way

*Wright Research & Development Center, U.S. Air Force

Source: Refs. 5.2.13 – 5.2.15

TEAM (Euler) Validation

1985-1988

- **NLR 7301 airfoil – Transonic Flow (2D)**
- **Wing/Body/Canard configuration – Subsonic & Transonic Flows (3D)**
  - *Subsonic (M = 0.6) and Transonic (M = 0.9)*
- **Three Internal Flow Test Cases – Subsonic & Supersonic Flow**
  - *Axisymmetric Diverging Nozzle*
  - *1-D Inlet Duct Hammershock*
  - *External Compression Mach 2.5 Axisymmetric Inlet*
- ***Cone-derived Waverider* – Hypersonic Flow**
- **Four Free-Vortex Flow Test Cases – Subsonic and Transonic Flow**
  - *Sharp-edged Cropped Delta Wing*
  - *Arrow Wing*
  - *Strake-Wing Body configuration*
  - *Double-Delta Wing Body configuration*

Improved Understanding of Predictive Capabilities and Shortcomings

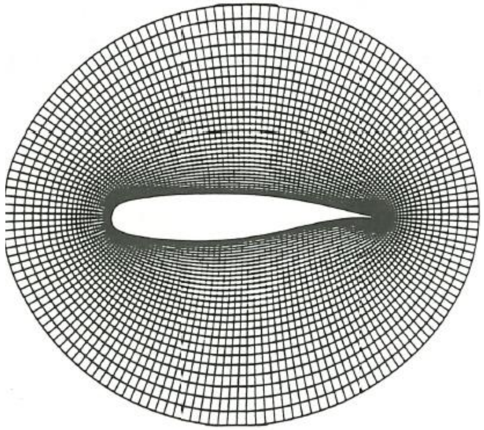
COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

TEAM (Euler) Validation

NLR 7301 Airfoil – *Transonic Flow (2D)*

Comparison with exact shock-free hodograph solution

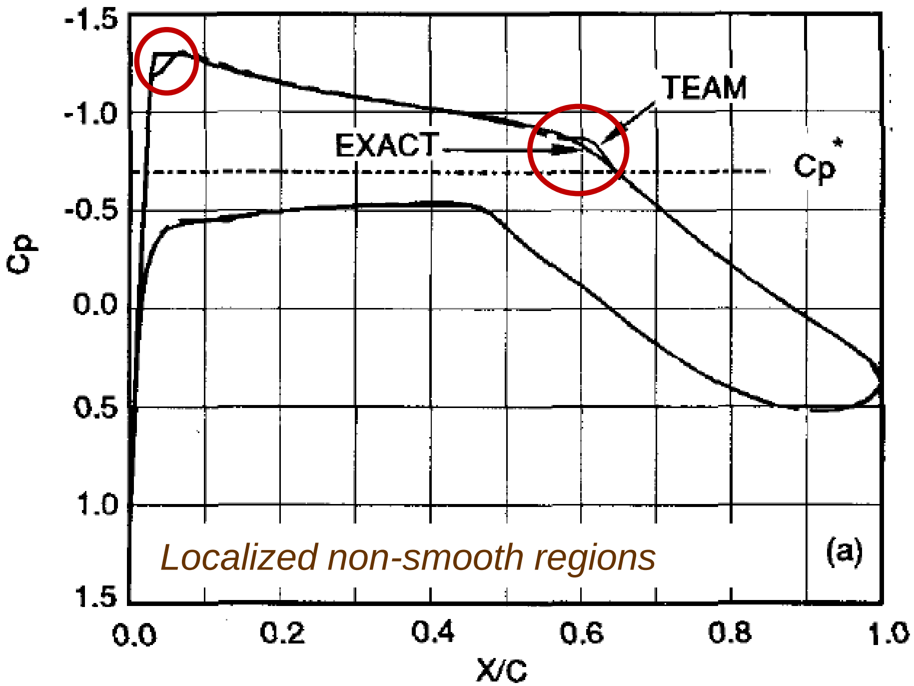
$M_\infty = 0.721$, $\alpha = -0.194^o$



321 x 321 O Grid

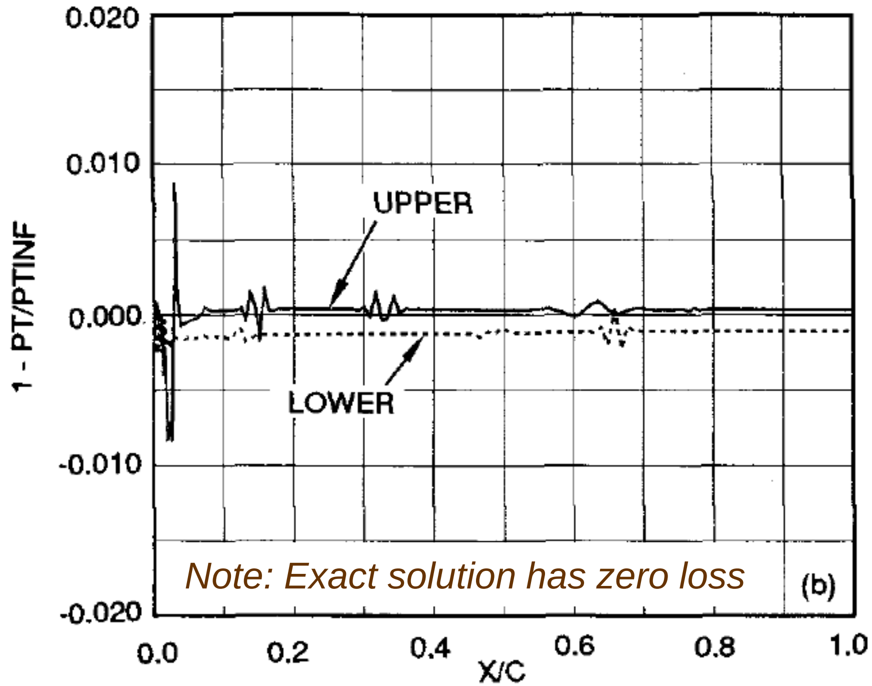
Far-field boundary 80 chords away

Surface pressure distribution



Localized non-smooth regions

Surface total pressure loss distribution



Note: Exact solution has zero loss

Source: Ref. 5.2.16 & 5.2.36

TEAM (Euler) Validation

NLR 7301 Airfoil – *Transonic Flow (2D)*

$M_\infty = 0.721$, $\alpha = -0.194^o$ **Shock-free "exact" solution:** $C_l = 0.5939$, $C_d = 0.0$

Sensitivity of Euler Solutions to Grid Density and Numerical Dissipation

- **Grid density (O grids)**
  - Far-field boundary 80 chords away to avoid using far-field vortex correction
  - Non-smooth C_p distribution near the leading edge on the upper surface most likely due to small 'non-smooth' region of the airfoil geometry defined by a discrete set of points
  - Computed solutions exhibit "wiggle" in transition from supersonic to subsonic flow
    - Wiggle amplitude *increases* as number of grid points around the circumference increase from 161 to 241 to 321 with grid points in radial direction (between surface and far-field boundary) fixed at 49
    - Wiggle amplitude *decreases* as grid density changes from 33x241 to 49x241 to 65x241 to 81x241
  - Exact shock-free solution should have zero drag; but numerical integration of discretized surface pressures (of "exact" hodograph solution) gives C_d of 0.0005 (and C_l of 0.5949)!
- **Sensitivity of computed drag coefficient to numerical dissipation and grid density**

Numerical Dissipation Scheme ⇩ / Grid Density ⇨	321 x 49	321 x 81	321 x 161	321 x 321
Standard Adaptive Dissipation (SAD)	0.000577	0.000294	0.00025	0.00027
Modified Adaptive Dissipation (MAD-1)	0.000464	0.000282	0.000241	0.000241
Modified Adaptive Dissipation (MAD-2)	0.000354	0.000245	0.000206	0.000207
Flux-limited Adaptive Dissipation (FAD)	0.000804	0.000505	0.000394	0.000367

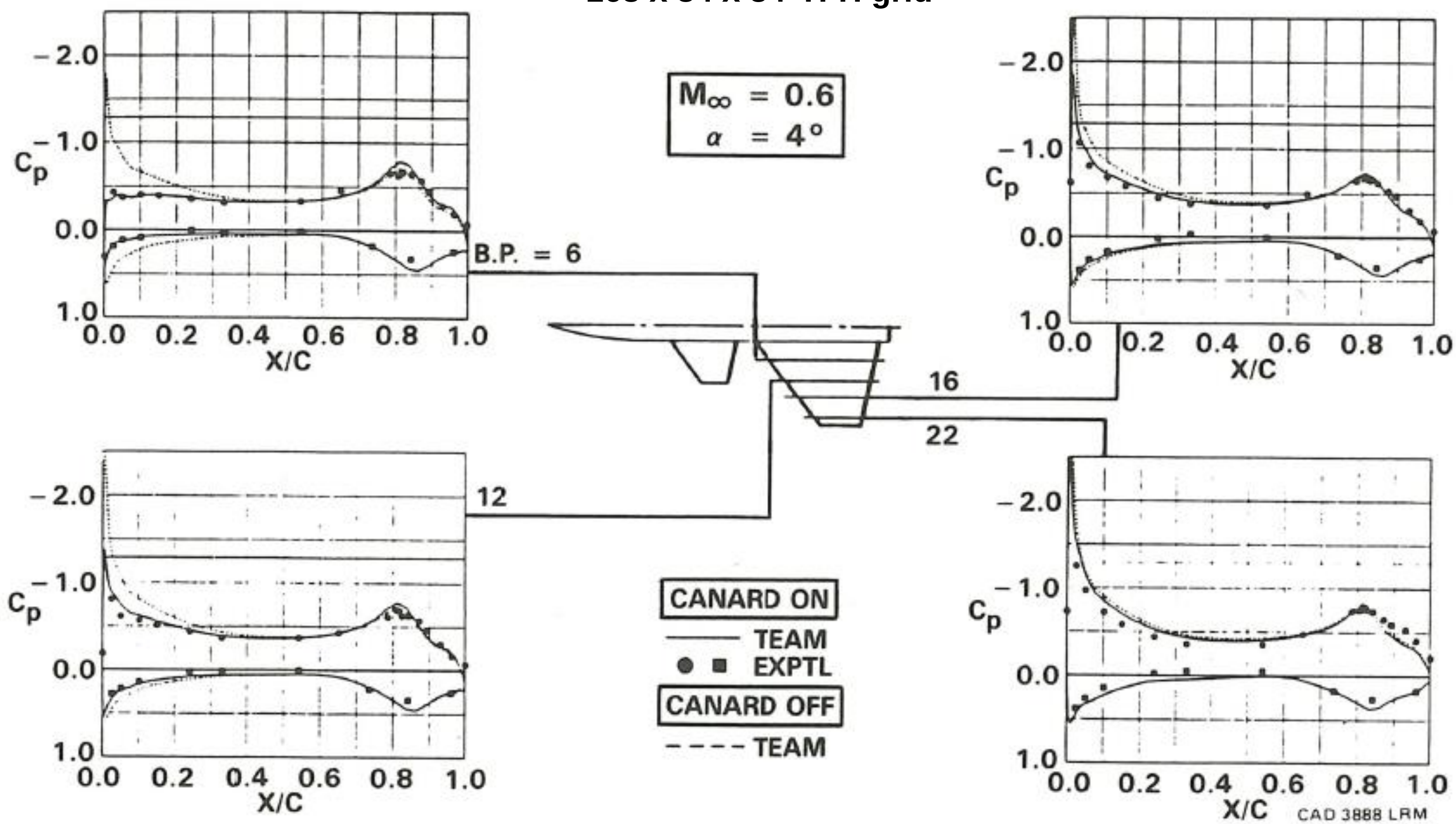
Source: Ref. 5.2.16 & 5.2.36

Team (Euler) Validation

Canard-Wing-Body Configuration – *Subsonic Flow (3D)*

Canard-Wing Interaction Effect

168 x 84 x 34 H-H grid



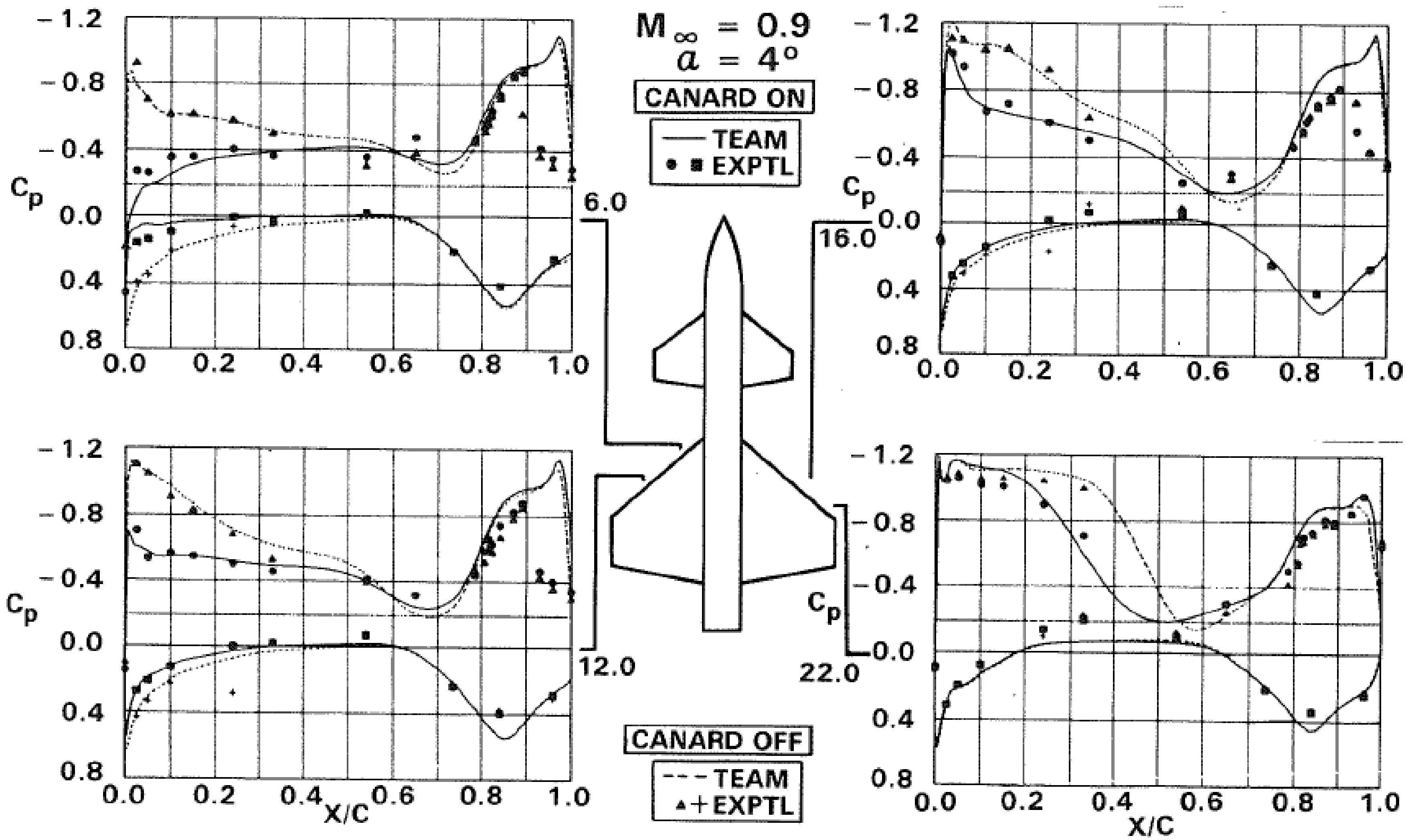
Source: Ref. 5.2.13 & 5.2.16

Team (Euler) Validation

Canard-Wing-Body Configuration – *Transonic Flow (3D)*

Canard-Wing Interaction Effect

168 x 84 x 34 H-H grid



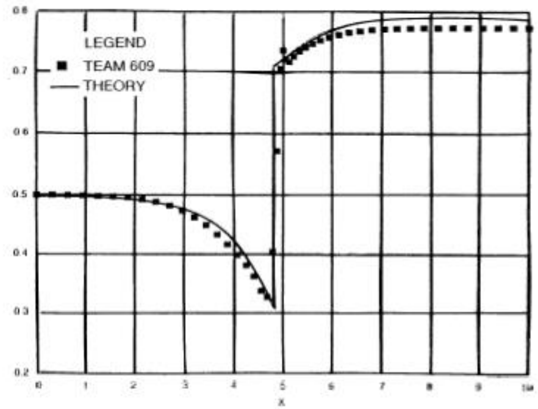
Source: Ref. 5.2.13 & 5.2.16

TEAM (Euler) Validation
Internal Flow – Three Test Cases

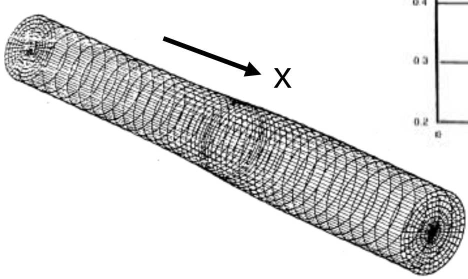
A. Axisymmetric Diverging Nozzle

$a(x) = 1.398 + 0.347\tanh(0.8x - 4) \quad \text{for } 0 < x < 10$

Density



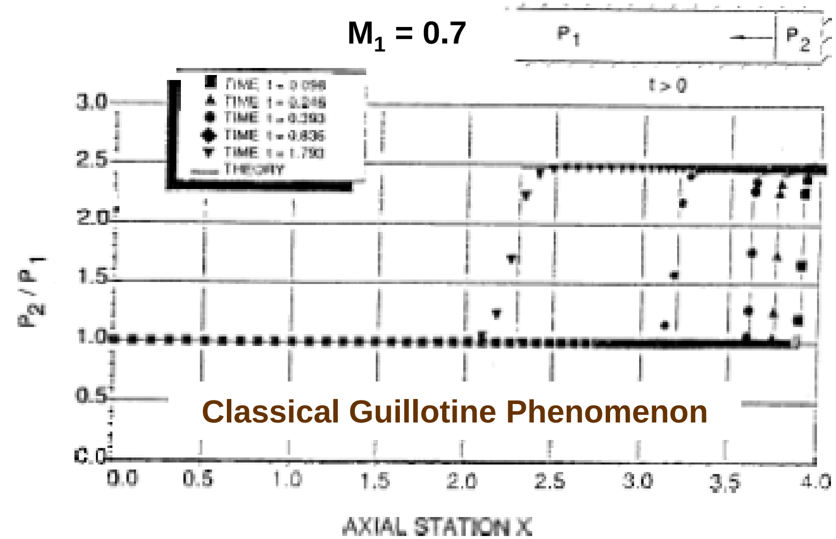
$M_\infty = 1.26$



Axial Station X

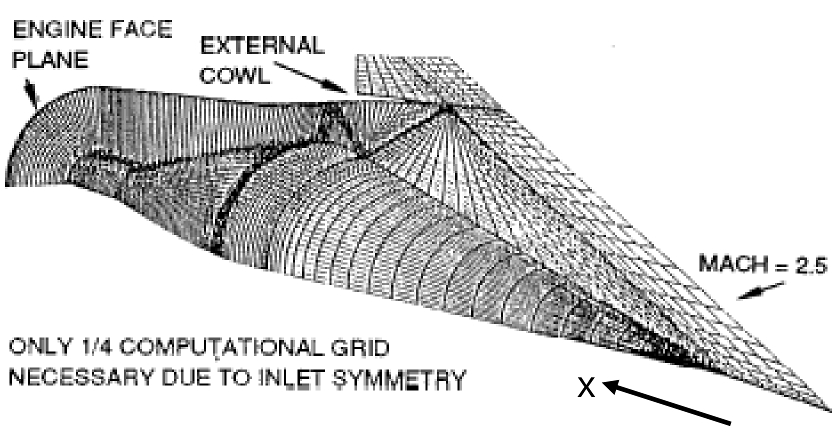
B. 1-D Inlet Duct Hammershock

$M_1 = 0.7$

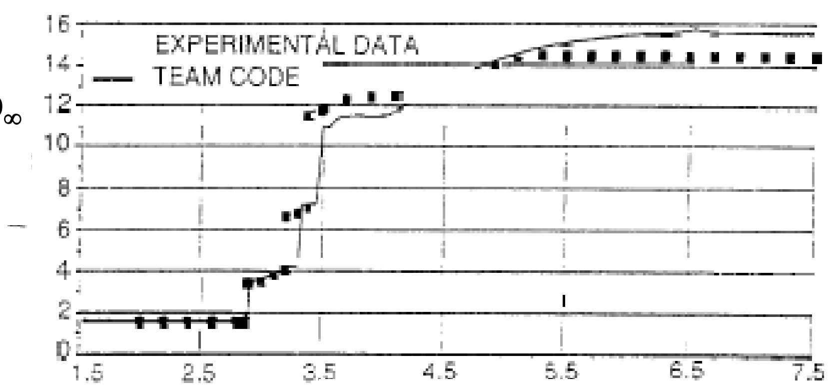


Classical Guillotine Phenomenon

C. External Compression Mach 2.5 Axisymmetric Inlet



p/p_∞

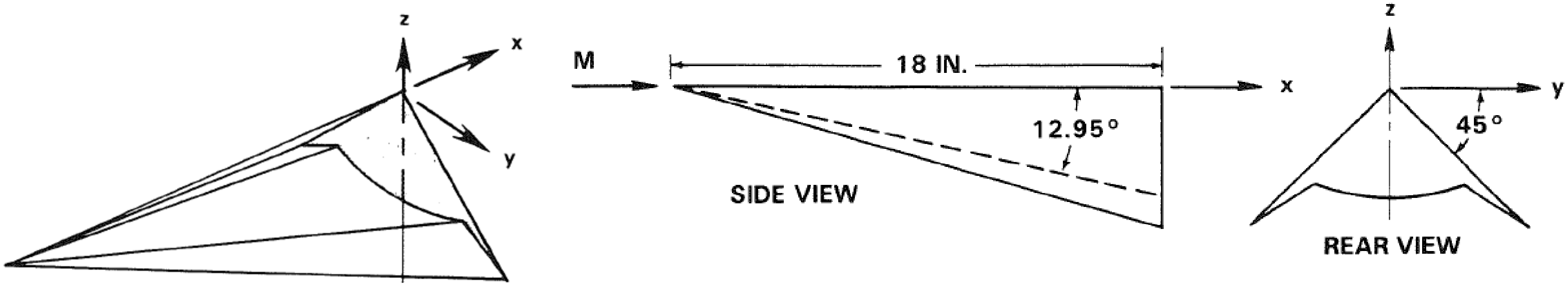


Axial Station x/h_{cowl}

Source: Ref. 5.2.17

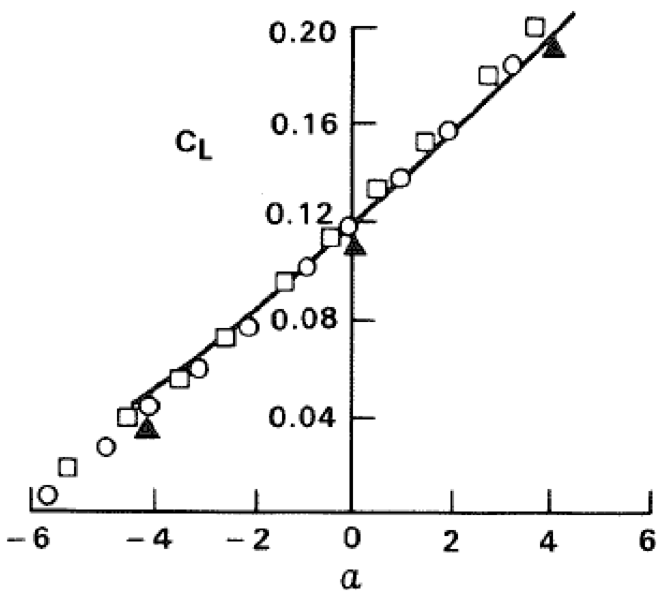
TEAM (Euler) Validation

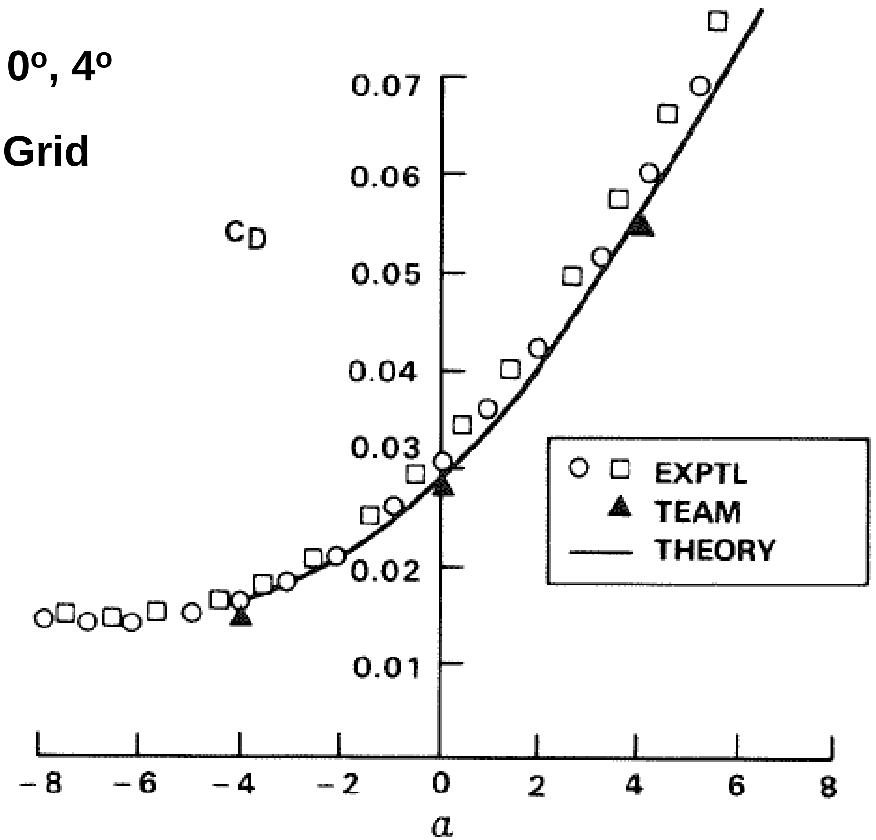
Cone-derived Mach 6 Waverider – *Hypersonic Flow*



M_∞ = 6, α = −4°, 0°, 4°

45 x 30 x 39 O-H Grid





Source: Ref. 5.2.13 & 5.2.16

Lecture 7: Key Takeaways

- **CFD in the 1980s: *Golden era of Euler methods!***
  - **Rapid progress characterized by advances in**
    - **Pre-processing**—*extract "watertight" surface geometry from CAD or other sources*
    - **Grid generation**—*discretize computational domain*
      - ✓ many new methods for structured hexahedral and unstructured tetrahedral grids
    - **Euler solver**—*solve unsteady form of Euler equations using the following algorithmic features*
      - ✓ Finite volume or finite element formulations
      - ✓ Node centered or cell-centered schemes
      - ✓ Central difference with explicitly added numerical dissipation or Upwind difference with implicit dissipation
      - ✓ Pseudo-time marching and multigrid for accelerated convergence to steady state
    - **Post-processing**—*plot forces, moments, surface pressures and flow field data*
- **Lockheed Focus: *Full Aircraft Euler Analysis* to Meet Advanced Tactical Fighter (ATF) Needs**
  - Development of **TEAM** code (**T**hree-dimensional **E**uler/Navier-Stokes **A**erodynamic **M**ethod) under a USAF contract managed by WRDC (Wright Research & Development Center)
  - Strategy for **Effectiveness**
    - ✓ Modular Computational System—*ease of incorporating technology advances*
    - ✓ Patched Zonal Hexahedral Grids—*analysis of complete aircraft*
    - ✓ Solver based on Jameson's FLO-57 code—*robust and economical method*
      - finite-volume formulation, cell-centered scheme
      - central differences with JST adaptive dissipation
      - Multistage pseudo time stepping to steady state
- **TEAM Validation: *Demonstration of Predictive Capability* Using Select Test Cases**

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5. Evolution of Applied Computational Aerodynamics *(1950-2000)*

5.2 Pursuit of Effectiveness (1980–2000)

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5.2.13 Raj, P, Olling, C.R., Sikora, J.S., Keen, J.M., Singer, S.W., and Brennan, J.E., “Three-dimensional Euler/Navier-Stokes Aerodynamic Method (TEAM), Volume I: Computational Method and Verification,” AFWAL-TR-87-3074, June 1989 (*supersedes December 1987 release*).

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Back-up Slides

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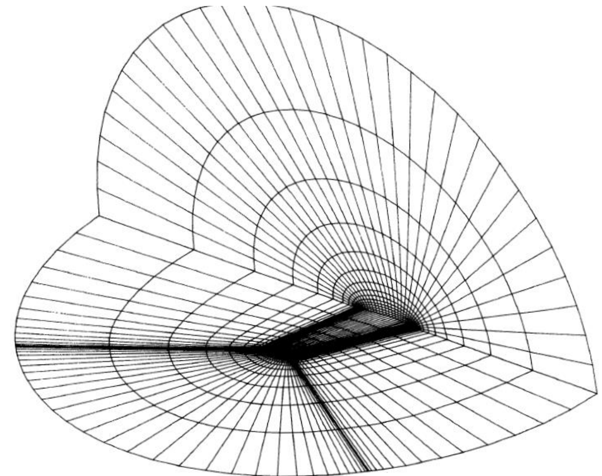
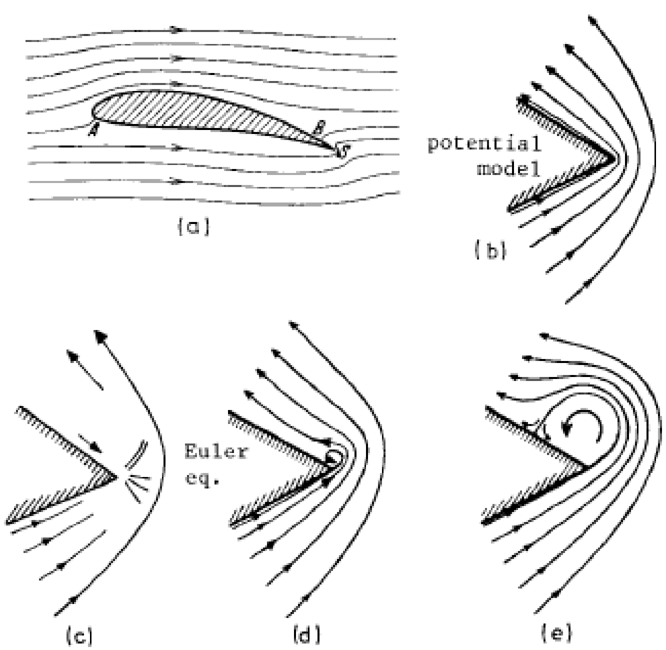
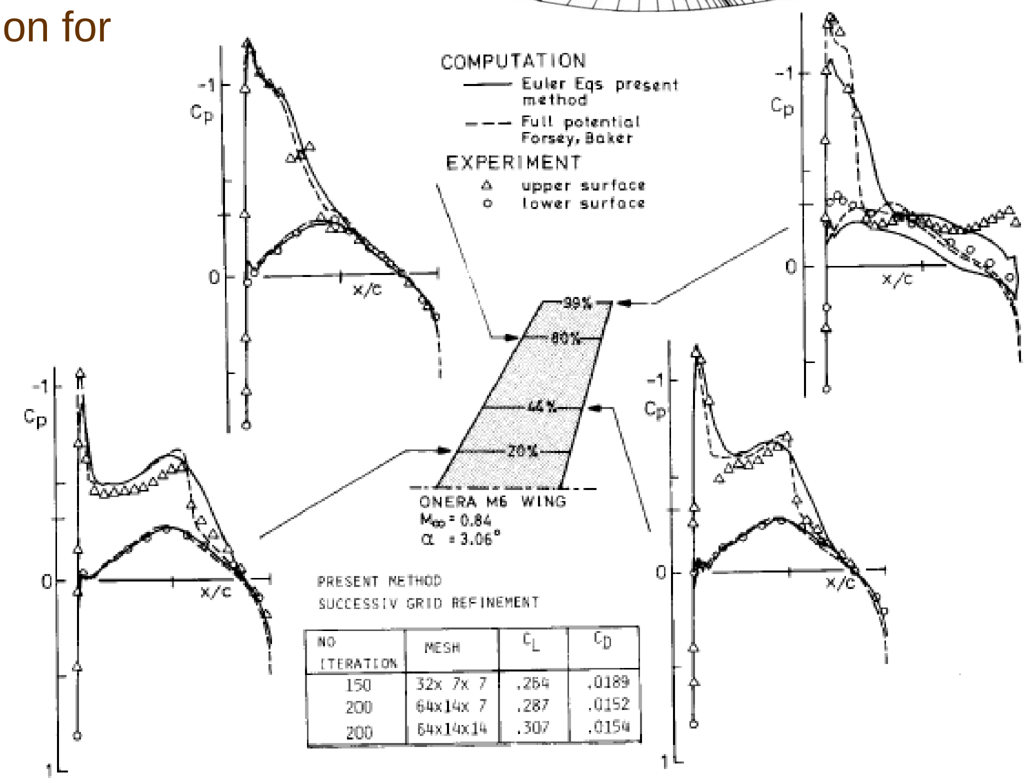
Pioneering Euler Solutions: *1981*

Rizzi and Eriksson (1981)

- *Grid generation*: Transfinite interpolation for 3-D boundary–conforming hexahedral grids on wings or wing-bodies; O-O and C-O topologies most efficient
- *Euler solver*: Explicit pseudo time-marching scheme; nonreflecting boundary conditions; damping filter to improve convergence—***AIAA Paper 81-0999***
- Shocks and wakes automatically “captured”; no explicit imposition of Kutta condition for sharp trailing edge





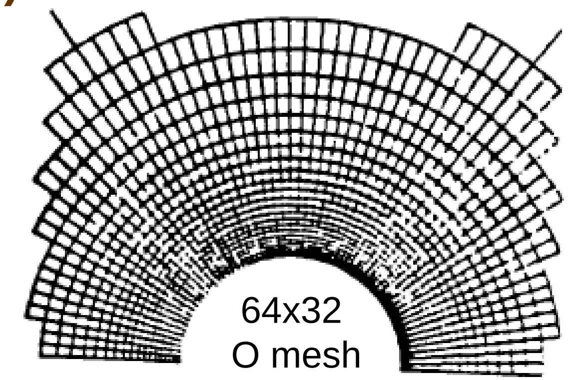


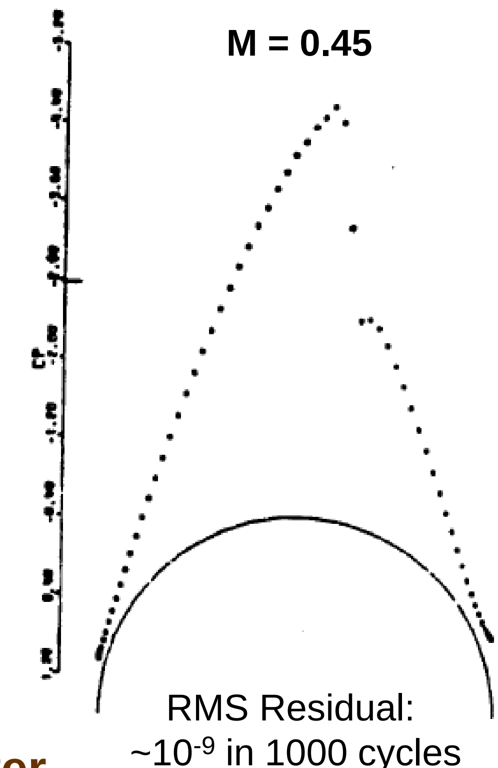
NO ITERATION	MESH	C_L	C_D
150	32x 7x 7	.264	.0189
200	64x14x 7	.287	.0152
200	64x14x14	.307	.0154

Source: Refs. 5.2.2

Efficient Euler Solver: *1981*

- **Jameson, Schmidt, and Turkel (AIAA Paper 81-1259)**
  - Purpose: *develop economical methods!*
  - Finite volume formulation decouples solver and grid
  - Investigation of alternative **2-D** schemes to answer four questions:
    1. ***What is the most efficient time stepping scheme?***
       - Fourth order Runge-Kutta time stepping scheme
    2. ***What is the optimal form of the dissipative terms?***
       - Adaptive blend of second and fourth differences with local pressure gradient sensor (*JST scheme*)
    3. ***What is the best way to treat the boundary conditions on the body surface and in the far field?***
       - Appropriate characteristic combinations of variables
    4. ***How can convergence to a steady state be accelerated?***
       - Variable time step at the maximum limit set by the local Courant number: $\sum(u_i \Delta t/\Delta x_i) \leq C_{max}$
       - Add a forcing term based on the difference between the local total enthalpy and its free stream value (*energy equation must be integrated in time, and not eliminated in favor of the steady state condition that the total enthalpy is constant*)
- **Jameson's FLO-57 (swept wings) followed soon after**



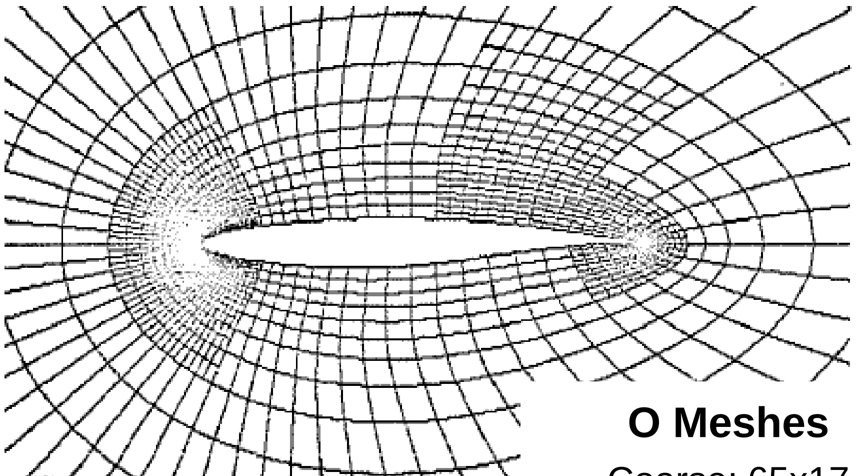


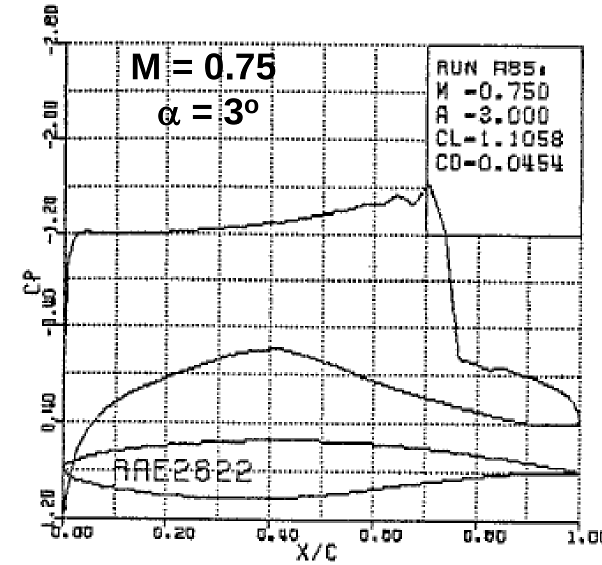
Source: Ref. 5.2.3

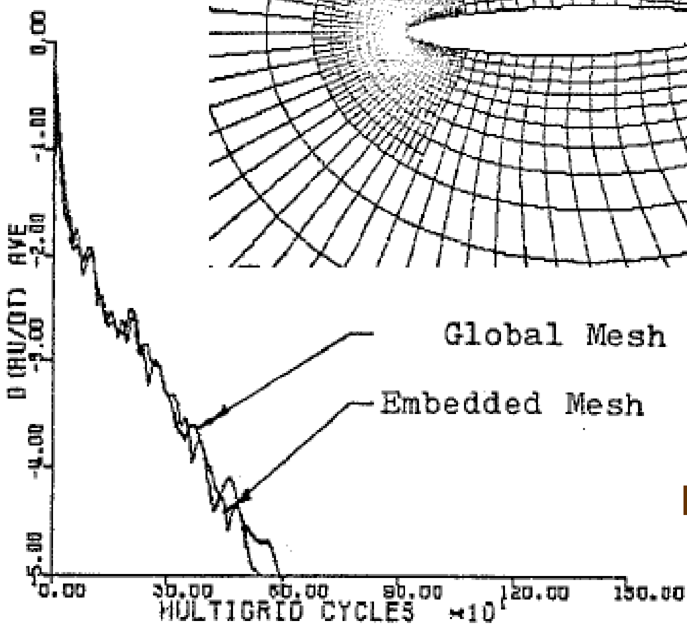
Towards Euler Solutions on Complex Geometries: *1983-84*

- **Usab and Murman (1983)**
  - Embedded Mesh Solutions Of The Euler Equation Using A Multiple-grid Method—***AIAA Paper 83-1946***

RAE 2822 Airfoil



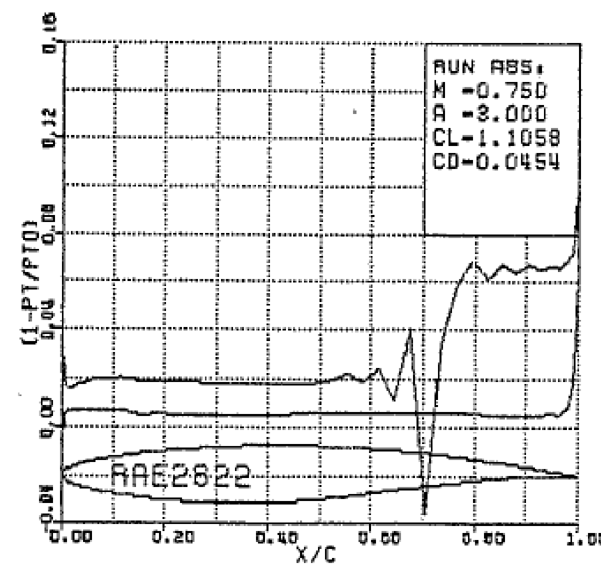




O Meshes

Coarse: 65x17

Global Fine: 129x33



Improved Accuracy for Comparable Work (Multi-grid Cycles)

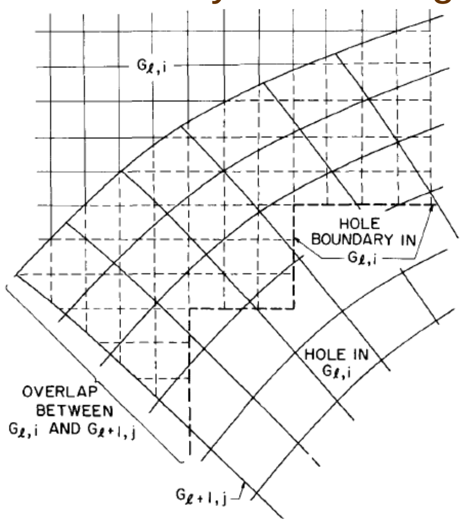
- **Jameson and Baker (1984)**
  - Multigrid solution for aircraft configurations—***AIAA Paper 84-0093***

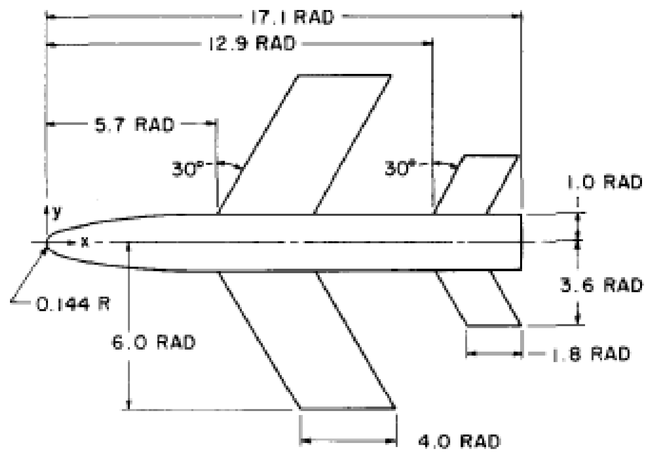
Source: Refs. 5.2.4 & 5.2.5

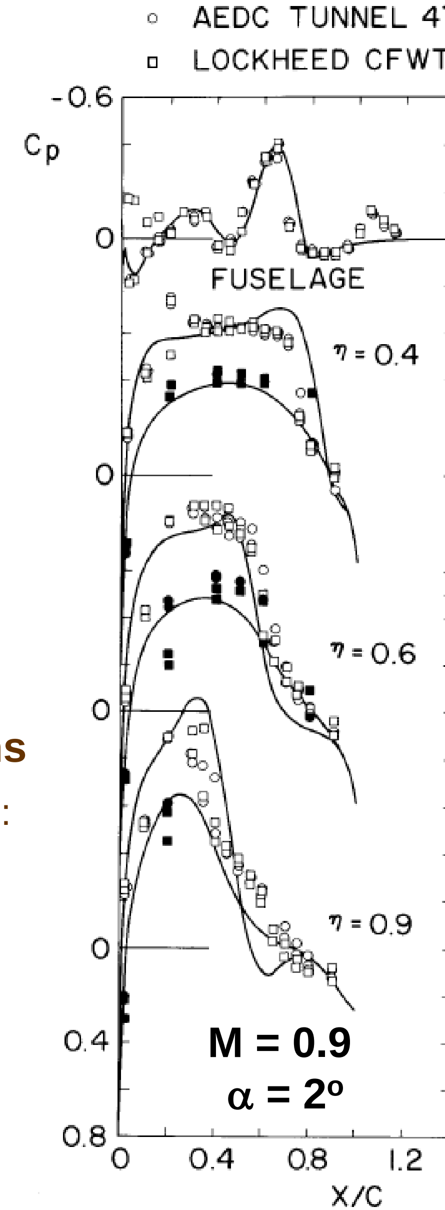
Overlapping Embedded Mesh Scheme for Complex Geometries: *1985*

Benek, Buning and Steger (1985)

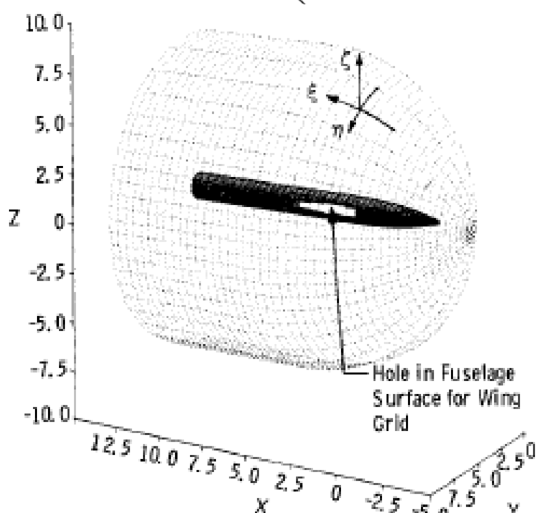
- A 3-D Chimera grid embedding scheme—***AIAA Paper 85-1523***
- Boundary conforming grids on component parts of the geometry

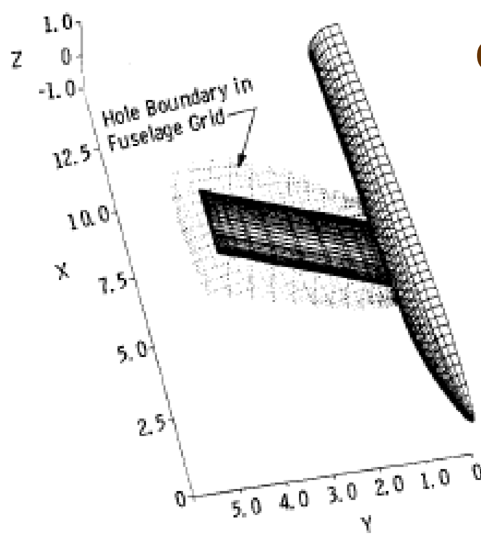






M = 0.9
α = 2°





Wing/Body Computations

Fuselage Grid: 47x25x25

Wing Grid: 66x23x11

Source: Ref. 5.2.6

Unstructured-grid Euler Solvers: *1985*

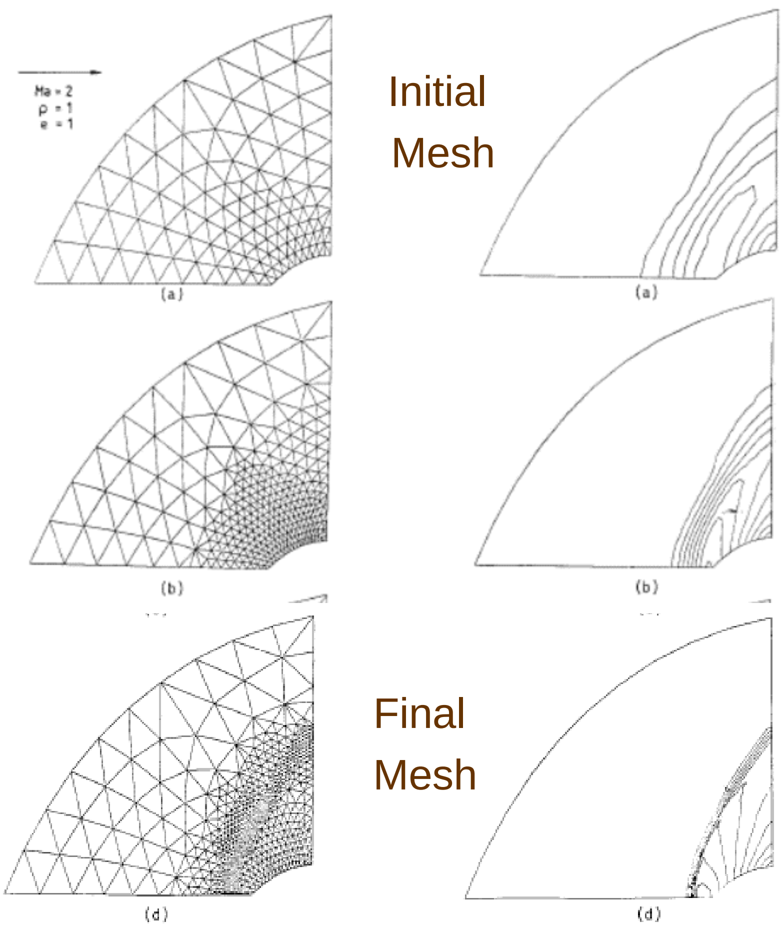
Löhner, Morgan, Peraire and Zienkiewicz (1985)

- Finite-element methods for high speed flows—***AIAA Paper 85-1531***

Mach 2 Inviscid Steady Flow

Simulated Nose Cone Section

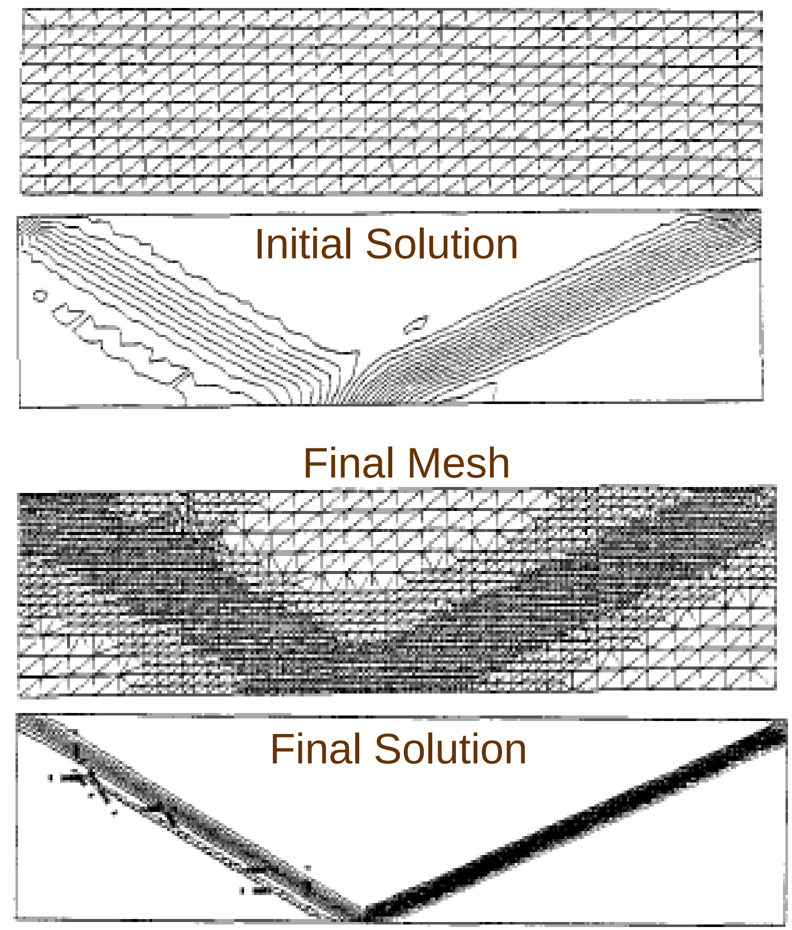
Adaptive Mesh Refinement



Inviscid Shock Reflection off Solid Wall

Adaptive Mesh Refinement

Initial Mesh



Source: Ref. 5.2.7

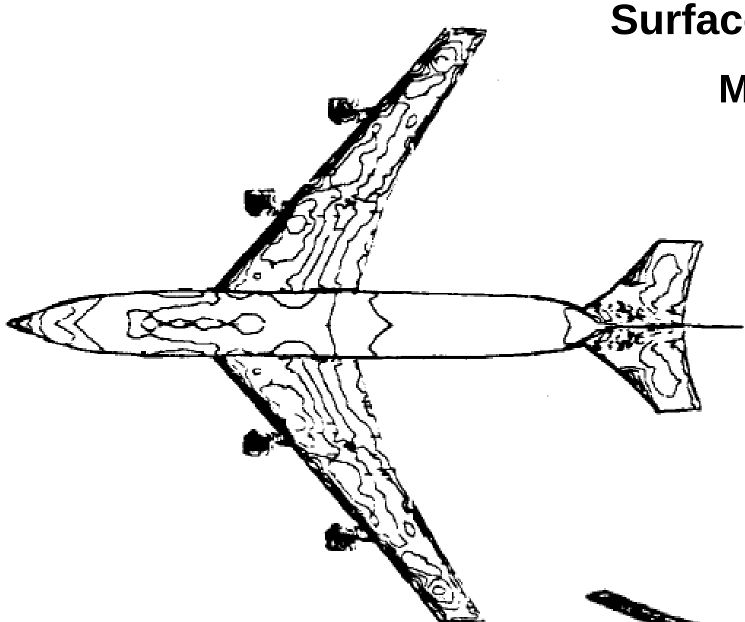
Complete Aircraft Euler Solution: *1986*

Jameson, Baker and Weatherill (1986)

- Calculation of Inviscid Transonic Flow over a Complete Aircraft—***AIAA Paper 86-0103***
- Generate separate meshes for each aircraft component
- Unite mesh points from several overlapping meshes to form a single cloud of points
- Use Delaunay triangulation to connect cloud of points to form tetrahedral cells
- Solve Euler equations using a new finite element approximation for polyhedral control volumes formed by the union of tetrahedra meeting at a common vertex

Preliminary Solutions for B747-200:
Surface Pressure Contours

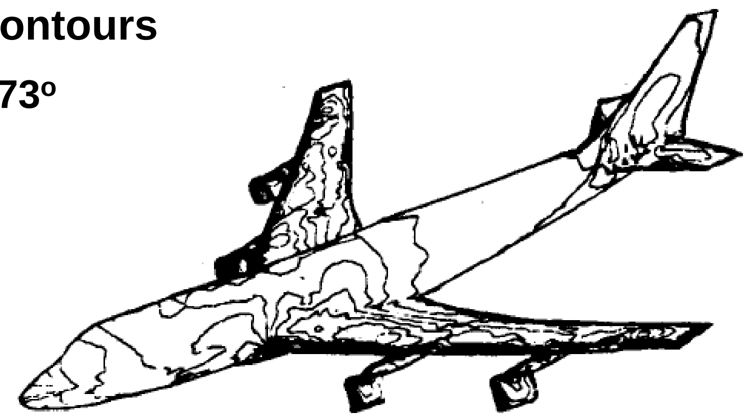
$M = 0.84$, $\alpha = 2.73^{o}$

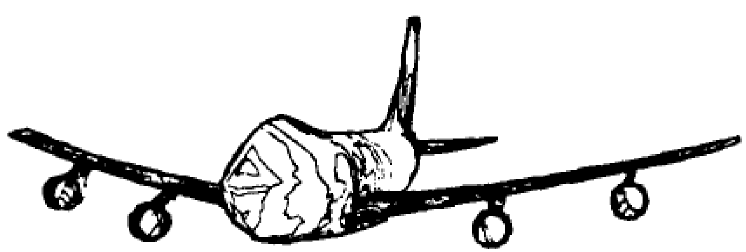


Tetrahedral Mesh

12038 Nodes

57914 Cells





Source: Ref. 5.2.8

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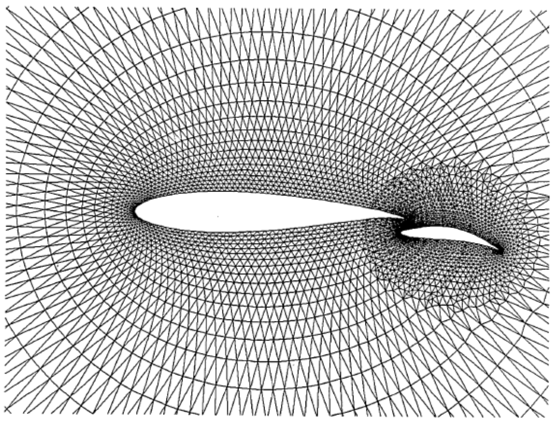
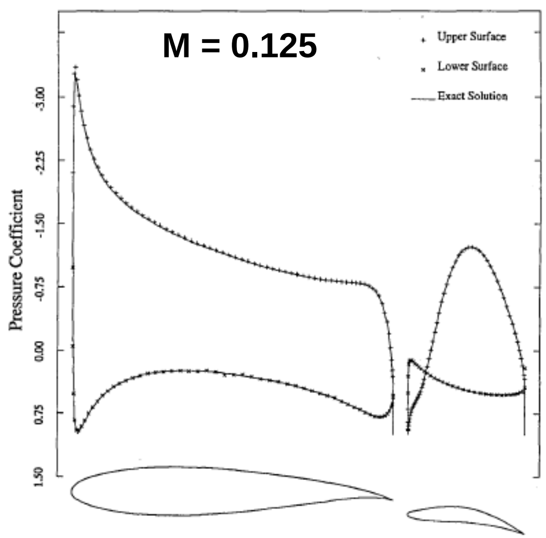
Accurate Euler Solutions on Unstructured Adaptive Meshes: *1988*

Mavriplis (1988)

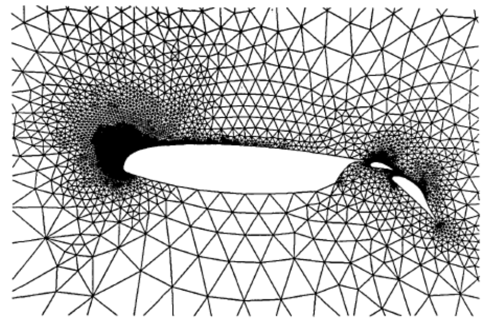
- Accurate multigrid solutions on unstructured and adaptive meshes—***NASA CR 181679***

Karman-Trefftz Airfoil and Flap

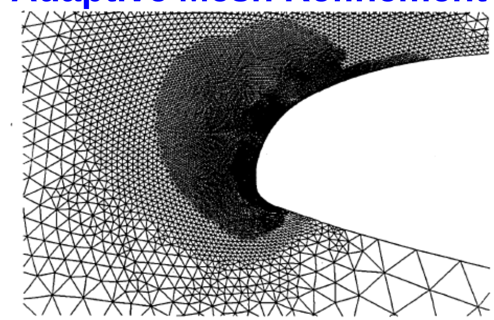




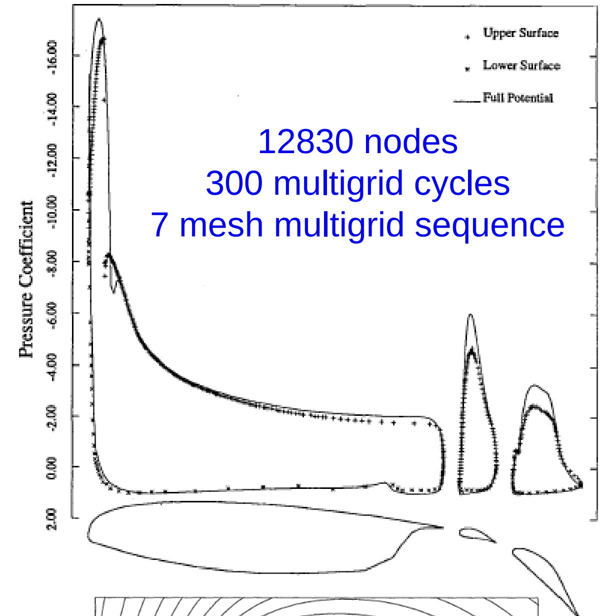
High-lift Three-element Airfoil

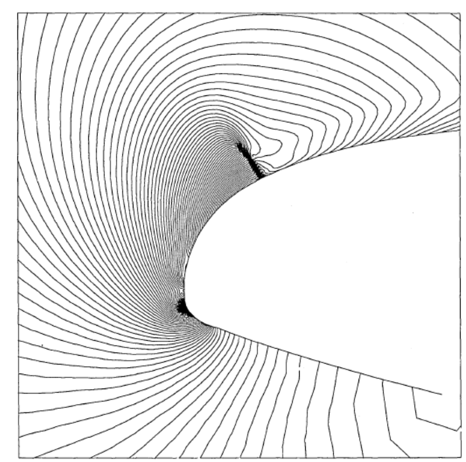


Adaptive Mesh Refinement



M = 0.25, α = 8°





	Main Airfoil		Flap		Total	
	Cl	Cd	Cl	Cd	Cl	Cd
Nodal Scheme	1.7005	-0.0906	0.3357	0.0890	2.0362	-0.0016
Analytical Incompressible Solution	1.6915	-0.0898	0.3366	0.0897	2.0281	-0.0001

Source: Ref. 5.2.9