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 9

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

List of Topics

TEAM (Euler) Application: F-22 EMD *(1991)*

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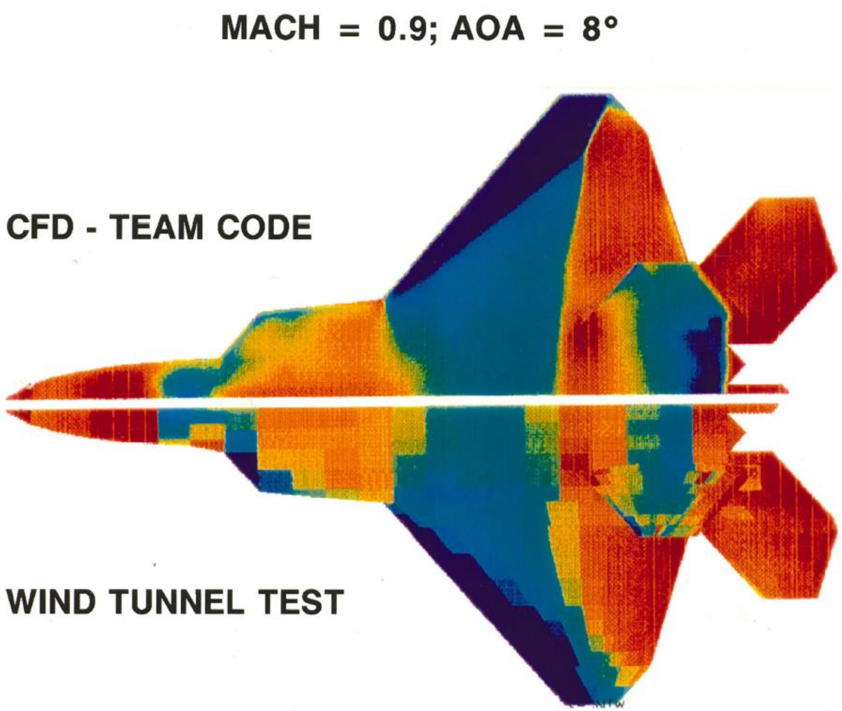
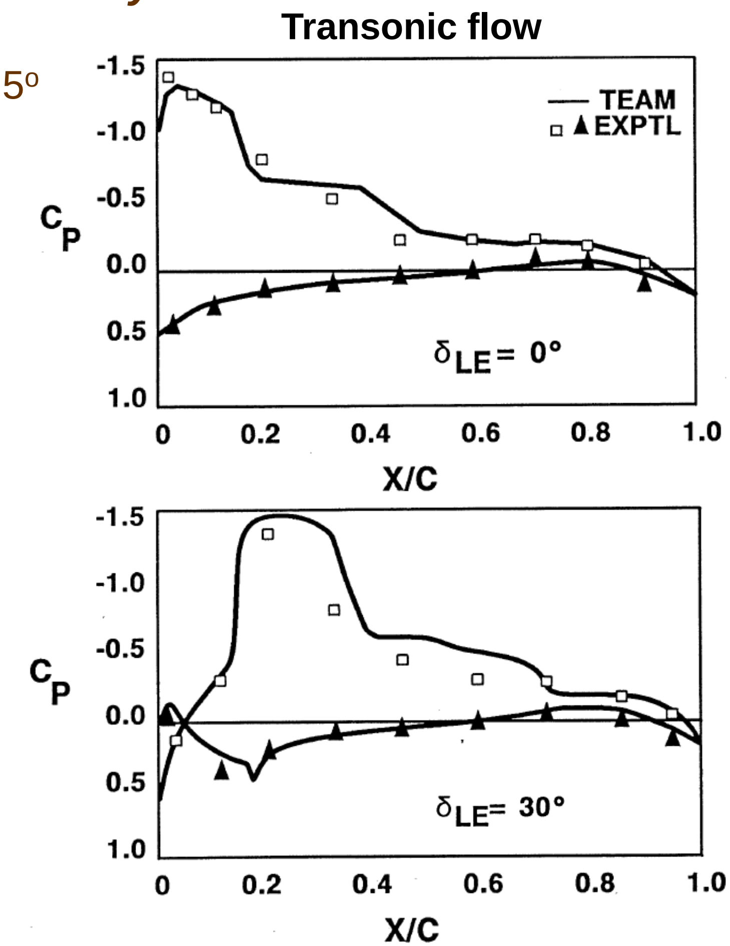
VIRGINIA TECH.

Full-aircraft forces, moments, and airloads prediction (Kinard & Harris)

- **42-zone grid, 1.25 million nodes** (for half the configuration)
  - ✓ Grid built using AFRL GRIDGEN in 6 weeks from CATIA design loft
- ***370 airloads cases; 3 months; 1600 CPU hours* on Cray-Y/MP 2/16***
  - ✓ Six Mach numbers (0.6 to max speed)
  - ✓ Angles of attack: - 4º to +24º; Side-slip angles: 0º to 5º
  - ✓ Leading and trailing-edge flaps, horizontal tail, and rudder deflections





$40M Estimated Cost Avoidance

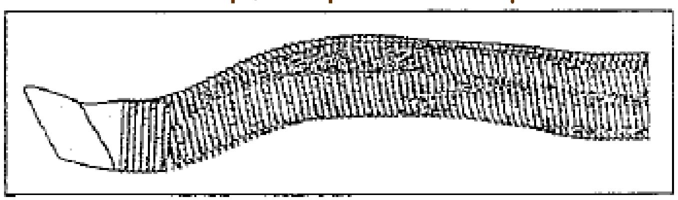
**Equivalent to 24 hours a day, 5 days a week, for 13 weeks! Probably an industry record at that time.*

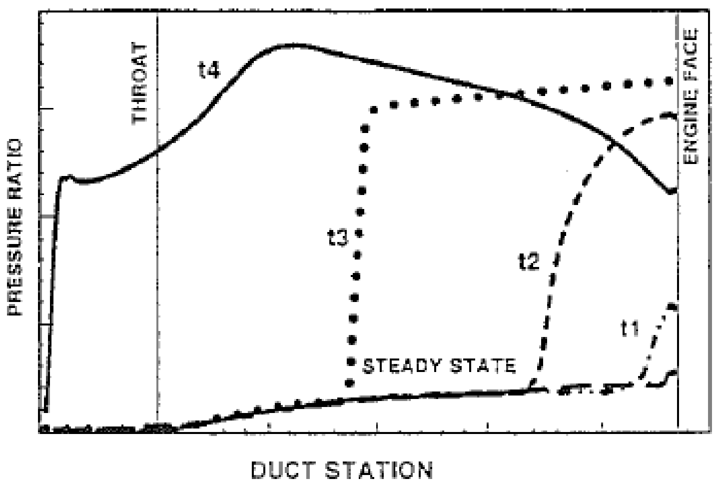
Source: Ref. 5.2.33 & 5.2.29

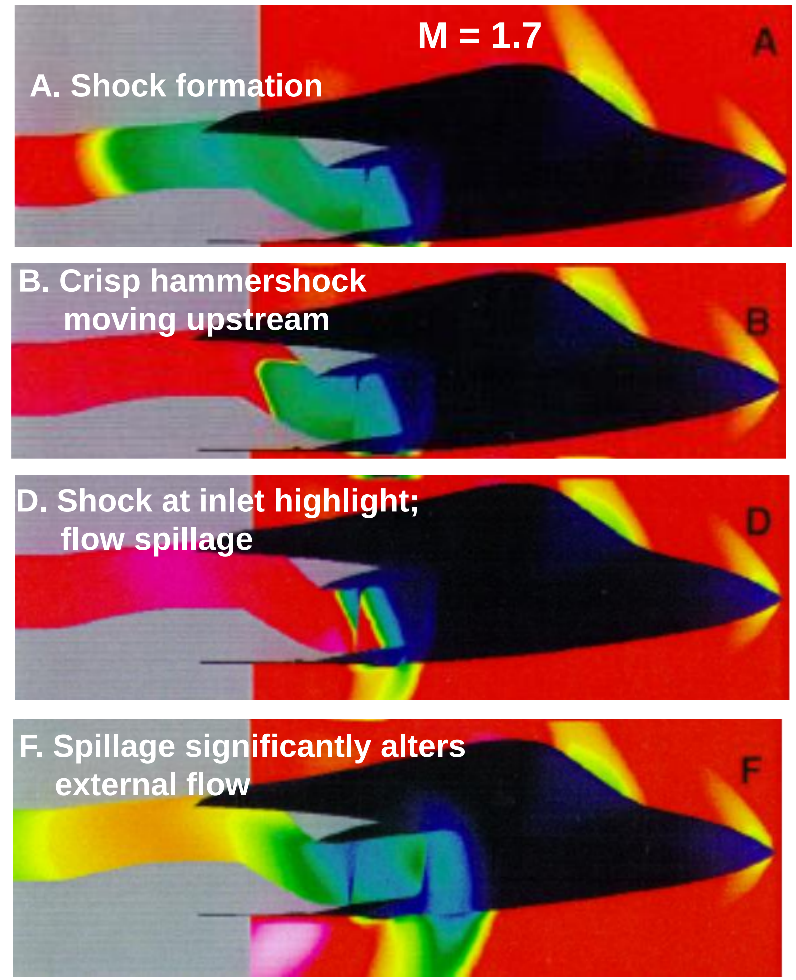
TEAM (Euler) Application: F-22 EMD *(1995)*

Inlet Hammershock Loads Estimation

- **Grid:** Built (for half the configuration) using AFRL GRIDGEN on geometry from CATIA design loft
  - **External geometry:** 49-zone grid with 1.535 million nodes
  - **Internal (inlet) geometry:** single-zone grid with 259,200 nodes
- **Time-accurate analyses:** performed using YF119 engine face surge overpressure waveform for three Mach numbers: 1.2, 1.5 and 1.7
- **Simulations used NASA NAS Cray C-90**
  - 35 sec/time step; step size 1.4 μs







Computed pressure loads replaced those from less-sophisticated analyses leading to significant weight savings

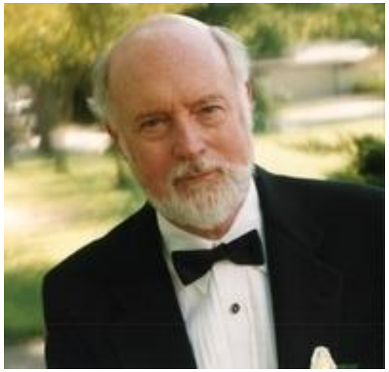
Source: Ref. 5.2.33 and 5.2.34

Raj's Tech Fellow Mission

Spurred by "A Jolt of Reality"

- **Engineer's Week Celebration, San Fernando Valley, California *(23 February 1991)***
  - Conversation over cocktails about CFD and YF-22
  - Caren asks: *How many more "design cycles" on YF-22 could we do because of [higher level] CFD?*
  - The answer: *ZERO!*
- **As Tech Fellow, Raj embarks on a mission in 1992 to better understand and address issues related to CFD effectiveness for aircraft design**
  - **1993–1997: AIAA Multi-disciplinary Design Optimization (MDO) TC member**
  - **1994: US Multi-disciplinary Aerodynamic Design Environment (US-MADE)** Proposal to DARPA by Jameson (IAI–Lead), Gregg (Boeing), Raj (Lockheed); *not funded*
  - **1997: CFD at a Crossroads*: An Industry Perspective (Invited),*** *Thirty Years of CFD and Transonic Flow* Symposium to honor Prof. Earll Murman on his 55th Birthday, Everett, WA [also in *Frontiers of Computational Fluid Dynamics*, Caughey & Hafez (eds.),1998, pp. 429-445]
  - **1998: Aircraft Design in the 21st Century: *Implications for Design Methods (Invited),*** AIAA Paper 98-2895, 29th AIAA Fluid Dynamics Conference, Albuquerque, NM
  - **2007: Computational Uncertainty: *Achilles' Heel* of Simulation Based Aircraft Design *(Invited),*** NATO/RTO Air Vehicle Technology (AVT) Symposium, Athens, Greece

Robert P. "Chris" Caren



Exec. VP, Sci. and Engineering
Lockheed Corp.
25 Dec 1932 – 3 Jul 2017

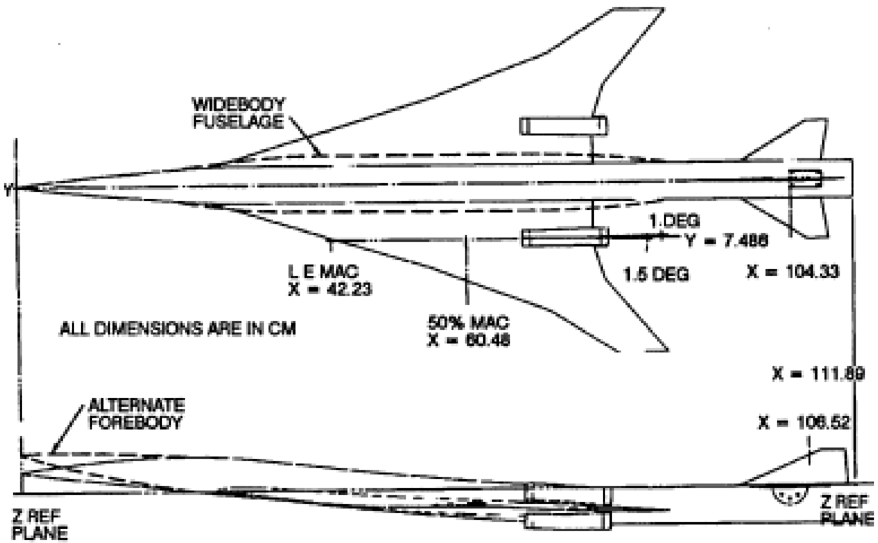
Source: Ref. 1.1 – 1.3

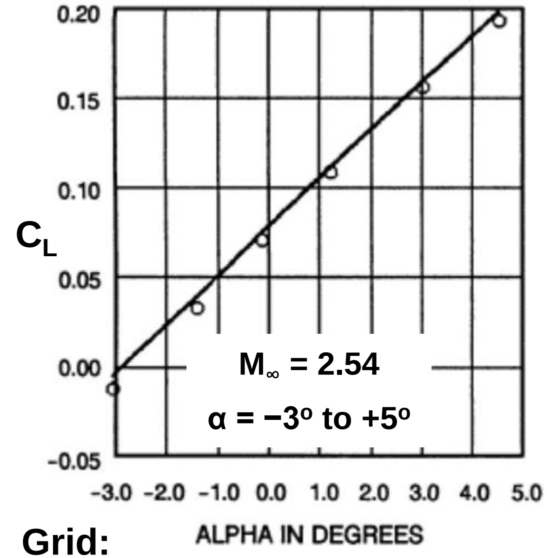
TEAM (Euler) *Effectiveness Status* *(Y/E 1991)*

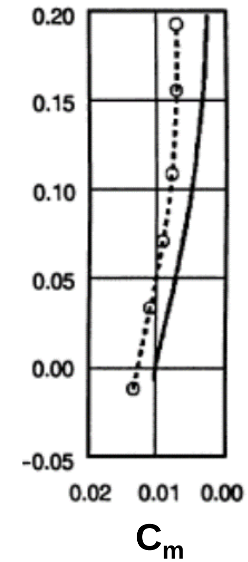
Mature Capabilities Demonstrated for Wide Range of Geometries & Flow Conditions

Example

Supersonic-Cruise Research Vehicle with Over/Under Engine Arrangement





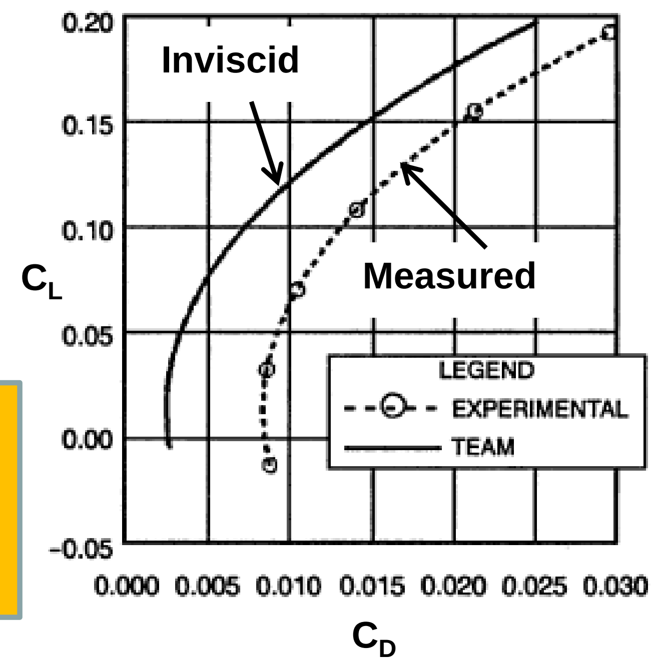


Grid:

10 Zones

H-O topology

185,520 Cells



Lift Values Well Predicted, Moment and Total Drag Not So Well…But Trends Captured Well!

Two Key Issues Hamper Effectiveness:
(1) Time & Labor Intensive Grid Generation
(2) Lack of Viscous Effects

Source: Ref. 5.2.26

Lockheed Addresses Grid Generation Issue

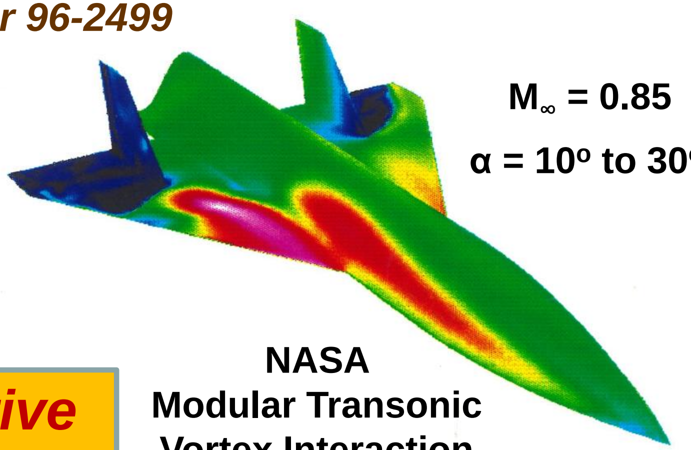
1990s: Explore Potential Benefits of Unstructured Grids

Participate in studies sponsored by Dr. Jim Luckring, NASA-LaRC (1993-1996)

- NASA Study Objective: To assess capabilities and limitations of rapidly evolving unstructured-grid **Euler** methods for preliminary design applications
- **Kinard and Harris, *Evaluation of two unstructured CFD methods—AIAA Paper 94-1877***
  - **AIRPLANE** code (Meshplane and FLOPLANE)
  - **TetrUSS** code (Vgrid and USM3D)
  - Three test cases: 74º delta wing; Wing C; and Arrow wing-body
  - Needs for improvement identified

	Memory (words/cell)	CPU time µs/cell/cycle
FLOPLANE	34	11
USM3D	45	18

- **Kinard, Finley and Karman, *Prediction of compressibility effects using unstructured Euler analysis on vortex dominated flow fields—AIAA Paper 96-2499***
  - **SPLITFLOW** code (Cartesian grids)
  - **TetrUSS** code (Vgrid/USM3D)
  - Compressibility increments predicted well for forces, but not for moments
  - More details in NASA CR 4710 and CR 4711



$M_\infty = 0.85$

$\alpha = 10^o$ to 30^o

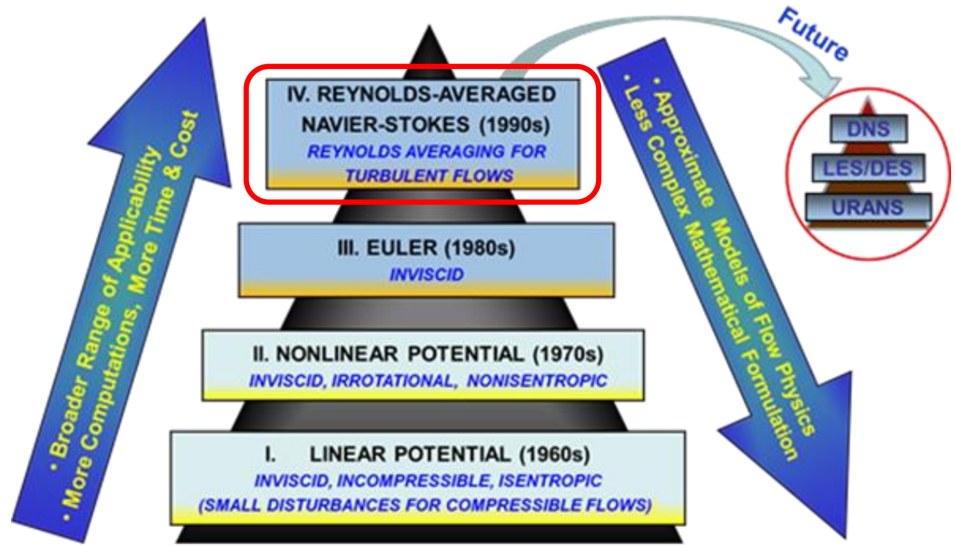
NASA Modular Transonic Vortex Interaction (MTVI) model

Unstructured Grid Methods More Effective Due to Automated Grid Generation

Source: Refs. 5.2.35 – 5.2.37

Lockheed Addresses Viscous Effects Issue

Level IV
RANS Methods
1990s - present



Flow Model

$$Q_t + F_x + G_y + H_z = Re^{-1}(R_x + S_y + T_z)$$

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

- Laminar flows—Navier-Stokes equations; no assumption (other than continuum)
- Turbulent flows—Reynolds-Averaged Navier-Stokes (RANS) equations
  - ✓ Turbulence models of nonlinear Reynolds stress terms needed for closure

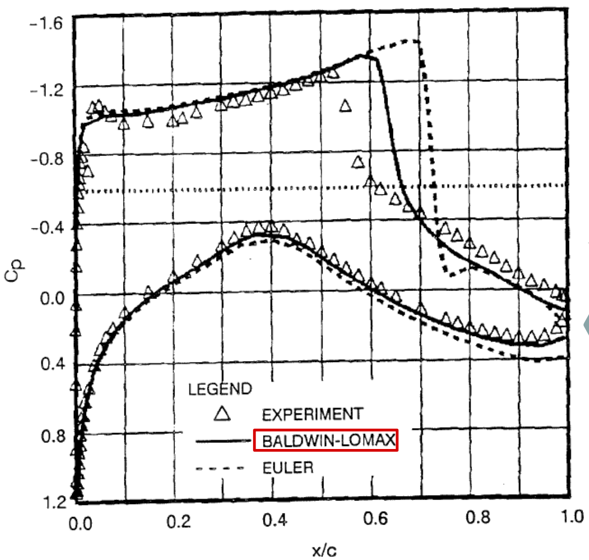
Range of Applicability

- All Mach numbers and all flow configurations

Motivation for RANS: *Increase "Quality"*

- **Olling, Raj, and Miranda (1986)**
  - Initiated **TRANSAM*** *(Three-dimensional Reynolds-Averaged Navier-Stokes Aerodynamic Method)* development by adding viscous terms to the TEAM Euler solver to serve as a testbed for turbulence models
    - ✓ Zero, one- and two-equation turbulence models incorporated; all with fixed transition location

- **Raj, Olling and Singer (1988)**
  - **TEAM** renamed (*Three-dimensional Euler/Navier-Stokes Aerodynamic Method*) with ability to perform either Euler or RANS analyses
  - Applied to many test cases: results for airfoils, wings, and full aircraft in ***ICAS-90-6.4.4*** *and* ***iPAC 911990***



RAE 2822 (AGARD Case 10)

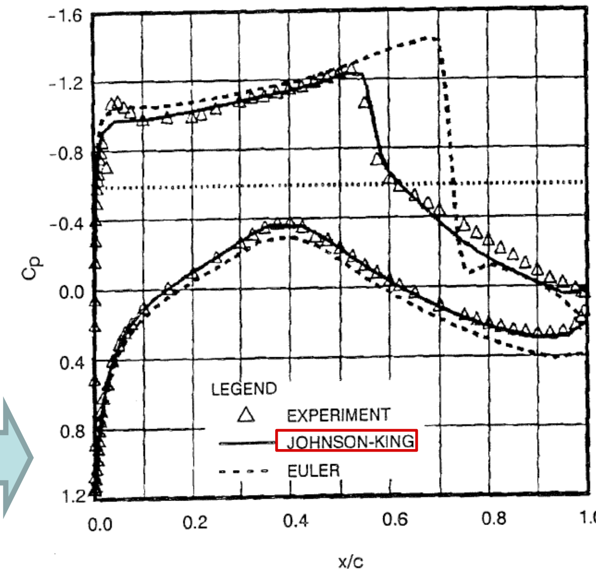
$M_\infty = 0.75$, $\alpha_{corrected} = 2.81^o$

$Re = 6.2 \times 10^6$

129 x 257 C Grid

Baldwin-Lomax algebraic turbulence model

Johnson-King half-equation turbulence model



Simulation of shock/boundary-layer interaction improves realism

- **Goble, Raj and Kinard (1993)**
  - USAF Wright Labs TEAM Version 713 User's Manual—***WL-TR-93-3115***
  - Many improvements along with Baldwin-Lomax and Chien k-ε turbulence models

Source: Refs. 5.2.35 – 5.2.37

TEAM (RANS) Validation

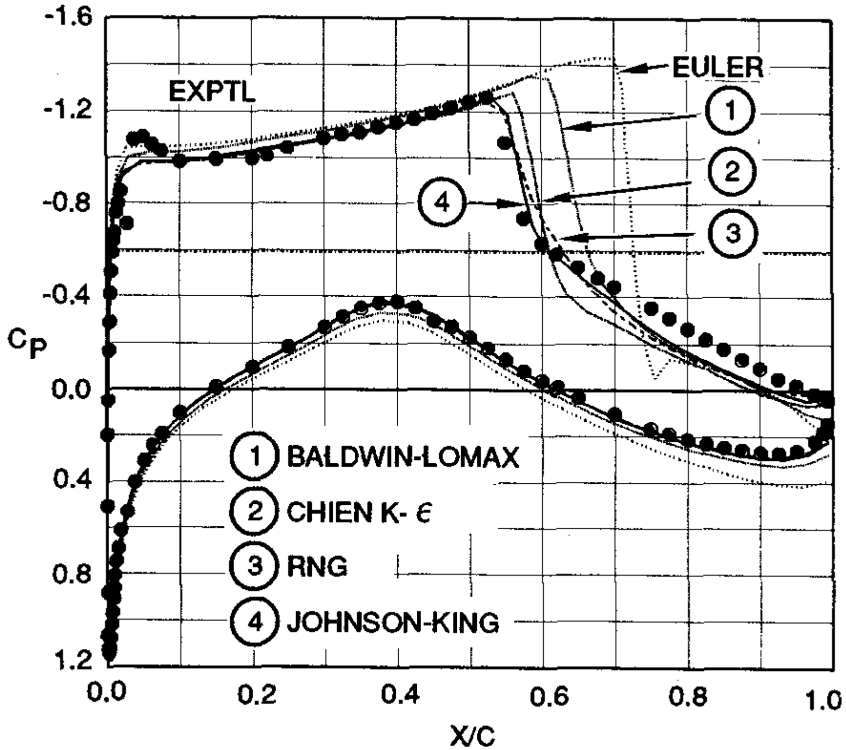
Transonic Flow (2D)

RAE 2822 Airfoil

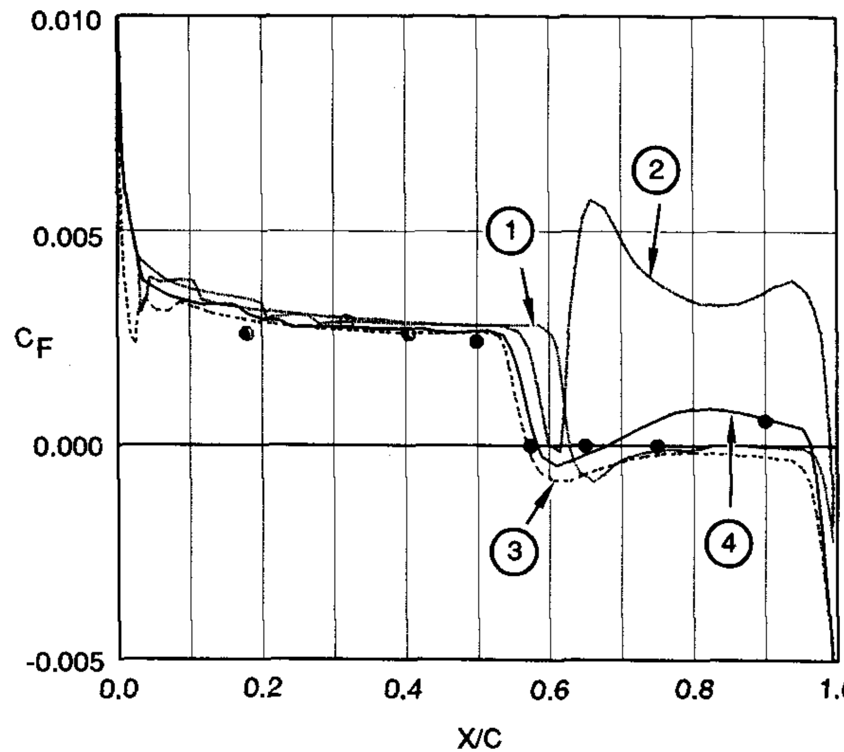
AGARD Test Case 10 **M_∞ = 0.75, α = 2.8°, Re_c = 6.2x10^6**

257 x 129 C Grid **y^+ $(= yu_\tau/\nu)$ < 1 in cells next to the surface**

Surface pressure distribution



Skin friction coefficient distribution



Solution Sensitive to Turbulence Models

Source: Ref. 5.2.36

TEAM (RANS) Validation

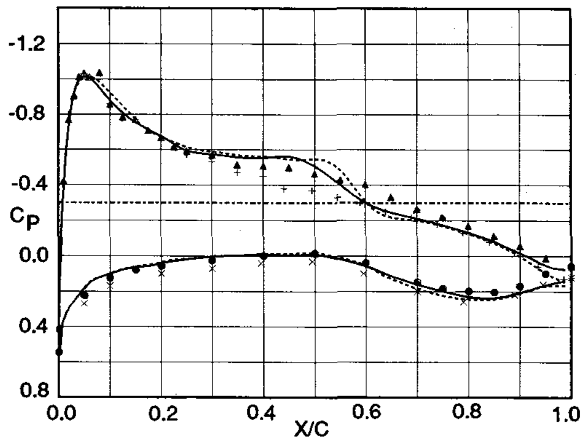
Transonic Flow (3D)

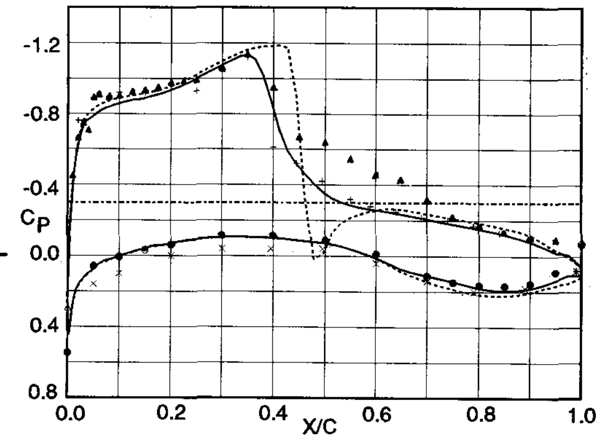
AFOSR-Lockheed Wing C: *Surface pressure correlations*

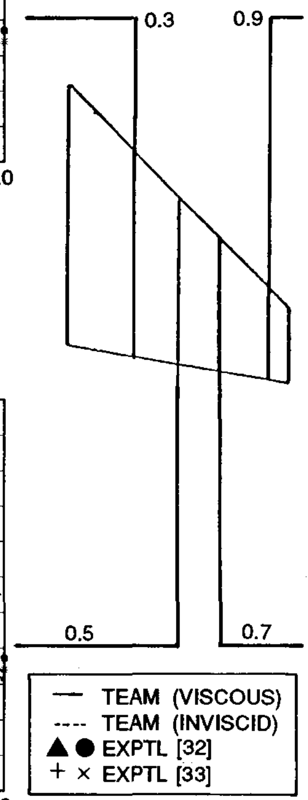
7 zone C-O grid (51 x 257 x 35)

Baldwin-Lomax turbulence model

$M_\infty = 0.85$
$\alpha = 5^o$
$Re_{mac} = 10 \times 10^6$

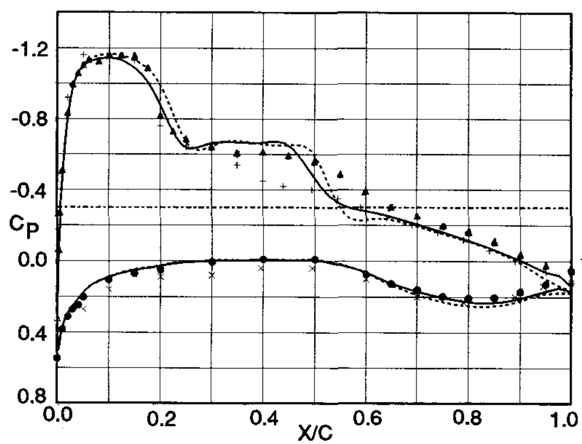


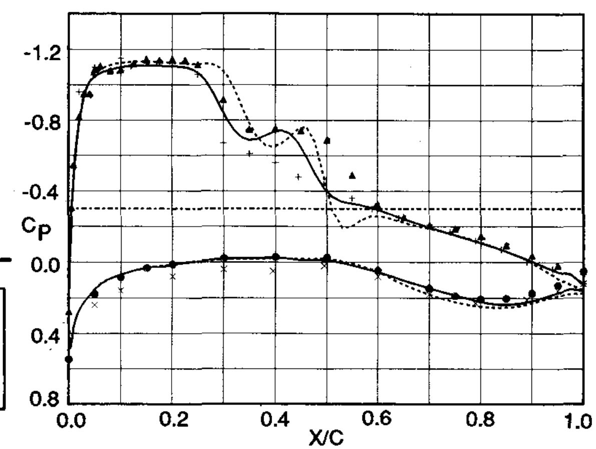




Viscous (RANS) analysis: 6 inner zones
Inviscid (Euler) analysis: 1 outer zone

▲ ● Large-scale test
+ × Small-scale test



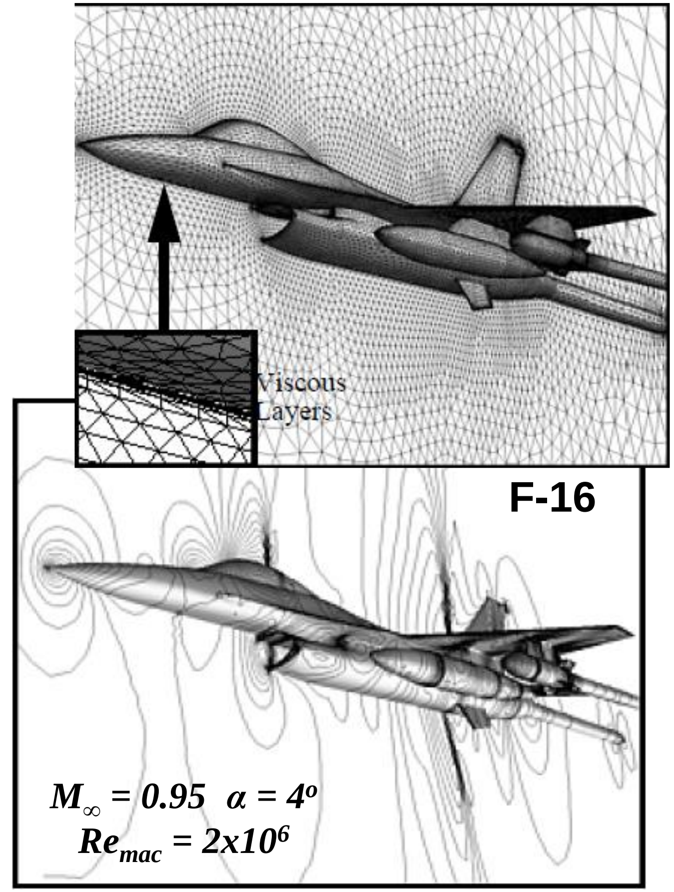


Source: Ref. 5.2.36

NASA TetrUSS*

Most Promising for Achieving RANS-based ACA Effectiveness Goal

- **TetrUSS: A Modular Loosely-Coupled System Developed by NASA-LaRC**
  - GridTool—Graphical User Interface (GUI) for surface definition
  - VGRID/ VGRIDns—advancing front method to generate **unstructured tetrahedral gri**ds
  - USM3D/ USM3Dns—cell-centered finite-volume upwind flow solver for **Euler** and **RANS** equations
  - VPLOT3D—interactive, menu-driven extraction and display of flow data
- **Rapid Capability Advancements in the 1990s**
  - Frink: *Three-dimensional Upwind Scheme for Solving Euler Equations on Unstructured Tetrahedral Grids*, Ph.D. dissertation, Virginia Tech, 1991
  - Pirzadeh: *Structured Background Grids for Generation of Unstructured Grids by Advancing Front Method*, AIAA J, 31(2), 1993
  - Frink, Pirzadeh, and Parikh: *An Unstructured-grid Software System for Solving Complex Aerodynamic Problems*, NASA CP-3291, 1995
  - **Frink and Pirzadeh: *Tetrahedral Finite-Volume Solutions to the Navier-Stokes Equations on Complex Configurations*, NASA/TM-1998-208961**



Decision Driven by Careful Cost-Benefit Assessment of the-then Prevalent Environment of Very Low In-house R&D Investments

*Tetrahedral Unstructured Software System

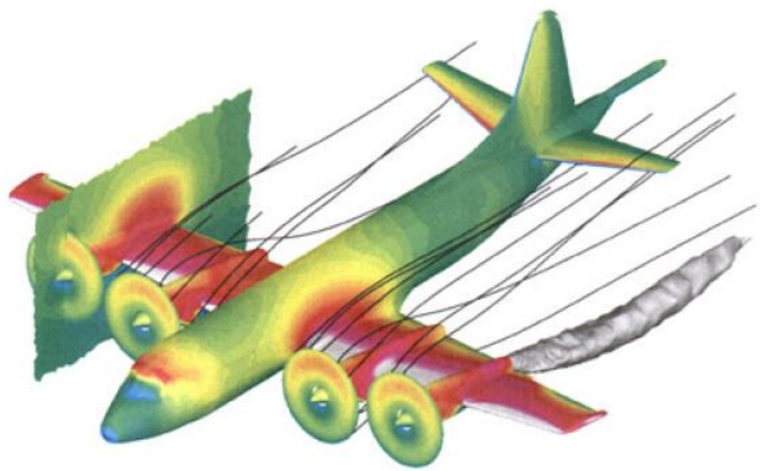
Source: Ref. 5.2.43 and 5.2.44

Y2K: *Mission Accomplished!*

Goal of 24-hour turnaround time of full aircraft RANS analysis, that was set in the early '90s, achieved using TetrUSS and cluster computing

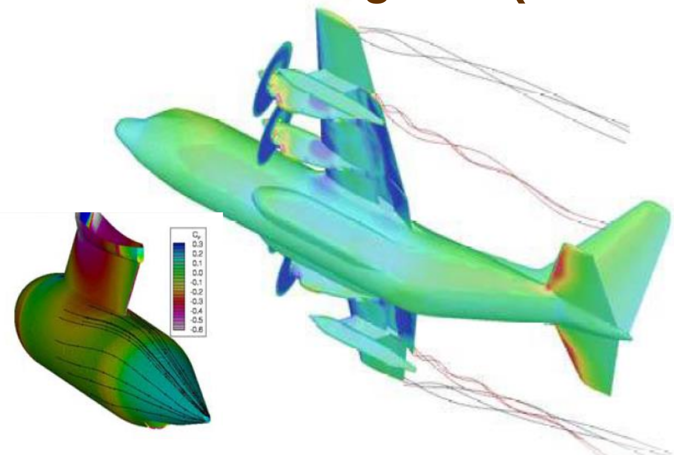
(Thanks to the hard work and dedication of the ACA team in Georgia)

- **P-3C Airloads (Goble and Hooker)**



  - Supported US Navy's Service Life Assessment Program (SLAP)
  - Full aircraft grids with 7 million+ cells
  - Nearly ***300 aerodynamic loads cases*** over entire flight envelope using **Cray T3E** and **SGI Origin 2000**
  - Details in ***AIAA 2001-1003***

- **KC-130J Refueling Pod (Hooker)**



  - Design and integration of refueling pods
  - Full aircraft viscous grid with 7 million cells
  - ***Six full aircraft viscous solutions per day*** with dedicated use of two **64-node PC clusters**; each node made up of **dual 850 MHz Intel Pentium III processors** with **768 MB RAM**
  - Details in *AIAA* ***2002-2805***

RANS: Full Steam Ahead!

Source: Refs. 5.2.45 & 5.2.46

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RANS-based ACA: *Full Aircraft Solutions*

Comparison of computed surface pressures with wind-tunnel test data for

full-span 4% scale model of C-5 aircraft with flow-through HBPR TF-39 nacelles

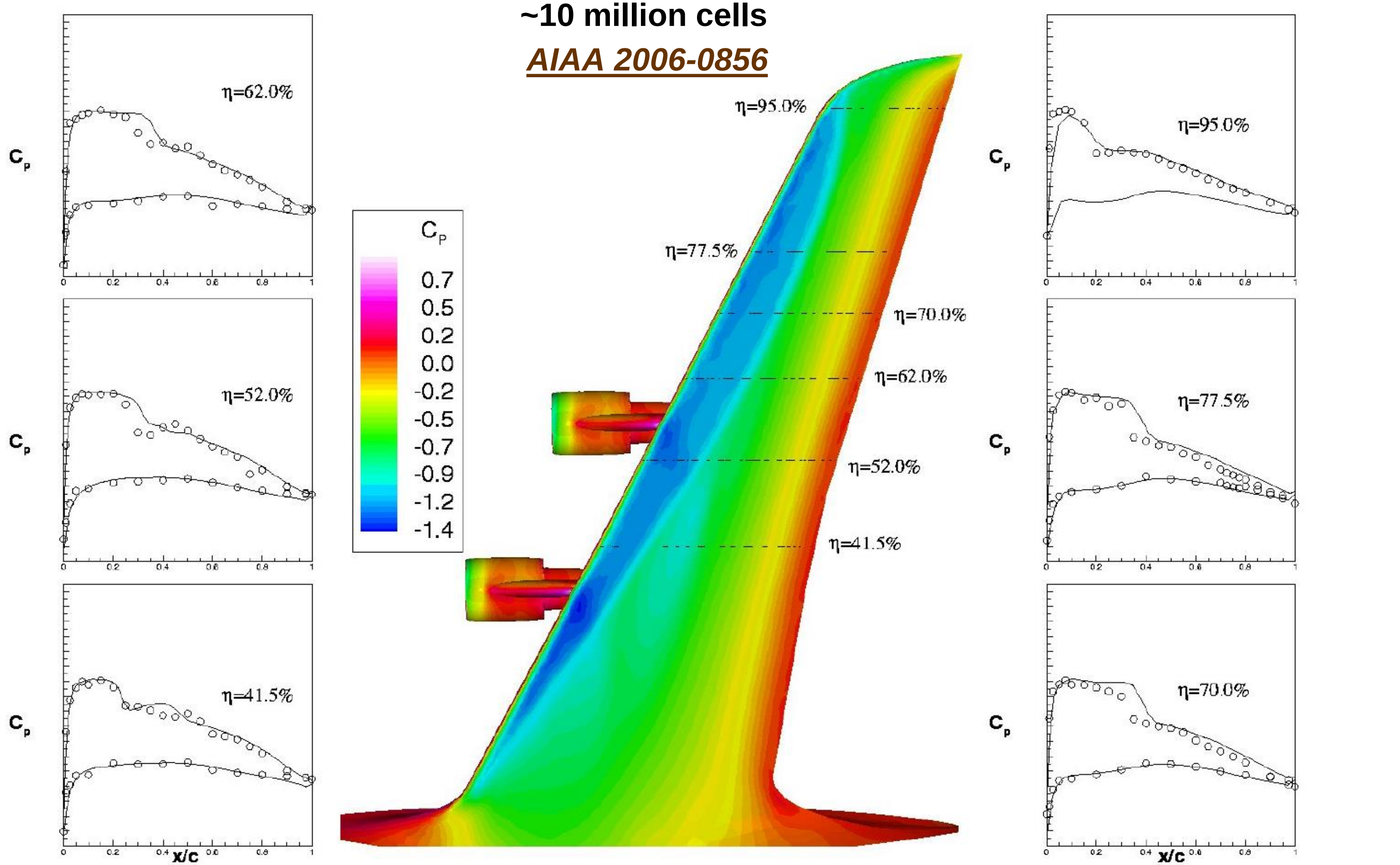
$M_\infty = 0.75$ $\alpha = 2^o$ $Re_{mac} = 4.5 \times 10^6$

TetrUSS

~10 million cells

AIAA 2006-0856

Spalart-Allmaras turbulence model

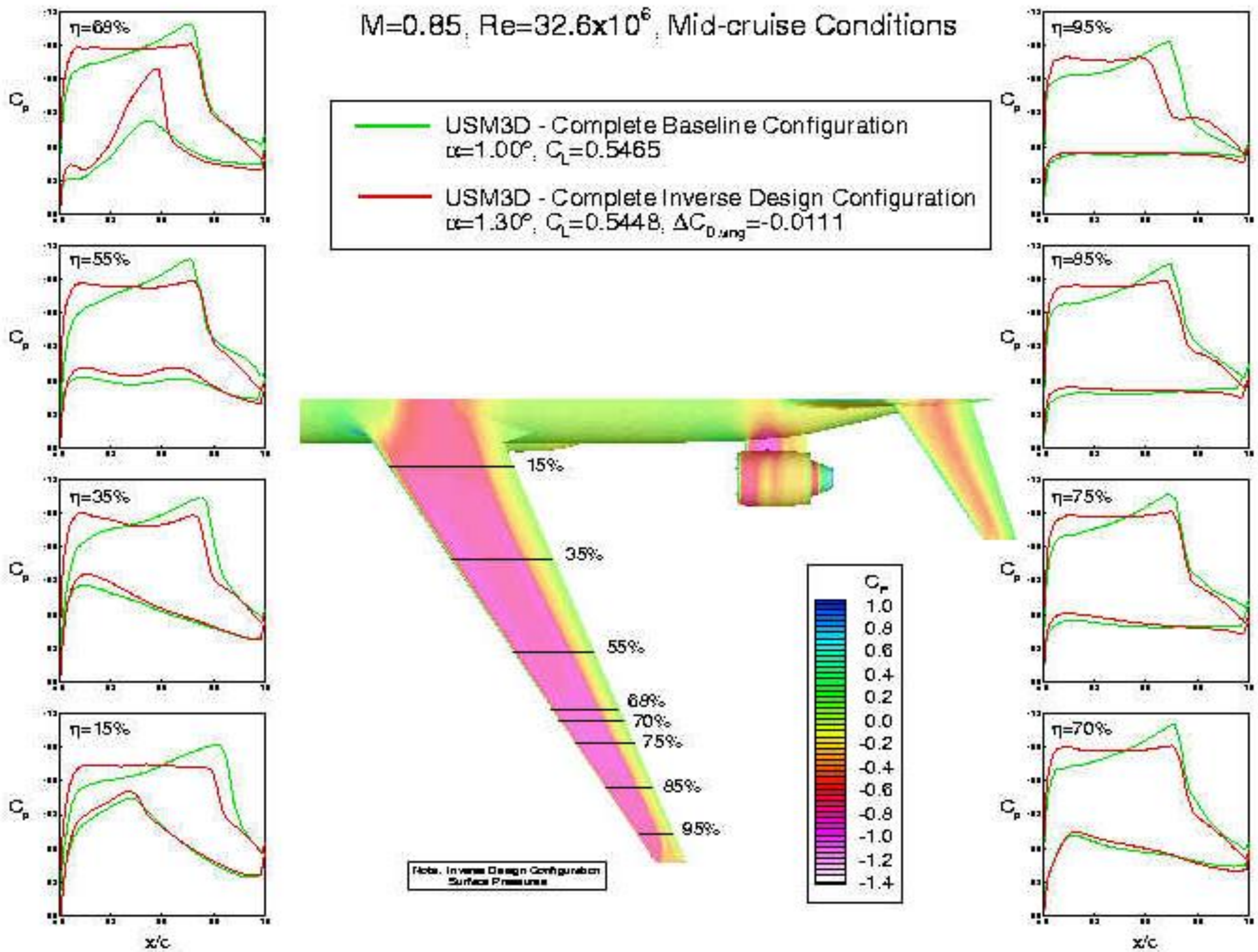


Good Agreement for Relatively Benign Flow Conditions

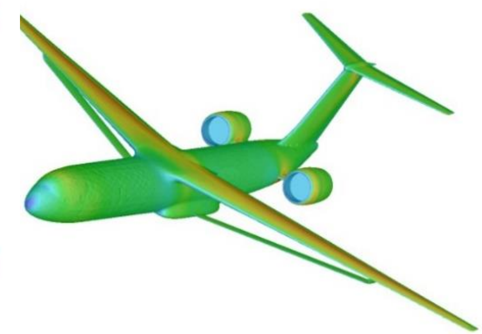
Source: Ref. 1.6

RANS-based ACA: *Full Aircraft Solutions*

Transonic Cruise Wing Design for a Strut Braced Wing (SBW) Concept



Comparison of computed surface pressures



Coupled Analysis Method with Knowledge-Based Inverse Design Methodology

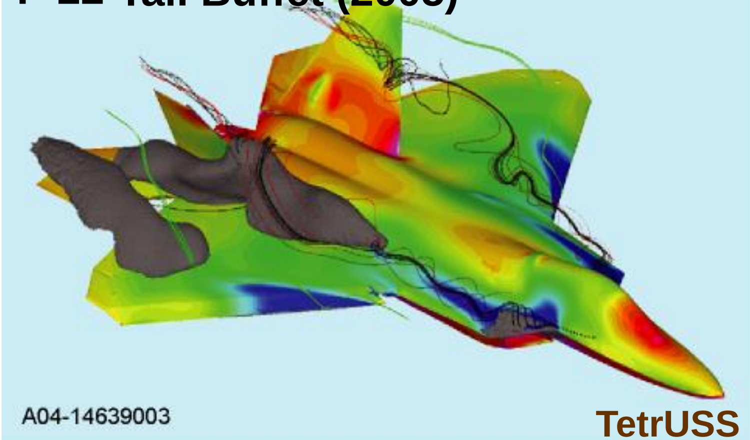
Wing Redesign Reduces C_D by 111 Counts

Source: Ref. 1.6

RANS-based ACA

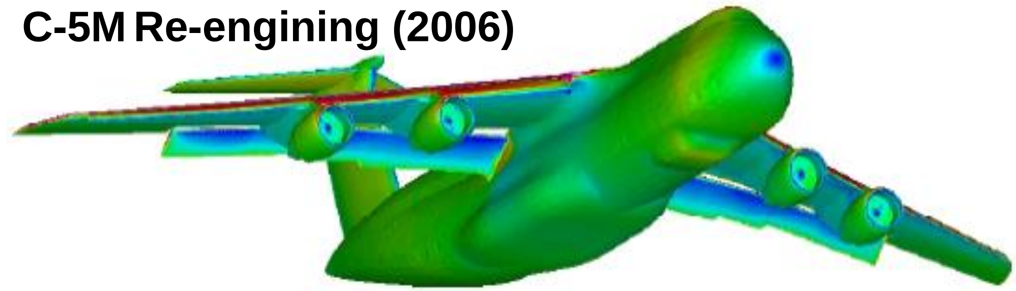
Impressive Capabilities Demonstrated throughout the 2000s

F-22 Tail Buffet (2005)



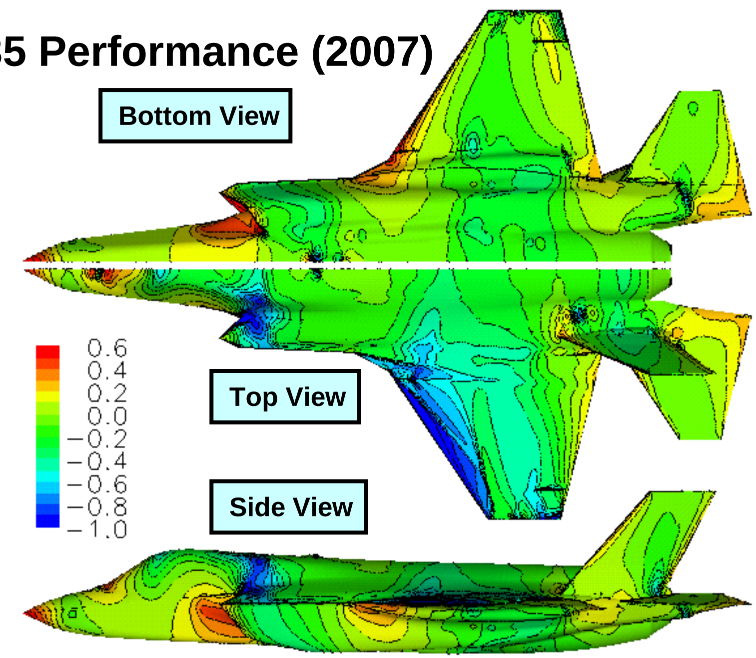
TetrUSS

C-5M Re-engining (2006)



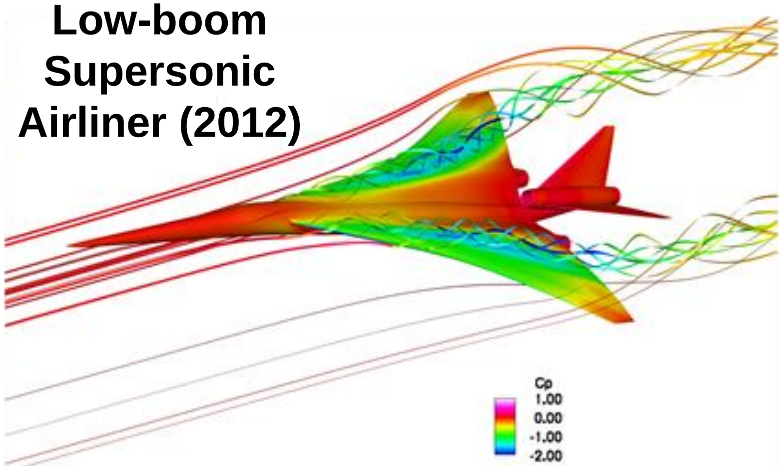
TetrUSS

F-35 Performance (2007)



Falcon

Low-boom Supersonic Airliner (2012)



CFD++

Reasonably Quick and Affordable Aerodynamic Simulations for a Wide Variety of Flows on Full Aircraft Configurations

Source: Refs. 6.1.1 – 6.1.4

Pursuit of Effectiveness: *A Key Takeaway*

Developing effective capability from research concepts is a long, arduous process!

- **Effective Capability (*High TRL*): *Slow Pace of Development***
  - ***Demonstration of Mature Capabilities is Essential!*** It requires extensive investigations of *Quality* and *Acceptance* tradeoffs. Overcoming challenges of software V&V, user training and timely incorporation of user feedback & demands is a *resource intensive undertaking*
  - *Achieving maturity is hard due to rapid pace of advances in enabling technologies!* Engineers have limited freedom to change technology-based building blocks chosen in the earliest stages of development. *"Final product" risks being perceived as obsolete—and most likely is!*
- **Research Concepts (*Low TRL*): *Rapid Pace of Advancement***
  - ***Demonstration of Basic Functionality is Sufficient****—typically proof of concept!*
  - **Computers**—ever higher performance demonstrated on *few* standard benchmarks
    - *Scalar Processors:* Single instruction, single data--one instruction at a time on one data item (integers or floating point numbers)
    - *Vector Processors*: Single instruction, multiple data--single instruction *simultaneously* on multiple data items
    - *Serial Computing*: stream of instructions executed serially on one computer
    - *Parallel & Massively Parallel Computing*: many instructions carried out simultaneously on one or many computers depending on level of parallelism—instruction, data, or task
  - **Grids**—many competing methods constantly proposed for generating grids of various types
    - Structured, Single or Patched Multi-block, Embedded, Overlapping, Cartesian, Unstructured
    - Boundary conforming or non-boundary conforming with Hexahedral, Tetrahedral, or Polyhedral cells
  - **Algorithms/Solvers**—new & improved algorithms, each with upsides and downsides to solve governing equations of fluid flow
    - Explicit, Implicit, Central difference, Upwind difference, Low order, High order, Cell centered, Node centered, Face centered, Multigrid, Grid Adaptive, etc.

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A Noteworthy Branch of CFD Evolution

In the 1980s, a new paradigm emerged that challenged/ complemented aerospace industry's dominance in *proprietary* CFD software development

Multiple Commercial Codes for Viscous Flow Simulation!

Software	Developer/ Vendor	Comment
PHOENICS	Spalding/ CHAM Ltd. [1981]	General purpose CFD package consolidating multiple niche codes developed from 1974 thru 1980
FIDAP	Engelman/ FDI Inc. [1982]	General purpose FEM code--incompressible viscous flow
FLUENT	Swithenbank/ Creare, Fluent (now ANSYS) [1983]	General-purpose CFD solver on single-block, structured hexahedral grids
FLOW-3D	Hirt/ Flow Science [1985]	Volume-of-Fluid CFD method for free-surface applications
FASTRAN	CFD RC (now ESI Group) [1988]	Density-based, finite-volume code for high-speed flows; coupled 6-DOF allows multiple and moving body simulations
STAR-CD	Grosman/ CD-adapco [1989]	General-purpose finite-volume unstructured-grid method
CFD++	Chakravarthy/ Metacomp [1995]	General-purpose CFD code with wide range of applicability
ACE+	CFD RC (now ESI Group) [1995]	General-purpose CFD code with wide range of applicability
Cobalt	Cobalt Solutions, LLC [2000]	General purpose CFD code for a wide variety of problems
STAR-CCM+	CD-adapco (now Siemens) [2004]	Uses FEM or FV to simulate viscous flow on polyhedral grids

CFD is now a "Commodity": $2.7B Global Market in 2024 with Compound Annual Growth Rate (CAGR) of 7 to 9%!

"Free" CFD Software!

An Alternative to *Proprietary* and *Commercial* CFD Software

Software	Developer/ Vendor	Comment
POTENTIAL FLOW CODES (PUBLIC DOMAIN)		
AVL	Drela/ MIT [1995]	Vortex Lattice Method code (http://web.mit.edu/drela/Public/web/avl/)
Tornado	Melin/ KTH [2009]	VLM code in MATLAB (http://tornado.redhammer.se/index.php)
VSPAero	Kinney/ NASA [2015]	VLM (http://openvsp.org/wiki/lib/exe/fetch.php?media=vsp_aircraft_analysis_user_manual.pdf)
Panair	Boeing/ PDAS [2002]	Surface panel method (http://ckw.phys.ncku.edu.tw/public/pub/Notes/Languages/Fortran/FORSYTHE/www.pdas.com/panair.htm)
RANS CODES (PUBLIC DOMAIN & OPEN SOURCE)		
TetrUSS	Frink/ NASA [1998]	Suite of computer programs for CFD simulations using unstructured grids (https://software.nasa.gov/software/LAR-16882-1) US release only
Cart3D	Aftosmis/ NASA [2000]	Only inviscid flow analysis using Cartesian grids is publicly available (https://software.nasa.gov/software/ARC-14275-1) USG & contractors only
OpenFOAM	OpenCFD/ ESI Group [2004]	Free, open source software framework for developing application executables using packaged functionality in approx. 100 C++ libraries (https://www.openfoam.com/)
Kestrel	DoD HPCMP/ CREATE™-AV [2009]	High-fidelity, multi-physics analysis of fixed-wing aircraft (https://www.hpc.mil/program-areas/computational-research-and-engineering-acquisition-tools-and-environments/create-air-vehicles-av)
SU2	Stanford Univ./ SU2 Foundation [2013]	Collection of C++ and Python software for PDEs and PDE-constrained optimization problems on unstructured meshes (https://su2code.github.io/)

Today's Users Have No Shortage of CFD Codes to Choose From!

Caution for ACA Engineers:

Not all CFD Codes Are Created Equal

- **Developers Typically Claim to Offer '*Validated CFD Code'***
  - Implies that simulated results can be trusted to accurately predict real-flow characteristics for *any* configuration. ***But 'validated CFD code' is a misnomer!***
- **Claims Might be Based on Traditional Code Validation Approach**
  - Correlate computed and test results for *a chosen set of test cases*.
- **But…Traditional Code Validation is of Limited Value**
  - Even extensive correlations of computed and test results on geometries and flow conditions *that differ substantially from those being considered for design* are of limited value.
  - Too Many Potential Traps: *Generation of grid-converged solutions; Availability of on- and off-surface data from the same test; Reynolds number scaling of test data; Accurate matching of boundary conditions; User proficiency; etc., etc., etc.*

"Commercial CFD packages are often marketed by claiming that a particular code can solve almost every fluid flow problem, while many users, both in industry and academia, stand aloof from quantitative error measures, instead being dazzled by colorful computer generated output." **-- Celik (1993)***

"Increasing number of industrial companies rely on commercial software to meet their CFD needs… It is no longer possible to teach CFD the traditional way. Instead we should teach our students how to use commercial CFD codes." **-- Pelletier (1998)***

ACA Provides Customer Value ONLY IF
Engineers Wisely Choose and Apply the "Right" CFD Codes

*Boysan, H.F., Choudhury, D., and Engelman, M.S., "Commercial CFD in the Service of Industry: The First 25 Years," Notes on Numerical Fluid Mechanics, NNFM 100, Springer-Verlag, 2009, pp. 451-461, Hirschel, E.H. *et al.* (Editors)

Source: Ref. 1.22 & 1.24

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A Sage Advice for ACA Engineers

As True Today as in 1990—If Not More So

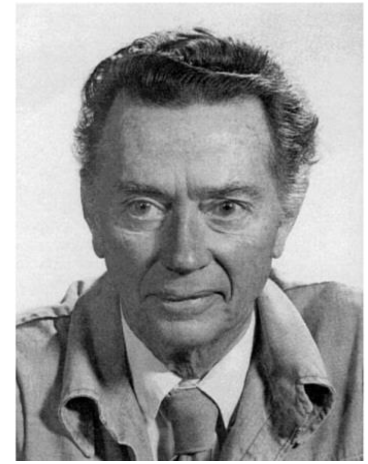
"Aeronautical calculations today rely on the awesome power of the computer. However, as has been observed, power can corrupt. Equipped with an appropriate address book, giving the location and availability of various programs, the aeronautical engineer can now command the solution of a great variety of aerodynamic problems. Moreover, the capacity of the computer has made possible the inclusion of many small physical influences that until now had to be neglected but sometimes create a false impression of high accuracy. However, the basic physical assumptions of calculations, if they are discussed at all, are often not given adequate treatment…"

If 'computer aerodynamics' is to realize its full potential, then more attention must be devoted to these underlying principles."

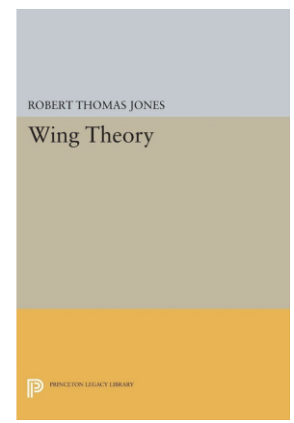
R.T. Jones, *Wing Theory*, Preface

Princeton University Press, Princeton, New Jersey, 1990

Robert T. "RT" Jones



Premier Aeronautical Engineer
28 May 1910 – 11 Aug 1999



CFD Competency is Necessary, *but not Sufficient*, to be an Effective Applied Computational Aerodynamics Engineer

It's the aerodynamics, stupid!*

*from famous snowclone *"It's the economy, stupid."* James Carville, 1992

Image Source: Wikipedia & Internet

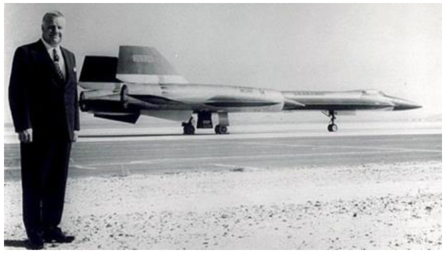
Talent Trumps Tools—*Everyday of the Week!*

Blackbirds: *A Unique Technological Achievement*

"Perhaps the most important characteristic of the Blackbirds is the fact that they were designed before the advent of supercomputing technology. *A small team of talented engineers, using slide-rules and know-how, built a family of operational airplanes capable of flying faster and higher than any air-breathing craft before or since*."

Peter W. Merlin,
Historian and Aerospace Archeologist, AIAA 2009-1022

"Everything about this airplane's creation was gigantic: Kelly Johnson rightly regarded the Blackbird as the crowning triumph of his years at the Skunk Works' helm. All of us who shared in its creation wear a badge of special pride. Nothing designed or built by any other aerospace operation in the world, before or since the Blackbird, can begin to rival its speed, height, effectiveness, and impact. Had we built Blackbird in the year 2010, the world would still have been awed by such an achievement. But the first model, designed and built for the CIA as the successor to U-2, was being test-flown as early as 1962. Even today, that feat seems nothing less than miraculous."



Ben Rich, SKUNK WORKS: *A Personal Memoir of My Years at Lockheed* 1994, pp 192

It's the airplane, stupid!*

*from famous snowclone *"It's the economy, stupid."* James Carville, 1992

An Unexpected Turn in the Road for the Author

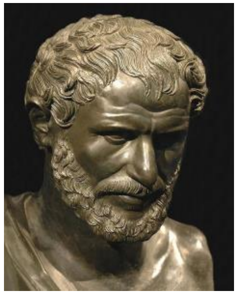
As the 1990s Wind Down

- **July 1999: *Author's Tech Fellow tenure ends! Management career begins!***
  - Raj *appointed* Department Manager, Aerodynamics, Lockheed Martin Aeronautical Systems (LMAS), Marietta, Georgia, to manage technical staff, technology base, tools and processes to support all lines of business including F-22, C-130J, C-5M, etc.

"When you come to a fork in the road, take it."
– Yogi Berra, American "Philosopher"

- **August 2000: Author's *Skunk Works*® *tenure begins!***
  - Lockheed Martin Aeronautics Company (LMAC) created in January 2000 by combining three legacy companies (LM Skunk Works, California; LM Aeronautical Systems, Georgia; LM Tactical Aircraft Systems, Texas) in Aeronautics Sector into *one with 3 sites* (California, Georgia, Texas) to improve chances of winning Joint Strike Fighter!
  - Raj selected to serve as Senior Manager, Vehicle Science & Systems, Technology Development & Integration, Advanced Development Programs (the Skunk Works®), LMAC--Palmdale, California, site
  - Primary Responsibility: lead high caliber teams to meet technology needs in *Aerodynamics & CFD, Acoustics, Airframe Propulsion Integration, Flight Control, Mass Properties, Vehicle Management System, Utility Systems Integration, and Electrical Power Distribution* for all LMAC product lines at the three sites

"The Only Constant in Life Is Change."
– Heraclitus of Ephesus
Ancient Greek pre-Socratic philosopher



Source: Wikipedia

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Lecture 9: Key Takeaways

- **Feb 1991: Realization [by author] that higher level CFD (Euler and Navier-Stokes) had little to no impact on reducing the number of YF-22 design cycles—*more design cycles in a given time is key to affordable quality*!**
  - An area of author's focus after assuming Tech Fellow position in Jan 1992
- **April 1991: Lockheed awarded F-22 EMD contract**
- **Fall 1991: F-22 EMD Team (Euler) application**
  - Full-aircraft forces, moments and airloads predictions for a wide range of flow conditions--with and without control surface deflections
  - **370 cases** run over three months, using 1600 CPU hours on Cray Y-MP/216
  - ***But…NO TOTAL DRAG! ACA wasn't ready. F-22 Program relied on wind-tunnel testing***
- **Throughout the 1990s: Focus on increasing TEAM effectiveness**
  - Extend TEAM to solving RANS equations for full configurations
  - Explore and implement means of automating grid generation and affordable HPC
- **Y2K: 24-hour turnaround time of full-aircraft RANS analysis using TetrUSS and cluster computing!**
- ***Developing effective capability from research concepts is a long and arduous process!***
- **CFD is now a commodity, but not all codes are created equal—choose & use wisely!**
- ***"The only constant in life is change"***

BIBLIOGRAPHY

Topic 5

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

5.2 Pursuit of Effectiveness (1980–2000)

5.2.1 Miranda, L. R., "Application of computational aerodynamics to airplane design", AIAA Journal of Aircraft, Vol. 21, No. 6 (1984), pp. 355-370. (Also AIAA Paper 82-0018, 20th Aerospace Sciences Meeting, Orlando, Florida, January 11-14, 1982) https://doi.org/10.2514/3.44974

5.2.2 Rizzi, A. and Eriksson, L.E., "Transfinite Mesh Generation and Damped Euler Equation Algorithm for Transonic Flow Around Wing-Body Configurations," AIAA Paper 81-0999, June 1981.

5.2.3 Jameson, A., Schmidt, W. and Turkel, E., "Numerical Solution of the Euler Equations by Finite-Volume Methods Using Runge-Kutta Time-Stepping Schemes," AIAA Paper 81-1259, June 1981.

5.2.4 Usab, Jr., W.J. and Murman, E.M., "Embedded Mesh Solutions of the Euler Equations Using a Multi-grid Method," AIAA 83-1946-CP, 6th Computational Fluid Dynamics Conference, Danvers, MA, 13-15 July 1983 https://doi.org/10.2514/6.1983-1946

5.2.5 Jameson, A. and Baker, T.J., "Multigrid Solution of the Euler Equations for Aircraft Configurations," AIAA-84-0093, 22nd Aerospace Sciences Meeting, Reno, Nevada, January 1984.

5.2.6 Benek, J.A., Buning, P.G., and Steger, J.L., "A 3-D Chimera Grid Embedding Technique," AIAA Paper 85-1523-CP, 7th Computational Physics Conference, Cincinnati, Ohio, 15-17 July 1985.

5.2.7 Löhner, R., Morgan, K., Peraire, J., and Zienkiewicz, O.C., "Finite Element Methods for High Speed Flows," AIAA-85-1531-CP, 7th Computational Physics Conference, Cincinnati, Ohio, 15-17 July 1985.

5.2.8 Jameson, A., Baker, T.J., and Weatherill, N.P., "Calculation of Inviscid Transonic Flow over a Complete Aircraft," AIAA Paper 86-0103, 24th Aerospace Sciences Meeting, Reno, Nevada, January 6-9, 1986.

5.2.9 Mavriplis, D.J., "Accurate multigrid solution of the Euler equations on unstructured and adaptive meshes," NASA CR 181679, June 1988.

5.2.10 Raj, P., "A Generalized Wing-Body Euler Code, FLO-57GWB," Lockheed-California Company Report, LR 30490, June 1983.

5.2.11 Sikora, J. S., and Miranda, L. R., "Boundary Integral Grid Generation Technique," AIAA Paper 85-4088, 3rd Applied Aerodynamics Conference, Colorado Springs, Colorado, October 14-16, 1985.

5.2.12 Singer, S.W., and Mattson, E.A., "Internal and External Flow Simulation Using Multizone Euler/Navier-Stokes Aerodynamic Method," SAE Paper 901856, October 1990.

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*).

BIBLIOGRAPHY

Topic 5.2 (contd.)

5.2.14 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 II: Grid Generation User's Manual," AFWAL-TR-87-3074, June 1989 (*supersedes December 1987 release*).

5.2.15 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 III: Flow Analysis User's Manual," AFWAL-TR-87-3074, June 1989 (*supersedes December 1987 release*).

5.2.16 Raj, P., "Aerodynamic Analysis Using Euler Equations: Capabilities and Limitations," Chapter 18, Applied Computational Aerodynamics, Progress in Astronautics and Aeronautics, Vol. 125, AIAA, Washington D.C., 1990, Henne, P.A. (Editor).

5.2.17 Singer, S.W., and Mattson, E.A., "Internal and External Flow Simulation Using Multizone Euler/Navier-Stokes Aerodynamic Methods," SAE Paper 901856, Aerospace Technology Conference and Exposition, Long Beach, CA, October 1-4, 1990.

5.2.18 Eriksson, L.E., and Rizzi, A., "Computation of Vortex Flows Around Wings Using the Euler Equations," Proceedings of the 4th GAMM Conference on Numerical Methods in Fluid Mechanics, October 1981.

5.2.19 Hitzel, S.M. and Schmidt, W., "Slender Wings with Leading Edge Vortex Separation: A Challenge for Panel Methods and Euler Solvers," AIAA Journal of Aircraft, Vol. 21, No. 10, 1984, pp 751-759.

5.2.20 Raj, P., and Sikora, J.S., "Free-Vortex Flows: Recent Encounters with an Euler Code," AIAA Paper 84-0135, 22nd Aerospace Sciences Meeting, Reno, NV, January 9-12, 1984.

5.2.21 Murman, E.M., and Rizzi, A., "Applications of Euler Equations to Sharp Edge Delta Wings with Leading Edge Vortices," AGARD Symposium on Application of Computational Fluid Dynamics in Aeronautics, Aux-Ed-Provence, France, April 1986.

5.2.22 Raj, P., Sikora, J.S. and Keen, J.M., "Free-Vortex Flow Simulation Using a Three-dimensional Euler Aerodynamic Method," ICAS Paper 86-1.5.2, Proceedings of the 15th Congress of the International Council of the Aeronautical Sciences, London, England, U.K., September 7-12, 1986.

5.2.23 Raj, P., Keen, J.M., and Singer, S.W., "Applications of an Euler Aerodynamic Method to Free-Vortex Flow Simulation," AIAA paper 88-2517, Proceedings of the 6th Applied Aerodynamics Conference, Williamsburg, VA, June 6-8, 1988. (Also in AIAA Journal of Aircraft, Vol. 27, No. 11, November 1990, pp 941-949).

5.2.24 Raj, P., "An Euler Code for Nonlinear Aerodynamic Analysis: Assessment of Capabilities," SAE Transactions, Vol. 97, Section 1: JOURNAL OF AEROSPACE (1988), pp. 1305-1320. (Also SAE Paper 881486, October 1988)

5.2.25 Raj, P., "Recent Developments in the Computational Solutions of Euler Equations (Invited)," Third International Congress of Fluid Mechanics, Cairo, Egypt, January 1990.

5.2.26 Raj, P., and Singer, S.W., "Computational Aerodynamics in Aircraft Design: Challenges and Opportunities for Euler/Navier-Stokes Methods," SAE Transactions, Vol. 100, Section 1: JOURNAL OF AEROSPACE, Part 2 (1991), pp 2069-2081 (Also iPAC 911990, International Pacific Air & Space Technology Conference, Gifu, Japan, October 7-11, 1991).

BIBLIOGRAPHY

Topic 5.2 (contd.)

5.2.27 Steinbrenner, J.P., Chawner, J.R., and Fouts, C.L., "A Structured Approach to Interactive Multiple Block Grid Generation," Application of Mesh Generation to Complex 3-D Configurations, AGARD-CP-464, March 1990.

5.2.28 Steinbrenner, J.P., Chawner, J.R., and Fouts, C.L., "Multiple Block Grid Generation in the Interactive Environment," AIAA 90-1602, AIAA 21st Fluid Dynamics, Plasma Dynamics and Lasers Conference, Seattle, WA, June 18-20, 1990.

5.2.29 Steinbrenner, J.P., Chawner, J.R., and Fouts, C.L., 'The GRIDGEN 3D Multiple Block Grid Generation System," WRDC-TR-90-3022, July 1990.

5.2.30 Steinbrenner, J.P., and Anderson, D.A., "Grid Generation Methodology in Applied Aerodynamics," Chapter 4, Applied Computational Aerodynamics, Progress in Astronautics and Aeronautics, Vol. 125, AIAA, Washington D.C., 1990, Henne, P.A. (Editor).

5.2.31 Clarke, D.K., Salas, M.D.,, and Hassan, H.A., "Euler Calculations for Multielement Airfoils using Cartesian Grids," AIAA Journal, Vol. 24, No. 3, March 1986, pp. 353-358.

5.2.32 Raj, P., and Harris, B., "Using Surface Transpiration with an Euler Method for Cost-effective Aerodynamic Analysis," AIAA 93-3506, Proceedings of the 11th AIAA Applied Aerodynamics Conference, Monterey, CA, August 9-11, 1993.

5.2.33 Bangert, L.H., Johnston, C.E., and Schoop, M.J., "CFD Applications in F-22 Design," AIAA Paper 93-3055, July 1993.

5.2.34 Goble, B.D, King, S., Terry, J., and Schoop, M.J., "Inlet Hammershock Analysis Using a 3-D Unsteady Euler/Navier-Stokes Code," AIAA 96-2547, 32nd AIAA, ASME, SAE and ASEE, Joint Propulsion Conference and Exhibit, Lake Buena Vista, FL, July 1-3 1996

5.2.35 Olling, C.R., and Mani, K.K., "Navier-Stokes and Euler Computations of the Flow Field Around a Complete Aircraft," SAE paper 881488, October 1988.

5.2.36 Raj, P., Olling, C.R., and Singer, S.W., "Application of Euler/Navier-Stokes Aerodynamic Methods to Aircraft Configuration," ICAS Paper 90-6.4.4, Proceedings of the 17th Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, September 9-14, 1990.

5.2.37 Goble, B.D., Raj, P., and Kinard, T.A., "Three-dimensional Euler/Navier-Stokes Aerodynamic Method (TEAM) Upgrade, Version 713 User's Manual," WL-TR-93-3115, February 1994.

5.2.38 Kinard, T.A., and Harris, B.W., "Evaluation of Two Unstructured CFD Methods," AIAA Paper 94-1877, 12th Applied Aerodynamics Conference, Colorado Springs, Colorado, June 20-24, 1994.

5.2.39 Kinard, T.A., Finley, D.B., and Karman, Jr., S.L., "Prediction of Compressibility Effects Using Unstructured Euler Analysis on Vortex Dominated Flow Fields," AIAA 96-2499, 14th Applied Aerodynamics Conference, New Orleans, Louisiana, June 17-20, 1996.

5.2.40 Raj, P., Kinard, T.A., and Vermeersch, S.A., "Vortical Flow Simulation Using an Unstructured-Grid Euler Method," ICAS 96-1.4.5, Proceedings of the 20th Congress of the International Council of the Aeronautical Sciences, Sorrento, Italy, September 1996.

BIBLIOGRAPHY

Topic 5.2 (contd.)

5.2.41 Kinard, T.A., Harris, B.W., and Raj, P., "An Assessment of Viscous Effects in Computational Simulation of Benign and Burst Vortex Flows on Generic Fighter Wind-Tunnel Models Using TEAM Code," NASA Contractor Report 4650, March 1995.

5.2.42 Kinard, T.A, Harris, B., and Raj, P., "Computational Simulation of Benign and Burst Vortex Flows," AIAA Paper 95-1815, Proceedings of the 13th Applied Aerodynamics Conference, San Diego, CA, June 19-22, 1995.

5.2.43 Frink, N.T., Pirzadeh, S., and Parikh, P., "An Unstructured-Grid Software System for Solving Complex Aerodynamic Problems," NASA CP 3291, pp 289-308. (Also NASA Workshop on Surface Modeling, Grid Generation and Related Issues in Computational Fluid Dynamics (CFD) Solutions, NASA-Lewis Research Center, Cleveland, OH, May 9-11, 1995)

5.2.44 Frink, N.T., and Pirzadeh, S.Z., "Tetrahedral Finite-Volume Solutions to the Navier-Stokes Equations on Complex Configurations," NASA/TM-1998-208961, December 1998. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19990007832.pdf

5.2.45 Goble, B.D., and Hooker, J.R., "Validation of an Unstructured Grid Euler/ Navier-Stokes Code on a Full Aircraft with Propellers," AIAA Paper 2001-1003, 39th Aerospace Sciences Meeting, Reno, Nevada, 8-11 January 2001.

5.2.46 Hooker, J.R., "Aerodynamic Development of a Refueling Pod for Tanker Aircraft," AIAA Paper 2002-2805, 20th Applied Aerodynamic Conference, St. Louis, Missouri, 24-26 June 2002.

5.2.47 Cunningham, A.M., Jr., Anderson, W.D., Patel, S.R., and Black, C.L., "Lockheed Martin Aeronautics Perspective on Aircraft Buffet Prediction and Analysis," Symposium on Flow-Induced Unsteady Loads and Impact on Military Applications, Applied Vehicle Technology Panel (AVT), NATO, Budapest, Hungary, 25-28 April 2005.

5.2.48 Hooker, J.R., Hoyle, D.L., and Be6.1s, D.N., "The Application of CFD for the Aerodynamic Development of the C-5M Galaxy," AIAA 2006-0856, 44th Aerospace Sciences Meeting, Reno, Nevada, 9-12 January 2006.

5.2.49 Wooden, P.A., Smith, B.R. and Azevedo, J.J., "CFD Predictions of Wing Pressure Distributions on the F-35 at Angles-of-Attack for Transonic Maneuvers," AIAA-2007-4433, 25th Applied Aerodynamics Conference, Miami, Florida, 25-28 June 2007.

5.2.50 Morgenstern, J., Buonanno, M., and Norstrud, N., "N+2 Low Boom Wind Tunnel Model Design and Validation," AIAA 2012-3217, 30th Applied Aerodynamics Conference, New Orleans, LA, 27 June 2012.