6. Evolution of Applied Computational Aerodynamics (2 of 5)

The 6th of 12 lectures by Prof. Raj to share his perspective on effective application of computational aerodynamics to aircraft design.

Each lecture contains excerpts from the presentation shown below describing his exciting journey on a long and winding road for more than five decades!

Reflections on the Effectiveness of Applied Computational Aerodynamics for Aircraft Design

https://www.aoe.vt.edu/people/emeritus/raj/personal-page/reflections-on-ACA-effectiveness.html

Pradeep Raj, Ph.D.
Collegiate Professor Emeritus
Kevin T. Crofton Department of Aerospace and Ocean Engineering
Virginia Tech, Blacksburg, Virginia, USA
http://www.aoe.vt.edu/people/emeritus/raj.html

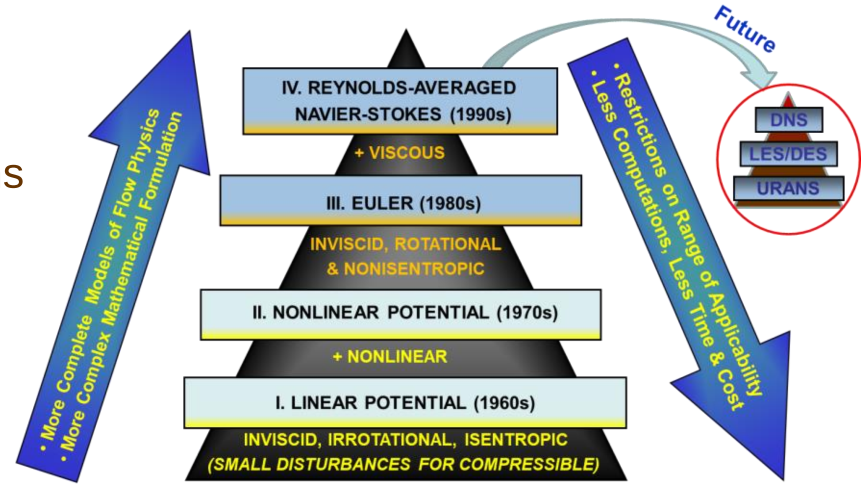
Program Management Director, Lockheed Martin (Retired)
Deputy Director, Technology Development & Integration
The Skunk Works®, Palmdale, California, USA

Advanced Development Programs

LOCKHEED MARTIN

Lecture 5: Key Takeaways

- **ACA evolution paced by impressive advances since the 1950s**
  - Capabilities directly related to four levels of CFD methods, each based on approximations of Navier-Stokes equations
    - *Level I:* linear potential methods for inviscid, irrotational, isentropic flows
    - *Level II:* nonlinear potential methods for inviscid, irrotational, isentropic flows
    - *Level III:* Euler methods for inviscid flows
    - *Level IV:* RANS methods for viscous flows



- **Linear Potential Methods (LPMs)**
  - Vortex Lattice Method (VLM) and Surface Panel Method: *1950s*
  - Technology comes of age in *1980s—Today's workhorse for early stages of design*
  - Range of applicability limited to purely subsonic or supersonic attached flows
- **"Computer-aided Aerodynamics" Demonstrated Its Usefulness for Meeting Supersonic Aircraft Design Needs: *1960s***
  - Harris Wave Drag analysis
  - Aerodynamic design integration of supersonic aircraft
- **Meeting Transonic Aircraft Design Needs: 1960s**
  - **LPMs woefully inadequate**

Topics

Preface

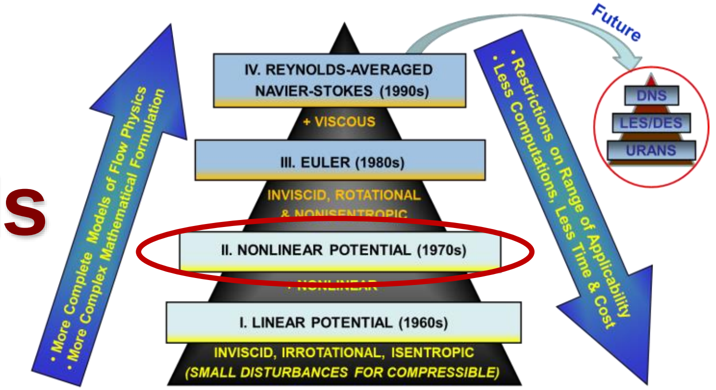
1. **Introduction**
2. **Genesis of Fluid Dynamics *(Antiquity to 1750)***
3. **Fluid Dynamics as a Mathematical Science *(1750–1900)***
4. **Emergence of Computational Fluid Dynamics *(1900–1950)***
5. **Evolution of Applied Computational Aerodynamics *(1950–2000)***
   - ***5.1 Infancy through Adolescence (1950–1980)***
     - Level I: Linear Potential Methods (LPMs)
     - Level II: Nonlinear Potential Methods (NPMs)
   - ***5.2 Pursuit of Effectiveness (1980–2000)***
     - Level III: Euler Methods
     - Level IV: Reynolds-Averaged Navier-Stokes (RANS) Methods
6. **ACA Effectiveness: Status and Prospects *(2000 and Beyond)***
   - ***6.1 Assessment of Effectiveness (2000–2020)***
   - ***6.2 Prospects for Fully Effective ACA (Beyond 2020)***
7. **Closing Remarks**

Appendix A. An Approach for ACA Effectiveness Assessment

Level II

Nonlinear Potential Methods

1970s - present



Flow Model

- **Inviscid, Irrotational, Isentropic**

$$U = (u,\ v,\ w) = \nabla\Phi$$

$$\Phi_{tt} + 2\,U.U_t = a^2\,\nabla^2\Phi - U.\nabla(U^2/2)$$

  - ✓ Nonlinear second-order PDEs with appropriate boundary conditions
  - ✓ Transonic Small Disturbance (TSD) or Full Potential formulations
    - ○ Mass conserved across discontinuities
    - ○ Momentum deficiency provides an estimate of wave drag
    - ○ *Wakes not captured as part of the solution—must be explicitly modeled*

Applicability

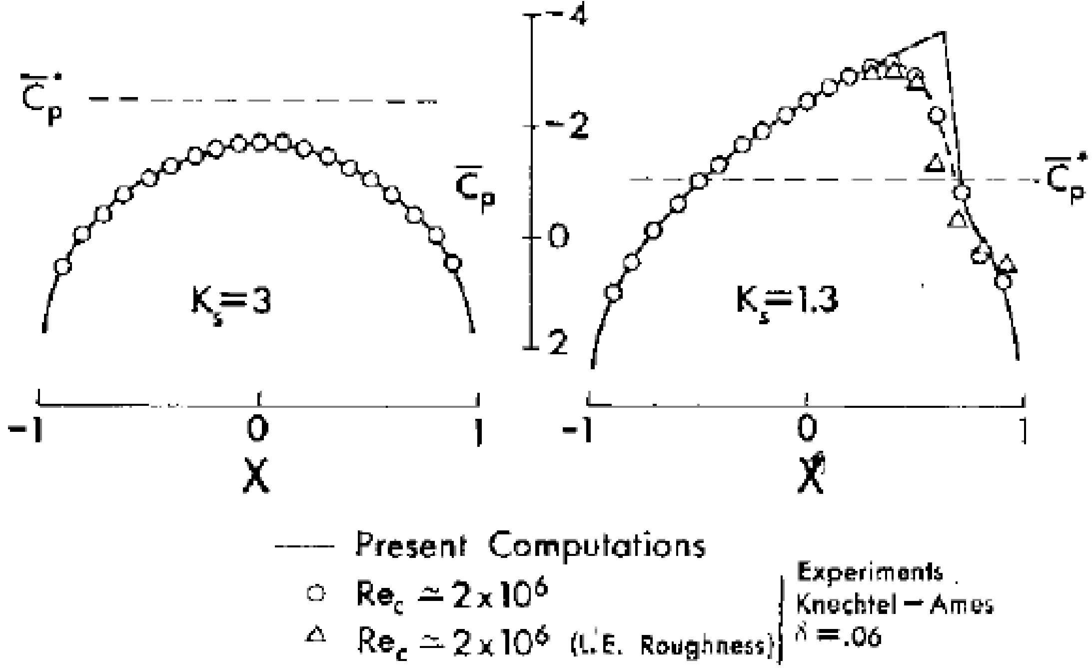
- Transonic flows with weak shocks
- Flows with no distributed vorticity and/or boundary-layer separation

Birth of Nonlinear Potential Methods

1970s

Murman and Cole (1970)

- **Landmark paper** AIAA 70-188, Jan 1970; *published in the AIAA Journal, 9 (1), 1971*
- **Mixed finite difference scheme** for perturbation potential equation of plane steady transonic flow; *requires meshing a domain surrounding the geometry*



$K_s = (1 - M_\infty^2)/(M_\infty^2\delta)^{2/3}$ Transonic similarity parameter after Spreiter

> ***"Supersonic zone and shock waves appear naturally in the course of the solution."***

Earll Murman

Hon Fellow AIAA
Boeing, Flow Research, NASA
MIT Professor Emeritus
Born: 12 May 1942

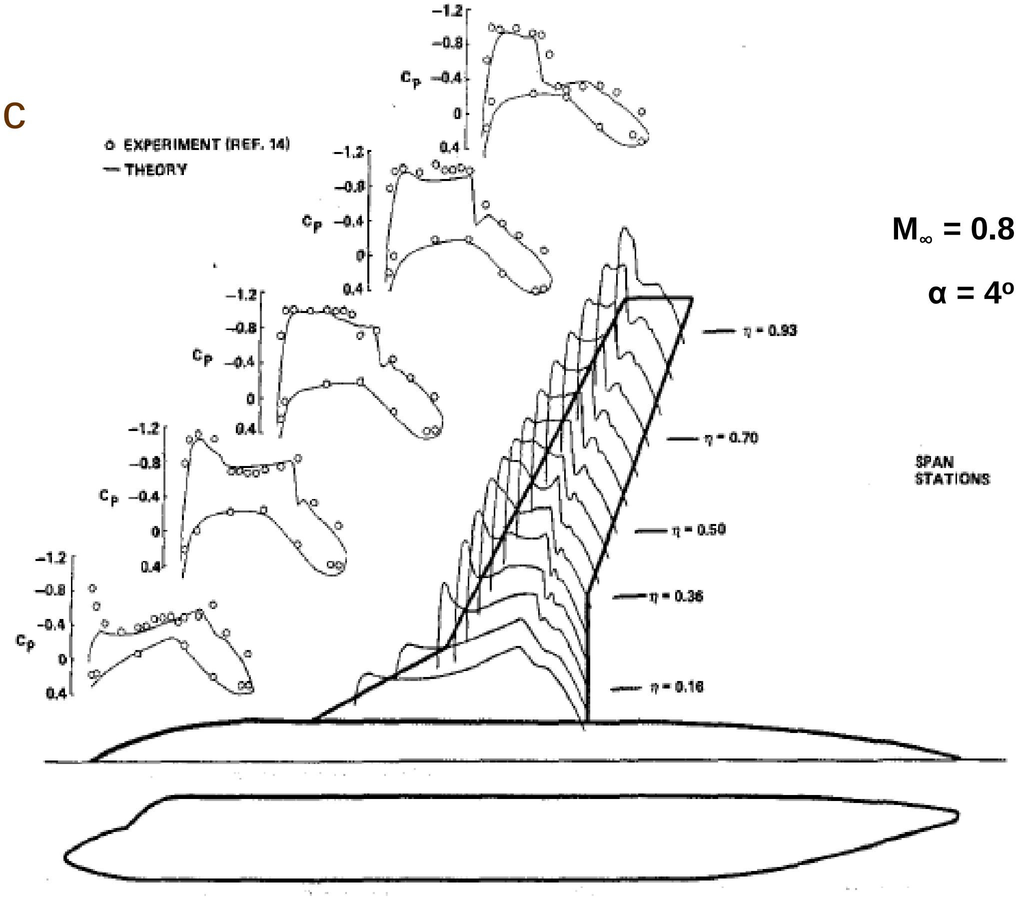
Circular Arc Airfoil

- 74x41 mesh points
- 400 iterations
- ***30 minutes on IBM 360/44***

Source: Refs. 5.1.35

Transonic Small Disturbance (TSD) Equations
Methods for Wing and Wing-Fuselage Configurations

- **Bailey and Ballhaus (1975)**
  - Good comparisons of computed and measured pressures for transonic flows on wing and wing-fuselage configurations—*NASA SP-347*
- **Boppe (1978)**
  - Transonic flow about realistic aircraft configurations—*AIAA Paper 78-104, 1978*
  - Finite-difference scheme applied to an improved TSD equation
    - ✓ *Unique grid embedding scheme to improve solution accuracy*
  - Approx. **45 minutes on IBM 370** (15 mins. on CYBER 175)



$M_\infty = 0.825$

$\alpha = 4^o$

A New Transonic Aerodynamic Analysis and Design Capability!

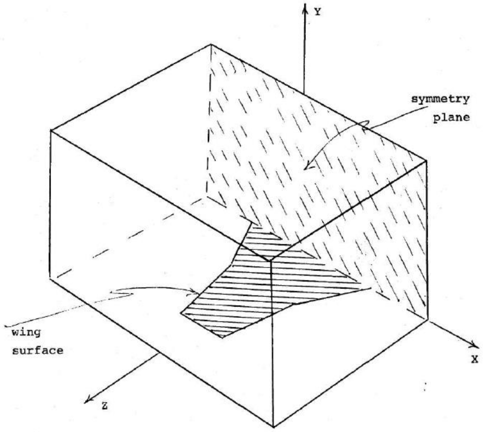
Source: Refs. 5.1.36 & 5.1.37

Transonic Full Potential Equations (FPE)

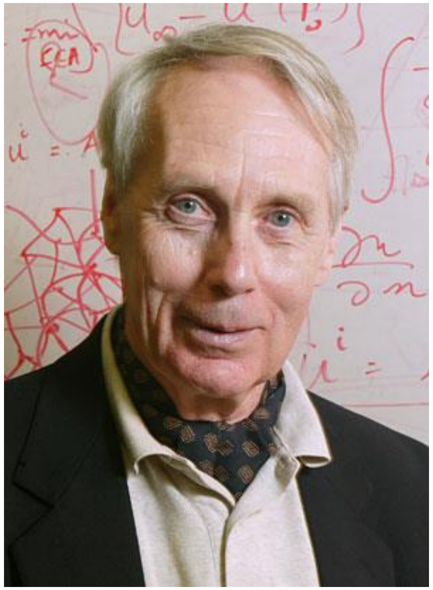
A Method for Swept Wings

Jameson and Caughey (1976)

- **FLO 22: 3-D swept wings**
  - ✓ Full Potential Equations transformed into sheared parabolic coordinates
  - ✓ Solved using Jameson's coordinate invariant ***rotated difference scheme***
- **Final Mesh:** 192x24x32 cells; 100 relaxation sweeps; 85 minutes CPU time on CDC 6600



Antony Jameson



FRS, Hon Fellow AIAA,
Foreign Member NAE
'Father of FLO & SYN Series of CFD Codes'
Hawker Siddeley, Grumman
NYU, Princeton, Stanford, Texas A&M
Born: 20 Nov 1934

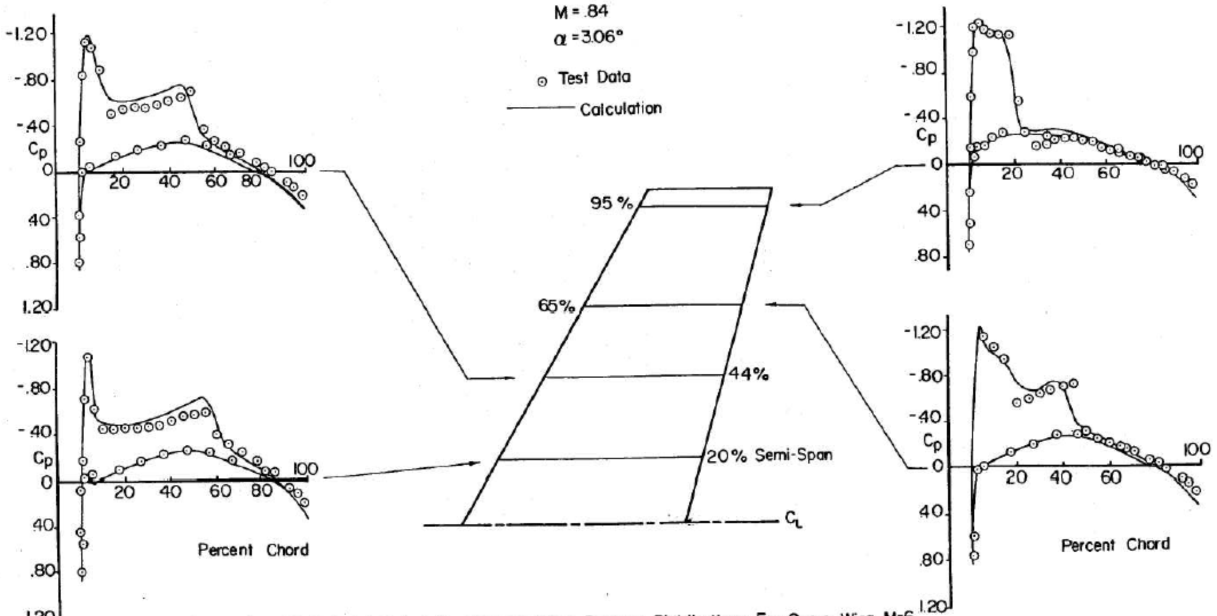


Figure 8. Comparison Of Calculated And Experimental Wing Pressure Distributions For Onera Wing M-6

- **Theory, Results, and Computer Program** in *ERDA Research and Development Report, COO-3077-140, 1977*

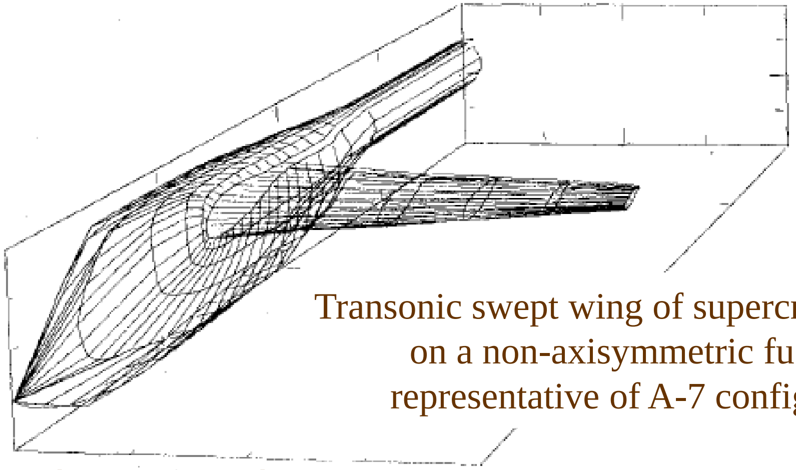
Source: Refs. 5.1.38 to 5.1.42

Transonic Full Potential Equations

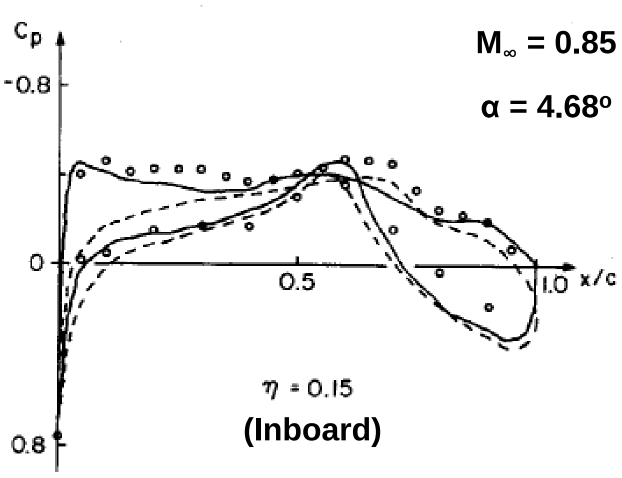
A Method for Wing-Body Combinations

Caughey and Jameson (1980)

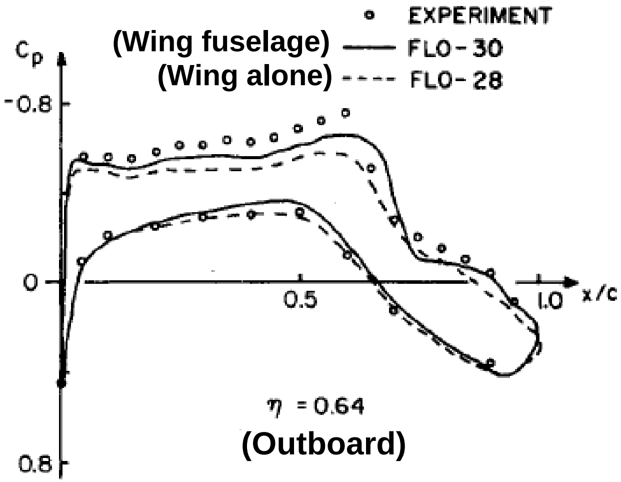
- ○ **FLO 28 & FLO 30**: transonic flow past **wing-body combinations** using **finite-volume method** on boundary conforming grids—*AIAA J, 18(11), 1980*
  - **FLO-28:** Fully conservative difference scheme in the Joukowsky/parabolic coordinate system.
  - **FLO-30:** Fully conservative difference scheme in the cylindrical/wind-tunnel coordinate system.



Transonic swept wing of supercritical section on a non-axisymmetric fuselage, representative of A-7 configuration



(Inboard)



(Outboard)

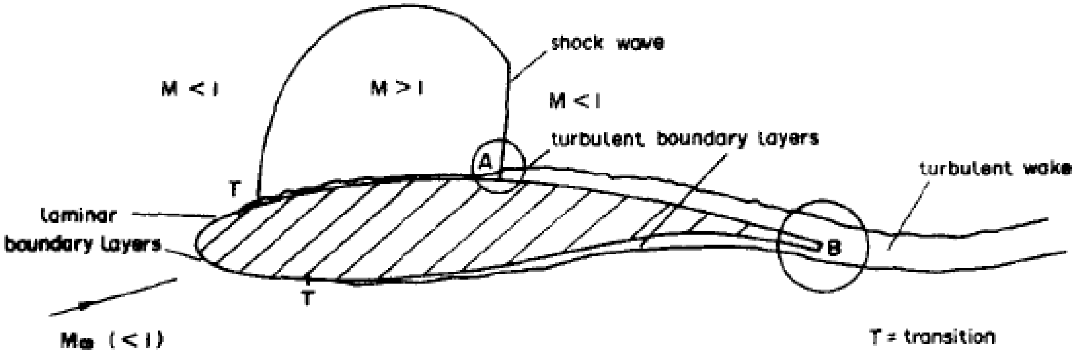
- ○ Three-mesh sequence; coarsest mesh: 40x6x8 cells; finest mesh: 160x24x32 cells
- ○ 200 iterations on two coarse meshes; 100 on finest mesh
- ○ **35 minutes of CPU time on CDC 7600**

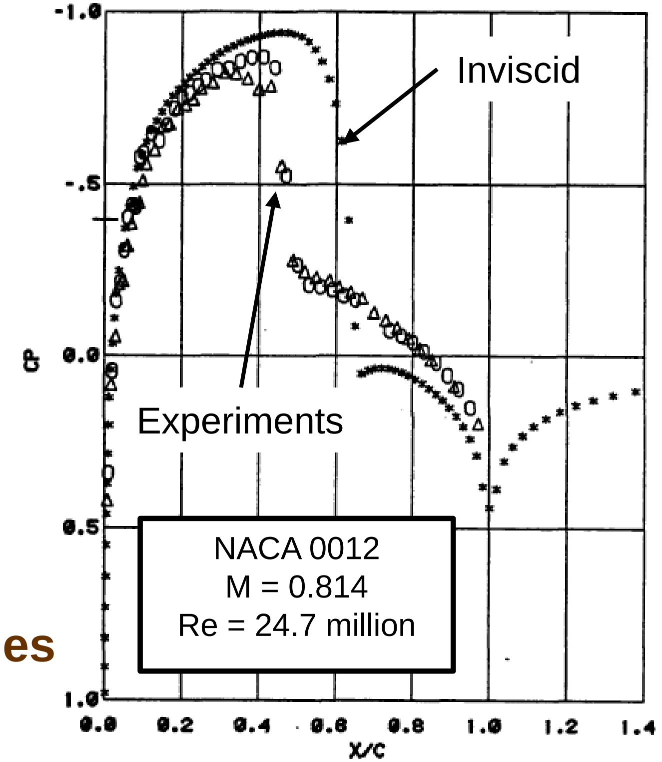
Source: Ref. 5.1.43

Limitations of Potential Flow Methods

Implications of Neglecting Viscosity

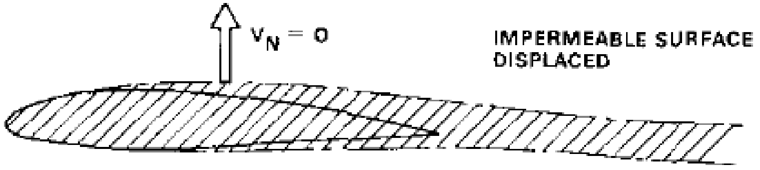
- **Potential Flow Methods, Linear and Nonlinear, *Being <u>Inherently Inviscid</u>*, Cannot Capture Effect of Viscosity on the Flow Field**
  - ○ ***Particularly problematic for transonic flows***

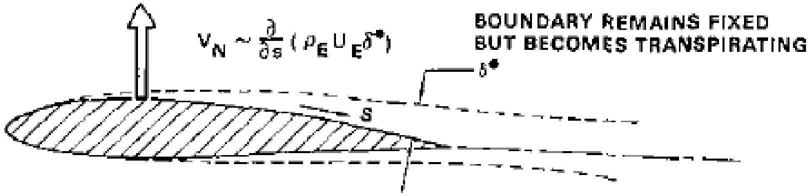




- **1970s: Two Viscous-Inviscid Interaction Schemes Developed to Simulate Effects of Viscosity**

1. Add boundary-layer (B.L.) displacement thickness, δ, to configuration surface and compute potential flow on the new surface
   - Estimate δ using integral B.L. equations
2. Use transpiration boundary condition on configuration surface to compute potential flow which simulates change in shape due to B.L.
   - More convenient; no need to regenerate mesh





Source: Refs. 5.1.44 and 5.1.45

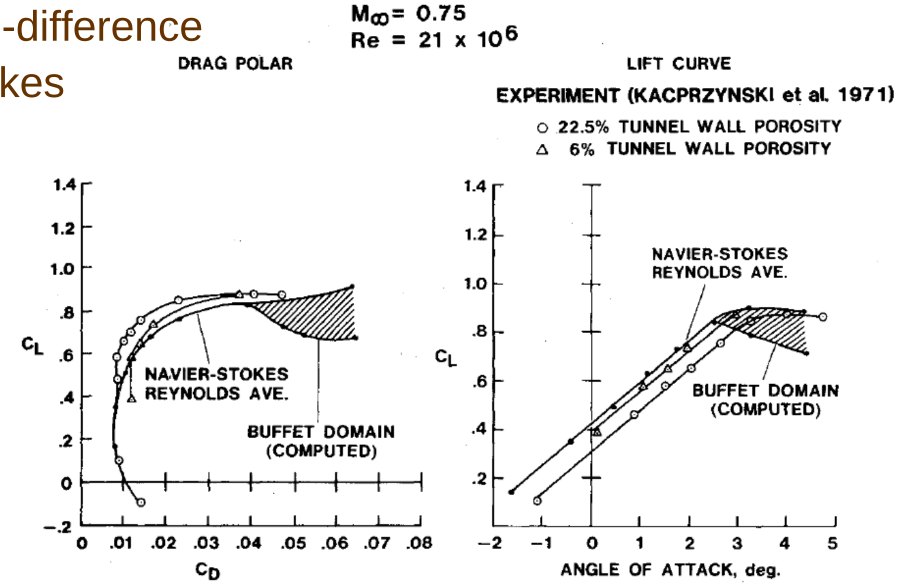
Why Not Use RANS Methods?

They Overcome Limitations of Potential Flow Methods!

Very Active Area of Research in the 1970s, But Not Many Practical Applications

- **Laminar Flows** *(Considered as a special case of RANS with Zero Turbulence!)*
  - **MacCormack (1971)—**Pioneering investigation of shock-wave interaction with laminar boundary layer
  - **Carter (1972)—**Supersonic laminar flow over a 2-D compression corner
  - **Li (1974)—**laminar flow separation on blunt flared cones at angle of attack
  - **Tannehill et al. (1976)—**2-D blunt-body flows with impinging shock
  - **Steger and Kutler (1976)—**implicit finite-difference procedures for computation of vortex wakes
- **Turbulent Flows**
  - **Wilcox (1974)—**turbulent boundary-layer shock-wave interaction
  - **Deiwert (1974)—**high Reynolds number transonic flow simulation
  - **Shang & Hankey (1975)—**supersonic and hypersonic turbulent flows over a compression ramp
  - **Deiwert and Bailey (1978)—**computing airfoil aerodynamics with RANS codes

Supercritical Airfoil



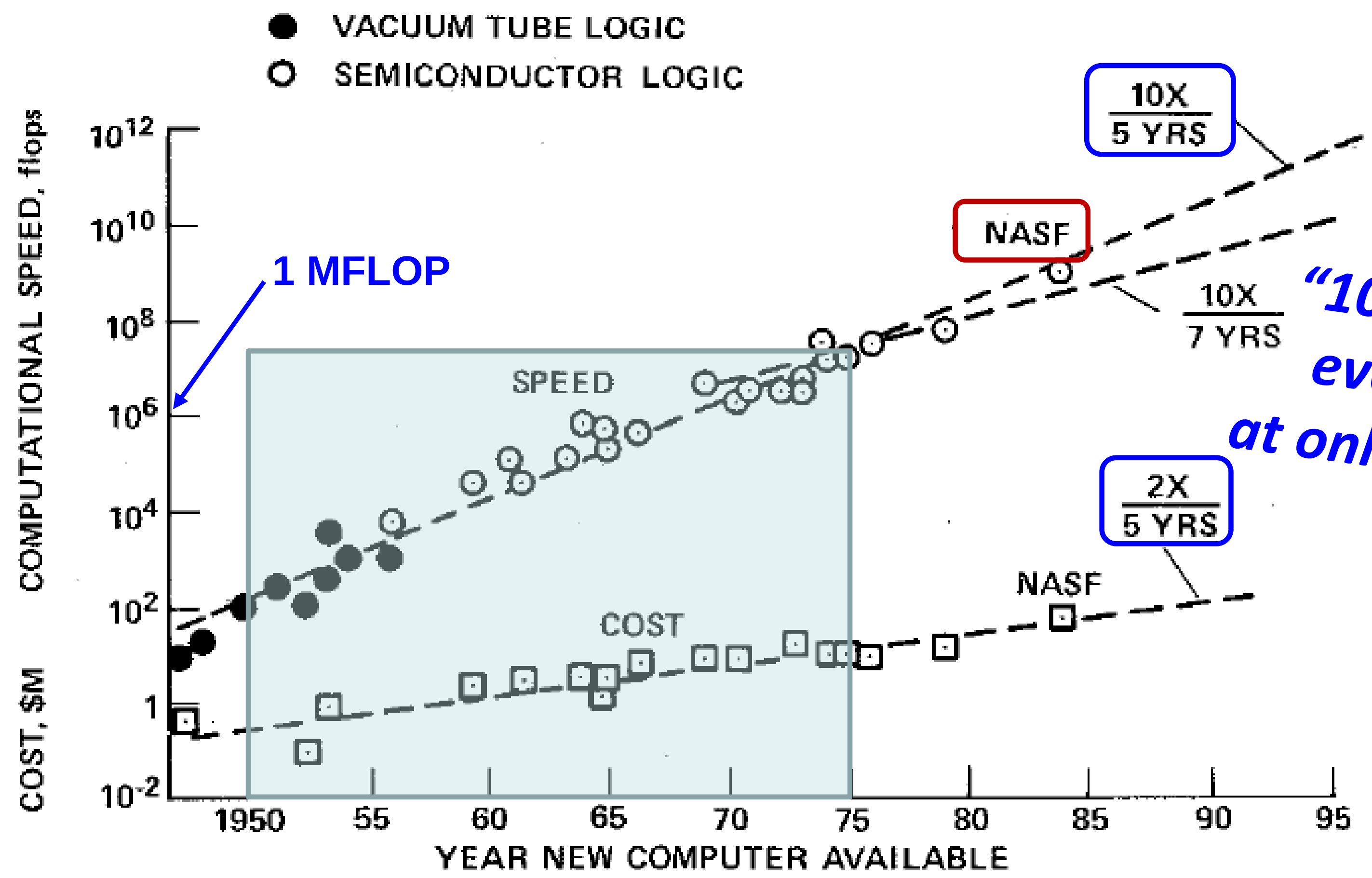
> ***"…RANS approximation…a more youthful stage of development."***
>
> ***— Dean Chapman, Director of Aeronautics, NASA Ames***

Source: Refs. 5.1.46 to 5.1.52

Digital Computers:

A Key Enabler for RANS CFD Research

Speed & Cost Trends (1950 to 1975)



NASF
Numerical
Aerodynamic
Simulation
Facility

"10X the speed every 5 years at only 2X the cost"

Factoid: early computing speed measure was ***kilo-girls***, roughly the calculating ability of a thousand women!

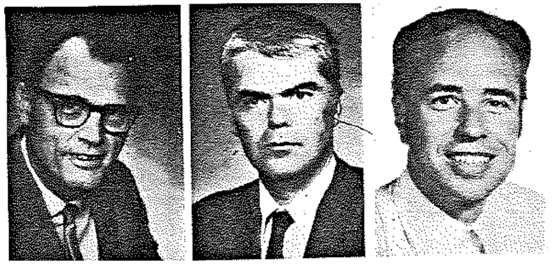
Phenomenal Cost-performance Increase Over 25 Years

Source: Ref. 5.1.53

Expert Assessment of CFD Future (*Mid-1970s*)

Computers vs. Wind Tunnels for Aerodynamic Flow Simulations

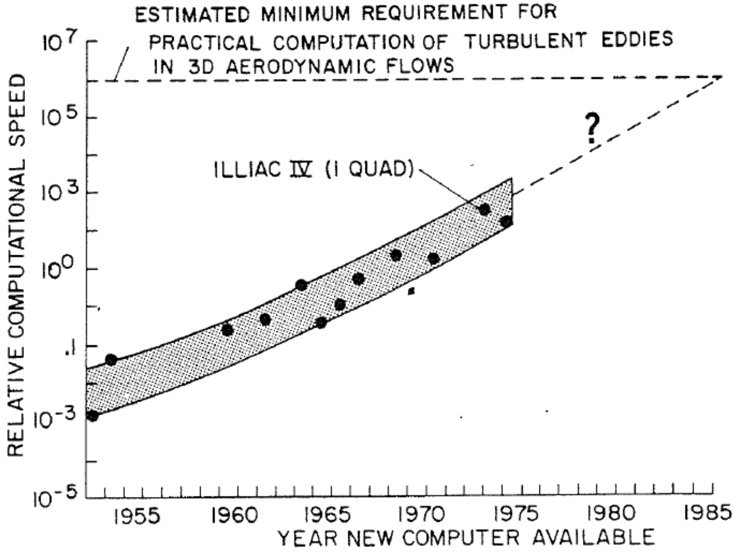
DEAN R. CHAPMAN, HANS MARK, and MELVIN W. PIRTLE
NASA Ames Research Center



AIAA Astronautics & Aeronautics
APRIL 1975 **VOLUME 13, NO. 4**

"…within a decade computers should begin to supplant wind tunnels in the aerodynamic design and testing process…"

"To *displace* wind tunnels as the principal source of flow simulations for aircraft design, computers must reach about 10^4 times the speed of ILLIAC IV…such computer performance should be available in the mid-1980s, or somewhat later..."



The Adolescent Years with Irrational Exuberance!

We got caught up in the euphoria of our promising accomplishments

Source: Ref. 5.1.54

"Imagining the Future"

Long After CFD Displaced Wind Tunnels!

"The most accurate aerodynamic prediction code available today, FLO-1234.5, is so complex and expensive that it has never been run. Many other codes, if run to completion, would require CPU time exceeding the average human lifespan."

"Fortunately there is an exciting new technology…Two workers at UNCAF (United Nations Computational Aerodynamics Facility) have recently made a **startling *discovery…by building a small wooden model of an airplane and then blowing air past it in an enclosed tunnel, reasonably accurate predictions may be made of what the flow codes would compute.*** Also, some factors, such as artificial viscosity (numerical diffusion), are neglected completely in wind tunnel modeling."

"While the wind tunnel may never fully replace the computer, it is almost certain to become the most useful engineering tool of the future."

Will the Wind Tunnel Replace the Computer?
By BOB COOPERSMITH
AIAA Student Journal
Summer 1985

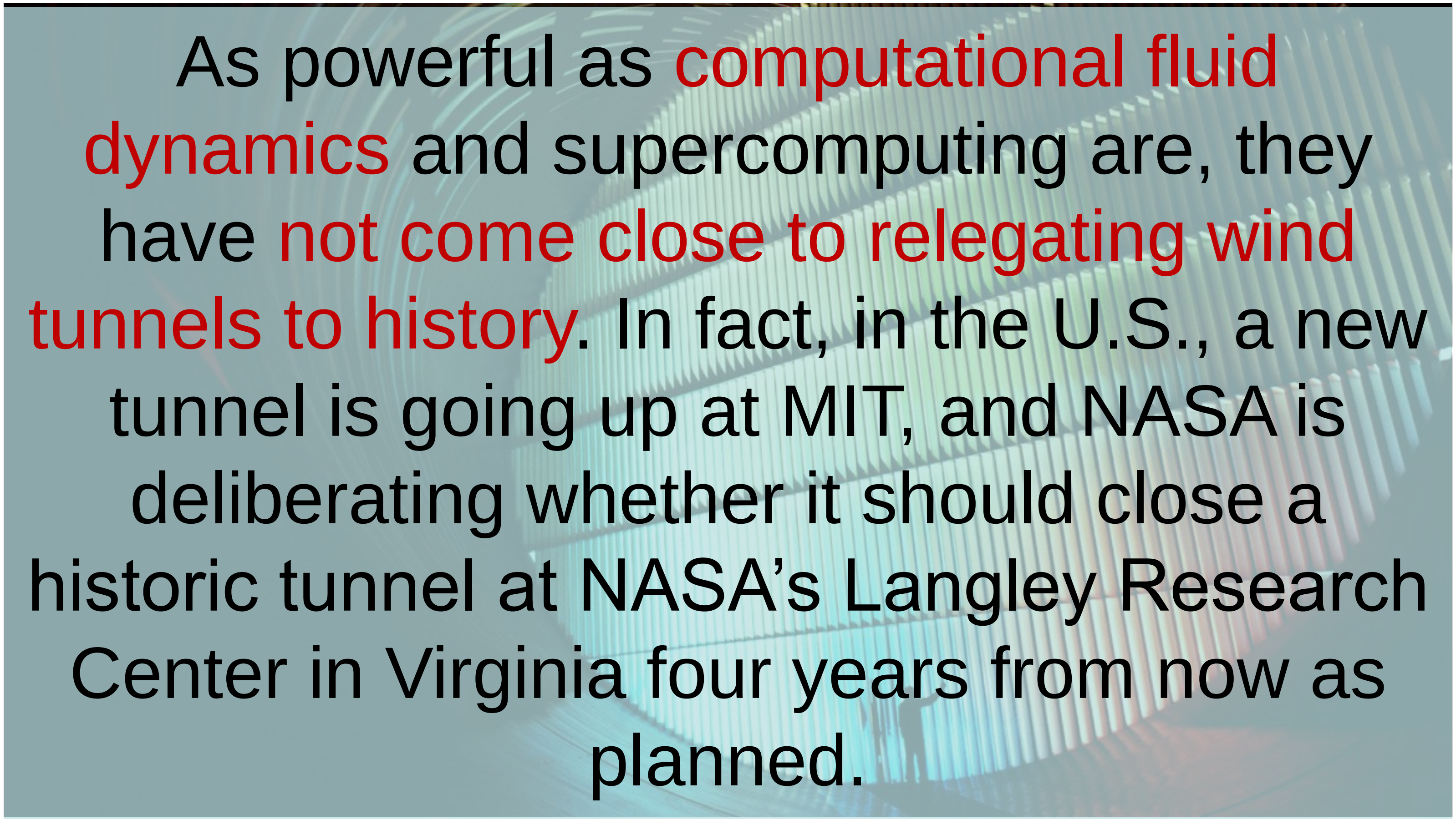
Wind Tunnels Are Here To Stay!

Symbiosis: Why CFD and wind tunnels need each other

By JOE STUMPE

AIAA Aerospace America

JUNE 2018



As powerful as computational fluid dynamics and supercomputing are, they have not come close to relegating wind tunnels to history. In fact, in the U.S., a new tunnel is going up at MIT, and NASA is deliberating whether it should close a historic tunnel at NASA's Langley Research Center in Virginia four years from now as planned.

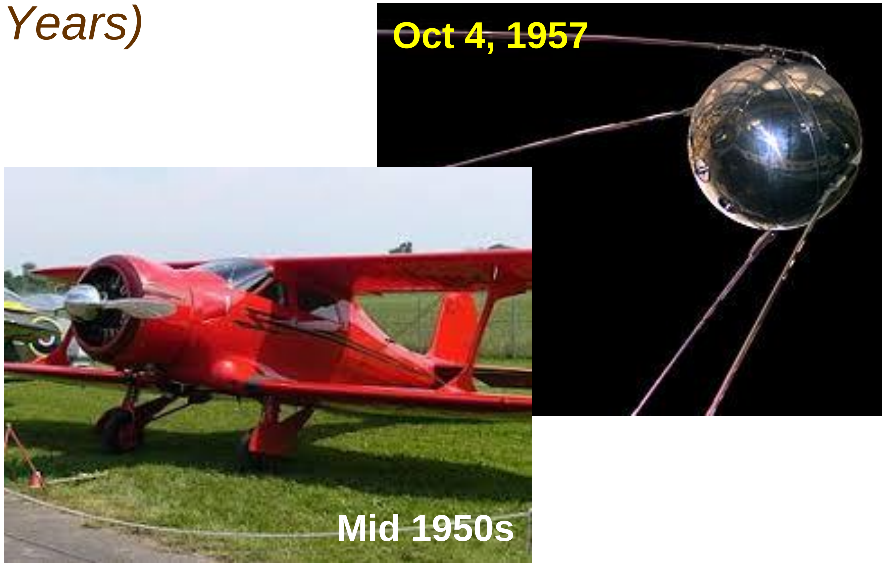
Computers Have Failed to Supplant W/Ts Defying Experts!

Source: Ref. 5.1.55

While the World of CFD Was Exploding in ’50s &’60s

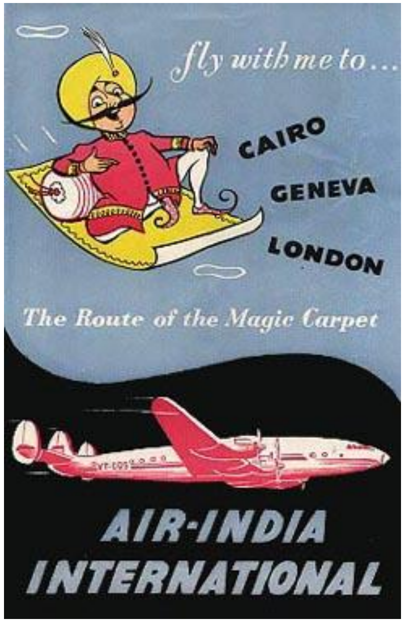
…a lad was growing up* completely oblivious to it all!

1950s *(Foundational Years)*



Oct 4, 1957

Mid 1950s



1950s

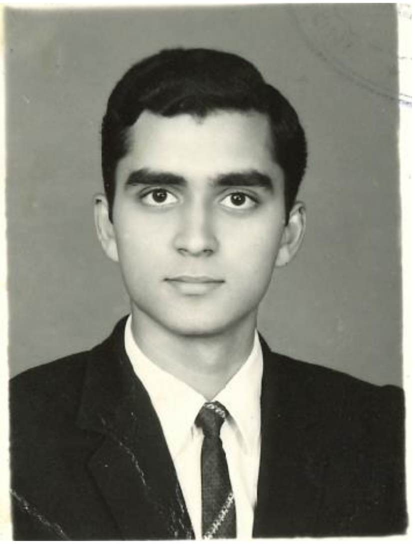
1960s *(Formative Years)*

1963 **High School** (10th grade): Government Higher Secondary School, Muzaffarnagar, U.P., India *(1st division; distinction in English, Mathematics, Science and Sanskrit; ranked 15th in statewide exam)*

1965 **Intermediate College** (12th grade): S.D. Intermediate College, Muzaffarnagar, U.P., India *(1st division; distinction in Physics, Chemistry and Mathematics; ranked 7th in statewide exams; too young for IIT)*

1967 **Bachelor of Science**: S.D. College, Muzaffarnagar, U.P., India; College affiliation—Agra University, now Meerut University *(1st division; distinction in Physics, Chemistry, and Math; graduated at the top of the class; Chancellor’s Medal)*

1970 **Bachelor of Engineering** (with Distinction), **Electrical Technology** Indian Institute of Science, Bangalore, India *(graduated at the top of the class; recipient of Hay Medal)*



**has grown old now (born 15 Dec 1949), but debatable if he ever grew up!*

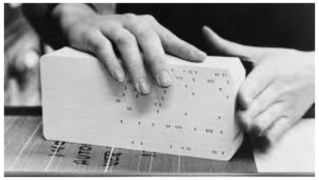
Source: Personal archives and Internet

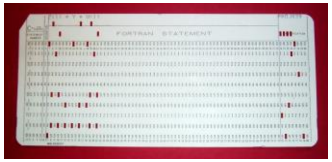
A Budding Aerospace Engineer in the ‘70s

1970s *(Young Adult Years)*

1970 - 1972

- **Master of Engineering** (with Distinction), **Aeronautical Engineering**
  Indian Institute of Science, Bangalore, India
- Advisor: **Dr. Suresh M. Deshpande**
- Project: *Numerical Determination of Periodic Solutions for Gravity Gradient Stabilized Satellites*
  - **First exposure to FORTRAN programming & computer codes**
    - ✓ Integrated two coupled 1st order ODEs
    - ✓ Used **IBM 360/44** for processing





1972 - 1976

- **Ph.D.**, **Aerospace Engineering**
  Georgia Institute of Technology, Atlanta, Georgia, USA
- Advisor: **Dr. Robin B. Gray**
- Dissertation: *A Method of Computing the Potential Flow on Thick Wing Tips*
  - Developed **LPM** using **surface vorticity distribution**
    - ✓ Vorticity strength determined using iterative procedure; avoided inverting large ill-conditioned matrices
    - ✓ **CDC Cyber 70/74** NOS 1.1-419/420
  - 2-D results in *AIAA Journal of Aircraft, 15 (10), 1978*
  - 3-D results in AIAA *Journal of Aircraft, 16 (3), 1979*

Source: Refs. 5.1.56 & 5.1.57; images from internet

Entrée into the *"World of CFD"*!

1976 - 1978

- **Research Assistant Professor**, Aerospace Engineering, Iowa State University, Ames, Iowa
- NASA-Ames sponsored project: *Alleviation of wake-vortex hazard through **merging of co-rotational vortices***
- Principal Investigator: **Dr. James D. Iversen**
- Raj conducted computational investigations to complement experimental research of **Steve Brandt**
  - ✓ ***Immensely fortunate** to have a chance to work with, and learn from, **Dr. Joseph L. Steger—a CFD pioneer, a professional, and a gentleman—**at NASA-Ames Research Center*
  - ✓ ***Experienced the challenge of simulating vortical flows using zero, one, and two equation turbulence models in Steger & Kutler's implicit finite-difference procedure for computation of vortex wakes***

Joseph L. Steger

CFD Pioneer
NASA Ames, Stanford,
Univ. of California-Davis
(1944-1992)

1978 - 1979

- **Assistant Professor**, University of Missouri-Rolla
- **Taught Undergraduate courses**: Fluid Mechanics, Thermodynamics, and Heat Transfer

1979

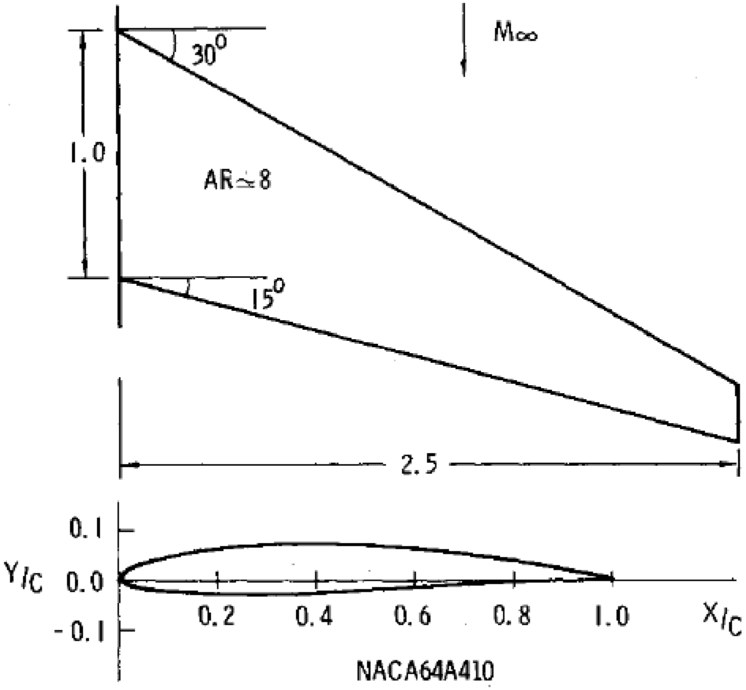
- **Sr. Aerodynamics Engineer**, Computational Aerodynamics Group, **Lockheed-California Co., Burbank, California**
- Group Engineer: **Mr. Luis R. Miranda**

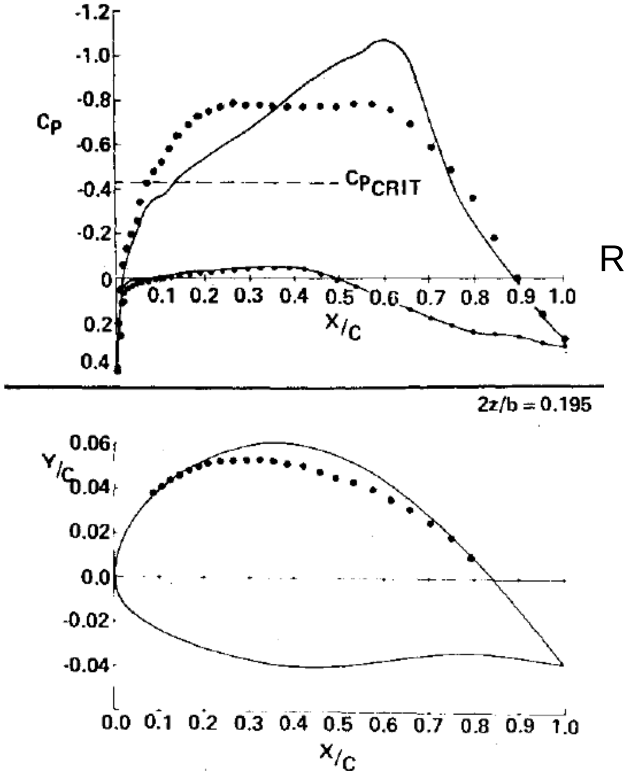
Source: Refs. 5.1.58 to 5.1.60

First Day on the Job: *May 1979*

Dr. A. Richard Seebass (University of Arizona, Tucson) visits Lockheed in Burbank!

- Raj assigned to work with Dick Seebass on ***shock-free supercritical wing design*** procedure using ***fictitious gas concept*** [motivation: wing design for future L-1011-500 aircraft]
- Results using **FLO-22** in *AIAA Paper 81-0383*; also in *AIAA Journal of Aircraft, 19(4), 1982*





A. Richard Seebass

Renowned Aerodynamicist and Educator (1936-2000)

M_∞ = 0.8

C_L = 0.63

Inviscid Drag reduced by ~35%

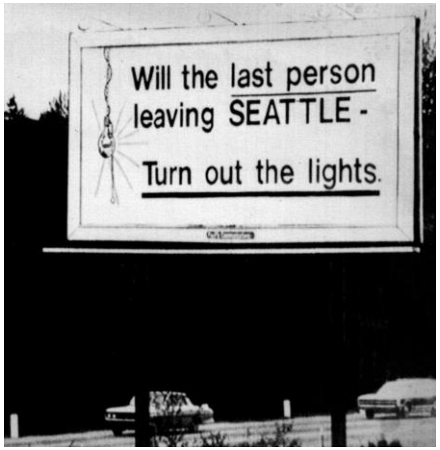
Overnight Immersion into Transonic Aerodynamics!

Source: Ref. 5.1.40

The Strange Seventies!

- **"The Lockheed Debacle"**
  - **1969-71: C-5 Galaxy cost overruns** and serious wing design issues
  - **1971: Saved from bankruptcy** by U.S. Congress approval of $250 million 'Loan Guarantee'
  - **1974: Stock Price drops** to a Low of $3^{3/8}$ *(High of $73^{7/8}$ in 1967!)*
  - **1976: Foreign Bribery Scandals** for sale of aircraft to Japan, Italy, Saudi Arabia, The Netherlands; top management resigned in disgrace

- **Rolls-Royce Bankruptcy**
  - **1971:** Could not proceed with RB-211 engine for Lockheed's L-1011 Tristar
    - **Cost of each engine increased by 30%** over fixed-price contract estimate
    - **Additional $360 million required** to put the new engine into production
- **"The Great Boeing Bust"**
  - ***Business***
    - 1969: **Introduced** now **iconic B747**
    - 1970-71: **Not a single new order** from any U.S. airline for 17 months
    - 1971: **SST program cancelled** by U.S. Government
  - ***Workforce***
    - 32,500 employees by late 1971—down from about 80,000 in 1969
    - ***"Optimists brought lunch to work, pessimists left the car running in the parking lot"***



- **Few Exciting Endeavors!**
  - **1970:** Pan Am 747 NY–London service
  - **1970:** First operational C-5A Galaxy
  - **1975:** New starts: GD F-16 and MDC F/A-18
  - **1976:** Concorde entered service

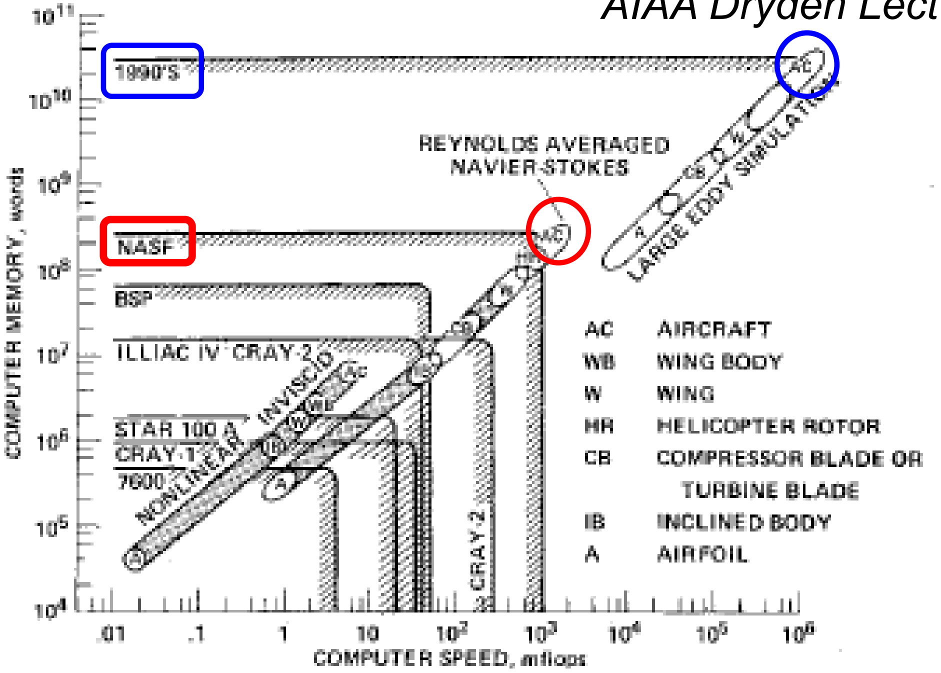
Image Source: Internet

Computational Aerodynamics Outlook

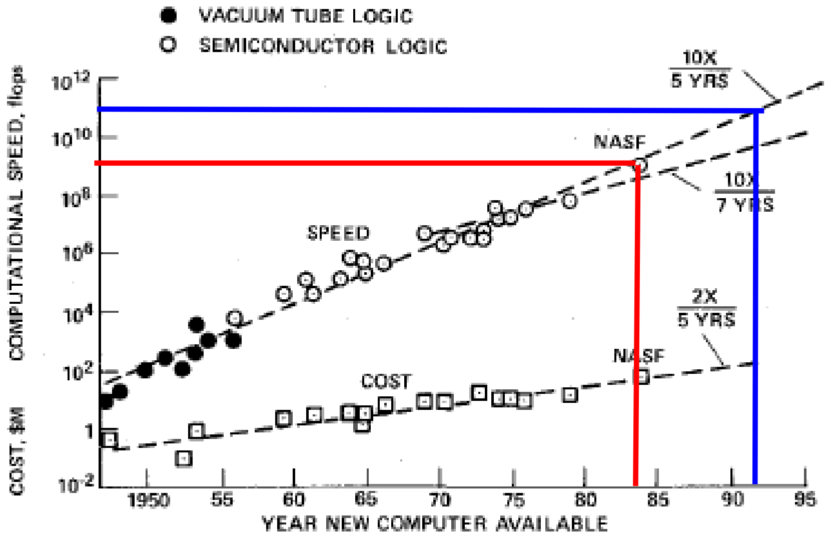
At the End of the 1970s

Computational Aerodynamics Development and Outlook
DEAN R. CHAPMAN, Director of Aeronautics,
NASA Ames Research Center, Moffett Field, California
AIAA Journal, Vol 17, No.12, Dec 1979
"AIAA Dryden Lectureship in Research"

Prof. Emeritus Stanford University
8 Mar 1922 – 4 Oct 1995



Computer requirements for steady-flow simulation: 1-hour run using 1978 algorithms



Outlook didn't quite pan out!

It's difficult to make predictions, especially about the future. – Anon.

Source: Ref. 5.1.53 & 5.1.54

BIBLIOGRAPHY

Topic 5

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

5.1 Infancy through Adolescence (1950–1980)

5.1.1 Smith, A.M.O., “The Panel Method: Its Original Development,” Chapter 1, Applied Computational Aerodynamics, Progress in Astronautics and Aeronautics, Vol. 125, AIAA, Washington D.C., 1990, Henne, P.A. (Editor).
5.1.2 https://en.wikipedia.org/wiki/Apollo_M._O._Smith
5.1.3 Falkner, V.M., “The Scope and Accuracy of Vortex Lattice Theory,” R & M No. 2740, A.R.C. Technical Report, 1949.
5.1.4 Rubbert, P.E., “Theoretical Characteristics of Arbitrary Wings by a Nonplanar Vortex Lattice Method,” Boeing Report D6-9244, The Boeing Company, 1964.
5.1.5 Margason, R.J. and Lamar, J.E., “Vortex-Lattice FORTRAN Program for Estimating Subsonic Aerodynamic Characteristics of Complex Planforms,” NASA TN D-6142, 1971.
5.1.6 “Vortex Lattice Utilization,” NASA SP-405, May 1976.
5.1.7 Miranda, L.R., Elliott, R.D., and Baker, W.M., “A Generalized Vortex Lattice Method for Subsonic and Supersonic Flow Applications,” NASA CR-2865, 1977.
5.1.8 Hess, J.L., “Calculation of potential flow about bodies of revolution having axes perpendicular to the free-stream direction,” Journal of the Aerospace Sciences, Vol. 29, No. 6 (1962), pp. 726-742. https://doi.org/10.2514/8.9591
5.1.9 Hess, J.L. and Smith, A.M.O., “Calculation of potential flow about arbitrary bodies,” Progress in Aeronautical Sciences, Pergamon Press, Volume 8 (1967), pp 1-138
5.1.10 Rubbert, P.E. and Saaris, G.R., “A General Three-dimensional Potential Flow Method Applied to V/STOL Aerodynamics,” SAE Technical Paper 680304, 1968. https://doi.org/10.4271/680304
5.1.11 Hess, J. L., “Calculation of Potential Flow about Arbitrary Three-Dimensional Lifting Bodies,” Phase II, Final Report. McDonnell Douglas Report No. MDC J0971-01, October 1970.
5.1.12 Woodward, F.A., “An Improved Method for the Aerodynamic Analysis of Wing-Body-Tail Configurations in Subsonic and Supersonic Flow,” NASA CR-2228, 1973.
5.1.13 Magnus, A.E., Ehlers, F.E., and Epton, M.A., "PANAIR - A Computer Program for Predicting Subsonic or Supersonic Linear Potential Flow About Arbitrary Configurations Using a Higher-Order Panel Method," NASA CR-3251, April 1980.
5.1.14 Johnson, F.T., “A General Panel Method for the Analysis and Design of Arbitrary Configurations in Incompressible Flows,” NASA CR-3079, 1980.
5.1.15 Bristow, D.R. and Hawk, J.D., “Subsonic Panel Method for the Efficient Analysis of Multiple Geometry Perturbations,” NASA CR-3528, March 1982.

BIBLIOGRAPHY

Topic 5.1 (contd.)

5.1.16 Maskew, B., “Prediction of Subsonic Aerodynamic Characteristics: A Case for Low-Order Panel Method,” *Journal of Aircraft*, Vol. 19, No. 2, February 1982.

5.1.17 Maskew, B., “Program VSAERO: A Computer Program for Calculating the Non-linear Aerodynamic Characteristics of Arbitrary Configurations, User’s Manual” NASA CR-166476, December 1982.

5.1.18 Hess, J.L. and Friedman, D.M., “An Improved Higher-Order Panel Method for Three-Dimensional Lifting Flows,” NADC Report 79277-60, U.S. Naval Air Development Center, December 1981.

5.1.19 Maskew, B., “Prediction of Subsonic Aerodynamic Characteristics: A Case for Low-Order Panel Methods,” Journal of Aircraft, Vol. 19, February 1982, pp. 157-163.

5.1.20 Coopersmith, R.M., Youngren. H.H., and Bouchard, E.E., "Quadrilateral Element Panel Method (QUADPAN)", User's Manual (Version 3), Lockheed-California Company, LR 29671, June 1983.

5.1.21 Coopersmith, R.M., Youngren. H.H., and Bouchard, E.E., "Quadrilateral Element Panel Method (QUADPAN)", Theoretical Report (Version 3), Lockheed-California Company, LR 30500, July 1983.

5.1.22 Youngren, H.H., Bouchard, E.E., Coopersmith, R.M., and Miranda, L.R., “Comparison of Panel Method Formulations and Its Influence on the Development of QUADPAN, an Advanced Low Order Method,” AIAA Paper 83-1827, July 1983.

5.1.23 Fornasier, L., “HISSS—A Higher-Order Subsonic/Supersonic Singularity Method for Calculating Linearized Potential Flow,” AIAA Paper 84-1646, June 1984.

5.1.24 Margason, R.J., Kjelgaard, S.O., Sellers, W.L., Morris, C.E., Walkey, K.B., and Shields, E.W., “Subsonic Panel Methods—A Comparison of Several Production Codes,” AIAA Paper 85-0280, January 1985.

5.1.25 Johnston, C.E., Youngren, H.H., and Sikora, J.S., “Engineering Applications of an Advanced Low-Order Panel Method,” SAE Paper 851793, October 1985.

5.1.26 Donham, R.E., Dupcak, J.D., and Conner, F., “Application of a Panel Method (QUADPAN) to the Prediction of Propeller Blade Loads,” SAE Paper 861743, October 1986.

5.1.27 Tinoco, E.N., Ball, D.N., and Rice, F.A., II, “PANAIR Analysis of a Transport High-Lift Configuration,” Journal of Aircraft, Vol. 24, March 1987, pp. 181-187.

5.1.28 Fornasier, L. and Heiss, S., “Application of HISSS Panel Code to a Fighter Type Aircraft Configuration at Subsonic and Supersonic Speeds,” AIAA Paper 87-2619, August 1987.

5.1.29 Lednicer, D., “A VSAERO Analysis of Several Canard Configured Aircraft,” SAE Paper 881485, SP-757, October 1988.

5.1.30 Harris, R.V., “An Analysis and Correlation of Aircraft Wave Drag,” NASA TM X-947, March 1964.

5.1.31 Carlson, H.W. and Middleton, W.D., “A Numerical Method for the Design of Camber Surfaces of Supersonic Wings with Arbitrary Planforms,” NASA TN D-2341, June 1964.

BIBLIOGRAPHY

Topic 5.1 (contd.)

5.1.32 Baals, D.D., Robins, A.W., and Harris, R.V., “Aerodynamic Design Integration of Supersonic Aircraft,” Journal of Aircraft, Vol. 7, No. 5, Sept-Oct 1970.
5.1.33 Pearcy, H.H., “The Aerodynamic Design of Section Shapes for Swept Wings,” Advances in Aeronautical Sciences, Vol. 3, Pergamon Press, 1962.
5.1.34 Whitcomb, R.T., “Review of NASA Supercritical Airfoils,” 9th Congress of the International Council of the Aeronautical Sciences, Haifa, Israel, 25-30 August, 1974, Proceedings, Vol. I, pp 8-18. https://www.icas.org/ICAS_ARCHIVE/ICAS1974/Page%208%20Whitcomb.pdf
5.1.35 Murman, E.M. and Cole, J.D., "Calculation of plane steady transonic flows", AIAA Journal, Vol. 9, No. 1 (1971), pp. 114-121. https://doi.org/10.2514/3.6131
5.1.36 Bailey, F.R. and Ballhaus, W.F., “Comparisons of Computed and Experimental Pressures for Transonic Flows about Isolated Wings and Wing-Fuselage Configurations,” NASA SP-347, 1975, pp. 1213-1231.
5.1.37 Boppe, C.W., “Computational Transonic Flow About Realistic Aircraft Configurations,” AIAA Paper 78-104, 16th Aerospace Sciences, Meeting, Huntsville, Alabama, 1978.
5.1.38 Jameson, A. and Caughey, D.A., “Numerical Calculation of the Transonic Flow Past a Swept Wing,” COO-3077-140, ERDA Mathematics and Computing Laboratory, New York University, June 1977. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770020127.pdf
5.1.39 Caughey, D.A. and Jameson, A., “Progress in Finite-Volume Calculations for Wing-Fuselage Combinations,” AIAA Journal, Vol. 18, No. 11 (1980), pp 1281-1288. https://arc.aiaa.org/doi/pdf/10.2514/3.50883
5.1.40 Raj, P., Miranda, L.R., and Seebass, A.R., “A Cost-Effective Method for Shock-Free Supercritical Wing Design,” AIAA Journal of Aircraft, Vol. 19, No. 4, April 1982, pp 283-289.
5.1.41 Raj, P. and Reaser, J.S., “An Improved Full-Potential Finite-Difference Transonic-Flow Code, FLO-22.5,” Lockheed-California Company Resort, LR 29759, June 1981.
5.1.42 Raj, P., “A Multigrid Method for Transonic Wing Analysis and Design,” AIAA Journal of Aircraft, Vol. 21, No. 2, February 1984, pp 143-150.
5.1.43 Vassberg, J.C., “A Brief History of FLO22,” JRV Symposium, San Diego, California, 22-23 June 2013.
5.1.44 Wigton, L.B., “Viscous-Inviscid Interaction in Transonic Flow,” AFOSR-TR-81-0538, June 1981.
5.1.45 Lock, R.C., and Williams, B.R., “Viscous-Inviscid Interactions in External Aerodynamics,” Progress in Aerospace Sciences, Vol. 24, 1987, pp. 51-171.
5.1.46 MacCormack, R. W., "Numerical Solutions of the Interaction of a Shock Wave with a Laminar Boundary Layer," Lecture Notes In Physics, Vol. 8, Springer-Verlag, New York, 1971, pp. 151-163.

BIBLIOGRAPHY

Topic 5.1 (contd.)

5.1.47 Carter, J. E., "Numerical Solutions of the Navier-Stokes Equations for Supersonic Laminar Flow over a Two-Dimensional Compression Corner," NASA TR R-385, July 1972.

5.1.48 Li, C. P., "A Numerical Study of Laminar Flow Separation on Blunt Flared Cones at Angle of Attack," AIAA Paper 74-585, June 1974.

5.1.49 Wilcox, D. C., "Calculation of Turbulent Boundary-Layer Shock-Wave Interaction," *AIAA Journal*, Vol. 11, Nov. 1973, pp. 1592-1594.

5.1.50 Deiwert, G. S., "Numerical Simulation of High Reynolds Number Transonic Flow," AIAA Paper 74-603, June 1974.

5.1.51 Shang, J. S. and Hankey, W. L., "Numerical Simulation for Supersonic and Hypersonic Turbulent Flow over a Compression Ramp," AIAA Journal, Vol. 13, Oct. 1975, pp. 1368-1374.

5.1.52 Deiwert, G. S. and Bailey, H. E., "Prospects for Computing Airfoil Aerodynamics with Reynolds Averaged Navier-Stokes Codes," NASA CP 2045, 1978.

5.1.53 Dean R. Chapman, "Computational Aerodynamics Development and Outlook", AIAA Journal, Vol. 17, No. 12 (1979), pp. 1293-1313.

5.1.54 Chapman, D.R., Mark, H., and Pirtle, M.W., “Computers vs. Wind Tunnels for Aerodynamic Flow Simulations,” AIAA Astronautics & Aeronautics, Vol. 13, No. 4, April 1975.

5.1.55 Stumpe, J., “Symbiosis: Why CFD and Wind Tunnels Need Each Other,” Aerospace America, June 2018.

5.1.56 Raj, P. and Gray, R.B., “Computation of Two-Dimensional Potential Flow Using Elementary Vortex Distributions,” AIAA Journal of Aircraft, Vol. 15, No.10, October 1978, pp. 698-700.

5.1.57 Raj, P. and Gray, R.B., “Computation of Three-Dimensional Potential Flow Using Surface Vorticity Distribution,” AIAA Journal of Aircraft, Vol. 16, No. 3, March 1979, pp 162-169.

5.1.58 Raj, P. and Iversen, J. D., “Inviscid Interaction of Trailing Vortex Sheets Approximated by Point Vortices,” AIAA Journal of Aircraft, Vol.15, No.12, December 1978, pp. 857-859.

5.1.59 Raj, P. and Iversen, J.D., “Computational Simulation of Turbulent Vortex Merger and Decay,” AIAA Journal, Vol. 18, No. 8, August 1980, pp. 865-866.

5.1.60 Iversen, J.D., Brandt, S.A., and Raj, P., “Merging Distance Criteria for Corotating Trailing Vortices,” Proceedings U.S. Department of Transportation Conference on Aircraft Trailing Vortices, Cambridge, MA, March 15-17, 1977.