Reflections on the Effectiveness of Applied Computational Aerodynamics for Aircraft Design

A perspective based on my exciting journey on a long and winding road for more than five decades

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Advanced Development Programs

LOCKHEED MARTIN

25 January 2025

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ABOUT THE AUTHOR

Pradeep Raj

- **Virginia Tech, Blacksburg, VA (2012-present)**
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- **Lockheed Martin (1979–2011)**
  - **Technical (1979-1999): Aeronautics Company, California & Georgia**
  - **Leadership/Management (1999-2011): Aeronautics Co., Georgia; Advanced Development Programs, Skunk Works®, Palmdale, California**
- **UMR*, Rolla, Missouri**
  - **Asst. Prof. (1978–79)**

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  - **Ph.D. Aerospace Engineering (1976)**
- **ISU, Ames, Iowa**
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An Aside: "Why Join VT After Retiring From LM?"

Kelly's Rules for Happy Retirement

ADP

1. *Retirement is like a job and must be approached as such*
2. *Don't travel too much, you want to establish a daily grind*
3. *Don't think about living someplace new, that's why God created hotels*
4. *Drive till you can't remember where you parked*
5. *Be pleasantly reckless - but if you have never done it before, now may not be the time to start*
6. *Don't hang with the children too much - visit, give presents and then move on*
7. *Maintain your bad habits, but never get drunk more than once a day. You're not a kid anymore*
8. *Hang with young people; they mostly have it right*

Clarence Leonard "Kelly" Johnson (1910-1990)

Legendary Aircraft Designer

Founder of World-renowned Skunk Works®

"Hang with young people; they mostly have it right"

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ABOUT THIS PRESENTATION

In this presentation, the author shares his perspective on how we got to where we are today, and how we get to where we need to be.

The author places the evolution of Applied Computational Aerodynamics (ACA), its capabilities, and its shortcomings in a historical context, but the presentation is NOT a history of ACA.

This is a much expanded version of the Lead presentation:

Applied Computational Aerodynamics: *An Unending Quest for Effectiveness*

Royal Aeronautical Society Applied Aerodynamics Conference

The Future of Aerodynamics

Bristol, U.K., July 24-26, 2018

Here's the URL to access the current version of the presentation:

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

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MOTIVATION

The primary motivation is to convince budding and practicing engineers using CFD to predict aerodynamic characteristics of aircraft (and of other objects moving through the air) that they must dispel their mistaken notion:

CFD is a commodity now, so we just need to learn to use it for generating aerodynamic data

- Yes, we know that CFD may be considered a commodity today since users can choose from a large number of either commercial or open-source CFD software for aerodynamic flow simulation
- When I assumed the primary responsibility of teaching aircraft design courses at Virginia Tech in 2012, it became apparent rather quickly that
  - a large number of students—just a few months shy of being professionals—used CFD as a "black box", i.e., choosing default input parameters and generating aerodynamic data
  - students instinctively trusted the data, and almost never asked: *"So what that we can predict aerodynamic characteristics, do the predictions replicate reality?"*

Computational Aerodynamics Engineers Must Learn to Ask and Answer the "So What?" Question!

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SCOPE

To present a relatively complete yet concise perspective on

- ***the evolution of applied computational aerodynamics (ACA),***
- ***the impressive capabilities of today's ACA for meeting flight vehicle design needs,***
- ***the less-than-satisfactory effectiveness of ACA for meeting design needs due to serious shortcomings, and***
- ***the future prospects for fully effective ACA capabilities.***

The perspective reflects author's 50+ years of related experience in aerospace industry and academia.

This suggests the author must be OLD!

Más sabe el diablo por viejo que por diablo.

The devil knows more from being old than from being a devil.

"With age comes wisdom, but sometimes age comes alone!"

-- Oscar Wilde

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An Aside on *Experience*

"experience is direct observation of, or participation in, events as a basis of knowledge"— Merriam-Webster dictionary

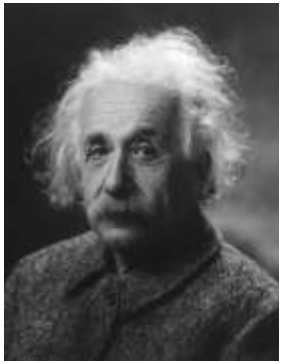
"experience is knowledge or skill in a particular job or activity that you have gained because you have done that job or activity for a long time— Collins online dictionary

C.S. Lewis

29 Nov 1898 – 22 Nov 1963

"Experience: that most brutal of teachers. But you learn, my God do you learn."

Albert Einstein



14 Mar 1879 – 18 Apr 1955

"The only source of knowledge is experience."

Randy Pausch

23 Oct 1960 – 25 Jul 2008

"Experience is what you get when you don't get what you wanted. And it can be the most valuable thing you have to offer."

Knowledge from experiences is crucial to developing wisdom you need to make good decisions; you can't get wise overnight from books alone.

This 'old devil' has much to offer…whether or not you agree with everything he has to say!

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Image & Quotes Source: Internet

DISCLAIMERS

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Being a perspective, the material reflects opinions shaped by author's knowledge, experiences, and biases.

The author has gathered and compiled this material from publicly available sources and personal archives solely for educational purposes. Although a good-faith attempt has been made to cite all sources of material, the author deeply regrets any inadvertent errors or omissions.

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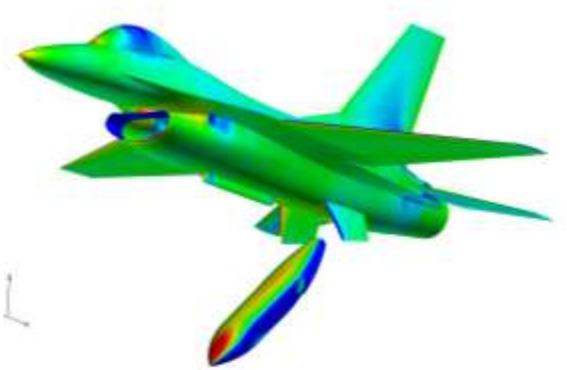
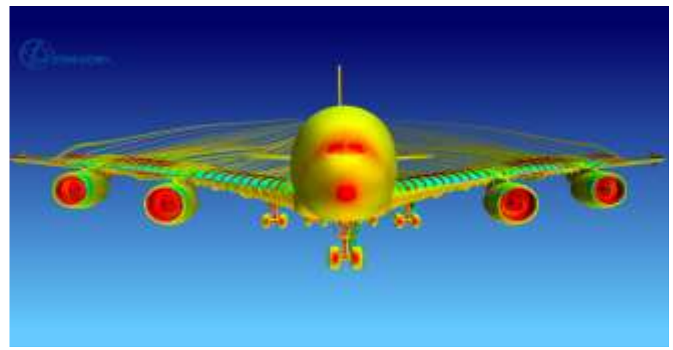
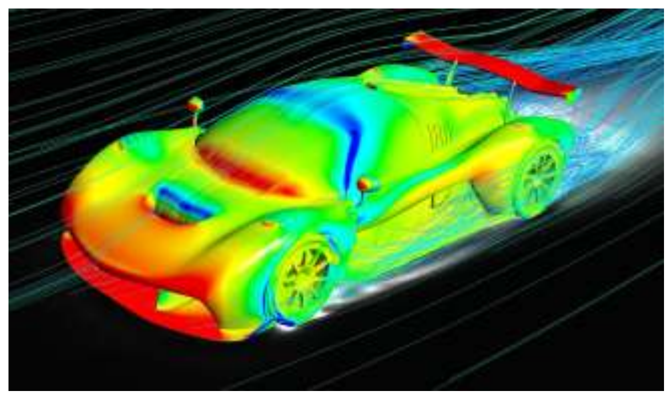
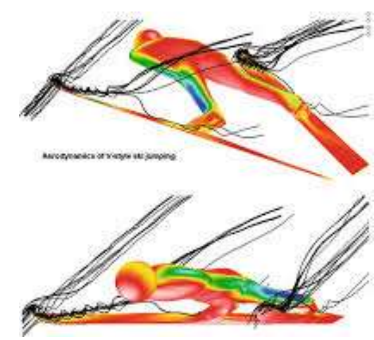
Applied Computational Aerodynamics (ACA)

__ACA__ is an engineering discipline that deals with the application of __C__omputational __F__luid __D__ynamics (CFD) to the __analysis__ and __design__ of arbitrarily shaped objects moving through the __air.__

Computational Aerodynamics is CFD when the fluid is air.

ACA puts CFD to *practical use* as opposed to CFD being only theoretical.

Adapted from https://dictionary.cambridge.org/us/dictionary/english/applied

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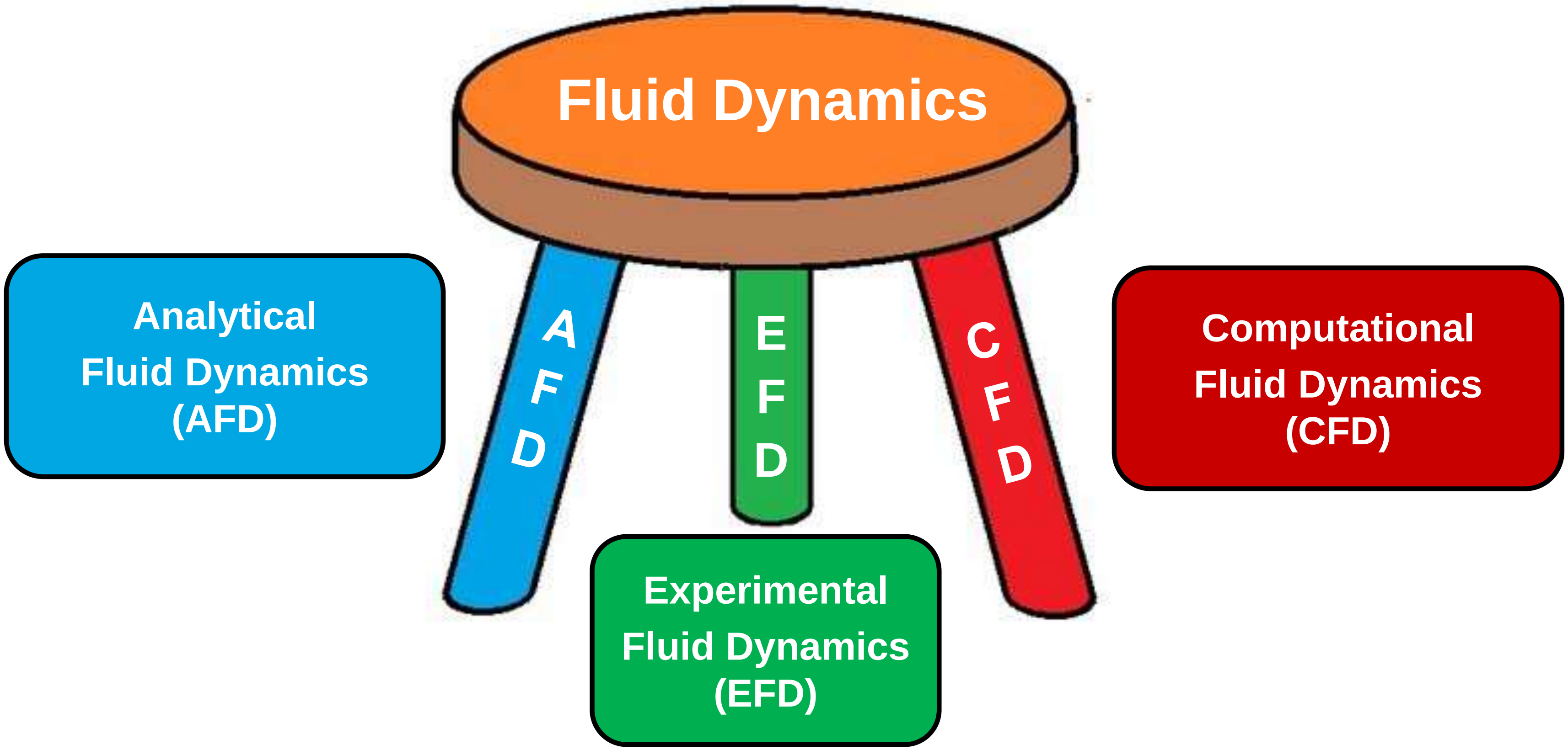
Image Source: Internet

Computational Fluid Dynamics (CFD)

The Newest Subdiscipline of Fluid Dynamics

Fluid Dynamics: The branch of applied science concerned with the movement of fluids (liquids and gases). -- *American Heritage Dictionary*



Aerodynamics: *A subset of Fluid Dynamics with air as the fluid.*

Synergistic Use of AFD, EFD, and CFD is Essential for Comprehensive Understanding of Fluid Dynamics

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CFD Ingredients

Governing Equations: Mathematical Formulations of Fluid Flow
(*Partial differential equations in continuous domain*)

Computer Platforms
(Digital computers to run computer programs, and for data processing & storage)

CFD

Numerical Models of Governing Equations
(*Difference equations in discretized domain*)

Computer Programs
(Software suite based on algorithms to solve the difference equations)

Today's CFD offers a powerful suite of numerical models, computer programs, and associated tools & processes for simulating fluid flows using digital computer platforms

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CFD "Perfectly" Complements EFD for Aerodynamic Simulations

	EFD (Experimental Fluid Dynamics)	CFD (Computational Fluid Dynamics)
Strengths	• Perceived as "Real" • Credible data ▪ Quantified uncertainties • Large excursions per entry	• Low cost • Relatively quick turnaround • No scale effects • No wall interference effects • No support interference effects • Can model aeroelastic distortions • Applicable to ***all*** flight conditions
Weaknesses	• Higher cost, longer elapsed time • Scale effects • Wall interference effects • Support interference effects • Aeroelastic distortions • Not practical for ***some*** flight conditions	• Perceived as "Virtual" • Lack of credibility due to ▪ Computational uncertainties caused by limitations or deficiencies in Numerical Models and Flow Physics Models

CFD Strengths Overcome EFD Weaknesses!

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Overarching Goal of ACA

The goal of applied computational aerodynamics (ACA) is to generate <u>credible solutions</u> of practical aerodynamic problems via aerodynamic analysis and design using computational fluid dynamics (CFD), and to deliver the solutions—<u>on time and on budget</u>—to engineers who are tasked with designing systems that move through the air, such as aircraft.

ACA is No Longer a Luxury, But a Necessity, to Support Engineering Design of All Types of Systems that Move Through the Air

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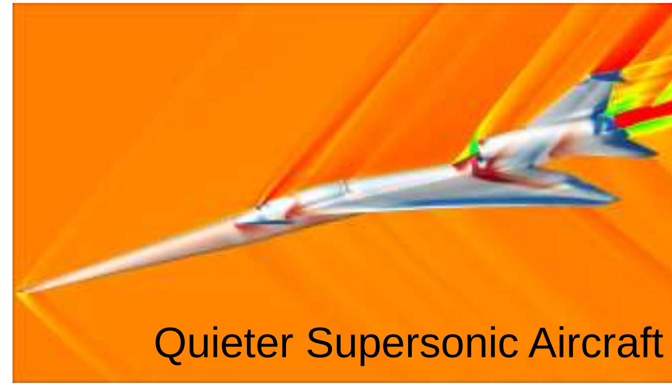
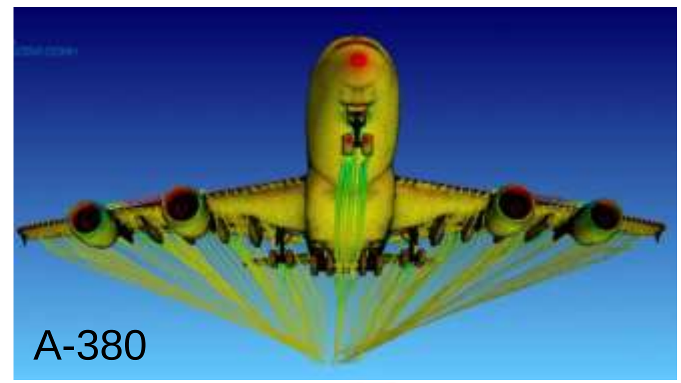
Pervasive Use of ACA in Air Vehicle Design

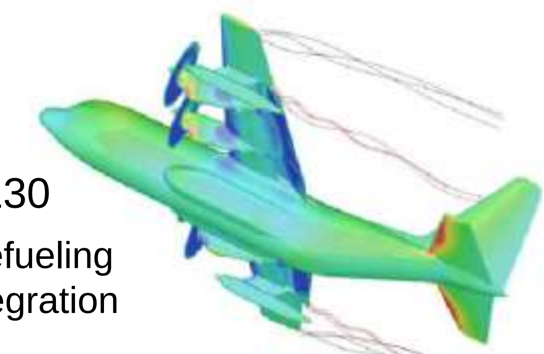
- **New Vehicles (“clean-sheet” designs)**
  - *Outer Mold Line (OML) Design:* Forces, moments, and surface pressure distributions
  - *Shape Optimization*: Sensitivity of aerodynamic data to design variables
  - *Flight Performance:* Validate take-off, climb, cruise, maneuver, descent, landing
  - *Airframe Propulsion Integration:* Minimize installation losses
  - *System Integration:* Off-body flow field for safe carriage and deployment of stores & weapons
  - *Structural Design*: Steady and unsteady flight loads
  - *Flight Control System Design*: Stability & Control coefficients and rate derivatives
  - Etc.
- **Derivative Vehicles (improvements, upgrades and/or modifications)**
  - Assess impact of shape change on flight performance when integrating new or improved subsystems to upgrade current product or design a derivative





KC-130

New Refueling Pod Integration



Indispensable for Engineering Design of Flight Vehicles

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Source: Refs. 1.1 – 1.6

Effectiveness

"The ability of producing a desired result or a desired output"

Richardson, 1910

*"Both for engineering and for many of the less exact sciences, such as biology, there is a demand for **rapid methods,** easy to be understood and **applicable to unusual equations and irregular bodies**. If they can be **accurate**, so much the better; but **1 per cent, would suffice** for many purposes."*

Hess and Smith, 1967

*"**Prospective users**…rarely interested in whether or not an accurate solution of an idealized problem can be obtained, but are concerned with **how well the calculated flow agrees with the real flow**."*

Miranda, 1982

*"The **effectiveness** of computational aerodynamics **depends not only on the accuracy** of the codes **but** to a very large degree—perhaps more than is generally appreciated—**on their robustness, ease and economy of use.***

Fast + Accurate + Affordable

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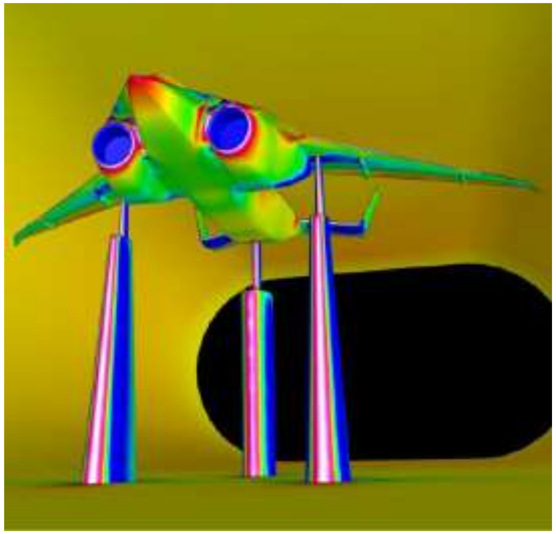
Image Source: Refs. 1.7 thru 1.9

CFD and ACA are *NOT* Synonymous

CFD *Produces Data*.

Computational Fluid Dynamics (CFD) offers a powerful *means* of *generating aerodynamic data*, à la wind tunnels, for bodies moving through air.



Both use a 3-step process

1. Build a model
2. Blow air on it
3. Gather and interpret data

(Data include: forces, moments, and flow quantities—on and off the surface)

ACA Produces Solutions!

Applied Computational Aerodynamics (ACA) is all about using CFD to deliver credible *solutions of engineering problems* to designers.

Aerodynamic Data is Needed to Solve Engineering Problems, But Don't Confuse Data with Solutions!

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Image Source: Ref. 1.10

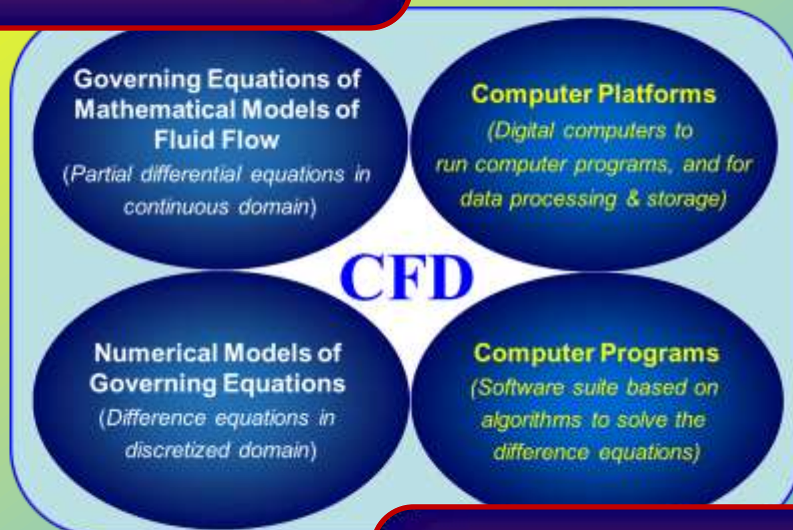
Relationship of CFD to ACA

CFD is to ACA as Airplane is to Air Transportation!

ACA

Customer

Engineering design problems, resources, and constraints



Value

Meeting customer needs and expectations

ACA Uses CFD to Create Value for the Customer

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Don’t We Already Know a Lot About CFD and ACA?

Then Why Say It Again?

Source: Refs. 1.11 to 1.18

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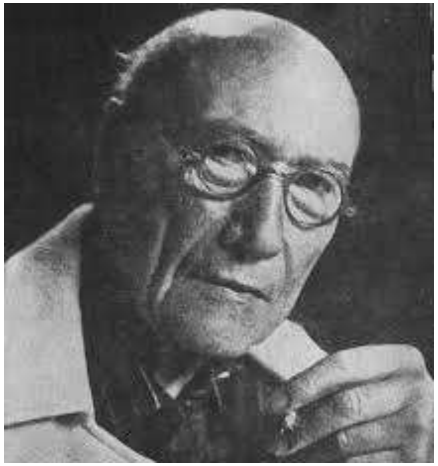
Everything has been said before, but since nobody listens we have to keep going back and beginning all over again.

André Gide



French author
Nobel Prize in Literature (1947)
22 November 1869 – 19 February 1951

- It is extremely difficult, if not impossible, for a single book to do justice to the multiple facets of CFD and ACA including theoretical aspects and practical applications.
- **Our main focus is on the current status and future prospects of the effectiveness of ACA for aircraft design.**
- The intention is *to* ***COMPLEMENT, NOT DUPLICATE,*** what is extensively covered in many excellent CFD and ACA books.

Source: Ref. 1.19

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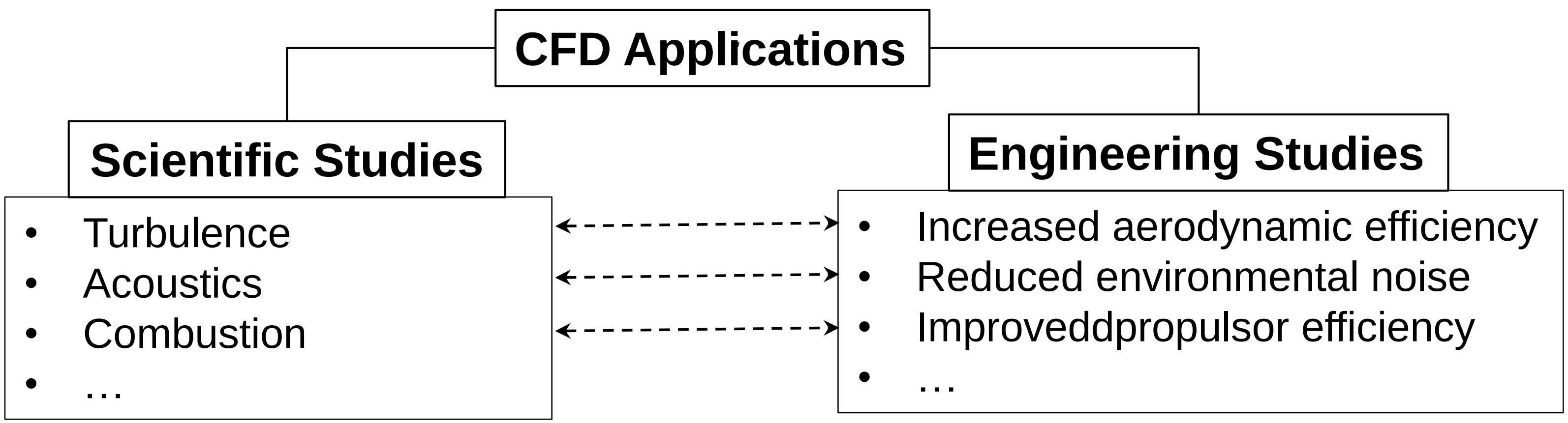
Objective & Approach of the Presentation

To discuss how we got to today's ACA which has less than satisfactory effectiveness, and how we get to fully effective ACA tomorrow that can best meet the needs of the engineering design of aircraft.

We shall examine evolution of CFD (computational fluid dynamics) as a sub-discipline of Fluid Dynamics, and its application to aerodynamic problems.

Since CFD is applicable to a broad range of problems in science and engineering, we use a highly simplified taxonomy of CFD applications to distinguish applications for scientific studies from those for engineering:



Next, We Briefly Address Three Topics To Place the Material in the Following Sections in Proper Context

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“Engineering isn’t Science!”

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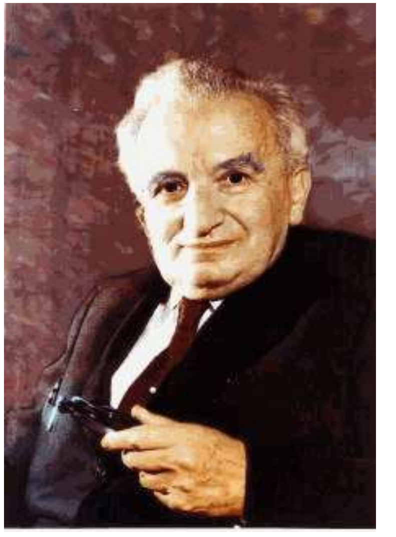
"Engineering isn't Science!"

Theodore von Kármán



Scientists discover the world that exists;
***engineers create* the world that never was.**

Hungarian-American mathematician, aerospace engineer, and physicist; Univ. of Göttingen; RWTH Aachen; Caltech; VKI for Fluid Dynamics

11 May1881 – 6 May 1963

Eugene E. Covert

American aerodynamics and aeronautics specialist, MIT

6 Feb 1926 – 15 Jan 2015

***Engineering is* in the end *about making something*.**

The Core Purpose of Engineering: Apply Knowledge and Skills to Develop New Devices

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Image Source: Internet

"An engineer is *not* a scientist"

"Throughout my years in Cal Tech I like to believe that I gave **engineering education** a little push in the right direction and this helped subsequently in creating the kind of engineers needed in the United States. But eventually a strange thing happened. During those years I had emphasized the importance of physics and chemistry in the engineering curriculum and urged **closer cooperation of science and engineering**. I even suggested **social sciences for engineers** interested in management. So, many educators started to think that *if a little science is good for engineers a whole lot is better*. They gave students more physics and more chemistry, until now the pendulum seems to have swung the other way and **engineering education has become indiscernible from science education**."

"I am sorry to say that I do not like this trend. ***An engineer is not a scientist.*** ***In addition to basic technical knowledge he must have the creative capacity to design new hardware.*** Engineering schools that fail to recognize and encourage this dual role are remiss in their duty to the profession."

"Whether we call future scientists physicists or engineers is not important. ***What is important I think is to repair the imbalance in the scientific world and turn out people who not only understand fundamental phenomena but can use this knowledge for developing new devices.*** This in turn will not only bring some glory to the engineer, but I think it will contribute substantially to the pace of progress."

-- **Theodore von Kármán (1881–1963)**
The Wind and Beyond, 1967, pp. 157 & 159

Note: Highlighting by the author of this presentation.

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Source: Ref. 1.20

"An Engineer's Mentality"

"In essence, the current engineering education paradigm consists of giving the students all the data at the top of the page, and the solution (?) consists of rearranging the data on the bottom of the page and handing it in as a "worked" assignment. In many years in industry I never encountered anything even remotely close to this process. "

"In my experience, *the overwhelming majority of the engineering problem is gathering information and interpreting results.* *Although this is the engineering problem it almost never occurs in our science-based engineering education system.*"

"**Engineering design** may be the student's only exposure to this process. The student response in evaluations comes across as "problem statements too vague." If that's the case with these problems, we have not yet helped the students develop an engineer's mentality."

William H. Mason
AIAA Paper 92-2661

William H. Mason

Professor Emeritus, Virginia Tech
Co-author of an ACA textbook
Engineer Grumman Corp.
19 Jan 1947 - 27 Mar 2019

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Source: Ref. 1.21

"An Engineer's Reality"

"One of the **characteristics of engineers which** I have frequently observed, and which **must be guarded against is** the ***search for exact answers***, and the feeling of frustration if the exact answer is not forthcoming. This probably stems from the many years of high school and college training where the answer is always to be found in the back of the book, and the feeling of elation which comes when, after trying several solutions, and looking furtively at the answer, the latest trial finally works.

Unfortunately, ***in real life, there are no exact or final answers***. In a job, which must go ahead at a rapid pace, we cannot withhold judgment "until all the facts are in". Rarely is all the evidence at hand. Decisions must be made, and action taken, before complete knowledge can be acquired.

I have for some time thought that ***a few of our present day ills stem from this childish faith in the existence of perfect answers***. It requires a degree of maturity to realize that all solutions are partial ones."

Adm. Hyman G. Rickover (1900–1986)
"Father of the Nuclear Navy," 63 Years of Active Duty in US Navy
Lecture on *Administering a Large Military Development Project* delivered to U.S. Naval Postgraduate School, Monterey, CA, 15 March 1954

Note: Highlighting by the author of this presentation.

Source: http://hdl.handle.net/10945/59370

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Engineers Make the World a Better Place!

"Engineers use science to <u>solve problems</u> and <u>make things</u>. Engineering <u>applies</u> a combination of <u>logic</u> and <u>intuition</u> to problem solving…It's a <u>way of thinking</u> that leaves one well suited to run a company."

Bill Nye on Sundar Pichai
The 100 Most Influential People
TIME, May 2/May 9, 2016

"Bill Nye the Science Guy"
American Science Educator
Mechanical Engineer

They Meet Highly Challenging Societal Needs!

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Source: Internet

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

Aerospace Engineers
Shape the Future!

Global Mobility

Shrink the Globe

Global Security

Change the Game

"Engineers Make a Difference!"

Source: Images from Internet

Engineering Design of Aircraft

Designing An Object: *A Creative Act*

But Creativity Alone May Produce Useless/Impractical Artifacts

The Coffeepot for Masochists

The Camouflage Cup (cut out plastic cup)

The Uncomfortable Wine Glass

Engineering Design is "Creativity with Purpose!"

"Engineering Design is an iterative decision-making activity performed by team of engineers to produce plans by which resources are converted, preferably optimally, into systems or devices to meet human need."

-- T.T. Woodson, *Introduction to Engineering Design*, 1966

Source: https://www.pinterest.com/laragtorres/impossible-objects/

Engineering Design Process

Adapted from "*The Mechanical Design Process*" by David G. Ullman

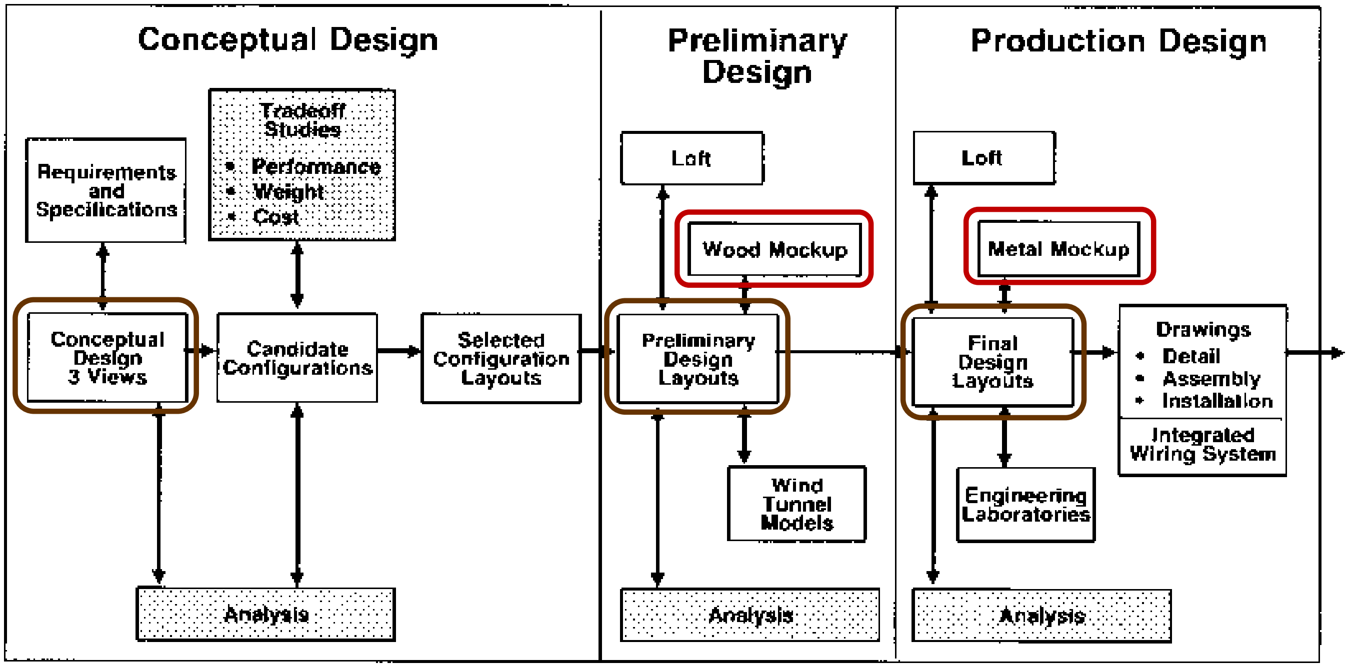
- **In engineering design, designer uses *three types of knowledge***
  - **A. knowledge to generate ideas**—comes from experience and natural ability
  - **B. knowledge to evaluate ideas**—comes from domain-specific knowledge
  - **C. knowledge to make decisions and structure the design process**—largely independent of domain-specific knowledge

- **Six basic actions are taken to solve any design problem**
  1) **Establish the need—**what is to be solved
  2) **Plan—**how to solve it
  3) **Understand the problem—**what the requirements are, and what existing solutions for similar problems are
  4) **Generate alternative solutions**
  5) **Evaluate the alternative solutions—**compare them to design requirements and to each other
  6) **Decide on acceptable solutions**

This Model Works for Entire Product or a Small Piece of It

Traditional Aircraft Design Process

With rapid increase in aeronautical knowledge in the early 20th century, a three-phase process evolved to systematically guide design of ever more complex aircraft in order to improve chances of achieving target performance



Schematic *of* Traditional Design Process ca 1980

Courtesy of Sam Smyth, Experienced Lockheed Designer

Activities in each phase (conceptual, preliminary and production) are dominated by Synthesis (*solution creation*) and Analysis (*feasibility assessment*)

Generation and Evaluation of Ideas Drive the Process

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In the Hands of Good Designers, the Traditional Design Process has Delivered…

…An Impressive Array of Aircraft With Phenomenal Performance!

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Dramatic Increase in Cost Has Accompanied Increasing Levels of Aircraft Performance

- **With each passing decade since 1903, increasingly sophisticated aircraft emerged to deliver phenomenal performance demanded by customers, but … *costs also escalated dramatically***
  - Boeing 707 (1955) 4 M USD
  - Boeing 777-9 (2022) 440 M USD

> ***"[Today's] Airplanes are some of the most sophisticated designs in the world, <u>four million parts flying in formation</u>, and it involves hundreds of thousands of people all around the world creating these vehicles."***
>
> **Alan Mulally,** *'Father of Boeing 777'*

(https://www.nytimes.com/2009/09/06/business/06corner.html)

US combat aircraft unit cost has grown <u>4X every 10 years</u>

- **Aircraft industry continues to face a daunting "affordability challenge"**
  - Incorporating advanced technologies, such as AI, may further exacerbates the *"affordability challenge"*

Challenge: Develop Technologically Superior Aircraft at Affordable Cost!

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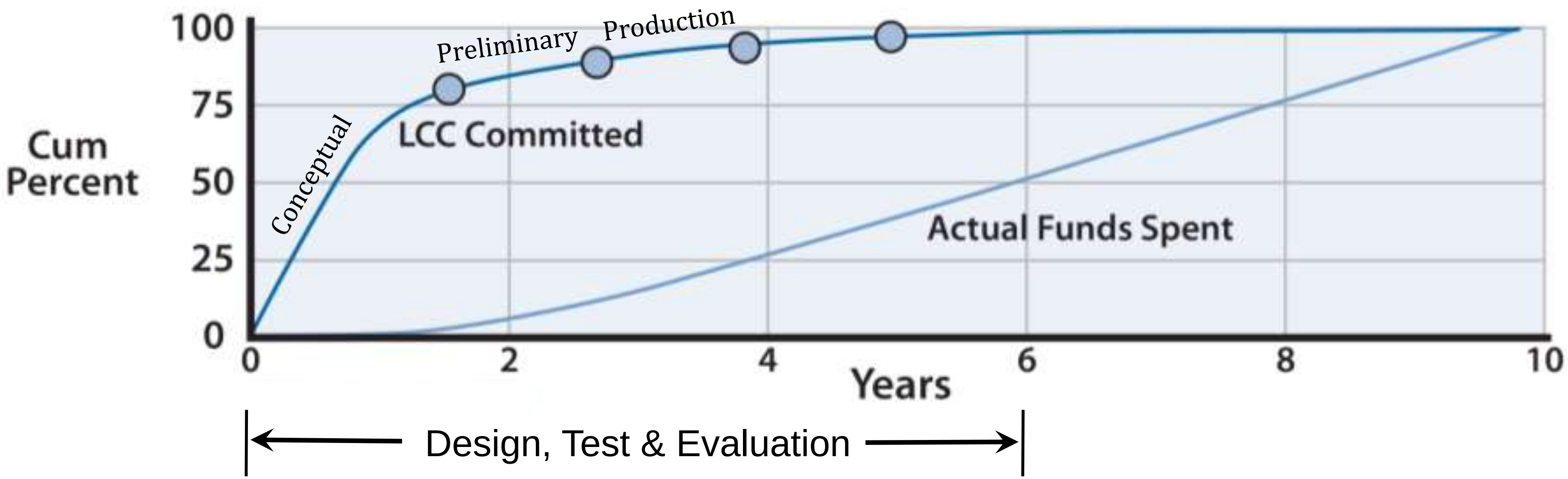
A Closer Look at Aircraft Costs

A Representative Military Program



Life Cycle Cost (LCC) =
DT&E + Production + Operations Costs

70% to 75% of (LCC) is <u>Committed</u> in Early Stages of Design!

US DoD Defense Systems Management College, 3 Dec 1991

Decisions in Early Stages of Design Have a Disproportionately Large Impact on Aircraft's LCC

Image adapted from Fig. 1.16, Nicolai & Carichner

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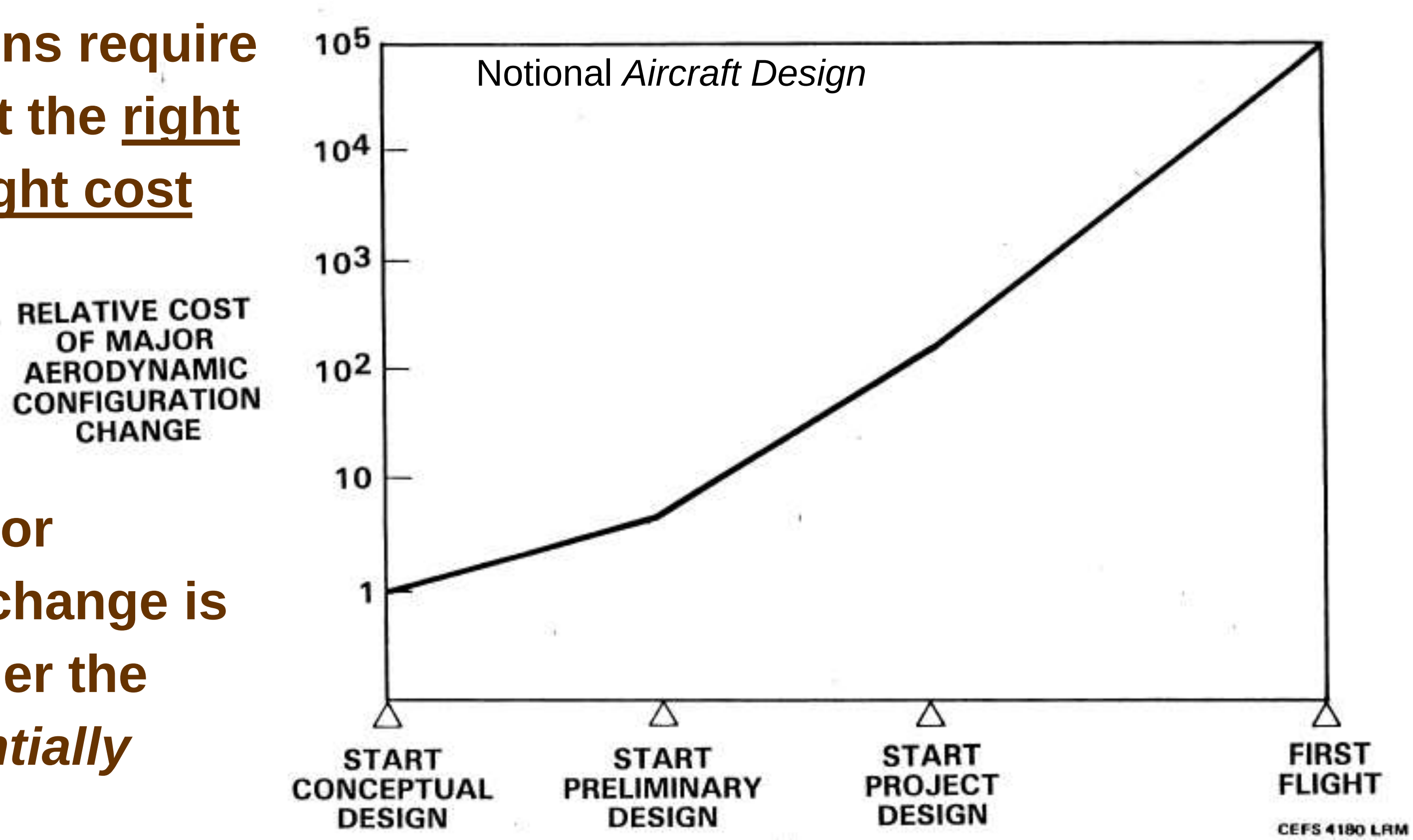
Key to Affordable Designs

- **Successful engineering design requires that quality decisions be made in a timely manner**
- **Quality decisions require credible data at the right time and the right cost**
- **The later a major configuration change is made, the higher the cost—*exponentially higher!***



Quality Decisions Early → Better Quality Affordable Product Later

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Image Courtesy of L.R. Miranda

A Few Undesirable Characteristics of Traditional Design Process

- **Large Disciplinary Groups:** From 1920s to 1980s, Disciplinary Groups grew in size due to the need to address ever increasing complexity of designs, and operated in a *“stovepipe”* environment with *“Throw it over the wall”* mindset
  - Much time spent in reconciling design changes proposed by various disciplines and cost went up
- **Long Cycle Times and High Cost:** Sequential nature of the process led to long elapsed time and high cost for completing each design cycle
- **Simplistic Methods for Analyses:** Decisions in early stages of design based on data from simplistic analyses to accommodate schedule and cost constraints
- **Not All Disciplines Adequately Considered:** Design activities did not adequately incorporate manufacturing, operations and support considerations
- **Very Few Candidate Designs Fully Explored:** Schedule and cost constraints limited the number of designs that could be fully explored in early stages
  - Not well suited for designing “optimal” configurations

Design Community Proposed New Paradigms to Address Undesirable Characteristics

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Novel Design Paradigms

Proposed to Address Undesirable Characteristics of Traditional Design Process

1980s: *Concurrent Engineering*

1990s: *Integrated Product & Process Development (IPPD) Concept*

Key Attributes of IPPD

- **Closer Relationship with Customer**
  - Better Understanding of Customer Requirements
- **Integrated Product Teams (IPTs)**
  - More Complete Understanding of Requirements
  - Broader and Balanced Discussion of Alternatives
  - Simultaneous Design of Product and Process
- **'Design for X' Methods**
  - Design for Manufacturability, Producibility, Maintainability, Reliability, Safety, Quality, Cost, etc.
- **Digital Product Model**
  - Integrate Design and Analysis Tools to Capture and Refine Product and Process Data
- **Integrated Design Automation Tools**
  - Streamline the Design Process and, Assure Understanding of Design Intent
- **Extensive Use of Physics-based Methods and Simulation Tools**
  - Achieve Improved Product Performance with Fewer Design/Build/Test Iterations

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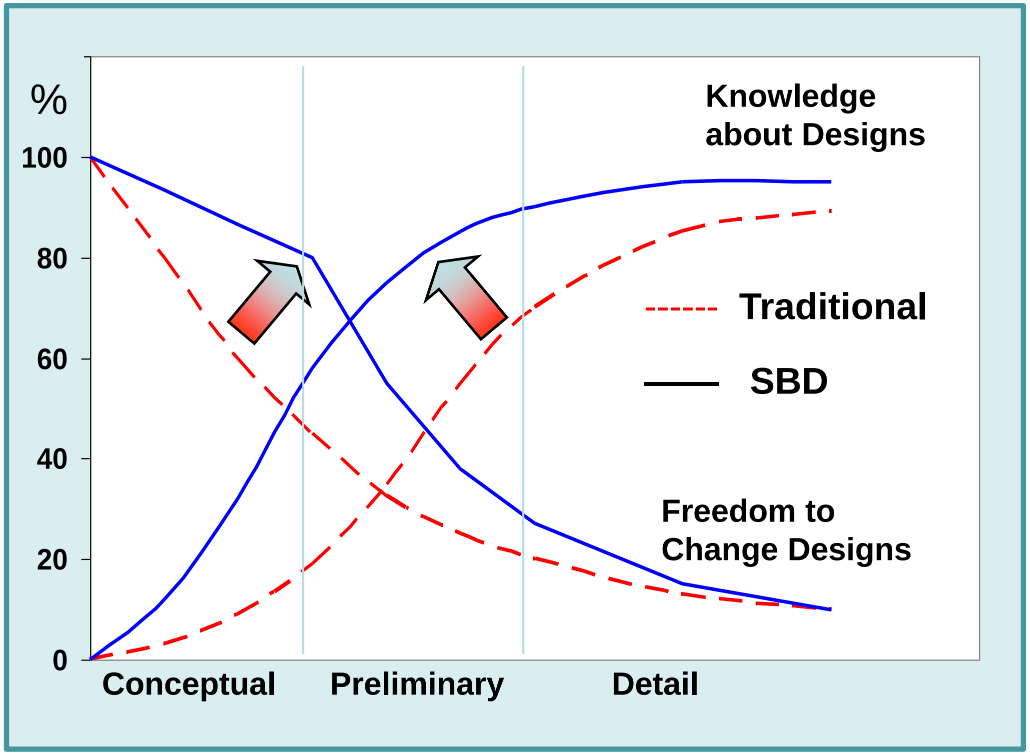
Simulation Based Design (SBD)

Implements *Integrated Product & Process Development (IPPD)* concept using *Multidisciplinary Design Optimization (MDO)* methodology

- **SBD employs integrated multidisciplinary models and computational simulations to develop *Virtual Prototypes (aka Digital Twins)***
- **Considers all aspects including manufacturing, operations and support simultaneously with all requirements and constraints from start**
- **Reduces chances of design changes in later stages**
- **Conducts cost/performance trade-offs *EARLY Using more Knowledge about designs***



SBD relies on computational methods as the primary means of all data required to make design decisions

A Paradigm for Designing Quality Affordable Vehicles

Source: Ref. 1.22

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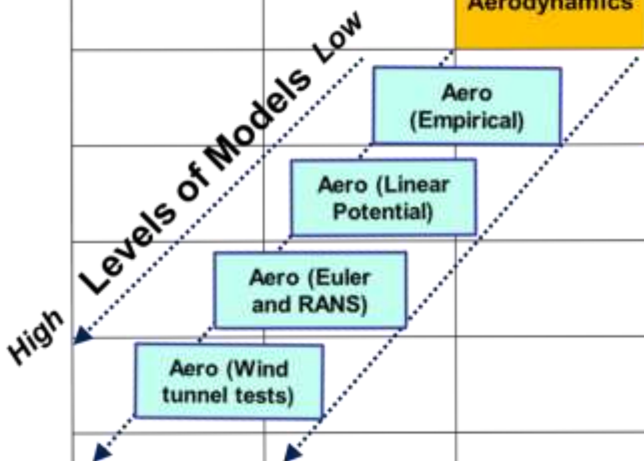
MDO Methodology for SBD of Aircraft

Multidisciplinary Design Optimization (MDO) Methodology

Best Suited for Simulation Based Design

Geometry	Cowl and Inlet Shape	Outer Mold Line	Cowl, Aft Deck	Internal Struc. Configuration	Mass Distribution	Wing Planform		Configuration
Flow behind Inlet Shocks	Propulsion	Inlet and nozzle Flow	Engine Thermal Loads	Engine Mechanical Loads	Engine Weight and Location	Engine Deck		Thrust, Altitude, Mach #, BPR, etc.
		Aerodynamics	Skin Temp., Loading	Airloads and Aeroelasticity		Polars in Flight Envelope		Response surface model
			Thermal Management	EEWS Weight, Inertial Loads	EEWS Weight			
				Structures	Structural Weight – Other	Flexible Wing		Response surface model
					Weights	Weight in Flight Envelope		Take-off Gross Weight
						Flight Performance		Feasibility
							Discipline X…	
Configuration	Thrust, Altitude, Mach#, BPR							Optimization



Enables Extensive Trade-off Studies and Rapid Design Closure

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Role of CFD in MDO Methodology

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VIRGINIA TECH.

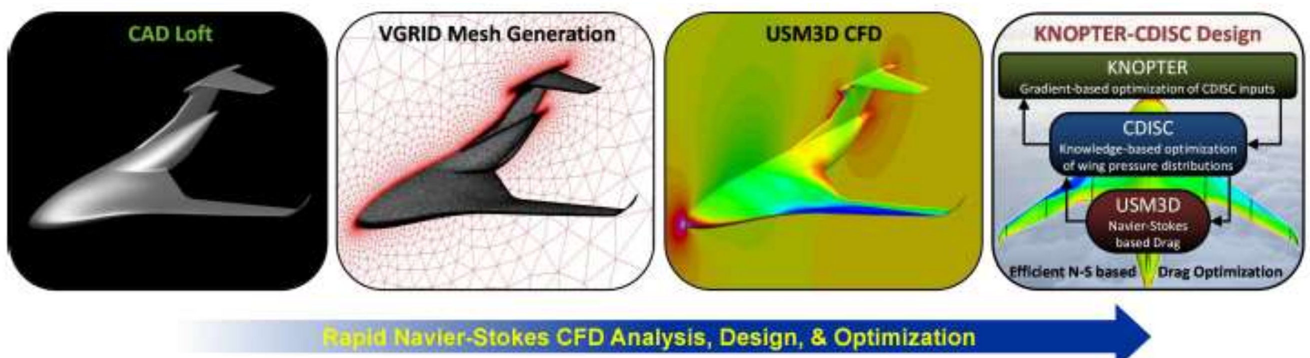
CFD Enables Use of Multidisciplinary Design Optimization (MDO) Methodology for SBD to Create Quality, Affordable Flight Vehicles

- CFD provides aerodynamic data for timely and cost-effective evaluation of the impact of geometric changes on vehicle performance, and of the sensitivity of performance to *numerous* design variables
- CFD offers the *most practical* (probably the only?) *means* of producing data required for rapid design closure through extensive trade-offs

Geometry	Cowl and Inlet Shape	Outer Mold Line	Cowl, Aft Deck	Internal Struc. Configuration	Mass Distribution	Wing Planform		Configuration
Flow behind Inlet Shocks	**Propulsion**	Inlet and nozzle Flow	Engine Thermal Loads	Engine Mechanical Loads	Engine Weight and Location	Engine Deck		Thrust, Altitude, Mach #, BPR, etc.
		Aerodynamics	Skin Temp., Loading	Airloads and Aeroelasticity		Polars in Flight Envelope		Response surface model
	Aero (Empirical)		**Thermal Management**	EEWS Weight, Inertial Loads	EEWS Weight			
	Aero (Linear Potential)			**Structures**	Structural Weight – Other	Flexible Wing		Response surface model
Aero (Euler and RANS)					**Weights**	Weight in Flight Envelope		Take-off Gross Weight
Aero (Wind tunnel tests)						**Flight Performance**		Feasibility
							Discipline X...	
Configuration	Thrust, Altitude, Mach#, BPR							**Optimization**

Levels of Models: Low → High

CFD provides inverse design and shape optimization capability that most clearly differentiates it from EFD



Enabler for Optimal Outer Mold Line (OML) Design

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Source: Ref. 1.23

Fully Effective ACA

Fully Effective ACA ≡ ACA Nirvana (a goal hoped for but apparently unattainable)!

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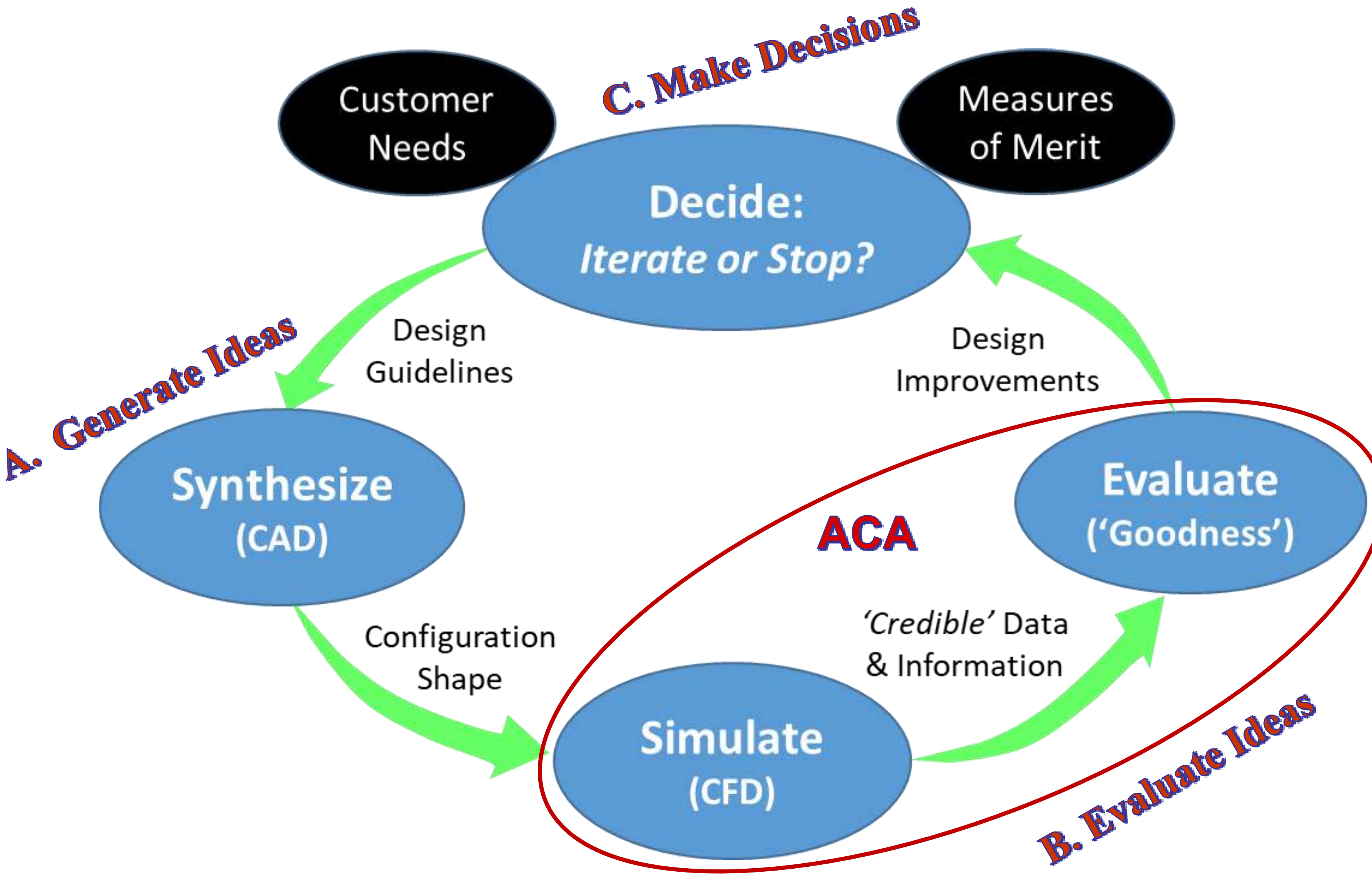
Role of ACA in Aircraft Design

"A Simplified Aerodynamic Design Loop"



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Fully Effective ACA

Ability to deliver credible solutions* of aerodynamic problems using CFD—on time and on budget—to support engineering design

**how faithfully the solutions replicate reality*

Miranda, in *AIAA 82-0018,* defined Effectiveness as a product of two factors:

***E**ffectiveness* = ***Q**uality* x ***A**cceptance*

"Quality" *(how well the results replicate reality)*

Credibility of the results of the comp aero simulation of flows about arbitrarily shaped configurations

"Acceptance" (*on time, on budget delivery of results*)

Ease of use; short turnaround time (elapsed time from go-ahead to delivery); low cost (labor hours & H/W+S/W costs)

Effectiveness of today's ACA is less than satisfactory due to shortcomings in Quality factor.

Luis R. Miranda

Manager
Computational Aerodynamics
Lockheed-California Co.

Fully Effective ACA Requires Simultaneous Maximization of Both Quality and Acceptance Factors

Pervasive Use of ACA in Engineering Design of Aircraft Drives the Pursuit of Fully Effective ACA

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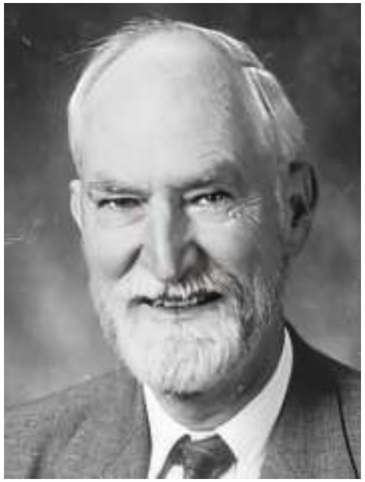
Source: Refs. 1.9, 1.24 & 1.25

Pursuit of Value with CFD

"…the value of CFD is directly related to its **contribution to RATE OF LEARNING during the process of designing an airplane**. Higher rates of learning lead to better designs. Rate of learning is comprised of the product of two terms, namely (i) **learning per design cycle**, **multiplied by** (ii) the **number of design cycles** that can be executed in a given amount of time. Earlier developments in CFD tended to focus on the former and to ignore or discount the latter. But the teachings of the 1990s created a greater focus on the latter, with the result that the processes in use for designing airplanes today are improving at a rate that is unprecedented."

On The Pursuit of Value with CFD
Frontiers of Computational Fluid Dynamics
World Scientific Publishing Co., November 1998, pp. 417-427

Paul E. Rubbert



Boeing Company (1960-1997)
Technical Fellow, Director of CFD
AIAA Fellow, Member NAE
18 Feb 1937 - 23 Dec 2020

Two areas of interest:
1. the conduct and management of research for effectiveness
2. the continued development and exploitation of computational fluid dynamics.

Note: Highlighting by the author of this presentation.

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Section 1.
Overarching Takeaways

CFD Produces Data, ACA Produces Solutions.
Don't Confuse Data with Solutions!

CFD is to ACA as Airplane is to Air Transportation!

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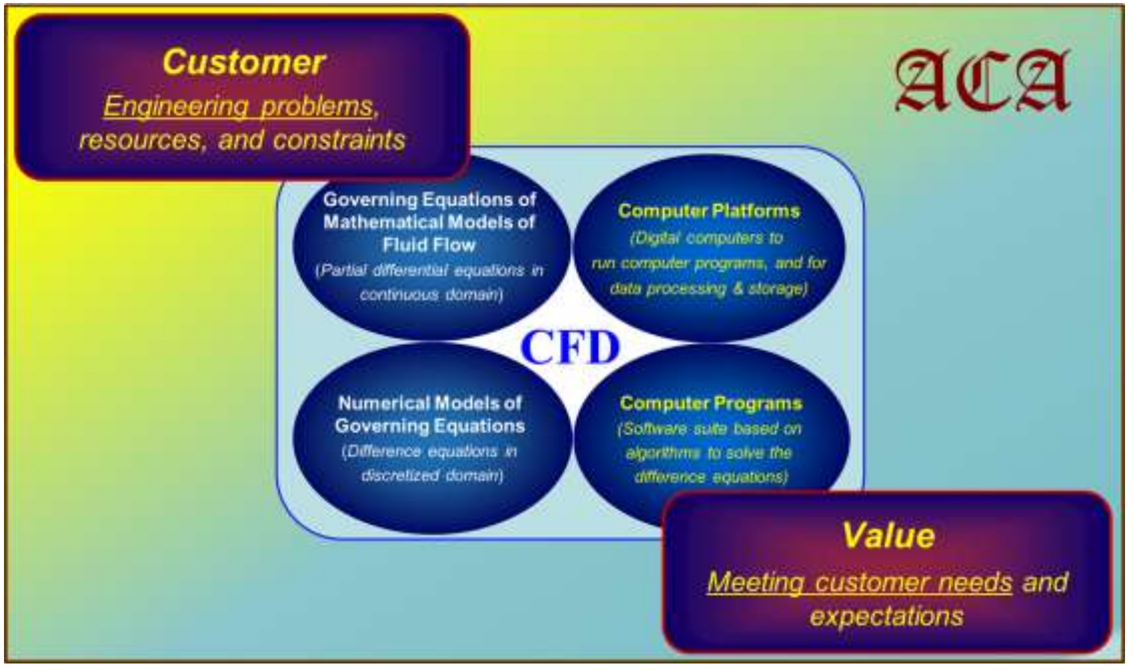
Section 1: Key Takeaways

- **ACA is an *engineering* discipline, CFD is an *applied science* discipline (being a sub-discipline of fluid dynamics)**
  - ACA is purpose-driven application of CFD…purpose is to deliver *credible* solutions of engineering problems *on time* and *on budget*
  - ***Fully Effective ACA*** delivers solutions that replicate reality, on time and on budget
- **ACA uses CFD to create value for the customer**



- **ACA is no longer a luxury, but a necessity, to support engineering design of all types of objects that move through air**

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VIRGINIA TECH.

Contents

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Why Look Back?

Study the past, if you would define the future.

— Confucius (551 – 479 BC)

The further backward you look, the further forward you can see.

— Churchill (1874 – 1965)

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Image and Quote Source: Internet

The Old Testament *(1200 – 165 BC)*

Proverbs 30:18-19

"There be three things which are too wonderful for me, yea four which I know not."

"The way of an eagle in the air, the way of a serpent upon a rock, the way of a ship in the midst of the sea, and the way of a man with a maid."

Two of the Three Things Involve Flow of Fluids and They Remain "Too Wonderful" Today!

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Quote Source: Internet

Early Days of Civilization

Two Crucial Needs

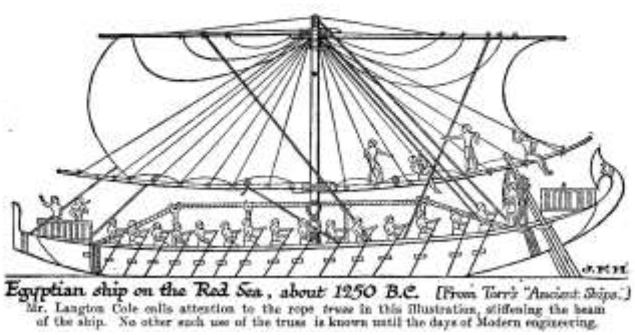
1. ***Water Distribution to villages and cities for farming and household use*****--canals and conduits were built to transport water**

Eupalinos underground aqueduct (ca 6th century BC)

Aqua Anio Vetus Roman aqueduct (ca 272 BC)

Aqueduct of Segovia (ca 100 AD)

2. ***Maritime Transport to supply essential goods*****--river boats and seafaring ships powered by sails or manual propulsion were built**



Ancient Egyptian ship (ca 1250 BC)

Vikings landing in Britain (ca 449 AD)

Vasco da Gama at Calicut, India (ca 1498 AD)

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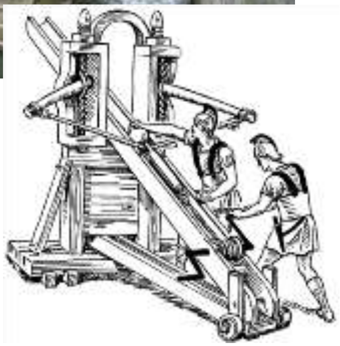
Source: Refs. 2.1 & 2.2; Images from Wikipedia

Early Days of Civilization

Two Sets of "Grand Challenge" Problems

1. Problems of Resistance

- Motivating societal needs:
  - navigation (ships)
  - fluid-driven machines (waterwheels and mills)
  - ballistics (projectiles)
- ***How does a fluid current affect a body in its path?***



2. Problems of Discharge

- Motivating societal needs:
  - water distribution
  - jet reaction machines
- ***How do fluids discharge themselves from reservoirs and through tubes or pipes?***

Impetus for the Genesis of "Fluid Dynamics"

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Source: Ref. 2.3; Images from Wikipedia

Addressing "Grand Challenge" Problems

Two Branches of Investigations Emerged

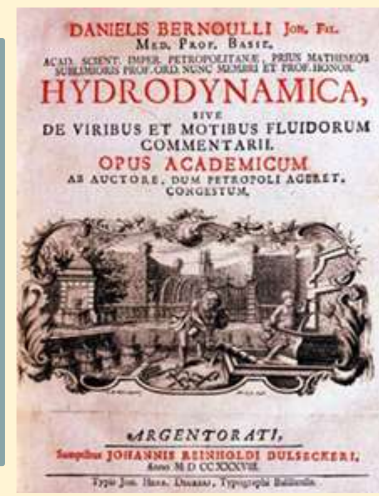
Hydraulics

Artisan Activity **based on *Empirical Knowledge* to devise *Practical Solutions* to problems of fluids in motion or at rest**

Flourished for Countless Millennia

Hydrodynamics

Scientific Activity **based on *Laws of Nature* to develop *Fundamental Understanding* and *Knowledge* of fluid flow**


DANIELIS BERNOULLI Joh. Fil.
Med. Prof. Basil.
HYDRODYNAMICA,
SIVE
DE VIRIBUS ET MOTIBUS FLUIDORUM
COMMENTARII.
OPUS ACADEMICUM
AB AUCTORE, DUM PETROPOLI AGERET, CONGESTUM.
ARGENTORATI,
Sumptibus JOHANNIS REINHOLDI DULSECKERI,
Anno M D CCXXXVIII.

Daniel Bernoulli

8 Feb 1700 – 17 Mar 1782

Formally Emerged in 1738

Evolved as the preferred approach to solve fluid flow problems!

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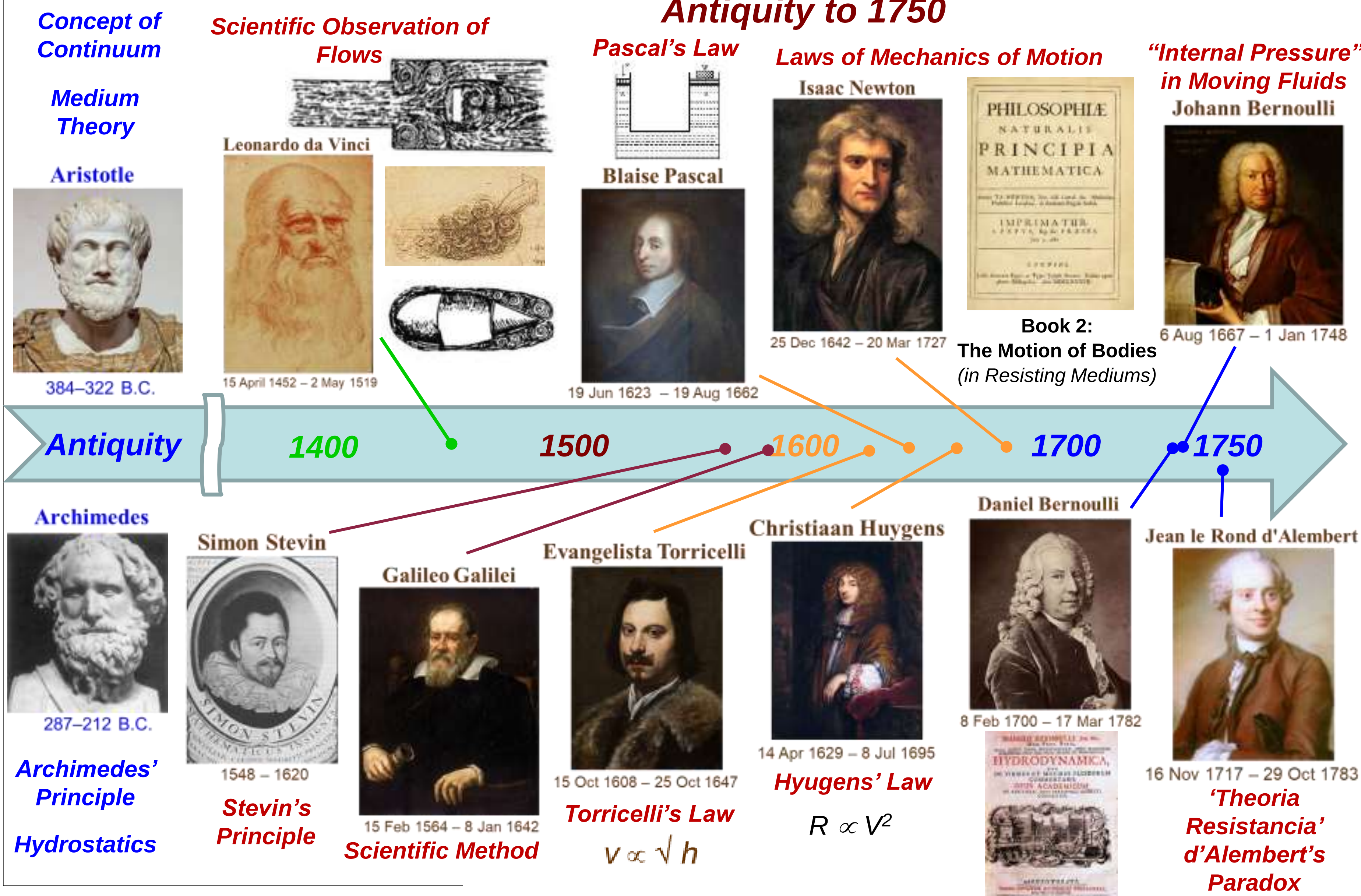
Source: Ref. 2.1; Wikipedia

Key Foundational Theories, Principles, and Laws of Fluid (Aero/Hydro) Dynamics:

Antiquity to 1750



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Source: Refs. 2.1 – 2.7, and Wikipedia

In the Beginning…*The Greek Ideas*

- **Four Basic Elements Theory**
  - Universe consists of four basic elements: *fire, air, water, earth*
  - Protagonists included Pythagoras (~580-500 BC), Empedocles (490-430 BC), Plato (427-347 BC), and Aristotle (384-322 BC)
    - Their theories significantly departed from mythology
  - Aristotle--a pure theorist--probably had the most influence on the growth of scientific knowledge in general, and fluid mechanics in particular, that lasted nearly 2,000 years

Aristotle

Greek Philosopher
384–322 B.C.

- **Nature Abhors Vacuum**
  - Space around us must be occupied by one element or another
  - Vacuums–*the absence of any and everything*–were simply an impossibility.

- **Concept of Continuum**

  "The continuous may be defined as that which is divisible into parts which are themselves divisible to infinity, as a body which is divisible in all ways. Magnitude divisible in one direction is a line, in three directions a body. Being divisible in three directions, a body is divisible in all directions. And magnitudes which are divisible in this fashion are continuous."

- **Theory of Motion**
  - In a void, a body at rest will remain at rest, and a body in motion will continue to have the same motion unless some obstacle comes into collision
  - Everything that is in motion must be moved by something. A body in motion is being driven by fluid closing in behind. [An arrow creates a vacuum in its wake, into which air rushes, pushing it from behind.] *Paradoxically, air also resists motion!*

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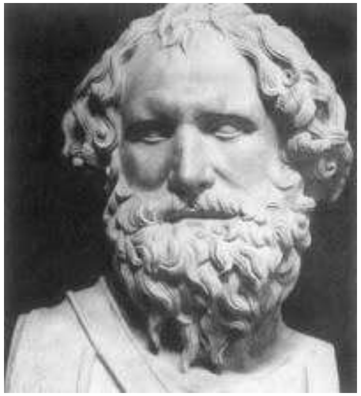
Source: Ref. 2.4 & 2.5, and Wikipedia

"The Birth of Hydrostatics"

Basic Principles

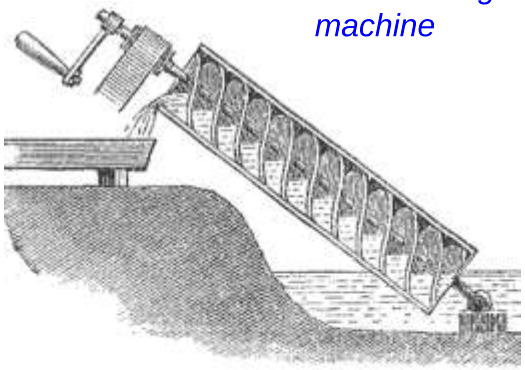
- *Proposition 3:* Of solids those which, size for size, are of equal weight with a fluid will, if let down into the fluid, be immersed so that they do not project above the surface but do not sink lower.
- *Proposition 4:* A solid lighter than a fluid will, if immersed in it, not be completely submerged, but part of it will project above the surface.
- *Proposition 5:* Any solid lighter than a fluid will, if placed in the fluid, be so far immersed that the weight of the solid will be equal to the weight of the fluid displaced.
- *Proposition 7:* A solid heavier than a fluid will, if placed in it, descend to the bottom of the fluid, and the solid will, when weighed in the fluid, be lighter than its true weight by the weight of the fluid displaced.
- *Postulates: Fluids* cannot have internal empty spaces, i.e., they *must be continuous. And* if fluid parts are continuous and uniformly distributed, then that which is the least compressed is driven along by that which is more compressed In a fluid "*each part is always pressed by the whole weight of the column perpendicularly above it.*"

Archimedes



Greek Mathematician
287–212 B.C.

Archimedes' Screw
a water elevating machine



Archimedes' Principle (or Law)

When a solid body is immersed in a fluid, it is pressed vertically upwards by the fluid with a force equal to the weight of the fluid displaced, the force is known as buoyancy.

[Arguably] No Major Advancements for Next 17 Centuries!

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Source: Ref. 2.4 - 2.6, and Wikipedia

Direct Study of Nature: *The Renaissance* *(15th Century)*

- The *First Scientific Observer of Flows*

Leonardo da Vinci

Italian Artist, Engineer, Scientist
15 Apr 1452 – 2 May 1519

- **Principle of Continuity**

"By so much as you will increase the river in breadth, by so much you will diminish the speed of its course." (i.e., *area x speed = constant)*

- **Principle of Relative Motion**

The air's action is the same whether the bird is at rest in a moving airstream—hovering at a cliff edge in a strong breeze—or is moving through still air.

- **Principle of Circulation**

"The helical or rather rotary motion of every liquid is so much the swifter as it is nearer to the center of its revolution…the motion of the [solid] circular wheel is so much the slower as it's nearer the center…[for water] we have the same motion, through speed and length, in each whole revolution of the water, just the same in the circumference of the greatest circle as in the least…"

- **Air Resistance is Directly Proportional to Speed**

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Source: Refs. 2.1 – 2.5, and Wikipedia

Scientific Method: *The Renaissance* *(16th Century)*

- **Emergence of Scientific Method**

  Galileo adds *Experimentation* and *Quantification* to Da Vinci's *Observation* for studying nature

- **Tenets of Scientific Method**
  - ***OBSERVE***: *Observe* phenomena
  - ***HYPOTHESIZE***: Formulate *hypotheses* via induction
  - ***TEST***: *Experimentally test* deductions from hypotheses
  - ***REFINE***: Use findings to *refine* or *eliminate hypotheses*

Galileo Galilei

Italian Philosopher, Astronomer and "Geometer" (Mathematician)
15 Feb 1564 – 8 Jan 1642

- **Galilean Principle of Inertia**

  A body in motion would remain in motion unless a force caused it to come to rest. It contradicted the widely accepted Aristotelian theory of motion

> ***"Philosophy is written in this grand book, which stands continually open before our eyes (I say the 'Universe'), but cannot be understood without first learning to comprehend the language...it is written in mathematical language, and its characters are triangles, circles and other geometric figures…"***
>
> -- *Galileo Galilei,* The Assayer, *Oct. 1623*

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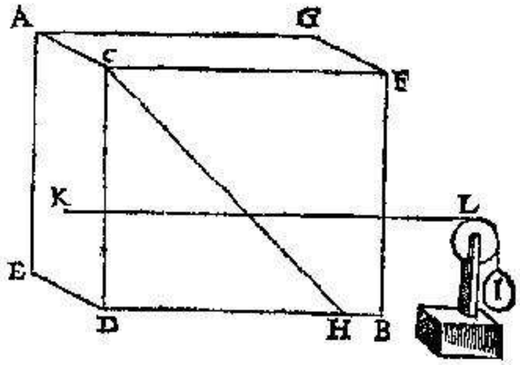
Source: Ref. 2.1, and Wikipedia

Advancement of Hydrostatics *(16th Century)*

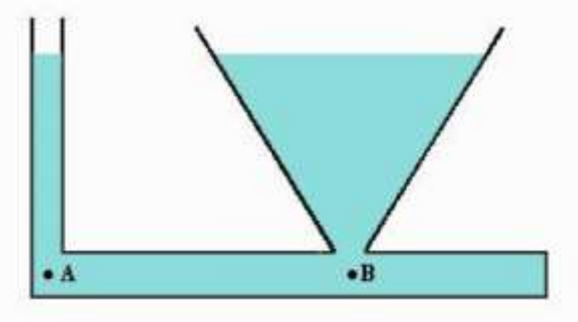
Simon Stevin

Flemish Mathematician
1548 – 1620

- **Principle of Solidification**
  In any fluid at rest, if any portion be replaced by a rigid solid, the forces exerted by the remainder will not be altered
- **Pressure on the Side of a Vessel**
  Used limit arguments to prove that water in the rectangular box exerts a force at the center of mass of the vertical wall ACDE equal to that of the weight of the water volume ACHDE



- **Genesis of *'Hydrostatic Paradox'***
  The ***hydrostatic pressure*** at the bottom of a container filled with a liquid depends, linearly, only on the height of the liquid column, and not on the particular shape (and thus on the volume) of the container



"Any column of water, however small, may be made to support any weight, however large."

First Notable Contributions Since Archimedes!

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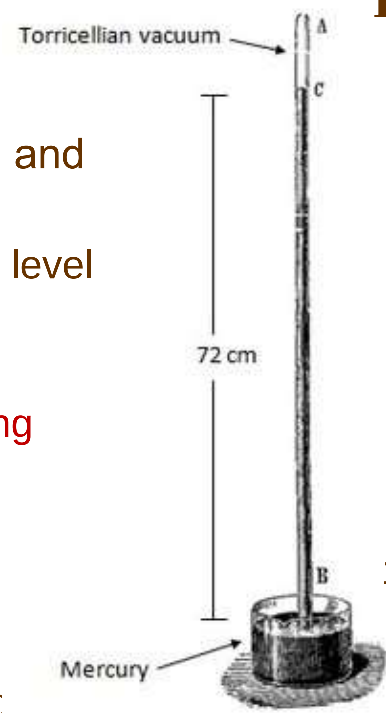
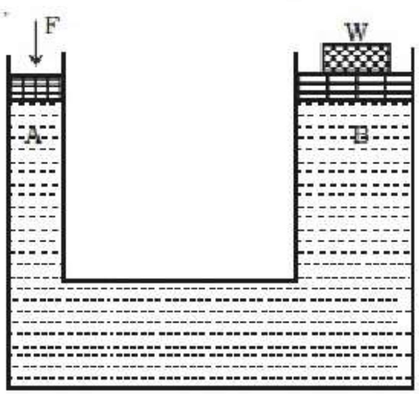
Source: Ref. 2.7, and Wikipedia

Advancement of Fluid Statics
(17th Century)

- **Barometric Pressure**
  - **Torricelli (1630)** invents mercury barometer; gives partial explanation of its operation
  - **Pascal (1647)** repeats Torricelli's experiment, and further studies atmosphere
    - Variation of atmospheric pressure cause liquid level to change from day to day
    - Atmospheric pressure reduces with altitude
    - *"Nature does <u>not</u> abhor vacuum"* -- contradicting prevailing Aristotelian wisdom
  - Pascal proves that pressure at any point in a fluid is *<u>the same</u>* in all directions
- **Pascal's Law (1647-48)**
  - A change in pressure at any point in an enclosed fluid *at rest* is transmitted undiminished to all points in the fluid
  - Resolves Hydrostatic Paradox, and enables development of hydraulic devices





> "In order to show that a hypothesis is evident, it does not suffice that all the phenomena follow from it; instead, *if it leads to something contrary to a single one of the phenomena, that suffices to establish its falsity*."
>
> -- Blaise Pascal

Evangelista Torricelli

Italian Physicist
15 Oct 1608 – 25 Oct 1647

Blaise Pascal

French Philosopher
19 Jun 1623 – 19 Aug 1662

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Source: Refs. 2.1 – 2.5 and Wikipedia

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Study of ***Discharge*** Problem

(17th Century)

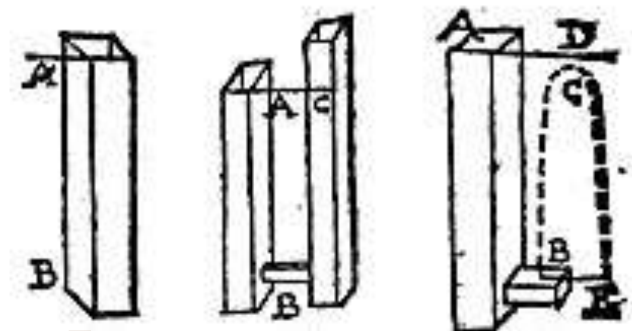
Efflux of Water from Vessels

Torricelli's Law (1644)

Efflux velocity is proportional to the square root of the depth: $v \propto \sqrt{h}$

Water jet from a small hole rises almost to the same height as the water level in the tank.

The upwards velocity at B is the same as the downwards velocity at E.



Applies Galilean Principle for falling motion of bodies to the efflux of liquids from vessels!

Evangelista Torricelli

Italian Physicist
15 Oct 1608 – 25 Oct 1647

Huygens Experiments (1668)

Confirmed Torricelli's Law!

However, disparate results obtained based on the geometry of the apparatus, such as, form of the vessel, type of spout, relative location of orifice to the surface of the vessel.

Modified Law: $v \propto k\sqrt{h}$

Proportionality constant, k, adjusted to match measurements!

Christiaan Huygens

Dutch Scientist
14 Apr 1629 – 8 Jul 1695

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Source: Refs. 2.1 – 2.5, and Wikipedia

Study of ***Resistance*** Problem
(17th Century)

Resistance of Fluid on Bodies

Huygens Law (1669)

Resistance is proportional to the *square* of the fluid velocity *(when the velocity doubles, the resistance quadruples)*

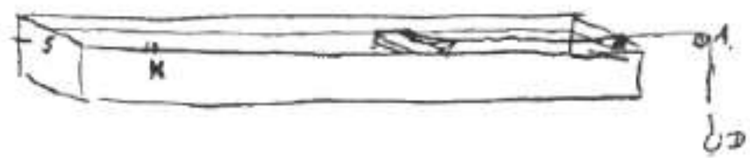
- Deduced from experiments with projectiles.

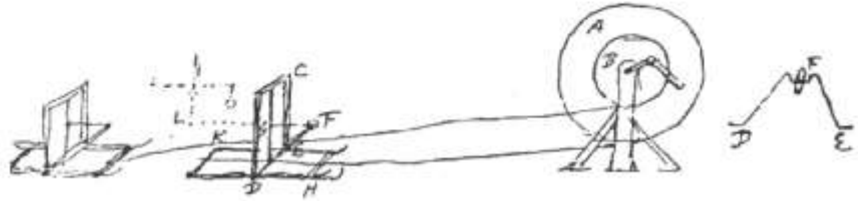
Corrects prevailing thought that resistance is proportional to the fluid velocity *(when the velocity doubles, the resistance doubles)*

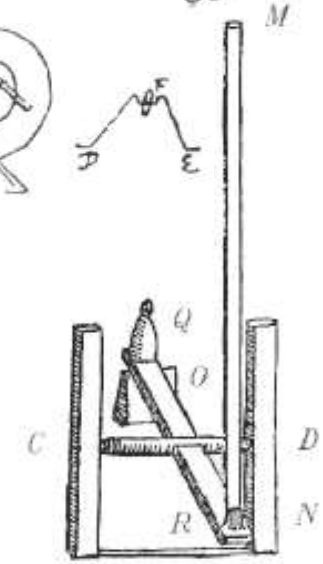
Experimentally measures resistance of

(i) a wooden cube being dragged through a water channel

(ii) fully submerged bodies moving through air







Mariotte's Principle (1673)

Resistance is proportional to the square of the fluid velocity *(when the velocity doubles, the resistance quadruples)*

- Deduced from experiments with moving fluid impacting on a flat surface.

Christiaan Huygens

Dutch Scientist
14 Apr 1629 – 8 Jul 1695

Edme Mariotte

French Physicist
1620 – 12 May 1684

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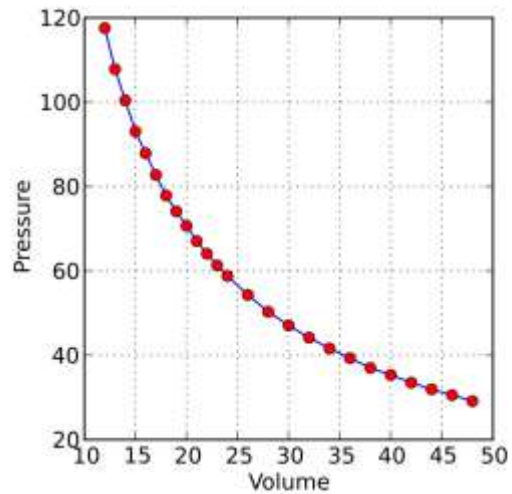
Source: Refs. 2.3 & 2.4, and Wikipedia

Insights into the Nature of Fluids
(17^{th} Century)

- **Boyle's Hypothesis (1661)**
  Matter consists of little particles in motion; every phenomenon is the result of *collisions of particles in motion*.
- **Two types of Fluids: Liquids (water) & Gases (air)**
  Liquids form a free surface not created by their container; Gases occupy the entire volume of the container.
- **Boyle's Law (1662)**
  "The product of pressure (*P*) and volume (*V*) is a constant for a given mass of confined gas as long as the temperature is constant."

$$P \propto \frac{1}{V}$$



  Liquids may be regarded as incompressible.

- **Charles' Law (*1780—a century later*)**
  "The volume (*V*) of a gas increases linearly with the absolute temperature (*T*) of the gas as long as pressure is constant."

$$V \propto T$$

Robert Boyle

Anglo-Irish Philosopher
25 Jan 1627 – 31 Dec 1691

Jacques Charles

French Physicist
12 Nov 1746 – 7 Apr 1823

Source: Wikipedia

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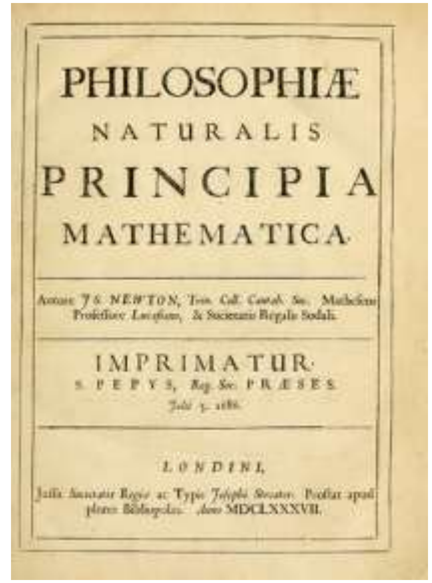
Basic Laws of Mechanics of Motion
(17th Century)

- **Mathematical Principles of Natural Philosophy (*July 5, 1687)***

  "…the basic problem of [natural] philosophy seems to be to discover the forces of nature from the phenomena of motions and then to demonstrate the other phenomena from these forces; and to this end the general propositions in the first and second Books are directed."



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore JS. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

"the greatest production of the human mind."
Lagrange (1736-1813)

Isaac Newton

English Physicist & Mathematician
25 Dec 1642 – 20 Mar 1727

- **Book I: Of the Motion of Bodies**
  - Deals with rigid bodies (point masses)
  - ***First complete, rational, theoretical derivation of all motions from a few axioms and laws***
- **Book II: Of the Motion of Bodies *(in Resisting Mediums)***
  - Deals with two types of fluids:
    - 'Rare Medium'—collection of disconnected, *non-interacting* perfectly spherical elastic particles which exchange momentum when they collide with a body
    - 'Continued Medium'—a continuous chain of particles
  - *Several different hypotheses added to the few in Book I*
  - ***Includes some small fudges and implausible constructions as well!***

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Source: Refs. 2.1 – 2.5, and Wikipedia

Newton's Theory of Fluid *Resistance* *(17th Century)*

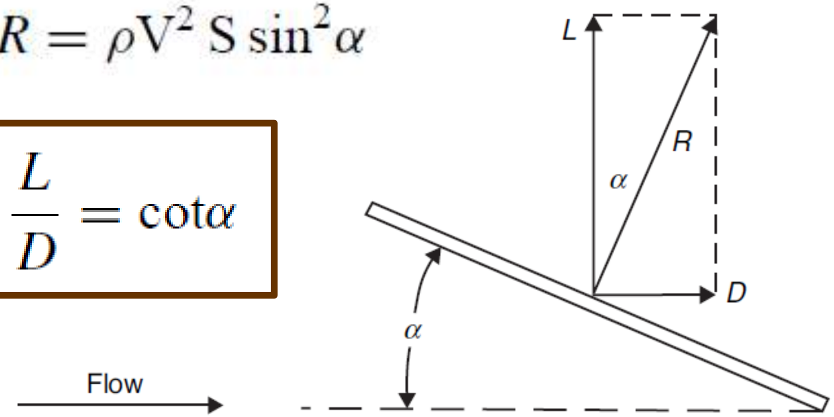
- **Mathematical Principles of Natural Philosophy (*July 5, 1687*)**
  - Book II: Of *the Motions of Bodies (in Resisting Mediums)*
- **Resistance of bodies moving through a fluid** (Proposition 33)

$$D \propto \rho S V^2$$

  - *First theoretical derivation of the drag (resistance) force of a body!*
- **Fluid dynamic force on a flat plate**

$$R = \rho V^2 S \sin^2\alpha$$

$$\frac{L}{D} = \cot\alpha$$



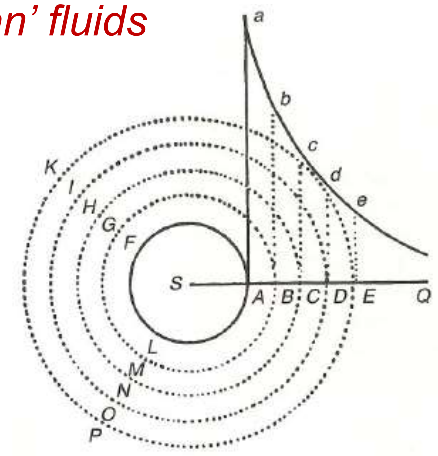
- **Internal resistance within a flow created by its own velocity gradients**

"The resistance arising from the want of lubricity in the parts of a fluid, is, proportional to the velocity with which the parts of the fluid are separated from each other."

  - *Provides the well-known linear relationship of shear stress and rate of strain for 'Newtonian' fluids*

$$\tau \propto dV/dn$$

  - *Explains creation of vortex motion about a rotating cylinder in a tank of water*



  - *Formula is based on Proposition 34…but the formula is not found in Newton's work!*
  - *'Rare Medium'* fluid model used for this formula

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Source: Ref. 2.4, and Wikipedia

Birth of "*Hydrodynamics*"

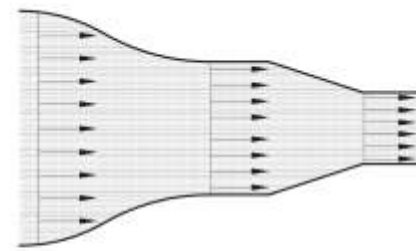
(18th Century)

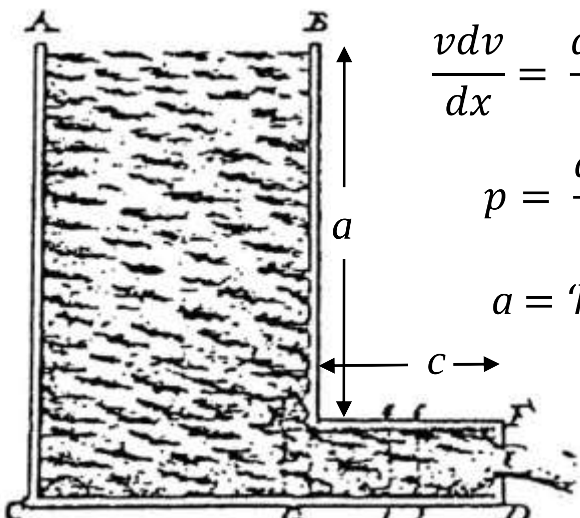
Daniel Bernoulli

Swiss Mathematician
8 Feb 1700 – 17 Mar 1782

1738

- Daniel Bernoulli successfully derived ***'hydraulic-static'* pressure exerted by a *moving fluid on the wall* of its container**--going beyond Stevin's and Pascal's Laws of hydrostatic pressure
- Employed elements of calculus for analysis using continuity and von Leibniz *'vis viva' ('live force')* *or* kinetic energy principles; *verified predictions using experiments!*
  - Devised parallel-slice hypothesis for flow through ducts





$$\frac{vdv}{dx} = \frac{a - vv}{2c}$$

$$p = \frac{a - v^2}{2c}$$

$$a = \text{'head'}$$

- Analyzed efflux through small opening at the bottom of a vessel that showed compliance with Torricelli's Law

Bernoulli Principle

In a flowing fluid, pressure decreases as velocity increases.

The Well-known Bernoulli's Equation is Not in the Book!

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Source: Refs. 2.1 – 2.5, 2.8, and Wikipedia

J. Bernoulli's *Hydraulica*
(18th Century)

Johann Bernoulli

Swiss Mathematician
6 Aug 1667 – 1 Jan 1748


N°. CLXXXVI.

JOHANNIS BERNOULLI HYDRAULICA

Nunc primum detecta ac demonstrata directe ex fundamentis pure mechanicis.

1742

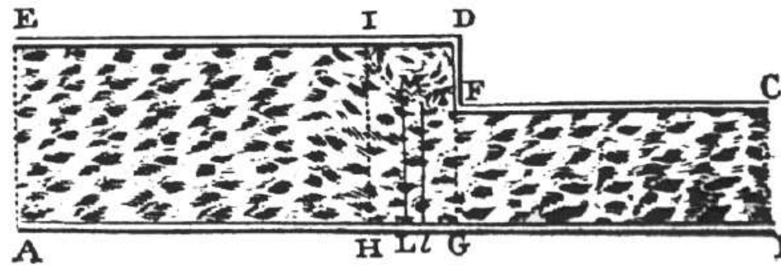

JOHANNIS BERNOULLI,

OPERA OMNIA,

TOMUS QUARTUS

MDCCXLII.

- Analyzed fluid flow through a duct with abrupt change in area using Newton's Laws—instead of '*vis viva*' theory used by his son, Daniel
  - Inserted whirlpools to convert jump into continuous area variation



- Developed equations of motion of accelerating flow by applying Newton's Second Law to parallel slices of fluid
- Introduced the new concept of convective derivative to account for acceleration due to broadening or narrowing of area—in addition to that due to instantaneous change in velocity
- Generalized Daniel Bernoulli's principle for pressure in non-steady flow

> ***A New Concept of Internal Pressure in Moving Fluids***
> "The force that acts on the side of a channel through which a liquid flows…is nothing but the force that originates in the force of compression through which contiguous parts of the fluid act on one another."

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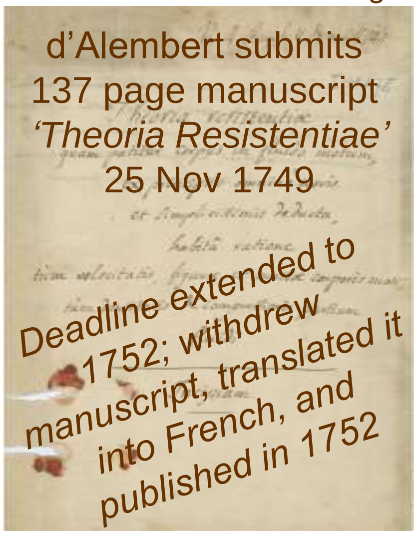
Source: Ref. 2.3, and Wikipedia

Theory of Resistance: *A Grand Milestone!*

(18th Century)

16 May 1748

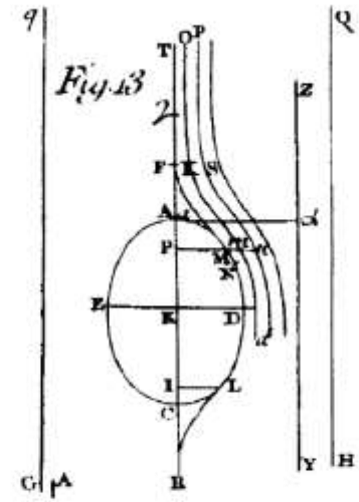
Berlin Academy Prize Announced for *Determination of Drag*



Jean le Rond d'Alembert

French Mathematician
16 Nov 1717 – 29 Oct 1783

- Flow of inviscid fluid about a body is a field of continuous variation in velocity
- Determine the fluid field, then integrate local pressures to find force exerted on the body
- *Introduces streamlines, and front and aft stagnation points and zones, for 2-D and axisymmetric bodies*
- Develops two equations relating partial derivatives of axial and lateral velocity components to force components for steady flow
- Used his dynamical principle and equilibrium principle to derive hydrodynamical equations for steady, inviscid, incompressible, 2-D and axisymmetric flows



- Uses complex variable transformation and developments in power series in attempts to determine velocity field that is uniform at infinity and tangent to the body along its surface—*but unable to solve the equations*
- Instead applies his knowledge of Bernoulli's work to estimate drag
- Conclusion: Due to symmetrical fluid field, a symmetrical body *"…would suffer no force from the fluid, which is contrary to experience."*

"…it seems to me that the theory, developed in all possible rigor, gives, at least in several cases, a strictly vanishing resistance, a singular paradox which I leave to future geometers* to elucidate."

Conclusion Gave Birth to <u>d'Alembert's Paradox</u>

**i.e. mathematicians - the two terms were used interchangeably at that time*

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Source: Refs. 2.1 – 2.5, 2.9, 2.10, and Wikipedia

d'Alembert's great strides in the use of mathematics to solve fluid dynamic problems were harbinger of the direction of the field of fluid dynamics for the next 150 years and beyond!

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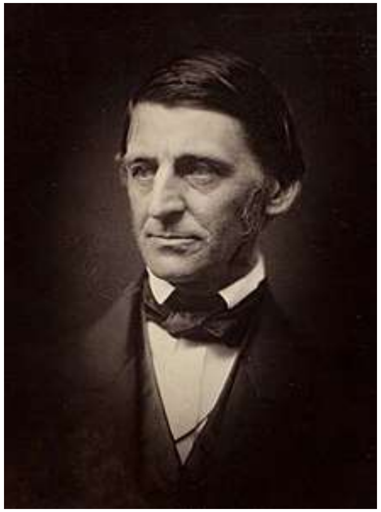
Section 2.
Overarching Takeaways

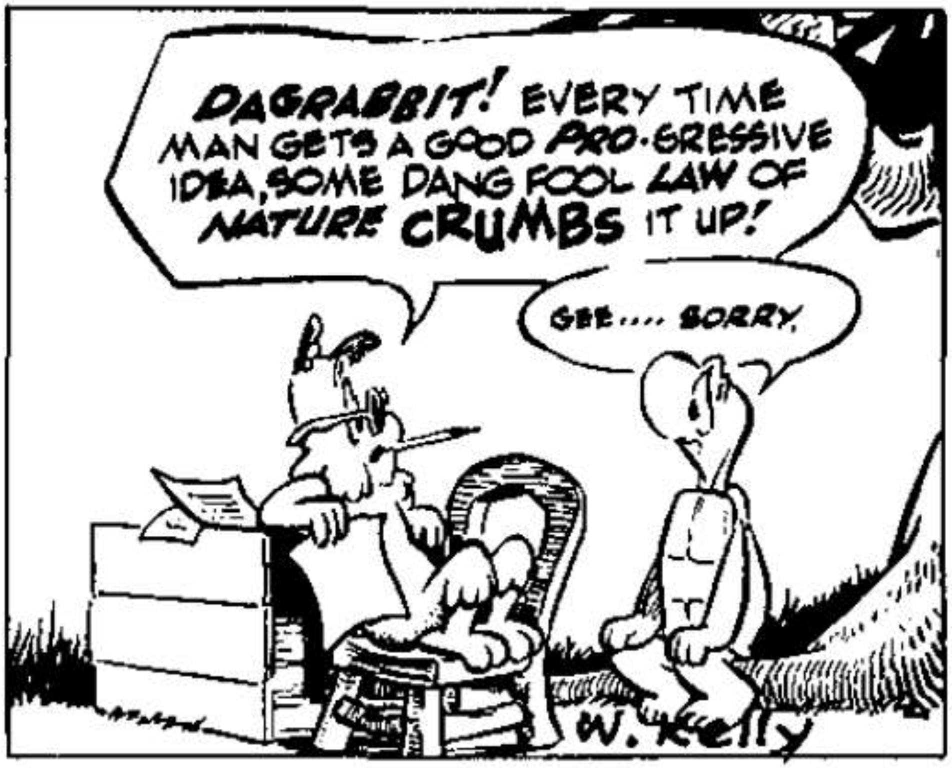
"Everything in Nature Goes by Law, and Not by Luck."

Ralph Waldo Emerson



25 May 1803 – 27 April 1882

Laws of Nature Serve as Universal Constraints on the Flow of Fluids



Source: AIAA-1982-0315

Source: Wikipedia

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Section 2: Key Takeaways

- **Early Days of Civilization**
  - **Two sets of "Grand Challenge" Problems**
    1. Problems of **Resistance** (ships, water wheels, projectiles,…)
    2. Problems of **Discharge** (water distribution, jet reaction machines,…)
  - **Two Branches of Investigations to Address Grand Challenge Problems**
    1. **Hydraulics** (artisan activity based on empirical knowledge)
    2. **Hydrodynamics** (scientific activity based on fundamental laws of nature)

- **Key Foundational Ideas for Fluid Dynamics *(Antiquity to 1750)***
  - **384-322 BC: Aristotle—*concept of continuum***
  - **287-212 BC: Archimedes—*principles of hydrostatics***
  - **1452-1519: Leonardo da Vinci—*principles of continuity and relative motion***
  - **1586: Stevin—*hydrostatic pressure depends only on the height of the fluid column***
  - **1644: Torricelli—*efflux velocity is proportional to the square root of depth***
  - **1669: Huygens—*resistance is proportional to <u>square</u> of velocity***
  - **1687: Newton—*Laws of Mechanics and theory of fluid resistance***
  - **1738: D. Bernoulli—*pressure decreases as velocity increases***
  - **1742: J. Bernoulli—*concept of internal pressure in moving fluids***
  - **1749: d'Alembert—*symmetrical body would suffer no fluid force--a Paradox!***

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2.3 Calero, J.S., The Genesis of Fluid Mechanics 1640-1780, Studies in History and Philosophy of Science, Vol. 22, Springer, 2008.

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Fluid Dynamics as a Mathematical Science *(1750 – 1900)*

The Euler Equations (1755-57)

Leonhard Euler

15 Apr 1707 – 8 Sep 1783

$$P - \frac{1}{q}\left(\frac{dp}{dx}\right) = \left(\frac{du}{dt}\right) + u\left(\frac{du}{dx}\right) + v\left(\frac{du}{dy}\right) + w\left(\frac{du}{dz}\right)$$

$$Q - \frac{1}{q}\left(\frac{dp}{dy}\right) = \left(\frac{dv}{dt}\right) + u\left(\frac{dv}{dx}\right) + v\left(\frac{dv}{dy}\right) + w\left(\frac{dv}{dz}\right)$$

$$R - \frac{1}{q}\left(\frac{dp}{dz}\right) = \left(\frac{dw}{dt}\right) + u\left(\frac{dw}{dx}\right) + v\left(\frac{dw}{dy}\right) + w\left(\frac{dw}{dz}\right)$$

$$\left(\frac{dq}{dt}\right) + \left(\frac{d.qu}{dx}\right) + \left(\frac{d.qv}{dy}\right) + \left(\frac{d.gw}{dz}\right)^{*} = 0$$

equation of state *(a relation between* p*,* q *and* r*)*

*misprint: g should be q.

"…it is not the laws of Mechanics that we lack…but only the Analysis, which has not yet been sufficiently developed…"

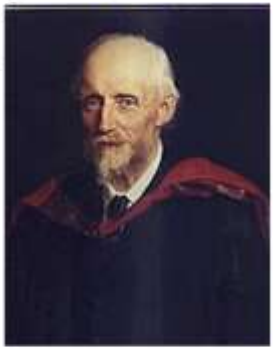
"…steady direct motion in round tubes is stable or unstable according as $\rho \mathbf{D} \mathbf{U}_m/\mu$ *<1900 or >2000,…"*

$$\rho\frac{d\bar{u}}{dt} = -\left\{\frac{d}{dx}\left(\overline{p_{xx}} + \rho\bar{u}\bar{u} + \rho\overline{u'u'}\right) + \frac{d}{dy}\left(\overline{p_{yx}} + \rho\bar{u}\bar{v} + \rho\overline{u'v'}\right) + \frac{d}{dz}\left(\overline{p_{zx}} + \rho\bar{u}\bar{w} + \rho\overline{u'w'}\right)\right\}$$

&c.

&c.

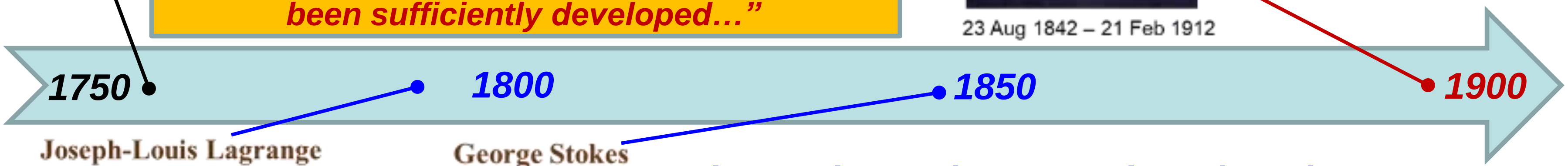
Osborne Reynolds



23 Aug 1842 – 21 Feb 1912

"…equations of mean-mean-motion…"

The Reynolds-Averaged Navier-Stokes (RANS) Equations (1895)



Joseph-Louis Lagrange

25 Jan 1736 – 10 Apr 1813

steady incompressible flow

$$\frac{\rho v^2}{2} + p = \text{const}$$

'Bernoulli's Equation'

George Stokes

13 Aug 1819 – 1 Feb 1903

The Navier-Stokes Equations (1849)

$$\rho\left(\frac{Du}{Dt} - X\right) + \frac{dp}{dx} - \mu\left(\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + \frac{d^2u}{dz^2}\right) - \frac{\mu}{3}\frac{d}{dx}\left(\frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz}\right) = 0,$$

$$\frac{d\rho}{dt} + \frac{d\rho u}{dx} + \frac{d\rho v}{dy} + \frac{d\rho w}{dz} = 0,$$

equation connecting p and ρ,

…conditions which must be satisfied at the surface of a solid in contact with the fluid…are unknown.

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Source: Refs. 3.1 – 3.7; Wikipedia

Foundations of Mathematical Fluid Dynamics

(18th Century)

'PRINCIPES GÉNÉRAUX DU MOUVEMENT DES FLUIDES'

Académie Royale des Sciences et des Belles-Lettres de Berlin

Presented 4 September 1755 [printed in 1757]

274

PRINCIPES GÉNÉRAUX DU MOUVEMENT DES FLUIDES.

PAR M. EULER.

- **Three *equations of motion* derived from the *first axioms of mechanics* using *'infinitesimal fluid particle'***

$$P - \frac{1}{q}\left(\frac{dp}{dx}\right) = \left(\frac{du}{dt}\right) + u\left(\frac{du}{dx}\right) + v\left(\frac{du}{dy}\right) + w\left(\frac{du}{dz}\right)$$

$$Q - \frac{1}{q}\left(\frac{dp}{dy}\right) = \left(\frac{dv}{dt}\right) + u\left(\frac{dv}{dx}\right) + v\left(\frac{dv}{dy}\right) + w\left(\frac{dv}{dz}\right)$$

$$R - \frac{1}{q}\left(\frac{dp}{dz}\right) = \left(\frac{dw}{dt}\right) + u\left(\frac{dw}{dx}\right) + v\left(\frac{dw}{dy}\right) + w\left(\frac{dw}{dz}\right)$$

P, Q, R: accelerative forces due to gravity

p, q, u, v, w: pressure, density, and three components of velocity

( ): partial derivatives

- **One *continuity equation***

$$\left(\frac{dq}{dt}\right) + \left(\frac{d.qu}{dx}\right) + \left(\frac{d.qv}{dy}\right) + \left(\frac{d.gw}{dz}\right)^{*} = 0$$

- **One *equation of state***, i.e., a relation between p, q and r
  - Here r expresses that other property [temperature] which, in addition to q, influences p in a compressible fluid (nature of fluid is assumed to be known.)

Leonhard Euler

Swiss Mathematician

15 Apr 1707 – 8 Sep 1783

"…five equations encompassing the entire theory of the motion of fluids." — Euler

*misprint in original paper: g should be q

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Source: Refs. 3.1 – 3.3, and Wikipedia

Tokaty on Euler's Equations

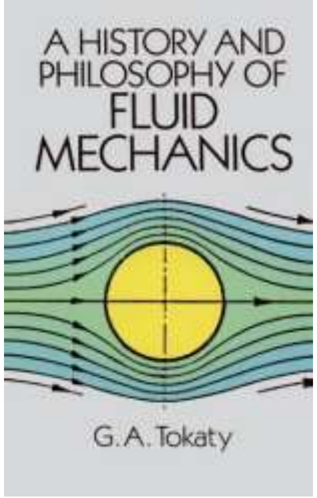
G.A. Tokaty, Soviet Scientist, Zhukovsky Academy (defected to Britain in 1947)

Emeritus Professor, Aeronautics and Space Technology, The City University, London

"…geometry is a branch of mathematics which treats the shape and size of things; while Fluidmechanics is the science of motion (and equilibrium) of bodies of deformable (and variable) shapes, under the action of forces…some theorems and **axioms of geometry do not meet the philosophical and physical needs of mechanics generally, and of Fluidmechanics in particular**… For example, a point is usually defined as an element of geometry which has position but no extension; a line as a path traced out by a point in motion…But motion and matter cannot be divorced. A **point** that has no extension lacks volume and, consequently, mass, therefore **is nothing**; and **nothing can have neither path nor momentum, or motion.**"

Grigori Tokaty

13 Oct 1909 – 23 Nov 2003



"***Euler was, perhaps, the first to overcome this fundamental contradiction, by means of the introduction of his historic 'fluid particle', thus giving Fluidmechanics a powerful instrument of physical and mathematical analysis."***

Euler imagined a fluid particle as an infinitesimal body, small enough to be treated mathematically as a point, but large enough to possess such physical properties as volume, mass, density, inertia, etc.

"The Blood, the Flesh, and the Bones of Fluid Mechanics"

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Euler's Observations on His Five Equations of Motion of Fluids

'PRINCIPES GÉNÉRAUX DU MOUVEMENT DES FLUIDES' 4 Sep 1755 [printed in 1757]

- "The equations contain four variables x, y, z and t which are absolutely independent of each other… the other variables u, v, w, p and q must be certain functions of the former."
- "…before we can begin to solve the equations, we need to know what sort of functions of x, y, z and t must be used to express the values of u, v, w, p and q …"
- "However, since very little work has yet been done…*we cannot hope to obtain a complete solution of our equations until the limits of Analysis have been extended much further*."
- "The best approach would therefore be to ponder well on the particular solutions of our differential equation that we are in a position to obtain…"
- "…if the three velocities are known, we can determine the trajectory described by each element of the fluid in motion." [streamlines]
- "If the shape of the vessel in which the fluid moves is given, the fluid particles that touch the surface of the vessel must necessarily follow its direction,…" [surface boundary condition]

"…it is not the laws of Mechanics that we lack…but only the Analysis, which has not yet been sufficiently developed for this purpose. It is therefore clearly apparent what discoveries we still need to make in this branch of Science before we can arrive at a more perfect Theory of the motion of fluids."

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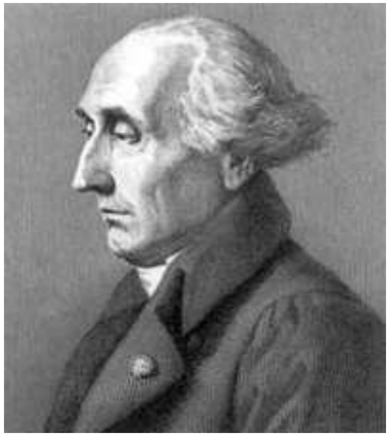
Source: Refs. 3.1 – 3.3

Analytical Solutions of Euler Equations
(18th Century)

Lagrange (1778) matured *'total differential' notion* into a powerful tool and applied it to Euler equations to conclude: *the equations could be solved only for two particular cases*

Joseph-Louis Lagrange



Franco-Italian Mathematician
25 Jan 1736 – 10 Apr 1813

1. **Unsteady Compressible Flow**

   By *introducing velocity potential, $\varphi\,(x,y,z,t)$*, and *gravitational potential, $\Phi\,(x,y,z)$*, Lagrange reduces Euler equations to a single total differential equation whose integral is

$$\frac{v^2}{2} + \int \frac{dp}{\rho} + \frac{\partial \varphi}{\partial t} - d\Phi = C(t)$$

2. **Steady Compressible Flow**

   Solution is the equation for case 1 (above) subject to $\partial\varphi/\partial t = 0$, and $C(t)$ just a constant.

- For **steady, incompressible flows**, the solution of the Euler equations is

$$\frac{v^2}{2} + \frac{p}{\rho} - \Phi = C = \text{const}$$

  The third term is typically negligibly small compared to the first two. and we get the now widely known '**Bernoulli's Equation**' $\frac{\rho v^2}{2} + p = \text{const}$

Lagrange's Concept of Velocity Potential Revolutionized Evolution of Fluid Dynamics—It Remains a Vital Part to This Day

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Source: Ref. 2.5 and Wikipedia

Mathematical Underpinnings of Potential Flow Theory
(18th Century)

- **Scalar Potential**
  - A fundamental mathematical concept that simplifies the study of quantities whose definition requires both magnitude and direction (vectors) over a given field or domain
  - Scalar potential is the scalar value associated with every point in a field. *Beware that all vector fields do not have scalar potential!*
  - In physics, it describes the situation where the difference in the potential energies of an object at two locations depends only on its location, not upon the path taken; examples include gravitational potential and electrostatic potential
  - In an orthogonal coordinate system, partial derivatives give the magnitude of the vector
- **Potential Theory**
  - **Laplace (1783)** applied the language of calculus to show that a scalar potential, $V(x,y,z)$, always satisfies the differential equation

$$\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial z^2}=0$$

  - Mathematicians developed many methods to solve this linear, second-order PDE subject to prescribed boundary conditions

Pierre-Simon Laplace

French Scholar
23 Mar 1749 – 5 Mar 1827

"All the Effects of Nature are only the Mathematical Consequences of a Small Number of Immutable Laws." — Laplace

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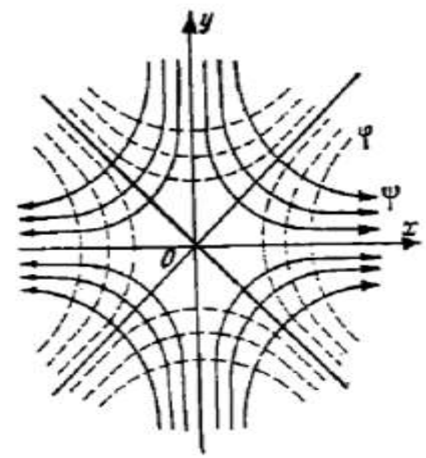
Source: Ref. 2.5 and Wikipedia

Advances in Fluid Dynamics
Driven by Mathematical Techniques
(19th Century)

Augustin-Louis Cauchy

French Mathematician
21 Aug 1789 – 23 May 1857

- **Cauchy (1841) *mathematically* proved that motion of a fluid particle consists of three parts**
  a. Translational motion at velocity $V\ (v_x, v_y, v_z)$
  b. Rigid Body Rotational motion with angular velocity $\boldsymbol{\omega}\ (\omega_x\ \omega_y\ \omega_z)$
  c. Deformational motion characterized by function $\boldsymbol{\Phi}\ (x, y, z)$ with nine numbers representing rate of normal and shear strains
- **When ω is zero, the flow is *irrotational* consisting of translational and deformational motions only; the vorticity of the fluid is zero**
- **For 2D, steady, incompressible, irrotational flow, Cauchy showed that the stream function, $\psi(x,y)$, too satisfied Laplace's equation, much like the velocity potential, $\varphi(x,y)$**
  - $\varphi(x,y)$ and $\psi(x,y)$, are associated through the Cauchy-Riemann conditions, and are called conjugate functions
  - Fluid flows can be represented by equipotential (φ = *const.) lines* and streamlines (ψ = *const.*) that are orthogonal
  - Associated theory of *analytic functions of complex variables* offers many interesting and important solutions



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Source: Ref. 2.5, 3.4 and Wikipedia

Green's Theorem

A Key Theorem for Mathematical Analysis of Potential Flows

(19th Century)

AN ESSAY ON THE APPLICATION OF MATHEMATICAL ANALYSIS TO THE THEORIES OF ELECTRICITY AND MAGNETISM

Originally published as a book in Nottingham, 1828.

Reprinted in three parts in Journal für die reine und angewandte Mathematik Vol. 39, 1 (1850) p. 73–89; Vol. 44, 4 (1852) p. 356–74; and Vol. 47, 3 (1854) p. 161–221. From there transcribed by Ralf Stephan (ralf@ark.in-berlin.de)

Before proceeding to make known some relations which exist between the density of the electric fluid at the surfaces of bodies, and the corresponding values of the potential functions within and without those surfaces, the electric fluid being confined to them alone, we shall in the first place, lay down a general theorem which will afterwards be very useful to us. This theorem may be thus enunciated:

Let U and V be two continuous functions of the rectangular co-ordinates x, y, z, whose differential co-efficients do not become infinite at any point within a solid body of any form whatever; then will

$$\int dx\,dy\,dz\,U\delta V + \int d\sigma U\left(\frac{dV}{dw}\right) = \int dx\,dy\,dz\,V\delta U + \int d\sigma V\left(\frac{dU}{dw}\right);$$

the triple integrals extending over the whole interior of the body, and those relative to $d\sigma$, over its surface, of which $d\sigma$ represents an element: dw being an infinitely small line perpendicular to the surface, and measured from this surface towards the interior of the body.

Note that: $\delta V = \dfrac{d^2V}{dx^2} + \dfrac{d^2V}{dy^2} + \dfrac{d^2V}{dz^2}$

George Green

British Mathematician
14 Jul 1793 – 31 May 1841

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Source: Ref. 3.5 & 3.6 and Wikipedia

Ideal Fluid Dynamics

Application of Green's Theorem to Irrotational Flows

(19th Century)

Horace Lamb

British Mathematician
27 Nov 1849 – 4 Dec 1934

Extensions of theoretical and mathematical advances in electrostatics and magnetism to ideal fluid dynamics followed naturally due to the analogy of velocity potential, ϕ, with electrostatic potential, and magnetic potential

(Lamb: *Treatise on the Mathematical Theory of the Motion of Fluids,* 1879; *Hydrodynamics,* 1895, 6th ed. 1932)

- If we denote the two continuous, single-valued functions, U and V, in the Green's theorem by ϕ and ϕ' *respectively,* satisfying $\nabla^2\phi = 0$ and $\nabla^2\phi' = 0$ throughout a given region bounded by the surface S, then

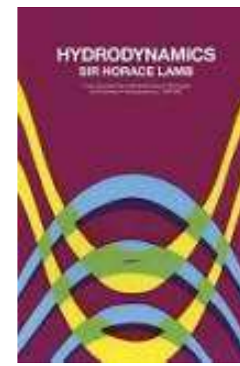
$$\iint \phi \frac{\partial \phi'}{\partial n}\, dS = \iint \phi' \frac{\partial \phi}{\partial n}\, dS$$

- Taking ϕ to be the velocity potential and choosing $\phi' = 1/r$, the velocity potential ϕ_P at any point P in the space occupied by the fluid may be written as:

$$\phi_P = -\frac{1}{4\pi}\iint \frac{1}{r}\frac{\partial \phi}{\partial n}\, dS + \frac{1}{4\pi}\iint \phi \frac{\partial}{\partial n}\left(\frac{1}{r}\right) dS.$$

Only surface integrals!

1st term is surface distribution of simple sources with density of $-\,\partial\phi/\partial n$; and 2nd term is surface distribution of double sources (doublets) with axes normal to the surface and density ϕ. *This is only one of infinite distributions that give the same value of* ϕ



Dover edition, 1945
(republication of 1932 6th edition)

- The irrotational flow of fluids in a simply-connected region is determined when either ϕ or inward normal velocity $-\,\partial\phi/\partial n$ is prescribed at all points of the boundary, or ϕ over part of the boundary and $-\,\partial\phi/\partial n$ over the remainder
- Lamb (*Ch. III, 6th ed.*) shows that representations of ϕ_P in terms of simple sources *alone*, or of double sources *alone*, are unique

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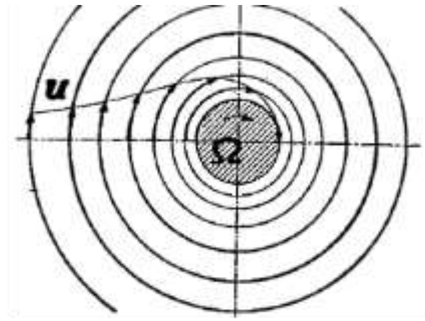
Source: Ref. 3.5 & 3.6 and Wikipedia

Ideal Fluid Dynamics:

Key Theorems for Flows with Vorticity (Rotational Flows)

(19th Century)

- **Helmholtz postulated three theorems (1858) based on his proof of indestructability and uncreatability of vorticity in inviscid, barotropic* fluid subjected to conservative body forces only**
  1. The strength of a vortex filament is constant along its length.
  2. A vortex filament cannot end in a fluid; it must extend to the boundaries of the fluid or form a closed path.
  3. In the absence of rotational external forces, a fluid that is initially irrotational remains irrotational.



Induced velocity field of a vortex filament

[Cauchy had mathematically proven (1841) that the motion of a fluid particle consisted of translational, rigid body rotational, and deformational motions; when rotational motion is <u>not</u> zero, the flow contains a string of rotating elements or vortex lines.]

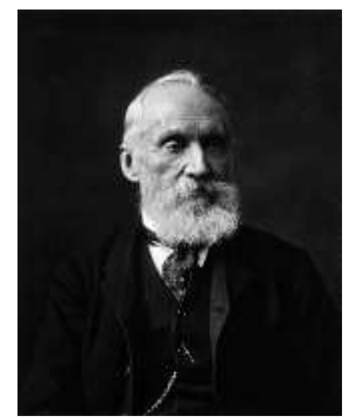
- **Kelvin Circulation Theorem (1867)**
  - Circulation (Γ) around a closed curve moving with the fluid remains constant with time, that is, $D\Gamma/Dt = 0$

*density is a function of only pressure

Hermann von Helmholtz

German Scientist & Philosopher
31 Aug 1821 – 8 Sep 1894

William Thomson
1st Baron Kelvin



British Mathematical Physicist
26 Jun 1824 – 17 Dec 1907

Source: Ref. 2.5, 3.7, 3.8 and Wikipedia

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Modified Euler Equations

(19th Century)

Claude Louis Marie Henri Navier

French Engineer
10 Feb 1785 – 21 Aug 1836

Mémoire sur les lois du Mouvement des Fluides (1823)

Mémoires de l'Académie Royale des Sciences de l'Institut de France

- Contains modified Euler equations for incompressible flow based on a different model of fluid to account for ***attractive and repulsive intermolecular forces***

$$P-\frac{dp}{dx}=\rho\left(\frac{du}{dt}+u\frac{du}{dx}+v\frac{du}{dy}+w\frac{du}{dz}\right)-\varepsilon\left(\frac{d^2u}{dx^2}+\frac{d^2u}{dy^2}+\frac{d^2u}{dz^2}\right)$$

$$Q-\frac{dp}{dy}=\rho\left(\frac{dv}{dt}+u\frac{dv}{dx}+v\frac{dv}{dy}+w\frac{dv}{dz}\right)-\varepsilon\left(\frac{d^2v}{dx^2}+\frac{d^2v}{dy^2}+\frac{d^2v}{dz^2}\right)$$

$$R-\frac{dp}{dz}=\rho\left(\frac{dw}{dt}+u\frac{dw}{dx}+v\frac{dw}{dy}+w\frac{dw}{dz}\right)-\varepsilon\left(\frac{d^2w}{dx^2}+\frac{d^2w}{dy^2}+\frac{d^2w}{dz^2}\right)$$

- ε is a function of spacing between molecules

- **Slip boundary condition**: e.g., for a wall perpendicular to z-axis

$$Eu+\varepsilon\frac{du}{dz}=0,\quad Ev+\varepsilon\frac{dv}{dz}=0$$

- ε, a function of nature of fluid and wall, is to be determined experimentally

Navier's Modified Euler Equations <u>Resemble</u> Those for Viscous Fluids Derived by Stokes Based on His Theory of Internal Friction

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Source: Ref. 3.9, and Wikipedia

Theory of Viscous Fluids in Motion

(19th Century)

On the Theories of the Internal Friction of Fluids in Motion and of the Equilibrium and Motion of Elastic Solids, Transactions of Cambridge Philosophical Society, Vol. 8, pp 287-319, 1849 (Read April 14, 1845)

"The equations of Fluid Motion commonly employed depend upon *the fundamental hypothesis that the mutual action of two adjacent elements of the fluid is normal to the surface which separates them.*"

"But *there is a whole class of motions* of which the common theory takes no cognizance whatever, namely, those *which depend on the tangential action called into play by the sliding of one portion of a fluid along another, or of a fluid along the surface of a solid*, or of a different fluid, that action in fact which performs the same part with fluids that friction does with solids."


XXII. *On the Theories of the Internal Friction of Fluids in Motion, and of the Equilibrium and Motion of Elastic Solids.* By G. G. Stokes, M.A., *Fellow of Pembroke College.*

[Read April 14, 1845.]

George Stokes

British Mathematician & Physicist
13 Aug 1819 – 1 Feb 1903

"Again, suppose that water is flowing down a straight aqueduct of uniform slope, what will be the discharge corresponding to a given slope, and a given form of the bed? Of what magnitude must an aqueduct be, in order to supply a given place with a given quantity of water? Of what form must it be, in order to ensure a given supply of water with the least expense of materials in the construction? *These, and similar questions are wholly out of the reach of the common theory of Fluid Motion, since they entirely depend on the laws of the transmission of that tangential action which in it is wholly neglected.*"

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Source: Ref. 3.10, and Wikipedia

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The Navier-Stokes Equations

(19th Century)

George Stokes

British Mathematician & Physicist
13 Aug 1819 – 1 Feb 1903

On the Theories of the Internal Friction of Fluids in Motion and of the Equilibrium and Motion of Elastic Solids
Transactions of Cambridge Philosophical Society, Vol. 8, pp 287-319, 1849 (Read April 14, 1845)

$$\frac{d\rho}{dt} + \frac{d\rho u}{dx} + \frac{d\rho v}{dy} + \frac{d\rho w}{dz} = 0, \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

$$\rho\left(\frac{Du}{Dt} - X\right) + \frac{dp}{dx} - \mu\left(\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + \frac{d^2u}{dz^2}\right) - \frac{\mu}{3}\frac{d}{dx}\left(\frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz}\right) = 0, \ \&c.\ldots\ldots(12)$$

equation connecting p and ρ,

μ is assumed to be constant, not dependent on *pressure* or *temperature*

Boundary condition for fluid in contact with a solid

"The most interesting questions connected with this subject require for their solution a knowledge of the conditions which must be satisfied at the surface of a solid in contact with the fluid, which, *except perhaps in case of very small motions*, are unknown."

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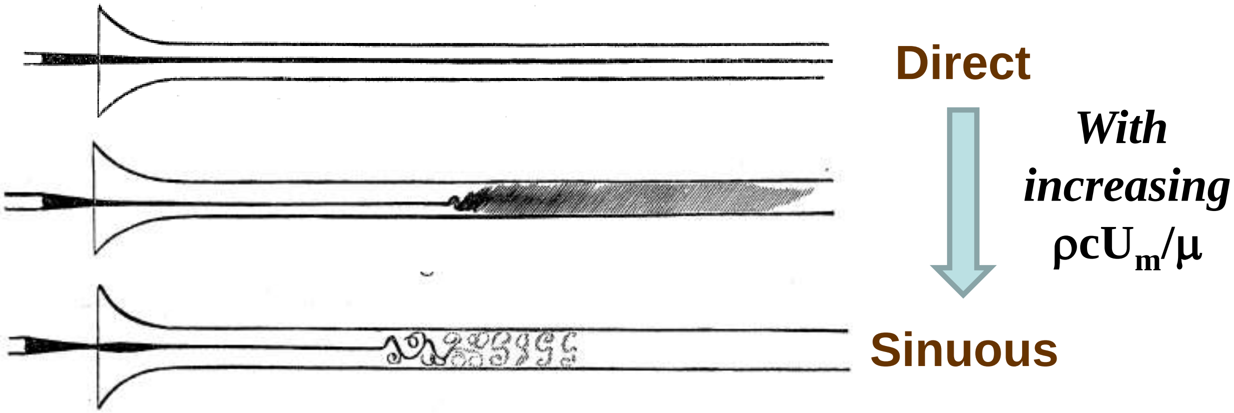
Source: Ref. 3.10, and Wikipedia

Distinct Types of Viscous Flows

(19th Century)

An Experimental Investigation of the Circumstances which determine whether the Motion of Water shall be Direct or Sinuous, and of the Law of Resistance in Parallel Channels

Philosophical Transactions of the Royal Society of London, 174, 1883, pp 935-982 (Read March 15, 1883)



Osborne Reynolds

British Engineer and Physicist
23 Aug 1842 – 21 Feb 1912

"…the broad fact of there being a critical value for the velocity [U_m] at which the steady motion becomes unstable, which critical value is proportional to $\mu/\rho c$ where c is the diameter of the pipe and μ/ρ the viscosity by the density, is abundantly established."

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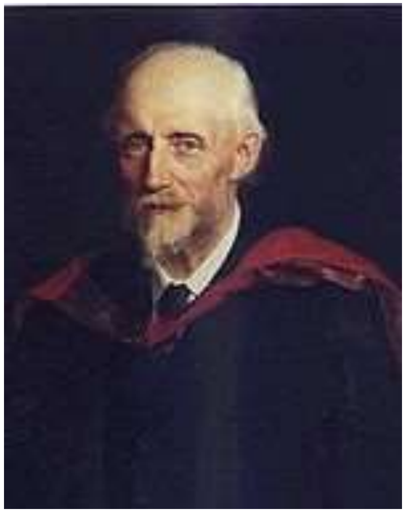
Source: Ref. 3.11, and Wikipedia

Governing Equations of Turbulent Flows

(19th Century)

Osborne Reynolds



British Engineer and Physicist
23 Aug 1842 – 21 Feb 1912

On the Dynamical Theory of Incompressible Viscous Fluids and the Determination of the Criterion, Philosophical Transactions of the Royal Society of London (A), 186, 1895, pp 123-164 (Read May 24, 1894)

- **Experimental criterion**: ***"…steady direct motion in round tubes is stable or unstable according as $\rho D U_m/\mu$ <1900 or >2000…a criterion for the possible maintenance of sinuous or eddying motion."***
- **Theoretical development**: **introduced concepts of '*mean-mean-motion*' and '*relative-mean-motion*'**

$$\bar{u} = \frac{\Sigma(\rho u)}{\Sigma \rho}, \ \&c., \&c. \quad \ldots \quad (4).$$

$$\rho u = \rho \bar{u} + \rho u' \quad \ldots \quad (5)$$

- **Equations of mean-mean-motion of turbulent flows**

$$\left.\begin{aligned}\rho\frac{d\bar{u}}{dt} = -\Big\{&\frac{d}{dx}\left(\overline{p_{xx}} + \rho\bar{u}\bar{u} + \overline{\rho u'u'}\right) + \frac{d}{dy}\left(\overline{p_{yx}} + \rho\bar{u}\bar{v} + \overline{\rho u'v'}\right)\\ &+ \frac{d}{dz}\left(\overline{p_{zx}} + \rho\bar{u}\bar{w} + \overline{\rho u'w'}\right)\Big\}\\ \&c. = \quad &\&c.\\ \&c. = \quad &\&c.\end{aligned}\right\} \quad . \quad . \quad (15),$$

Reynolds stresses

The Reynolds-Averaged Navier-Stokes (RANS) Equations!

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Source: Ref. 3.12, 3.13 and Wikipedia

Reynolds' 1895 Paper with RANS Equations

A Transformative Achievement!

- **Reynolds' Motivation for the 1895 Paper**
  - **Response to Lord Rayleigh's review comment on Reynolds' landmark 1883 paper:** *'In several places the author refers to theoretical investigation whose nature is not sufficiently indicated.'*
  - **In the 1895 paper, Reynolds offers proof of the existence of the criterion for the values of $K = \rho D U_m/\mu$ when direct motion changes to sinuous**
- **Expert Reviewer Comments on the Paper**
  - **Sir George Stokes:** *'…the author…himself considers it [paper] as of much importance. I confess I am not prepared to endorse that opinion myself, but neither can I say that it may not be true.'*
  - **Sir Horace Lamb:** *'…the paper should be published in the Transactions as containing the views of its author on a subject which he has to a great extent created, although much of it is obscure.'*
- **The "Closure Problem" needs to be solved for RANS equations to be usable**
  - *"…**one needs a means for determining the Reynolds stresses in terms of known or calculable quantities**…Reynolds himself only obliquely touched on this." – Launder (2015)*
- **Turbulence Modeling (determining Reynolds stresses) for RANS equations**
  - **G.I. Taylor (1915):** *"…to consider the disturbed motion of layers of air [in the atmosphere], we can take account of the eddies by introducing a coefficient of eddy viscosity…which we can express as* $\tfrac{1}{2}\rho\left(\overline{w}d\right)$ *where* d *is an average height through which an eddy moves before mixing with its surroundings, and* $\overline{w}$ *roughly represents the average vertical velocity…where* w' *is positive."*

For more than 100 years, quest for 'better' turbulence models has remained the *"holy grail"* of science!

"Indeed, its impact on all our lives is incalculable." — Launder

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Source: Ref. 3.13 & 3.14

Section 3.
Overarching Takeaway

"Leonhard Euler was not a contributor to, but the founder of, Fluidmechanics, its mathematical architect, its great river."

- Grigori Tokaty

13 Oct 1909 – 23 Nov 2003

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Section 3: Key Takeaways

- **1755-57: The Euler Equations for inviscid, compressible flows**
  - Euler derived three *equations of motion* from the *first axioms of mechanics* which, combined with continuity equation and equation of state, gave *"…five equations encompassing the entire theory of the motion of fluids."*
  - Solving the equations was hampered by *"…the Analysis, which has not yet been sufficiently developed for this purpose."*
- **1778: Lagrange solved the Euler equations for two particular cases**
  - The case for steady, incompressible flow gave us the famous **Bernoulli's equation**
- **1849: The Navier-Stokes equations for viscous, compressible flows**
  - [boundary] conditions which must be satisfied at the surface of a solid in contact with the fluid…are unknown
- **1883: Reynolds characterized viscous flows:** *"…steady direct motion in round tubes is stable or unstable according as $\rho D U_m/\mu$ <1900 or >2000,…"*
- **1895: The Reynolds-averaged Navier-Stokes (RANS) equations for viscous, compressible, turbulent flow (*mean-mean* and *relative-mean* motions)**
  - For RANS equations to be usable, need to address the Closure Problem: express Reynolds stresses in terms of known or calculable quantities—turbulence modeling
  - For more than 100 years, quest for 'better' turbulence models has been the *"holy grail"*
- **Throughout the 1800s: Impressive advances in *Ideal-Fluid Dynamics* [*rotational (w/ vortex filaments) and irrotational (no vorticity) flows of ideal fluids (inviscid, incompressible)*]—fueled by advances in mathematics**

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SECTION 3 (contd.)

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3.12 Reynolds, O., “On the Dynamical Theory of Incompressible Viscous Fluids and the Determination of the Criterion,” Philosophical Transactions of the Royal Society of London (A), 186 (1895), pp 123-164. (Read May 24, 1894) https://doi.org/10.1098/rsta.1895.0004

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Contents

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At the Dawn of the 20th Century…

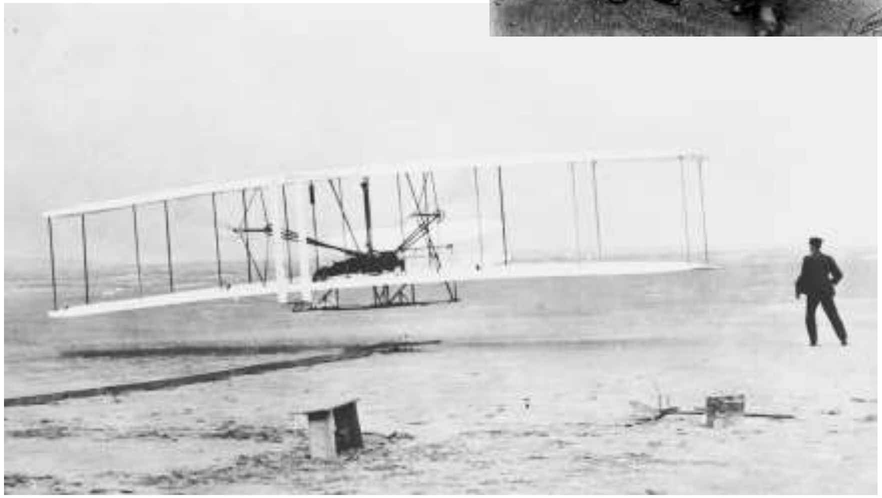
- **17 December 1903 to be precise—the first manned, controlled, powered flight by the Wright brothers!**

Orville Wright's telegram to his father:

Success. Four flights Thursday morning. All against twenty one mile wind. Started from level with engine power alone. Average speed through air thirty one miles. Longest 57 seconds. Inform press. Home Christmas.

"This flight lasted only twelve seconds, but it was nevertheless the first in the history of the world in which a machine carrying a man had raised itself by its own power into the air in full flight, had sailed forward without reduction of speed and had finally landed at a point as high as that from which it started.

- Orville Wright



- **Dramatic evolution of civil and military aviation followed**

…12 Seconds Changed Human History Forever!

Source: Ref. 4.1 (p 87) and Internet

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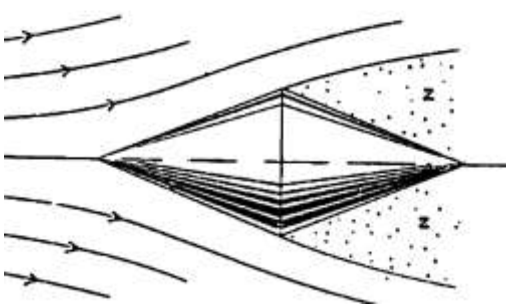
Analytical Fluid Dynamics

State of the Art at the Dawn of the 20th Century

- **AFD witnessed notable advances over preceding 150 years (1750–1900)**
  - Development of the governing equations of inviscid (Euler) and viscous flows (Navier-Stokes & RANS)
  - Advances in mathematics provided novel tools and techniques (such artifacts as sources, sinks, doublets, vortex filaments, etc.) that could be used to obtain *analytical solutions* of irrotational (potential) and rotational flows of perfect or ideal fluids
- **But available AFD capabilities woefully inadequate to meet the emerging need of airplane engineering design**
- **AFD offered no satisfactory solution for the problem of resistance—a key need for airplane design!**
  - ***d'Alembert's paradox (1749-1752) remains unresolved!***
    - *"In a velocity field that is uniform at infinity and tangent to the body along its surface… [body] would suffer no force from the fluid, which is contrary to experience"*
  - **"Surface of Discontinuity" Theory proposed by Hermann von Helmholtz *(1858-1868)***
    - *"Any geometrically complete sharply-defined edge at which fluids flow past must tear itself from the most typical velocity of the remaining fluid and define a separation surface."*
    - Whole resistance being then due to the excess pressure region in front of the body, the dead-water or wake being at approximately the hydrostatic pressure of the fluid.



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Source: Refs. 3.7, 4.1, 4.2

Analytical Fluid Dynamics

The Problem of Resistance Challenged Even the Brightest Minds!

On the Resistance of Fluids (Lord Rayleigh F.R.S.)

The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 2:13, 430-441, 1876

(Nearly 125 years after d'Alembert's Paradox was published!)

"There is no part of hydrodynamics more perplexing to the student than which treats the resistance of fluids. According to one school of writers a body exposed to a stream of perfect fluid would experience no resultant force at all, any augmentation of pressure on its face due to the stream being compensated by equal and opposite pressures on its rear…On the other hand it is well known that in practice an obstacle does experience a force tending to carry it downstream and of magnitude too great to be the direct effect of friction; while in many of the treatises calculations of resistance are given leading to results depending on the inertia of the fluid without any reference to friction."

John William Strutt
3rd Baron Rayleigh

Nobel Prize in Physics (1904)
12 Nov 1842 – 30 Jun 1919

Prevailing Wisdom:
Fluid Friction Too Small to Produce Significant Resistance Force!

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Source: Ref. 4.4; Wikipedia

Finally a Breakthrough in 1904!

Prandtl's Boundary Layer Theory

Über Flussigkeitsbeweging bei sehr kleiner Reibung.

Verhandlungen Des Dritten Internationalen Mathematiker-Kongresses, Heidelberg, Vom 8, Bis 13, August 1904, pp 484-491

"The most important aspect of the problem is the behavior of the fluid on the surface of the solid body. The physical processes in the boundary layer [Grenzschicht] between fluid and solid body can be calculated in a sufficiently satisfactory way if it is assumed that the fluid adheres to the walls, so that the total velocity is either zero or equal to the velocity of the body. If, however, the viscosity is very small and the path of the fluid along the wall not too long, the velocity will have its normal value very near to the wall. In the thin transition layer (Ubergangsschicht) the sharp changes of velocity, in spite of the small viscosity coefficient, produce noticeable effects."


Über Flüssigkeitsbewegung bei sehr kleiner Reibung.

Von

L. Prandtl aus Hannover.

(Hierzu eine Figurentafel.)

In der klassischen Hydrodynamik wird vorwiegend die Bewegung der reibungslosen Flüssigkeit behandelt.

2D BL equations

$$\varrho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)+\frac{dp}{dx}=k\frac{\partial^2 u}{\partial y^2}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0.$$

Ludwig Prandtl

German Physicist

4 Feb 1875 – 15 Aug 1953

2D BL velocity profile

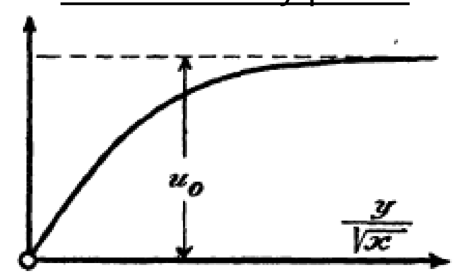

Fig. 1.

"A Most Extraordinary Paper of the 20th Century, and Probably of Many Centuries!" — Sydney Goldstein, Harvard Univ.

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Source: Ref. 4.5 & 4.6, and Wikipedia

Resistance Formula for Thin Flat Plate!

Prandtl's Solution of Boundary Layer Equations

Über Flussigkeitsbeweging bei sehr kleiner Reibung.
Verhandlungen Des Dritten Internationalen Mathematiker-Kongresses, Heidelberg, Vom 8, Bis 13, August 1904, pp 484-491

"If, as usual, dp/dx is given throughout, and furthermore the variation of u for the initial cross-section of the flow, then every problem of this kind may be mastered numerically, in that one can obtain from every value of u the corresponding $\partial u/\partial x$ by quadrature. With this and the help of one of the familiar approximate methods, one can repeatedly move a step at a time in the x direction. Of course a difficulty exists with various singularities arising at solid boundaries. The simplest case of the flow situations considered here is the one in which water flows along a thin flat plate. A reduction in the variables is possible here; one can put $u = f\left(\frac{y}{\sqrt{x}}\right)$. One comes up with a formula for the flow resistance using a numerical result of the resulting [ordinary] differential equation

$$R = 1.1 \cdots b\sqrt{k\rho l u_0^3}$$

(b width, l length of the plate, u_0 the velocity of the undisturbed water opposite the plate)."

Ludwig Prandtl

German Physicist
4 Feb 1875 – 15 Aug 1953

- The corresponding skin-friction drag coefficient (for both surfaces of the plate) is

$$C_F = 2.2/\sqrt{Re} \text{ where } Re = \frac{(\rho\, u_0\, l)}{k}$$

- More accurate calculations later corrected the factor 2.2 to 2.656

A Remarkable Achievement!

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Source: Ref. 4.5 & 4.6, and Wikipedia

Boundary Layer Separation and Vortex Generation

Über Flussigkeitsbeweging bei sehr kleiner Reibung.
Verhandlungen Des Dritten Internationalen Mathematiker-Kongresses, Heidelberg, Vom 8, Bis 13, August 1904, pp 484-491

"The most important result of the investigation for application is that, in certain cases, the flow will separate from the wall at a place completely determined by the external conditions. A fluid layer, which has been set in rotation by the friction at the wall, makes its way into the free fluid where, causing a complete transformation in the motion, it plays the same role as the Helmholtz surface of discontinuity."

Ludwig Prandtl

German Physicist
4 Feb 1875 – 15 Aug 1953

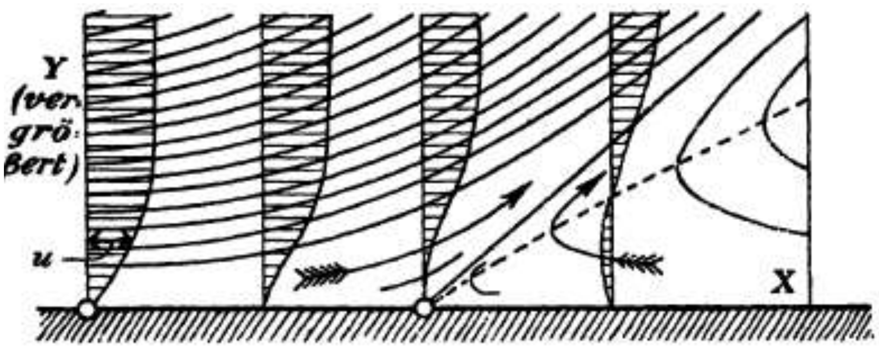

Fig. 2.

"A change in the viscosity coefficient k alters the thickness of the vortex layer (proportional to $\sqrt{kl/\rho u}$) but everything else remains unchanged. Therefore, one can go over to the limit k = 0 and obtain the same flow picture."

Necessary condition for flow separation:
pressure increase along the surface in the flow direction

A Singular Contribution of Enormous Lasting Influence for Explaining Otherwise Baffling Fluid Flow Phenomena

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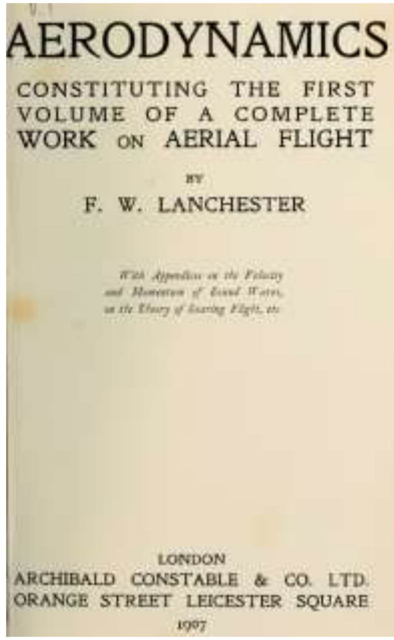
Source: Ref. 4.5 & 4.6, and Wikipedia

Aerodynamics: *State of the Art (1907)*

F. W. Lanchester

British Engineer
23 Oct 1868 - 8 Mar1946


AERODYNAMICS

CONSTITUTING THE FIRST VOLUME OF A COMPLETE WORK ON AERIAL FLIGHT

BY

F. W. LANCHESTER

LONDON
ARCHIBALD CONSTABLE & CO. LTD.
ORANGE STREET LEICESTER SQUARE
1907

"Numerical work has been done by the aid of an ordinary 25 cm. slide rule, with a liability to error of about 1/5th of 1 percent, an amount which is quite unimportant."

"…the author desires to record his conviction that <u>the time is near when the study of Aerial Flight will take its place as one of the foremost of the applied sciences</u>, one of which the underlying principles furnish some of the most beautiful and fascinating problems in the whole domain of practical dynamics."

"In order that real and consistent progress should be made in Aerodynamics and Aerodonetics, apart from their application in the engineering problem of mechanical flight, it is desirable, if not essential, that provision should be made for the special and systematic study of these subjects in one or more of our great Universities, provision in the form of an adequate endowment with proper scope for its employment under an effective and enlightened administration."

"…<u>the country in which facilities are given for the proper theoretical and experimental study of flight will inevitably find itself in the best position to take the lead in its application and practical development.</u>"

In Early 1900s, Aerodynamics Became a Most Exciting Research Frontier!

The First Half of the 20th Century: Golden Age of <u>Analytical Aerodynamics</u>

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Source: Ref. 4.3, and Wikipedia

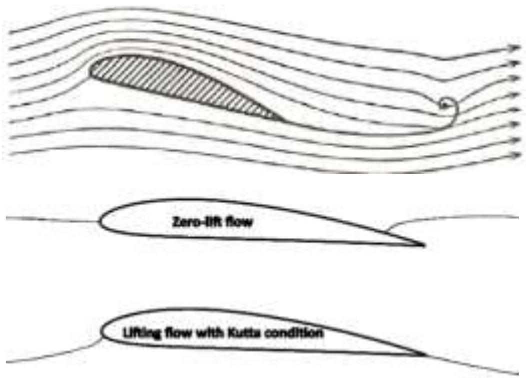
Analytical Aerodynamics: *1900s*

A Small Sampling of Pioneering Research

- **Kutta (1902)** – solution of inviscid 2D flow about circular-arc body at zero incidence with circulation and finite velocity at trailing edge

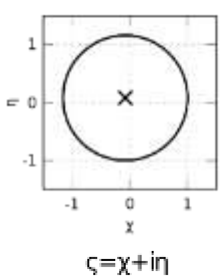
Martin Kutta

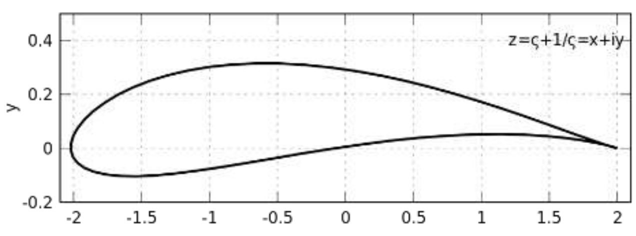
German Mathematician
3 Nov 1867 – 25 Dec 1944



$$l = \rho \, \Gamma V$$

- **Prandtl-Meyer (1908)** – oblique shocks and expansion fans in supersonic flows
- **Zhukovskii (1910)** design of airfoil sections using graphical construction





- **Prandtl (1904)** – boundary layer theory and vortex generation
- **Zhukovskii (1906)** – circulation theory of lift on 2D airfoils
- **Chaplygin (1910)** **Postulate:** *"out of infinite number of theoretically possible solutions past an airfoil with sharp trailing edge, the flow that's nearest to experiment is the one with finite velocity at the trailing edge"*

Nikolay Zhukovsky

Russian Scientist,
Mathematician
5 Jan 1847 – 17 Mar 1921

Sergey Chaplygin

Russian Physicist,
Mathematician, Engineer
5 Apr 1867 – 8 Oct 1942

Source: Wikipedia; Refs. 4.6 to 4.9

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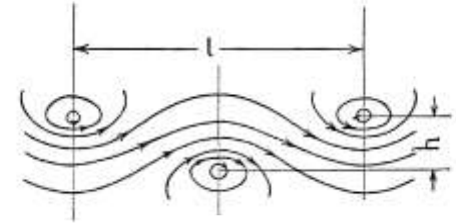
Analytical Aerodynamics: *1910s*

A Small Sampling of Pioneering Research

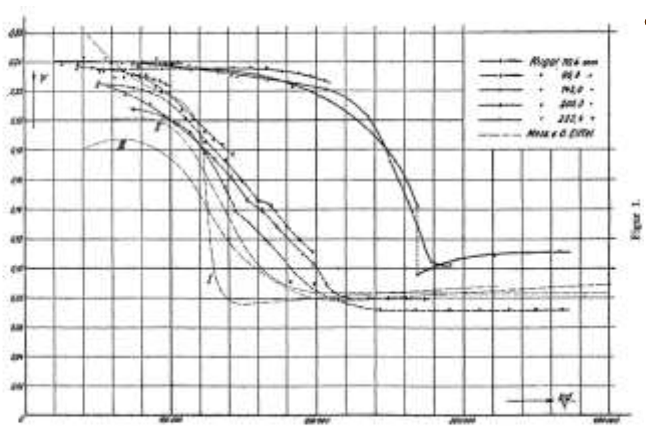
- **Kármán (1911)** – first paper on vortex street in the wake of 2D cylinders; referred to Boundary Layer theory to explain vortex formation

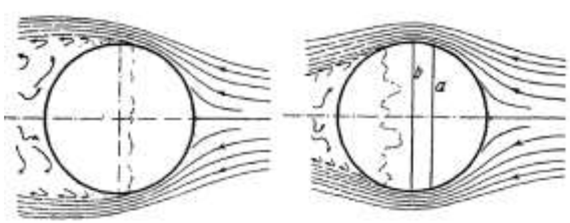


$$\mathfrak{Cos}\,\frac{\pi h}{l} = \sqrt{3}.$$

- **Blasius (1912)** – friction factor in turbulent pipe flows varied as inverse of the 1/4th power of Reynolds number, and velocity as the 1/7th power of the distance from the wall

- **Prandtl (1914)** – explained small drag coefficients for spheres with turbulent boundary layer that were first demonstrated by Eiffel in 1912





Figur 3. Figur 4.

- **Prandtl (1918-1919)** – classic papers on 3D airfoil (wing) theory of large but finite aspect ratio

$$W = \varrho \int_a^b \Gamma w \, dx$$

$$w(x) = \frac{1}{4\pi} \int_a^b \frac{d\Gamma}{dx'} \cdot \frac{dx'}{x - x'}$$

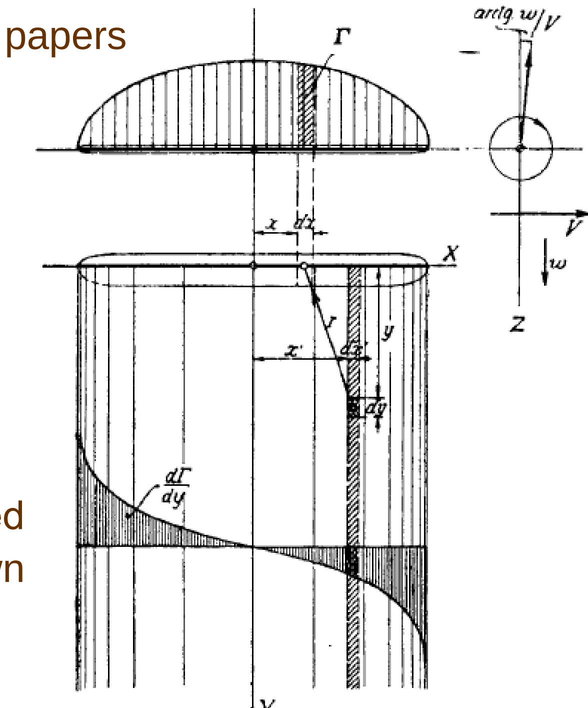


Fig. 4 1).

- **Munk (1918)** – the term “induced drag” and the now well-known “Munk’s stagger theorem”
- **Betz (1919) –** screw propeller with minimum energy loss

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Source: Wikipedia; Refs. 4.6, 4.10 to 4.13

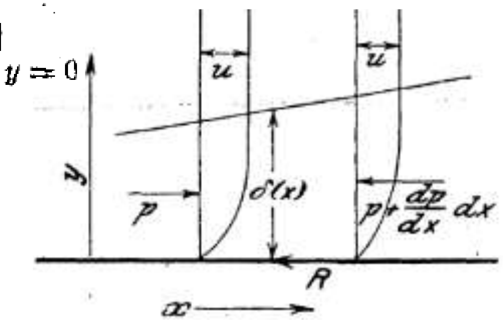
Analytical Aerodynamics: *1920s*

A Small Sampling of Pioneering Research

- **Trefftz (1921)** – extract induced drag from wake integral in a far downstream "Trefftz plane"
- **Kármán (1921)** – momentum equations of boundary layer, and Kármán-Pohlhausen approximate method of integration

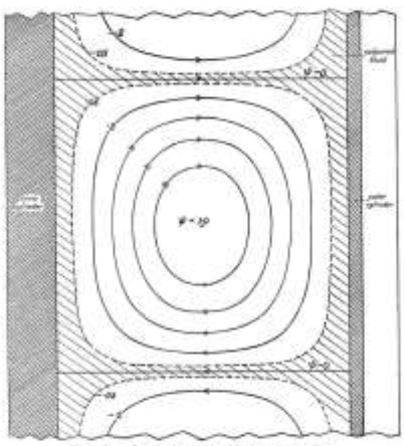
$$\frac{\partial}{\partial t}\int_0^\delta \varrho u\,dy + \frac{\partial}{\partial x}\int_0^\delta \varrho u^2\,dy - u_0\frac{\partial}{\partial x}\int_0^\delta \varrho u\,dy = -\delta\frac{\partial p}{\partial x} - R$$

$$\tau_0 = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}$$



Flat plate skin friction formulas for laminar & turbulent boundary layers!

- **Taylor (1923)** – "Stability of viscous liquid contained between two rotating cylinders"



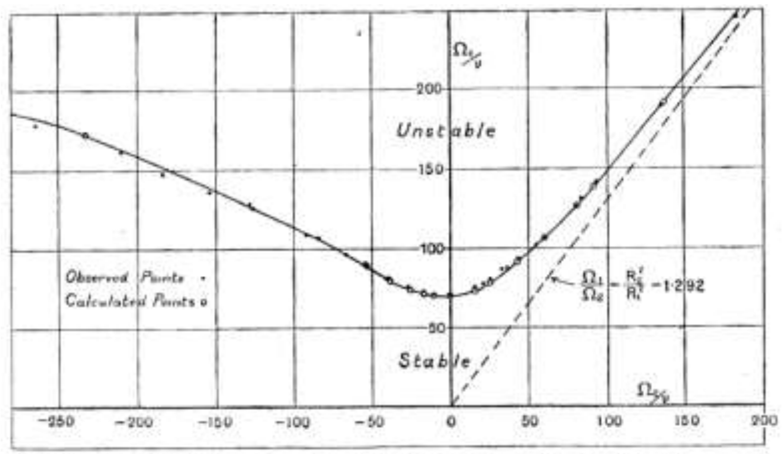


Fig. 18. Comparison between observed and calculated speeds at which instability first appears; case when $R_1 = 3{\cdot}55$ cm., $R_2 = 4{\cdot}035$ cm.

- **Prandtl (1925)** – "mixing path (or distance) theory" for turbulent flows with the proposition: *momentum is a transferable property*

$$\tau = \varrho l^2 \left|\frac{du}{dy}\right| \cdot \frac{du}{dy} \qquad \mu_T = \varrho l^2 \left|\frac{du}{dy}\right|$$

"…a first rough approximation."

- **Glauert (1928) –** Prandtl-Glauert rule for inviscid compressible flows: $C_p = C_{p0}/\beta \quad \beta^2 = 1 - M_\infty^2$

Theodore von Kármán

Hungarian-American Mathematician, Physicist, Aerospace Engineer
11 May 1881 – 6 May 1963

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Source: Wikipedia; Refs. 4.6, 4.14 to 4.18

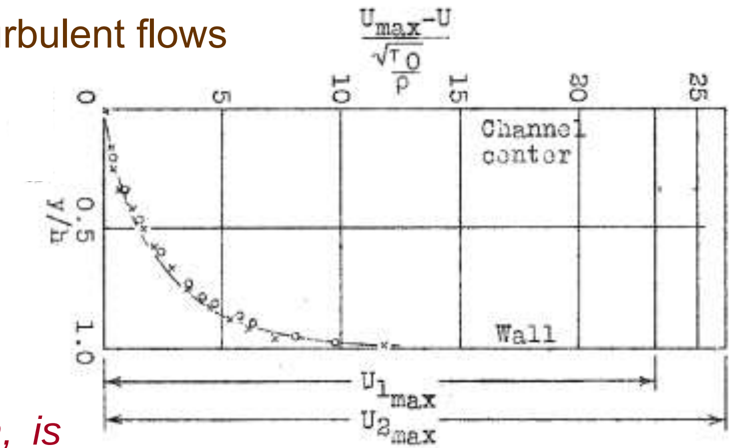
Analytical Aerodynamics: *1930s*

A Small Sampling of Pioneering Research

- **Kármán (1930)** – logarithmic "law of the wall" for planar turbulent flows

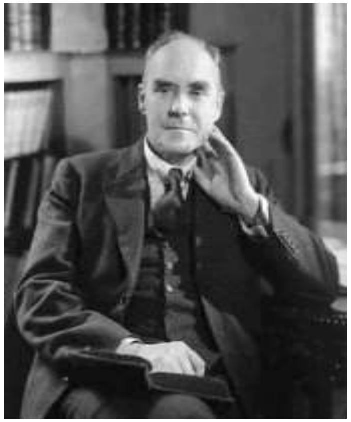
$$U_{max} - U = -\frac{1}{k}\sqrt{\frac{\tau_o}{\rho}}\left(\log\left(1 - \sqrt{\frac{y}{h}}\right) + \sqrt{\frac{y}{h}}\right)$$

  - U_{max} *is the difference between wall and channel center*
  - k *is a constant independent of dimensions and Reynolds number, appears to have a value 0.38*



- **Taylor (1932)** – Proposed that *vorticity, not momentum, is the transferable property* in his paper entitled "*The transport of vorticity and heat through fluids in turbulent motion*"

G.I. Taylor



British Physicist, Mathematician
7 Mar 1886 – 27 Jun 1975

- **Taylor-Maccoll (1933)** – Derived and solved an ordinary differential equation (O.D.E.) with one unknown for supersonic flow past a cone
- **Taylor (1935)** – "Statistical theory of turbulence" – whole new direction to turbulent flow research!

  Predicted Law of Decay of Turbulence behind grids and honeycombs

$$\frac{U}{u'} = \frac{5x}{A^2 M} + \text{constant.}$$

  A = a constant, *determined experimentally should be universal for all square grids;* M = *mesh length of a square mesh*

- **Taylor (1935-37)** – modified vorticity-transfer theory with application to flow in pipes

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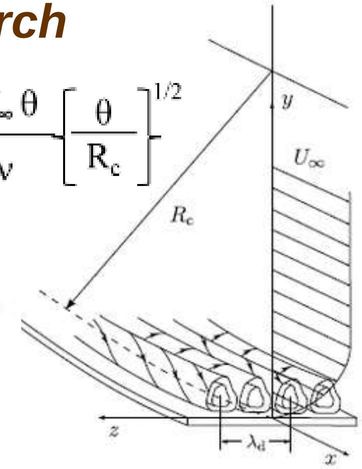
Source: Wikipedia; Refs. 4.6, 4.19 & 4.20

Analytical Aerodynamics: *1940s*

A Small Sampling of Pioneering Research

- **Görtler (1940)** – theoretical study of the instability of boundary layer flows on concave surfaces; instability occurs when **Görtler number**, G > 0.3

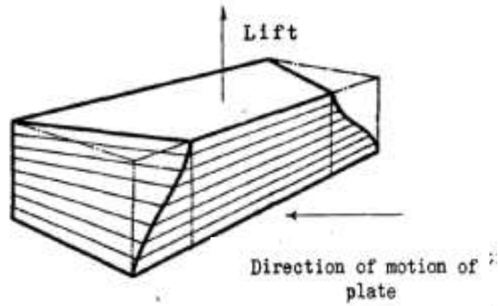
$$G = \frac{U_\infty \theta}{\nu}\left[\frac{\theta}{R_c}\right]^{1/2}$$



- **Busemann (1942-43)** – conical supersonic flow theory

Adolf Busemann

German Aerospace Engineer
20 Apr 1901 – 3 Nov 1986



Pressure distribution on a flat plate

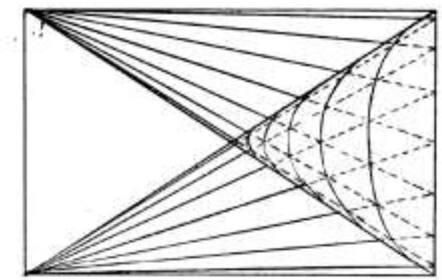


Figure 12. Superposition of edge influences for the rectangular plate at supersonic velocities

- **Jones (1946)** –theory of pointed wings (delta wings) of very small aspect ratio

$$C_L = \frac{\pi}{2} A\alpha$$

$$C_{D_i} = C_L \frac{\alpha}{2}$$

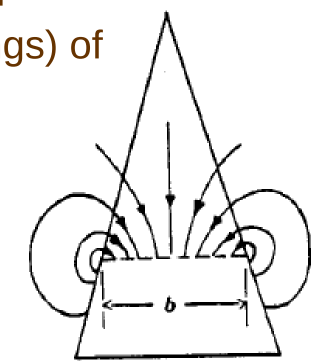


FIGURE 1.—Flow pattern.

$$c_l = \pi\alpha \frac{db}{dx}$$

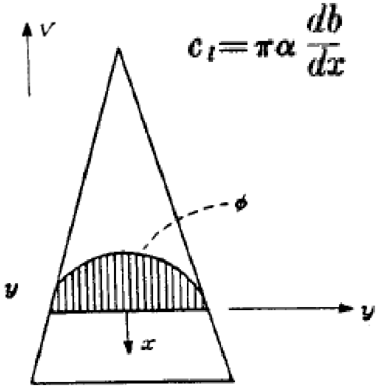


FIGURE 2.—Potential.

- **Tsien (1946) –** similarity laws of hypersonic flows

$$K = M_\infty (\delta/b)$$

- **Kármán (1947)** – similarity law of transonic flows

$$K = (1 - M_\infty)/(\tau\Gamma)^{2/3} \qquad \Gamma = (\gamma+1)/2;\ \gamma = C_p/C_v$$

If a series of bodies of same thickness distribution but different thickness ratios (δ/b *or* τ) are placed in streams of different M_∞, then the *flow patterns are similar* as long they all have equal values of K

- **Lighthill (1947)** – hodograph transformation in transonic flows

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Source: Wikipedia; Refs. 4.6, 4.21 to 4.25

Analytical Aerodynamics:
Summary Assessment of Capabilities

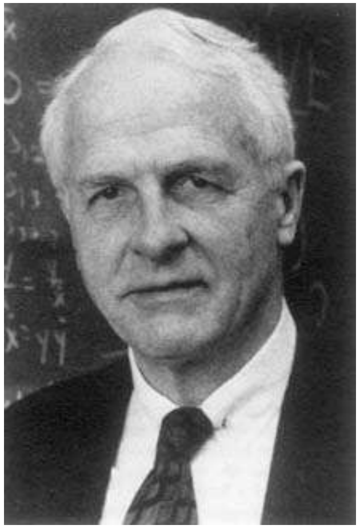
Author's Opinion

In spite of phenomenal advances in the first half of the 20th Century, analytical aerodynamics *(circa 1950)* remained inadequate for simulating realistic flows on *complex* geometries—*and remains so even today!*

"…no exact analytical model describing physically interesting flows that depend significantly on Re [Reynolds number] is known."

– Garrett Birkhoff, 1981

Garrett Birkhoff



American Mathematician
19 Jan 1911 – 22 Nov 1996

Source: Ref. 4.26, and Wikipedia

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Value of Analytical Aerodynamics

In spite of severely limited capabilities of simulating realistic flows on complex geometries, it offers unique insights that other approaches do not!

"…**skillful application of the equations from the dynamics of ideal fluids quite often brings *clarity* into such phenomena** which in themselves are not independent of the viscosity. The vortex equations, in particular, proved themselves very useful. I may be allowed to mention the **vortex street** by which we are able to reproduce the mechanism of the form resistance with suitable approximation under stated conditions, although such a resistance is precluded in a fluid which is perfectly inviscid…Another striking example is the **theory of the induced drag of wings**, which likewise shows the extent of applying the vortex equations without overstepping the bounds of the dynamics of ideal fluids."

– *Theodore von Kármán, 1931*

Analytical Aerodynamics (a subset of AFD) Remains Indispensable for Better Understanding of Complex Flow Phenomena

Source: Ref. 4.19

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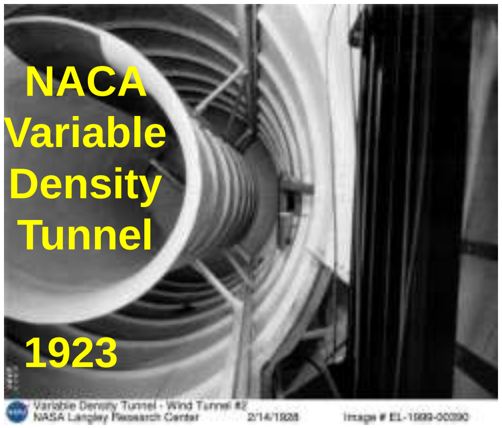
Experimental Aerodynamics: *1900 – 1950*

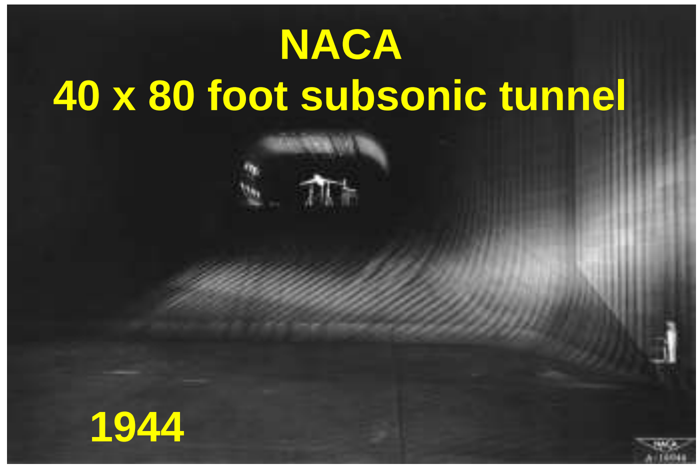
An Effective Means of Overcoming Inadequacies of AFD

Rapid advancements to support development of new airplane designs

- Bigger tunnels; high-speed tunnels; low-turbulence tunnels; special purpose tunnels; …



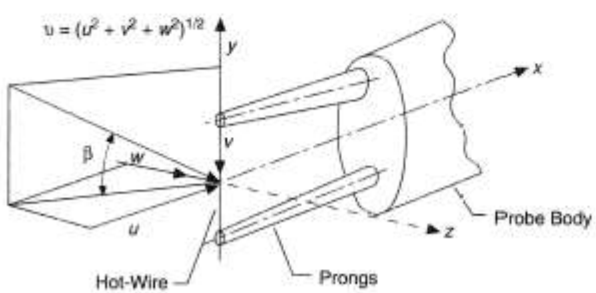
"data for 78 classical airfoil shapes: see TR 460, 1935"

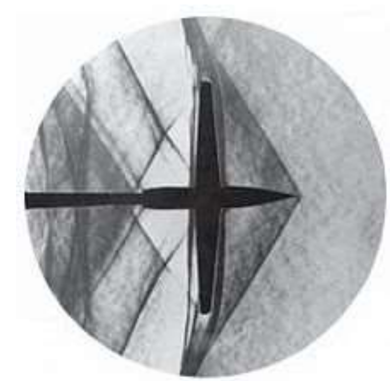


"aircraft development work"

"solve the mysteries of flight beyond Mach 1"

- Techniques and instruments for accurate measurements (e.g., hot-wire anemometry) and visualization (e.g., Schlieren, interferometry)





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Source: NASA websites; Refs. 4.27 & 4.28

Genesis of Numerical Aerodynamics: *1910*

The Approximate Arithmetical Solution by Finite Differences of Physical Problems involving Differential Equations, with an Application to the Stresses in a Masonry Dam.

By L. F. RICHARDSON, *King's College, Cambridge.*

Read January 13, 1910

IX. *The Approximate Arithmetical Solution by Finite Differences of Physical Problems involving Differential Equations, with an Application to the Stresses in a Masonry Dam.*

By L. F. RICHARDSON, *King's College, Cambridge.*

Communicated by Dr. R. T. GLAZEBROOK, *F.R.S.*

Received (in revised form) November 2, 1909,—Read January 13, 1910.

§ 1. INTRODUCTION.—§ 1·0. The object of this paper is to develop methods whereby the differential equations of physics may be applied more freely than hitherto in the approximate form of difference equations to problems concerning irregular bodies.

Though very different in method, it is in purpose a continuation of a former paper by the author, on a "Freehand Graphic Way of Determining Stream Lines and Equipotentials" ('Phil. Mag.,' February, 1908; also 'Proc. Physical Soc.,' London, vol. xxi.). And all that was there said, as to the need for new methods, may be taken to apply here also. In brief, analytical methods are the foundation of the whole subject, and in practice they are the most accurate when they will work, but in the integration of partial equations, with reference to irregular-shaped boundaries, their field of application is very limited.

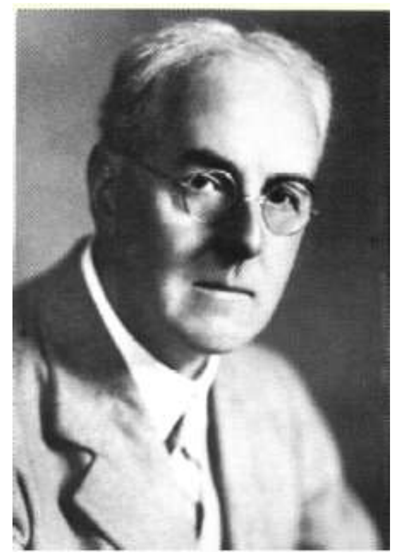
Both for engineering and for many of the less exact sciences, such as biology, there is a demand for rapid methods, easy to be understood and applicable to unusual equations and irregular bodies. If they can be accurate, so much the better; but 1 per cent. would suffice for many purposes. It is hoped that the methods put forward in this paper will help to supply this demand.

The equations considered in any detail are only a few of the commoner ones occurring in physical mathematics, namely:—LAPLACE'S equation $\nabla^2\phi = 0$; the oscillation equations $(\nabla^2+k^2)\phi = 0$ and $(\nabla^2-k^2)\phi = 0$; and the equation $\nabla^4\phi = 0$. But the methods employed are not limited to these equations.

The Number of Independent Variables.—In the examples treated in the paper this never exceeds two. The extension to three variables is, however, perfectly obvious. One has only to let the third variable be represented by the number of the page of a book of tracing paper. The operators are extended quite simply, and the same

VOL. CCX.—A 467. 2 R 2 24.5.10

Lewis Fry Richardson



FRS, British Mathematician, Physicist, Meteorologist, Psychologist

11 Oct 1881 – 30 Sep 1953

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Source: Refs. 4.29 & 4.30

Richardson's Observations: *1910 Paper*

*"The object of this paper is to **develop methods** whereby the **differential equations** of physics **may be applied** more freely than hitherto **in the approximate form of difference equations to problems** concerning **irregular bodies**."*

*"…**analytical methods** are the foundation of the whole subject, and in practice they are the most accurate when they will work, but in the integration of partial equations, with reference to **irregular-shaped boundaries**, their **field of application is very limited**."*

*"So far I have **paid** piece rates **for the** $\delta_x^2 + \delta_y^2$ **operation** of about **n/18 pence per co-ordinate point**, n being the number of digits. The chief trouble to the computers has been the intermixture of plus and minus signs. As to the rate of working, **one of the quickest boys averaged 2,000 operations** $\delta_x^2 + \delta_y^2$ per week, for numbers of three digits, **those done wrong being discounted**."*

Extension to Fluid Flows

TO SIMULATE FLOW ABOUT IRREGULARLY SHAPED BODIES

1. Use difference form of differential equations of *fluid flow* physics. **What**
2. Cannot apply analytical methods to irregularly shaped bodies. **Why**
3. Employ 'computers' [humans] to perform arithmetic operations. **How**

The What, the Why and the How of CFD (the rest is DETAIL!)

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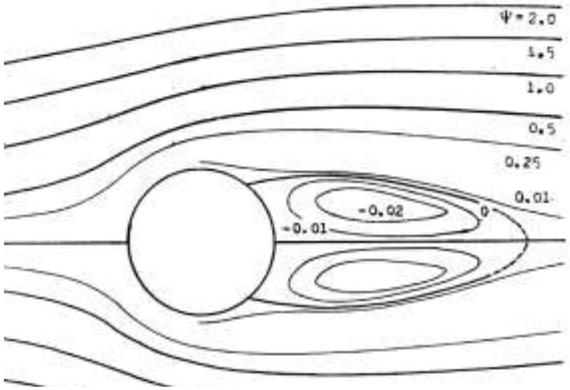
Source: Ref. 4.30

Numerical Aerodynamics: *1910 – 1950*

- **Pioneering Foundational Research in Numerical Methods Parallels Exciting Research in Analytical Aerodynamics**
  - **Richardson (1910)** – point iterative scheme for Laplace's equation
  - **Liebmann (1918)** – improved version of Richardson's method with faster convergence
  - **Courant, Friedrichs, and Lewy (1928)** – uniqueness and existence of numerical solutions of PDEs (*origins of the CFL condition well known to all "CFDers"*)
  - **Southwell (1940)** – improved relaxation scheme tailored for hand calculations
  - **Frankel (1950)** – first version of successive over-relaxation scheme for Laplace's equation
  - **O'Brien, Hyman, and Kaplan (1950)** – von Neumann method for evaluating stability of numerical methods for time-marching problems
- **Early Adopters**
  - **Thom (1929-1933)** – flow past circular cylinders at low speeds by numerically solving steady viscous flow equations: *stream function–vorticity (ψ–ζ) formulation of the N-S equations*
  - **Kawaguti (1953) –** flow past circular cylinder at Re = 40
    - 232 mesh points for half flow region
    - Iterative procedure is considered converged when difference between successive approximations for ψ and ζ does not exceed 0.3% of maximum value for the last 4 cycles
    - ***"The numerical integration in this study took <u>about one year and a half with twenty working hours every week</u>, with a considerable amount of labor and endurance."***



The Bottleneck: Slow & Laborious Computing

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Source: Refs. 4.26 & 4.31-4.33

A Vision for the Future (1946)

"Our ***present analytical methods seem unsuitable for the solution of*** *the important problems arising in connection with* ***non-linear partial differential equations****…The truth of this statement is particularly striking in the field of* ***fluid dynamics****."*

"The ***advance of analysis is,*** *at this moment,* ***stagnant*** *along the entire front of non-linear problems…Although the main mathematical difficulties have been known since the time of Riemann and of Reynolds, and although as brilliant a mathematical physicists as Rayleigh has spent a major part of his life's effort in combating them, yet* ***no decisive progress has been made*** *against them—indeed hardly any progress which could be rated as important…"*

"…many branches of both pure and applied mathematics are in ***great need of computing instruments to break the present stalemate*** *created by the failure of the purely analytical approach to nonlinear problems."*

John von Neumann

Hungarian-American
Mathematician, Physicist,
Computer Scientist
28 Dec 1903 – 8 Feb 1957
1999 Financial Times
Person of the Century

"… really efficient high-speed [digital] computing devices may, in the field of non-linear partial differential equations as well as in many other fields…provide us with those heuristic hints which are needed in all parts of mathematics for genuine progress."

These are excerpts from the first paper in Ref. 4.35 entitled "ON THE PRINCIPLES OF LARGE SCALE COMPUTING MACHINES. *This paper was never published. It contains material given by von Neumann in a number of lectures, in particular one at a meeting on* ***May 5, 1946****, of the Mathematical Computing Advisory Panel, Office of Research and Inventions, Navy Department, Washington, D.C. The manuscript from which this paper was taken also contained material (not published here) which was published in the Report, "Planning and Coding of Problems for an Electronic Computing Instrument".*

Source: Refs. 4.34 & 4.35

 Note: Highlighting by the author.

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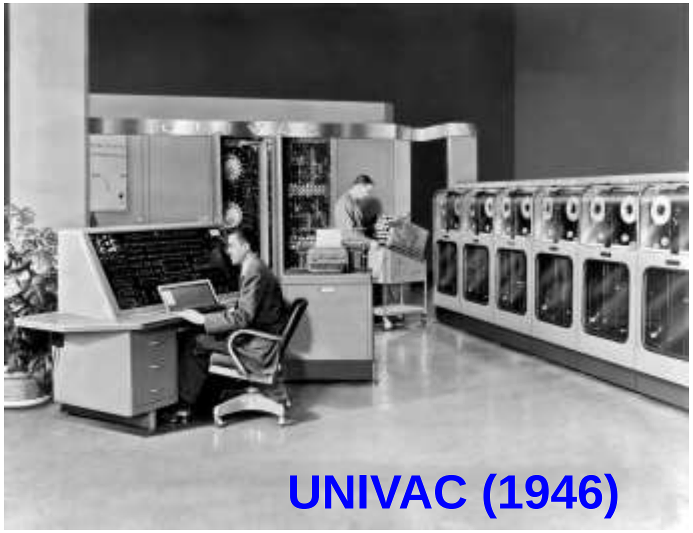
Digital Computers: *1930 – 1950*

- **Alan Turing (1936)** – *a universal machine capable of computing anything that is computable*
- **Atanasoff (1937)** – *first computer without gears, cams, belts and shafts*
- **Atanasoff and Berry (1941)** – *a computer that can solve 29 equations simultaneously, and store information on its main memory*
- **Mauchly and Eckert (1943-44)** – *Electronic Numerical Integrator and Calculator **(ENIAC)** using 18,000 vacuum tubes*
  - ✓ Speed: 500 floating point operations per second
  - ✓ Size: 1,800 square feet
- **Mauchly and Presper (1946)** – *Universal Automatic Computer **(UNIVAC)**, the first commercial computer for business and government*



The Key to Converting von Neumann's Vision into Reality!

Source: Ref. 4.36

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Section 4.
Overarching Takeaways

By 1950, all fundamental ingredients were in place for the evolution of an exciting new field of [what we call] Computational Fluid Dynamics (CFD).

In the second half of the 20th century, phenomenal advances in CFD methods and computing capabilities fueled the evolution of Applied Computational Aerodynamics (ACA).

ACA Evolution was Fueled by the Promise of CFD Serving as a Powerful "Alternative" to AFD and EFD for Simulating Aerodynamics of Irregularly Shaped Bodies!

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Section 4: Key Takeaways

- **1903: the first manned, controlled, powered flight by the Wright brothers!**
- **Even after 150 years of noteworthy progress, Analytical Fluid Dynamics woefully inadequate to meet the emerging airplane design needs**
  - No solution of the problem of resistance in sight. *d'Alembert's paradox rules!*
- **1904: A breakthrough—Prandtl's Boundary Layer theory!**
  - *"A most extraordinary paper of the 20th century, and probably of many centuries!"*
- **The first 50 years of the 20th century (1900-1950) witnessed phenomenal advances in Analytical Aerodynamics, but…analytical models remained inadequate for simulating realistic flows on irregularly shaped bodies**
  - EFD provided the best means of solving practical engineering problem
- **1910: Richardson laid the foundation of Numerical Fluid Dynamics**
  - Use difference form of differential equations; employ human computers to perform resulting arithmetic operations; applicable to irregularly shaped bodies, but…
  - Human computers were the bottleneck!
- **1930 - 1950: Digital computers evolved**
  - Key to realizing von Neumann's 1946 vision: "*really efficient high-speed [digital] computing devices may break the present stalemate created by the failure of the purely analytical approach to nonlinear problems*"

By 1950, all basic ingredients were in place for the evolution of Computational Fluid Dynamics (CFD)

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Contents

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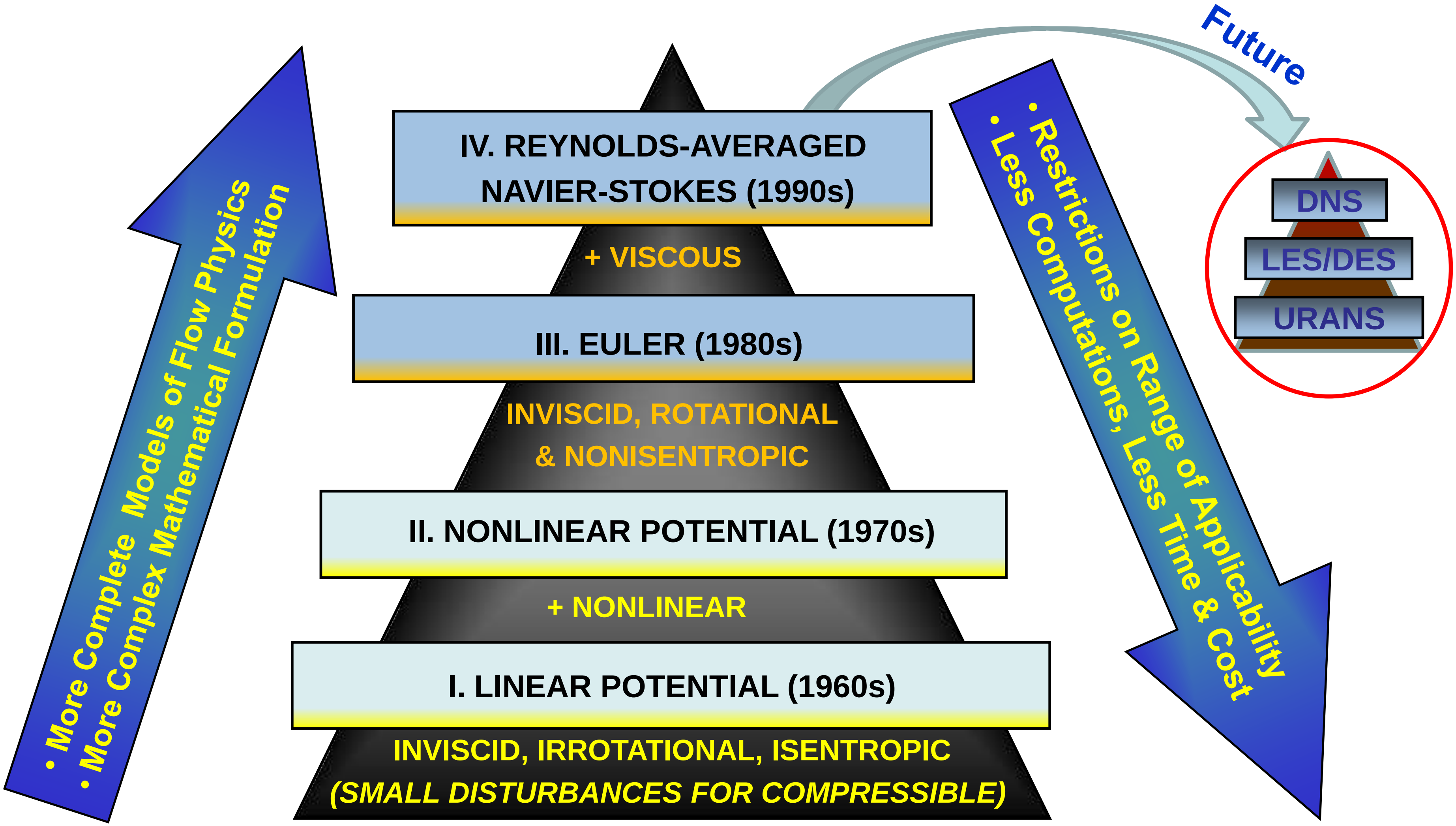
Evolution of ACA

Directly Related to Maturity of Four Levels of CFD Methods



Paced by Impressive Advances Since The 1950s

Note: Time frames in parenthesis indicate *widespread* adoption by industry

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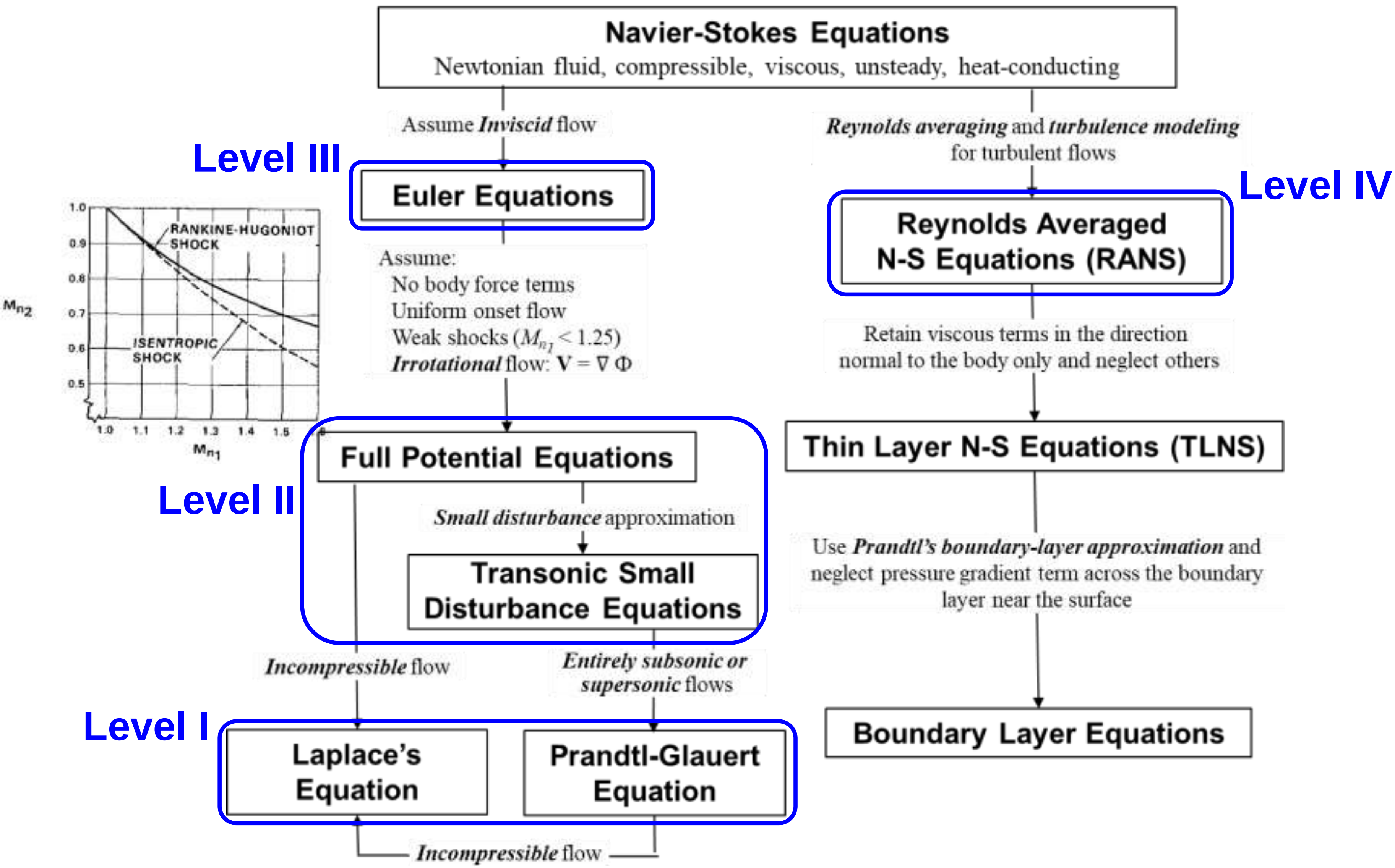
Approximations of N-S Equations Mapped to Four Levels of CFD



Adapted from Fig. 2-10, Configuration Aerodynamics by W.H. Mason

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On "Fidelity" and "Credibility" of CFD Methods for Aerodynamic Simulations

- Many CFD developers characterize ***"lower level"*** methods (potential [flow] methods) as ***"low fidelity"*** and ***"higher level"*** (Euler and RANS) as ***"high fidelity."*** It is best to interpret ***fidelity*** as *exactness with which governing equations approximate flow physics,* not necessarily the *accuracy with which computational solutions reproduce reality.* For ACA, ***credibility*** of solutions (*how closely solutions replicate reality*) is of ***paramount importance***.
- Experience has shown that ***higher level RANS methods do not necessarily produce credible results or solutions especially for complex flows*** that are dominated by vortices and boundary-layer separation. Therefore, one could argue that RANS methods for such applications should not be characterized as "*high fidelity*." When considering *fidelity,* more is <u>not</u> always better. **Using the "highest fidelity" CFD *in all instances* can lead to misuse of valuable resources.**
- Since each CFD method is (should be?) carefully designed to solve a selected set of equations as *accurately* as possible, a potential flow method may not be <u>inherently</u> *low fidelity*—as long as the method is *accurately* solving the governing potential flow equations, and *producing credible results for the target application*.
- **For ACA, it's the <u>*credibility of aerodynamic data*</u> that is of utmost importance. The data must be credible enough for customer <u>*to use in making decisions without incurring undue risk*</u>. This requires that data produced by a CFD method closely replicate reality. Validation is the most common approach for assessing credibility—albeit not without its own set of challenges to be highlighted later.**

What Matters to the Customer is Results, Not Tools!

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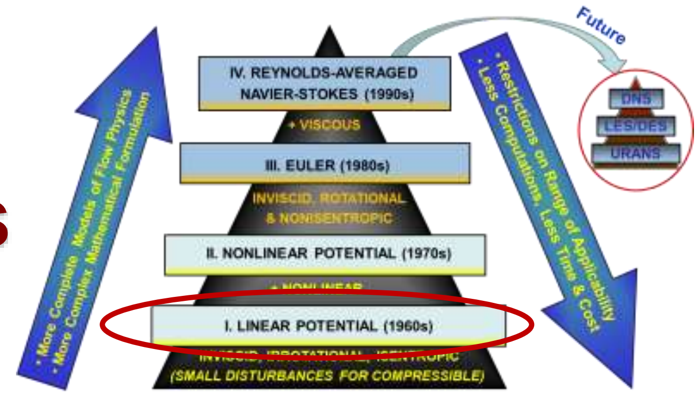
Level I
Linear Potential Methods
1950s – present



Flow Model

- **Inviscid, Irrotational, Isentropic** ***(Small Disturbances for Compressible Flow)***

$$U = U_\infty + \nabla\phi$$

$$(\phi_{tt} + 2U_\infty\phi_{xt})/a_\infty^2 = (1 - M_\infty^2)\phi_{xx} + \phi_{yy} + \phi_{zz}$$

- ✓ Linear second-order PDEs with appropriate boundary conditions
- ✓ Laplace’s equation for steady, incompressible flow
- ✓ Prandtl-Glauert equation for steady, compressible flow
- ✓ *Wakes not captured as part of the solution—must be explicitly modeled*

Applicability

- Attached flows that are entirely subsonic or supersonic; *not transonic*
- Flows not dominated by shocks, vortices, or boundary-layer separation

Refs. 5.1.1 to 5.1.45

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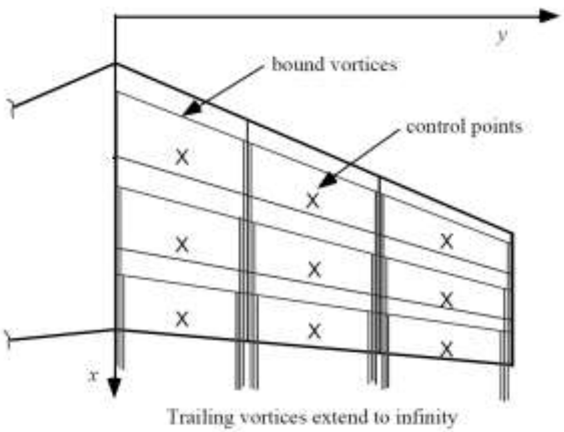
Linear Potential Methods (LPMs)

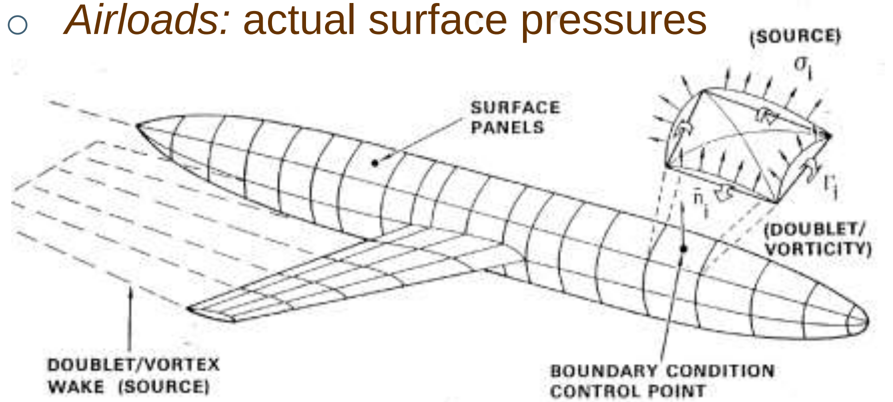
Overview

- **Basic Formulation**
  - Discretize geometry into small elements
  - Distribute singularities (source, doublets, vortex filaments) on each element
  - Impose no-normal-flow boundary condition (BC) at control points (one per element), and Kutta condition at sharp trailing edge
  - Solve system of linear algebraic equations to determine singularity strengths
  - Use Bernoulli's equation to compute airloads

- **Vortex Lattice Methods (VLMs)**
  - *Geometry:* mean surface
  - *Singularity type:* horseshoe vortices
  - *BCs:* control points on mean surface
  - *Airloads:* net pressure



- **Panel Methods**
  - *Geometry:* actual surface
  - *Singularity type:* sources, doublets or both
  - *Singularity distribution:* constant, linear or higher order
  - *BCs:* control points on actual surface
  - *Airloads:* actual surface pressures



LPMs (VLMs & Panel Methods): Today's Workhorse!

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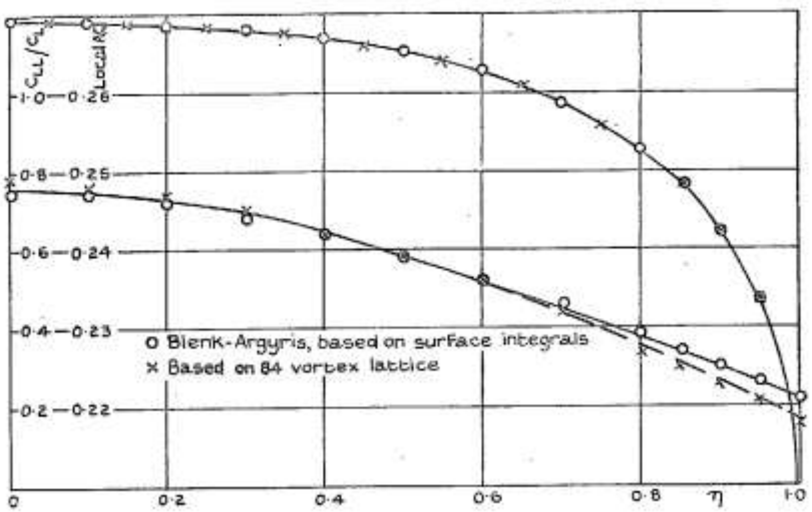
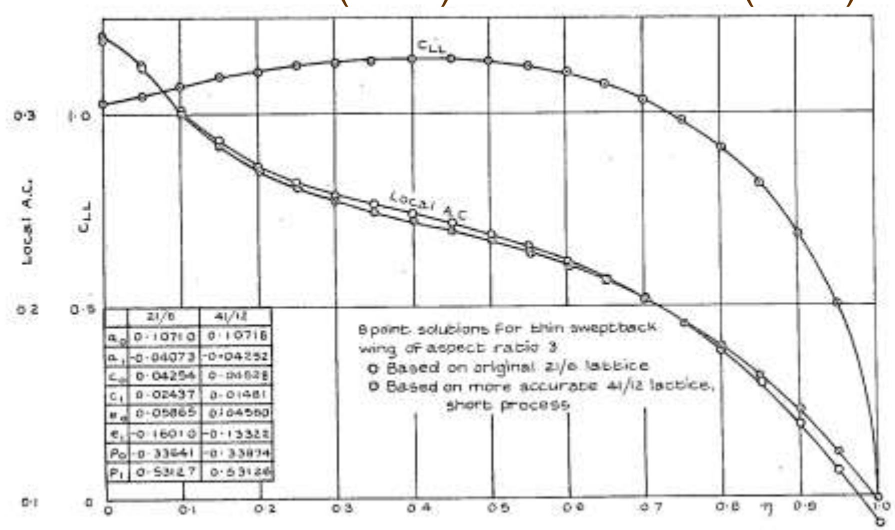
Birth of Vortex Lattice Methods

1940s

- **V.M. Falkner (1949) "The Scope and Accuracy of Vortex Lattice Theory"**
  Report & Memoranda 2740, Aeronautical Research Council
  - Research motivated by the need to calculate loading distribution on a wing of arbitrary plan form including wing twist, discontinuities due to flaps, compressibility, etc.
  - Outlines principles for solving potential flow problems in lifting plane theory by using a vortex lattice; highlights key developments from Falkner's R&M 2591 (1947) and R&M 1910 (1943)



Thin Rectangular Wing: $\Lambda = 0^o$, AR = 6
84 vortex lattice: 14 spanwise, 6 chordwise



Thin Sweptback Wing: $\Lambda = 45^o$, AR = 3
21 spanwise, 6 chordwise and 41 spanwise, 12 chordwise

- **Variations were tried extensively throughout industry during the 1950s**

Advances in Electronic Computers and Numerical Methods in 1960s Made Practical VLM Applications Possible

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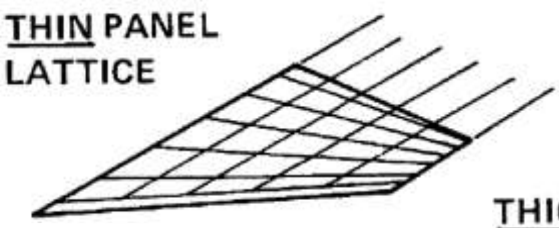
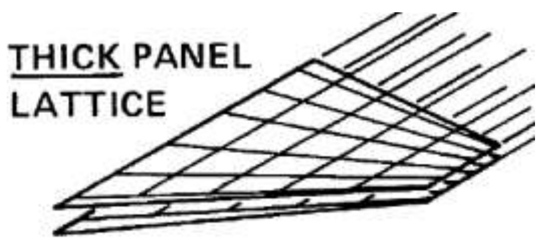
Source: Ref. 5.1.1

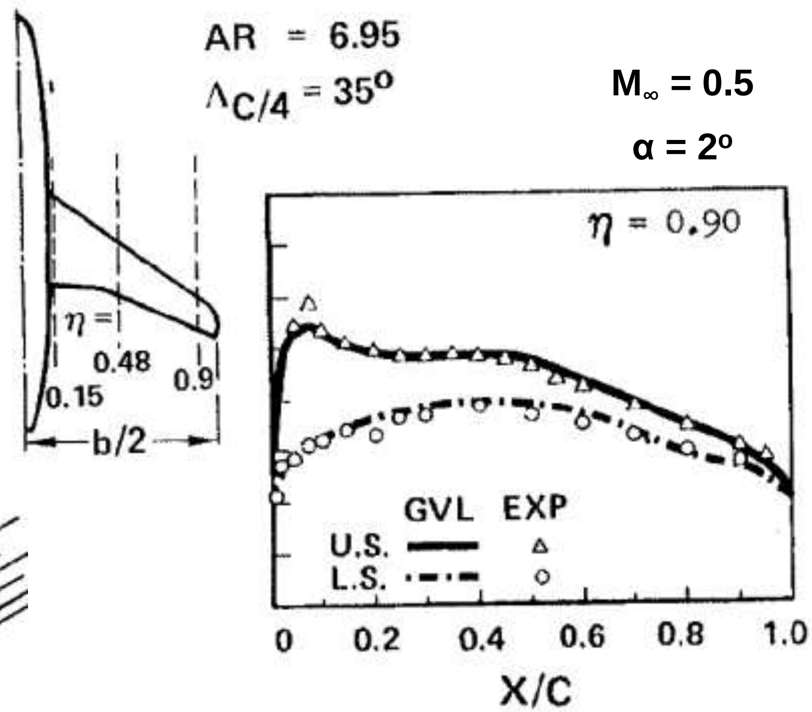
Vortex Lattice Methods (VLMs)

Rapid Development (1960s & 70s)

- **Rubbert (1964)**
  - Non-planar Vortex Lattice Methods; arbitrary wings—*Boeing Co. Document D6-9244*
- **Margason and Lamar (1971)**
  - Vortex-lattice Fortran program for estimating subsonic aerodynamic characteristics of complex planforms—*NASA TN D-6142*
- **Vortex-Lattice Utilization workshop (1976)**
  - Compilation of many papers—*NASA SP-405*
- **Miranda, Elliott and Baker (1977)**
  - A generalized vortex-lattice (GVL) method for subsonic and *supersonic* flow applications, the VORLAX code—*NASA CR 2865*







Falkner's Method Extended and Adapted to Electronic Computers

Source: Refs. 5.1.2 – 5.1.5

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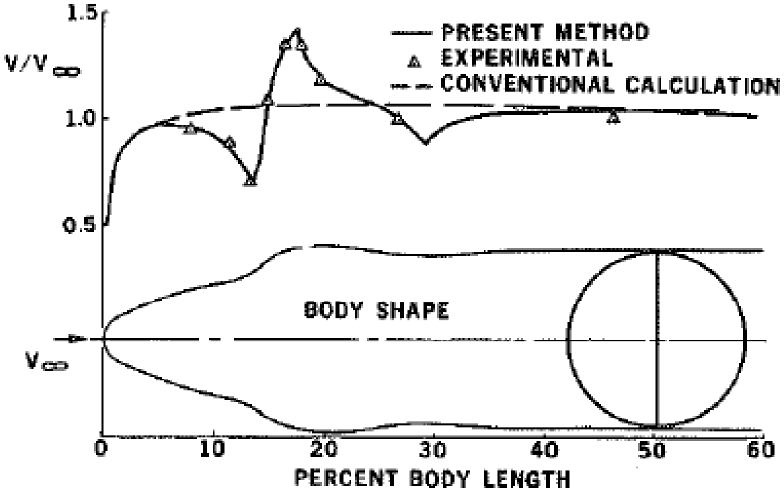
Birth of Panel Methods
1950s

- **A.M.O. Smith and J. Pierce, Douglas Aircraft Co., Long Beach, CA**
  - **Non-circulatory plane [2-D] and axially symmetric flows**
  - **1953**--Serious work began to solve **Neumann problem**
    - ***Continuous source distribution on surface panels***
  - **1954**--Programming on **IBM/701** *in machine language!*
  - Test cases selected based on availability of theoretical [analytical] solutions
  - From 24-point body of revolution solutions in 1954 to **150-points** by the end of **1955**!
  - DAC financed all work through **1958**
  - ONR contract: extend the method to 3-D non-lifting flows
- **DAC Report E.S. 26988, April 1958**

A.M.O. Smith

Chief Aerodynamics Engineer, Research
2 July 1911 – 1 May 1997



And the Rest is History!

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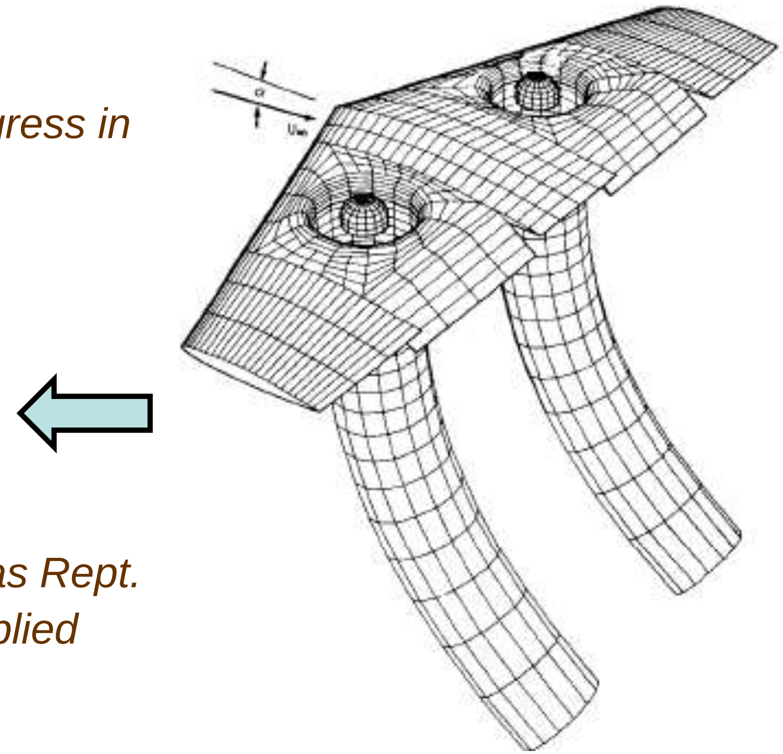
Source: Refs. 5.1.6 & 5.1.7

Panel Methods

Rapid Development (1960s & 70s)

- **Hess (1962)**
  - Arbitrary bodies of revolution with axes perpendicular to the free stream direction—*Journal of the Aerospace Sciences*
- **Hess and Smith (1967)**
  - Extensive description of panel methods—*Progress in Aeronautical Sciences, Vol. 8* (138 pages!)
- **Rubbert and Saaris (1968)**
  - Incompressible flow; arbitrary configurations; source and doublet distributions—Fan-in-wing simulation, *SAE Paper 680304*
- **Hess (1970)**
  - Arbitrary 3-D lifting bodies—*McDonnell Douglas Rept. MDC J0971-01 (Also in Comp. Methods in Applied Mechanics and Engineering, 1974)*
- **Woodward (1973)**
  - Subsonic or *supersonic* flow; wing-body-tail configurations; source and vortex distributions—*NASA CR-2228*



Panels for a fan-in-wing configuration

Offer Powerful Capability to Simulate Flow About Realistic Geometries to Support Aircraft Design Needs

Source: Refs. 5.1.8 – 5.1.12

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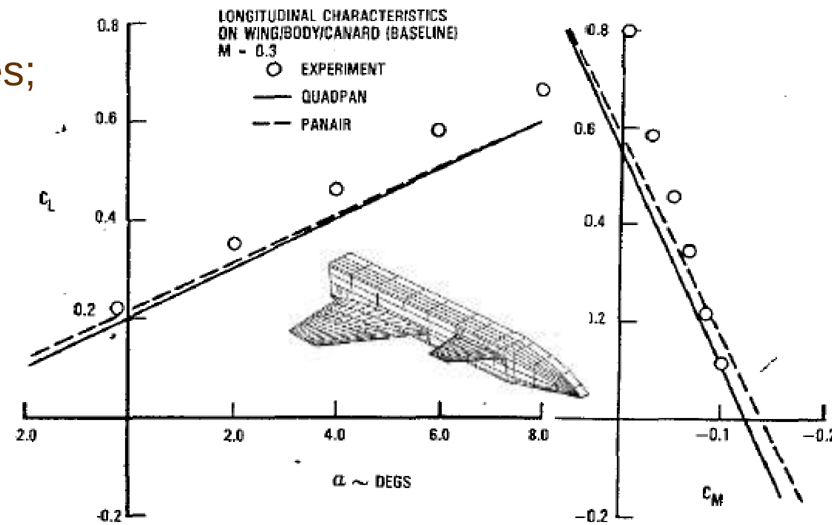
Panel Methods

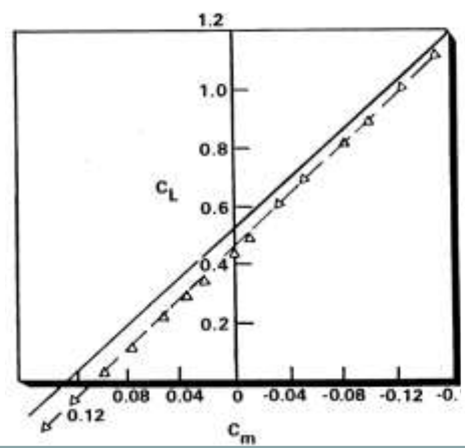
Technology Comes of Age (1980s)

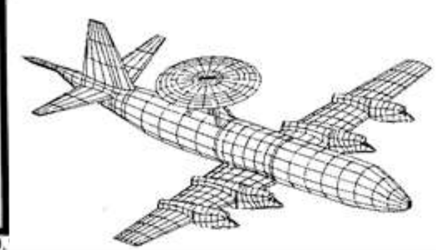
- **PANAIR (Boeing):** Magnus, Ehlers and Epton—*NASA CR 3251, April 1980*
    - Subsonic or supersonic flow; arbitrary bodies; higher order singularity distribution
- **MCAIR (McDonnell):** Bristow and Hawk—*NASA CR 3528, March 1982*
    - Subsonic flow; arbitrary bodies; constant source, quadratic doublet singularities
- **VSAERO (AMI):** Maskew—*NASA CR 166476, Dec 1982*
    - Subsonic flow; arbitrary bodies; piecewise constant doublet and source singularities
- **QUADPAN (Lockheed):** Youngren, Bouchard, Coopersmith, and Miranda—*AIAA 83-1827, July 1983*
    - QUADriletral PANel code: subsonic flow; arbitrary bodies; low-order constant sources and doublet singularities

Wing-Body-Canard Analysis



P-3 AEW&C Development





Applicable to Simulating Entirely Subsonic or Supersonic Attached Flows on Full Aircraft Configurations

Source: Refs. 5.1.13 – 5.1.29

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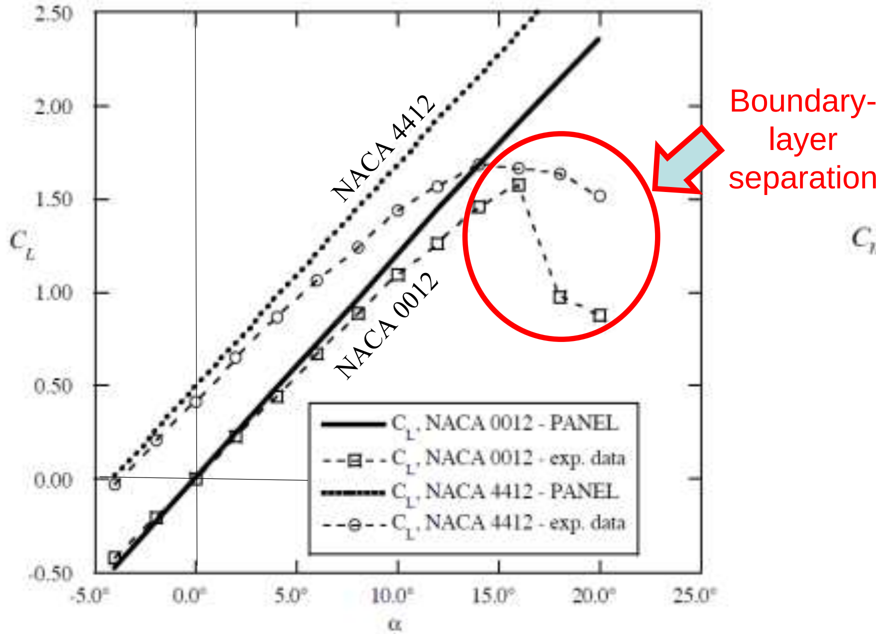
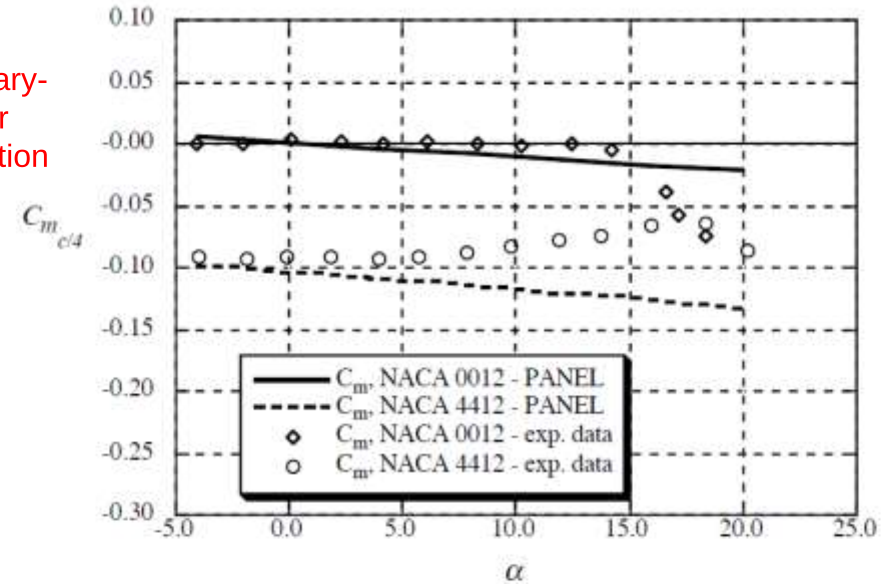
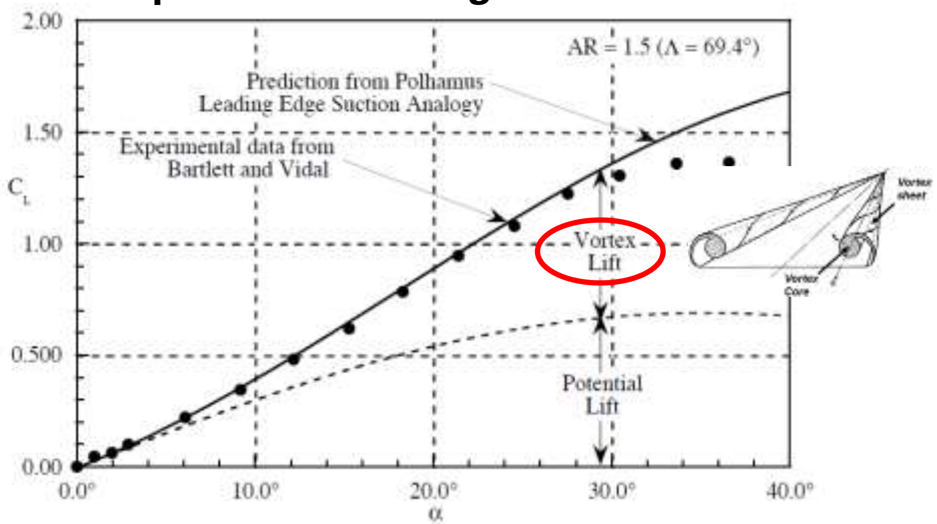
Limitations of LPM's Applicability

Example 1: *Symmetric and Cambered Airfoils Flow Simulation*





Example 2: *Delta Wing Flow Simulation*



LPMs applicable to simulate

- ***attached*** **flows that are entirely subsonic or supersonic; *not* transonic**
- **flows *not dominated by* shocks, vortices, or boundary-layer separation**

Assessment Based on Comparing LPM Results With Experimental Data!

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Source: Mason (Configuration Aerodynamics)

"Higher, Faster, Farther" Jet Transports
US SST (Supersonic Transport) Aircraft (*1960s*)

- **June 5, 1963: FAA launched the SST program to *improve upon the Anglo-French Concorde* with quite aggressive targets**
  - 250 passengers
  - M_{cruise} = 2.7 – 3.0
  - 4,000 miles Range

- **January 15, 1964: Proposals submitted**
  - Boeing and Lockheed entries downselected for further development
  - Boeing developed swing-wing B 2707, and Lockheed's L-2000

- **January 1, 1967: Boeing won the competition**
- **May 20, 1971: Development work stopped; US Congress canceled funding**
  - Rising costs and lack of a clear market were likely factors

SST Design Needs Stimulated Research in Many Areas

Image Source: Internet

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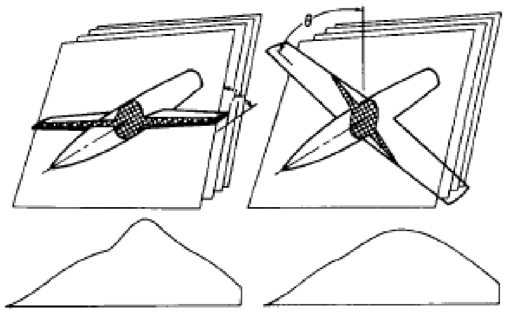
"Computer-Aided Aerodynamics"

Utilize Computers to Meet SST Aerodynamic Design Needs (1960s)

- **Wave Drag Analysis–Harris (1964)**
  - Analysis and correlation of aircraft wave drag—*NASA TM X-947*

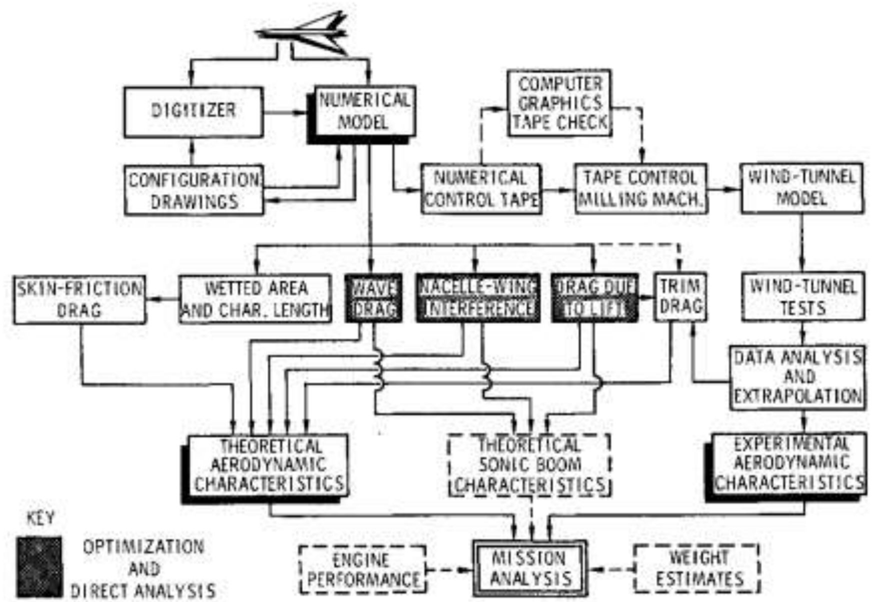


$$D(\theta) = -\frac{\rho V^2}{4\pi}\int_0^l\int_0^l A''(x_1)\,A''(x_2)\,\mathrm{LOG}\,|x_1 - x_2|\,dx_1\,dx_2$$

$$D = \frac{1}{2\pi}\int_0^{2\pi} D(\theta)\,d\theta$$

- **Supersonic Wing Camber Design – Carlson and Middleton (1964)**
  - Numerical method for designing camber surfaces of supersonic wings with arbitrary planform corresponding to specified load distributions—*NASA TN D-2341*

- **Supersonic Aircraft Design Integration –Baals et al (1968)**
  - Aerodynamic design integration of supersonic aircraft—*AIAA Paper 68-1018; also in Journal of Aircraft, 7(5), 1970*



Key operational Langley computer programs for estimating aerodynamic characteristics of a numerical model of the configuration for mission performance analysis

"Computer-Aided Aerodynamics" Demonstrated Its Usefulness

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Source: Refs. 5.1.30 through 5.1.32

"Higher, Faster, Farther" Jet Transports

Transonic Aircraft (*1960s*)

- **Jet transport designs in the 1960s pushed cruise speed into transonic regime to maximize Range Factor, M_{cruise} *(L/D)***
    - C-5A (1968): $M_{cruise} = 0.77$
    - B747 (1969): $M_{cruise} = 0.84 – 0.88$
    - L-1011 (1970): $M_{cruise} = 0.86$
- **Drag rises with speed due to added wave drag + shock-induced separation drag**
    - ***The higher the drag rise Mach number, the better!***
    - Sweep helps…but design tradeoffs limit it to about 35º in practice

LPMs of Little Use for Accurate Transonic Flow Simulation

Image Source: Internet

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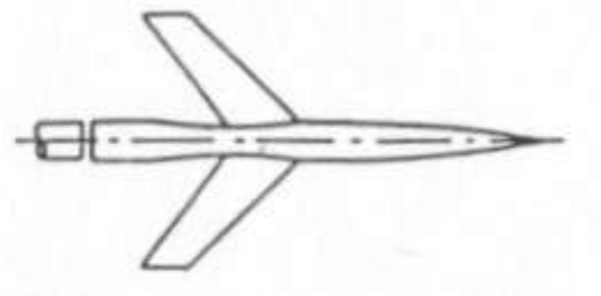
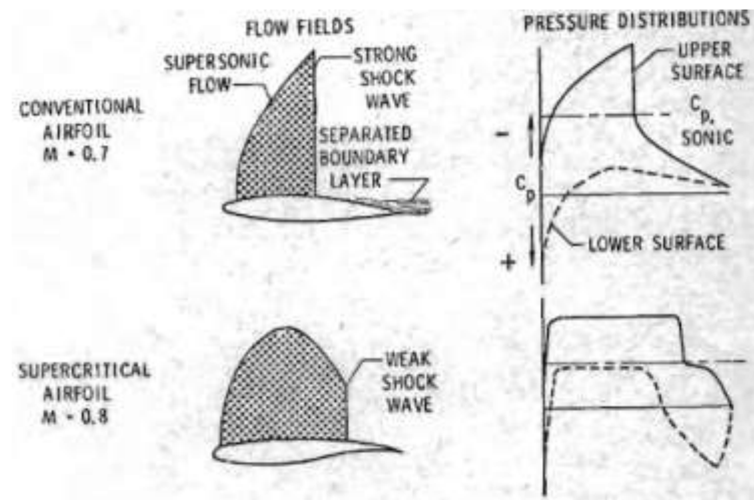
Transonic Aircraft Design

EFD: Primary Means of Flow Simulation

- **Whitcomb (1954 Collier Trophy)**
  - "Area Rule"



- **Pearcy (1962)**
  - "Peaky" airfoils: 0.02 to 0.03 increase in drag rise Mach number over NACA 6-series
- **Whitcomb (1967)**
  - Supercritical "roof top" airfoils



ACA Capability Urgently Needed to Support Design Needs!

Source: Refs. 5.1.33 & 5.1.34

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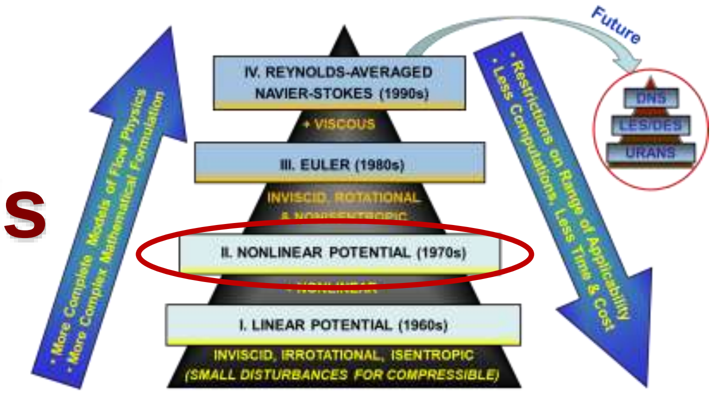
Level II
Nonlinear Potential Methods
1970s - present



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

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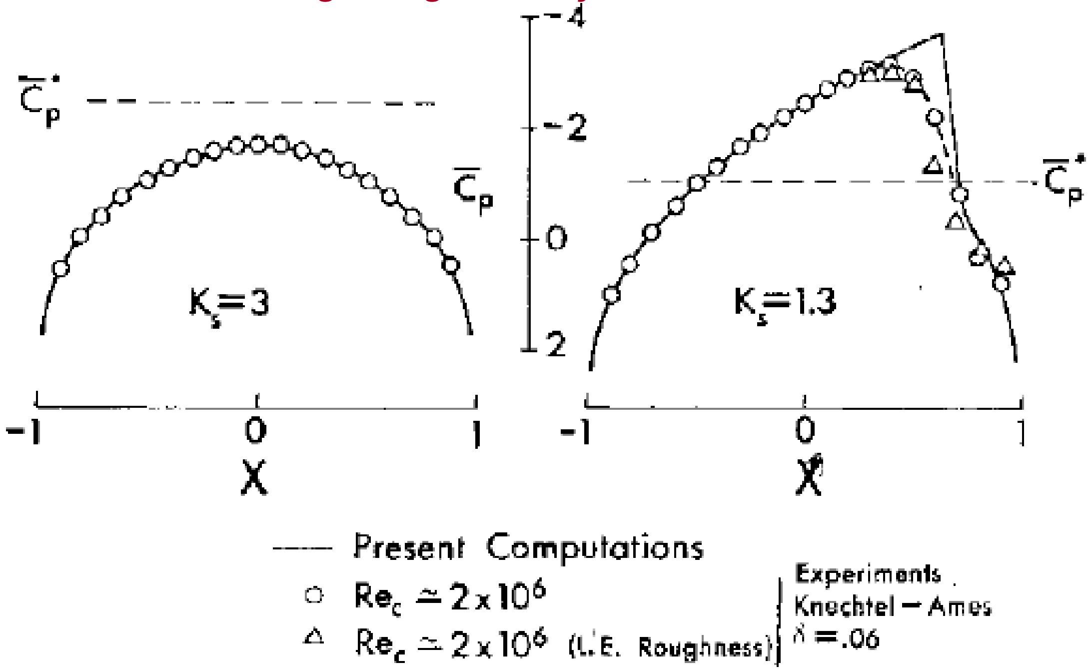
Birth of Nonlinear Potential Methods

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

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***

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

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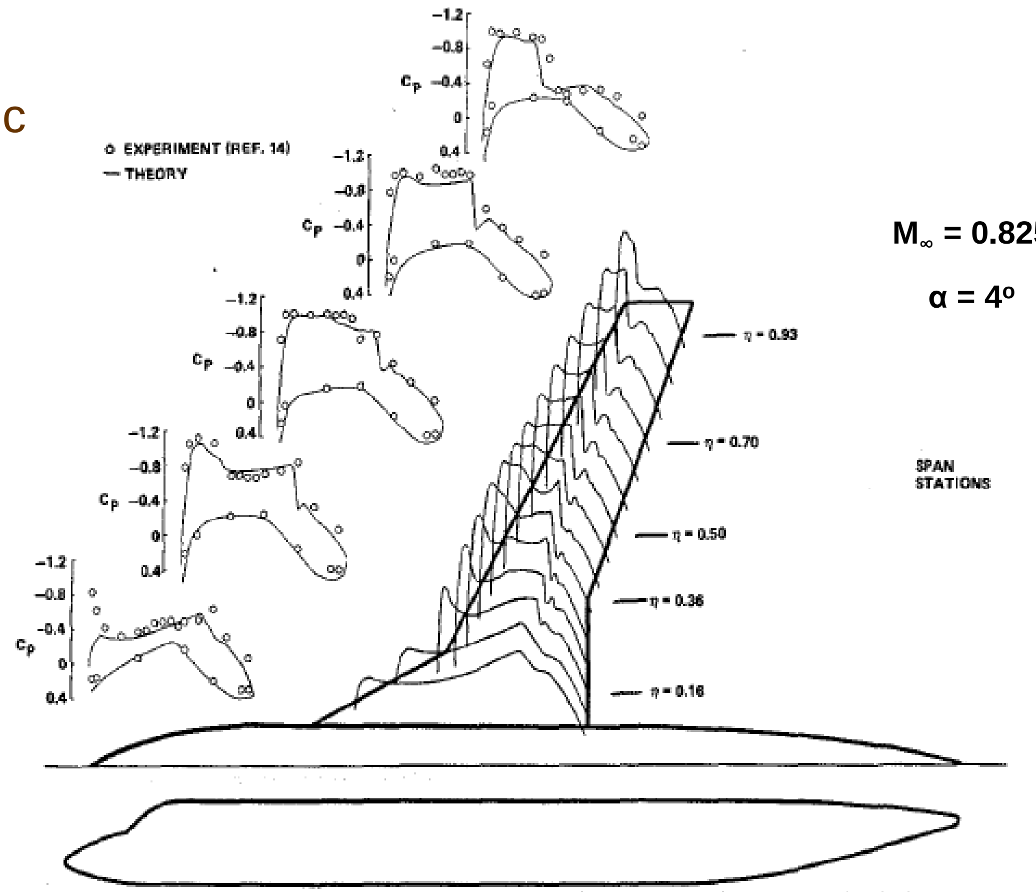
Source: Refs. 5.1.35

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)



A New Transonic Aerodynamic Analysis and Design Capability!

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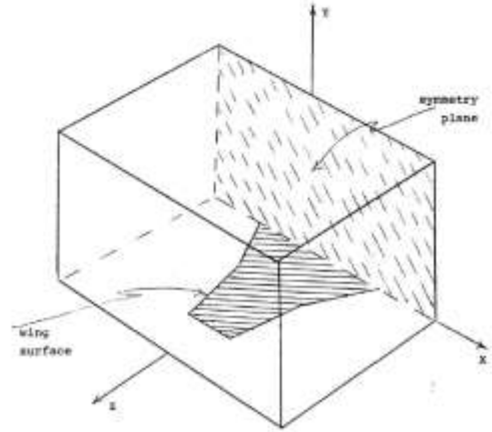
Source: Refs. 5.1.36 & 5.1.37

Transonic Full Potential Equations (FPE)

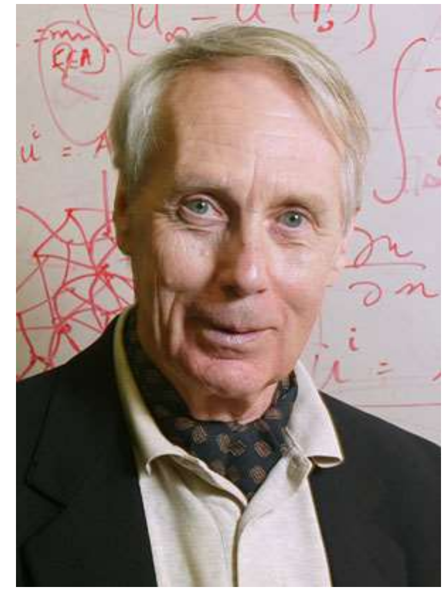
A Method for Swept Wings

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

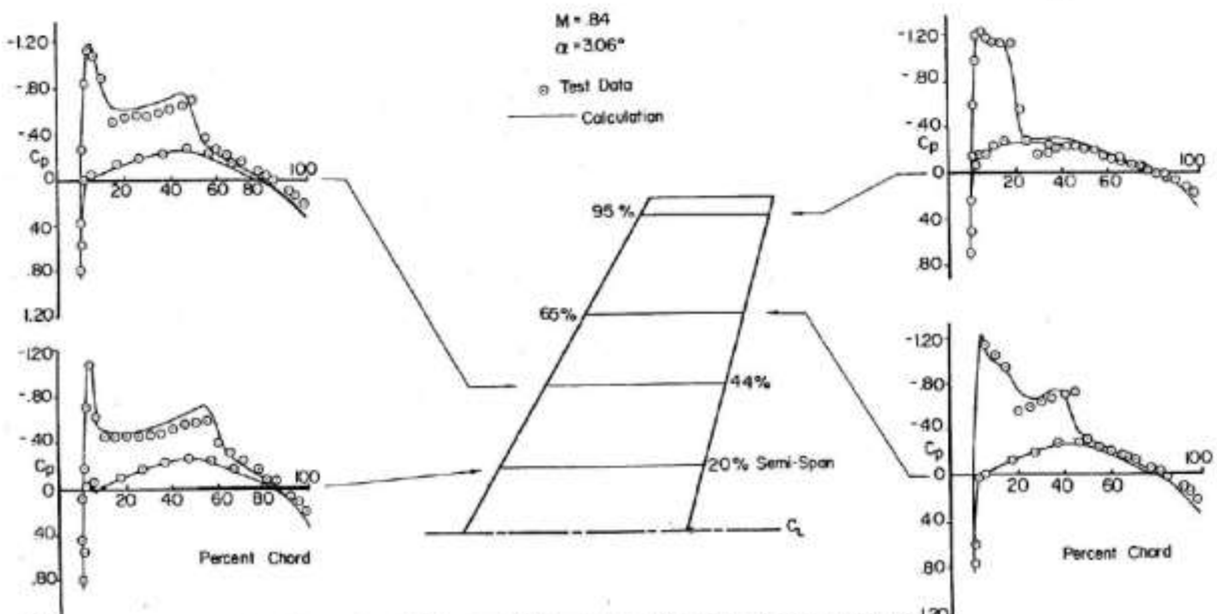


Figure 8. Comparison Of Calculated And Experimental Wing Pressure Distributions For Onera Wing M-6

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

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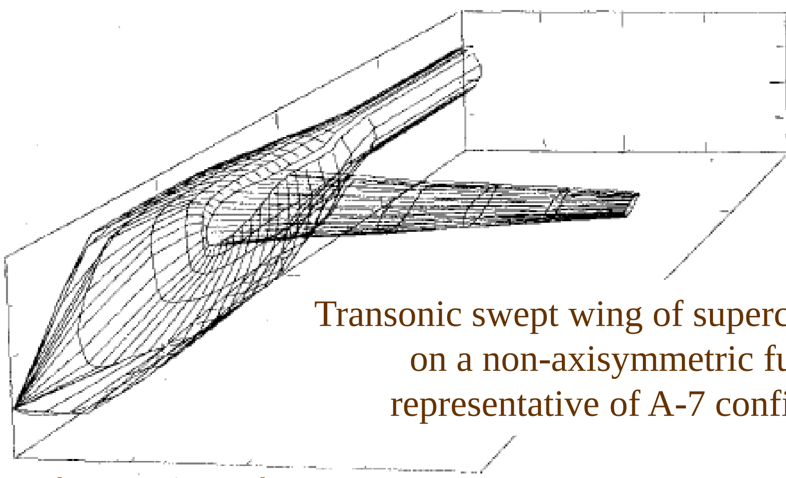
Source: Refs. 5.1.38 to 5.1.42

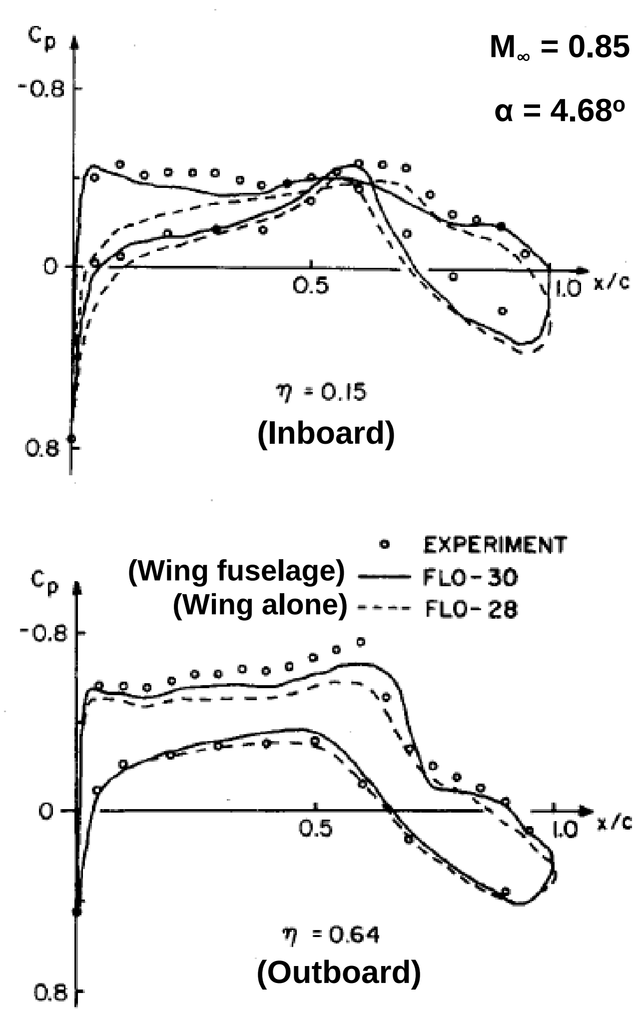
Transonic Full Potential Equations
A Method for Wing-Body Combinations

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



- 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**

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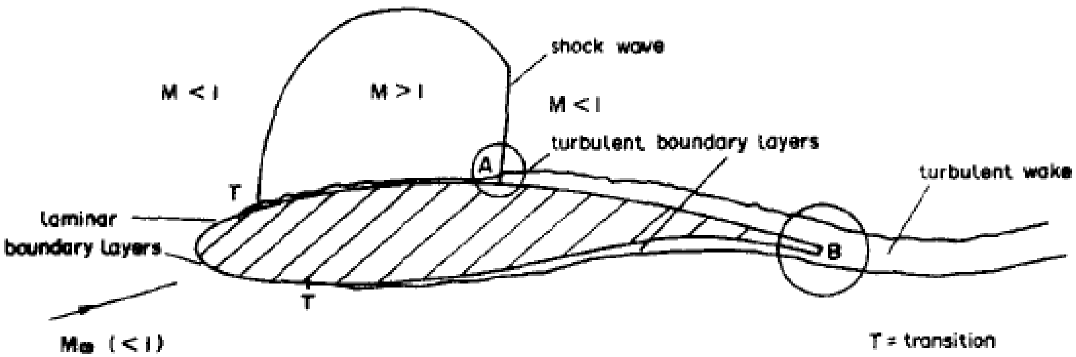
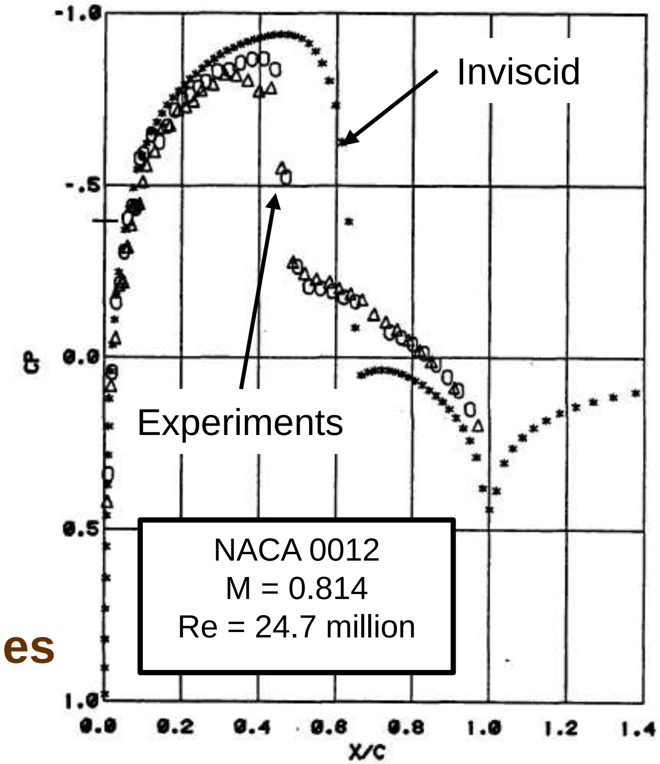
Source: Ref. 5.1.43

Limitations of Potential Flow Methods

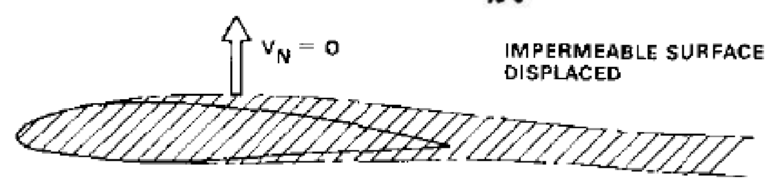
Implications of Neglecting Viscosity

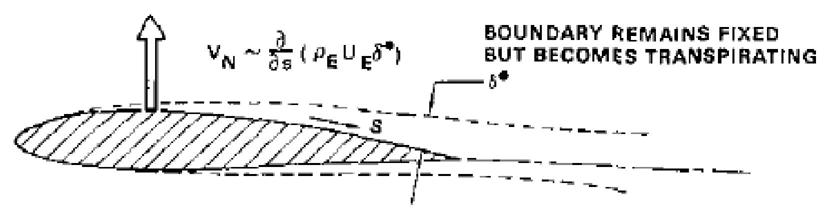
- **Potential Flow Methods, Linear and Nonlinear, *Being Inherently Inviscid*, Cannot Capture Effect of Viscosity on the Flow Field**
  - ***Particularly problematic for transonic flows***





- **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

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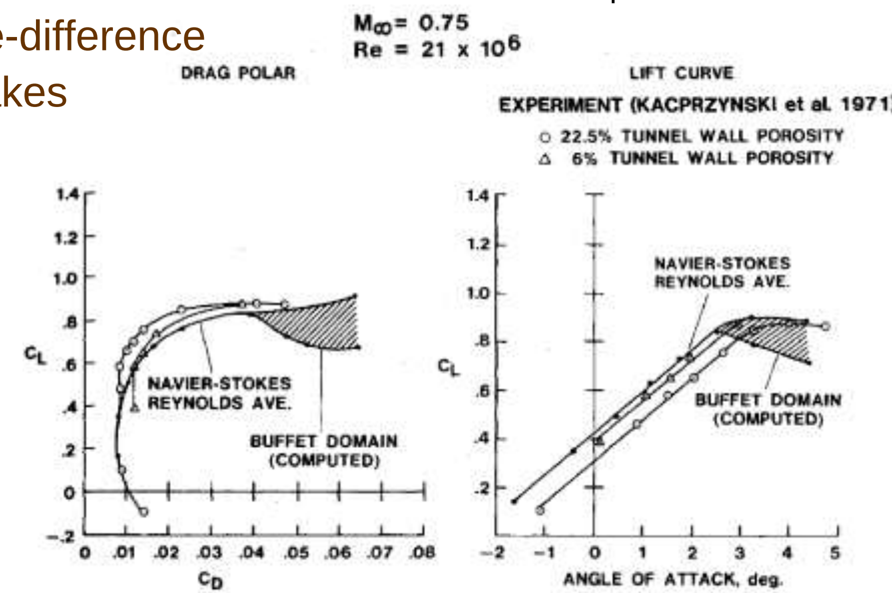
Why Not Use RANS Methods?
They Overcoming Limitations of Potential Flow Methods!

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

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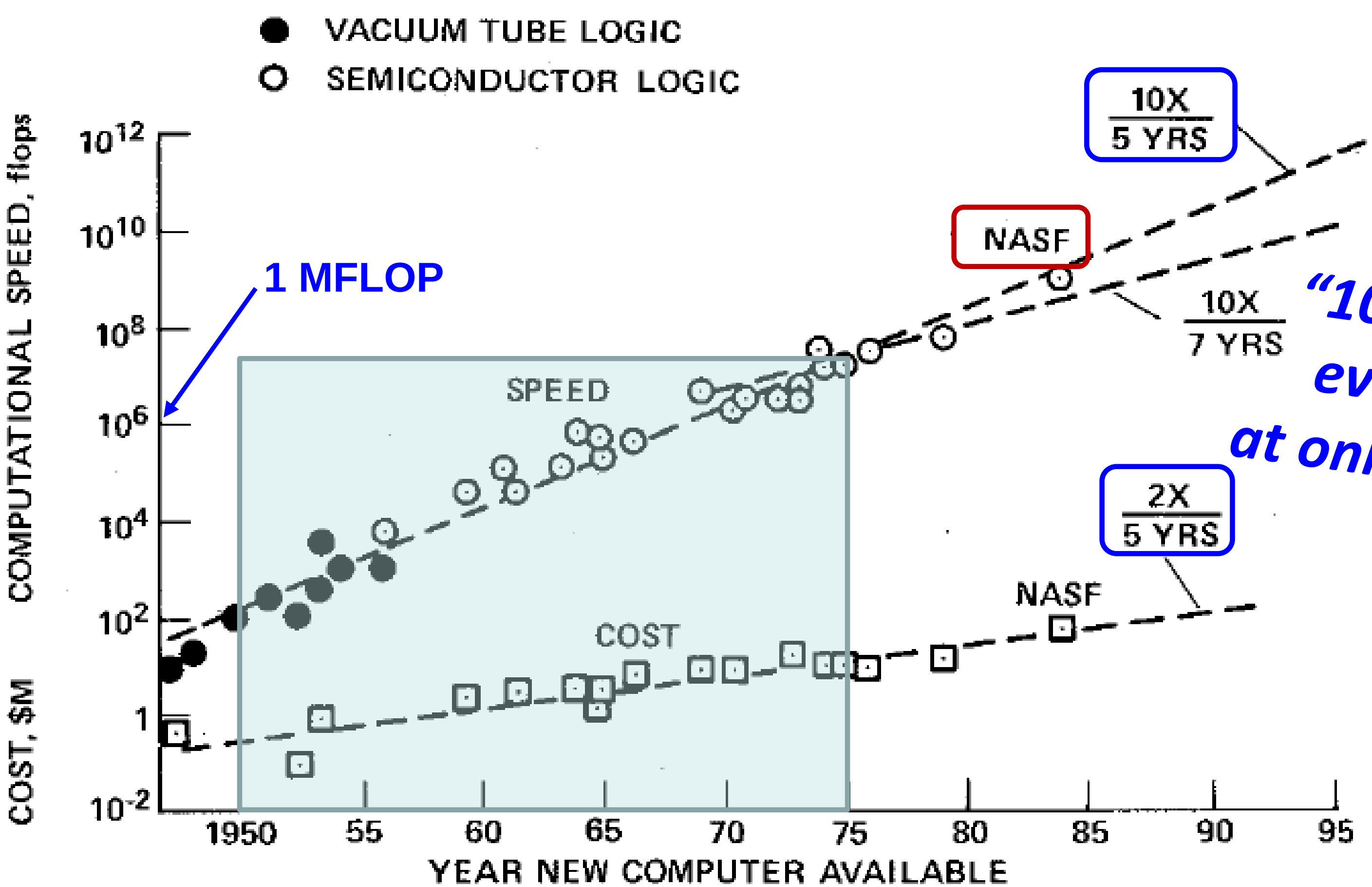
Source: Refs. 5.1.46 to 5.1.52

Digital Computers:

A Key Enabler for RANS CFD Research in the 1970s

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

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Source: Ref. 5.1.53

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

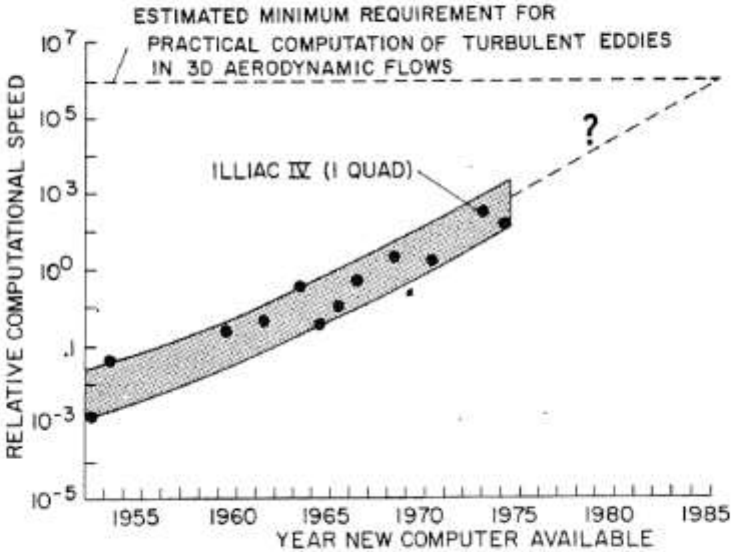
Computers vs. Wind Tunnels for Aerodynamic Flow Simulations

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

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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

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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

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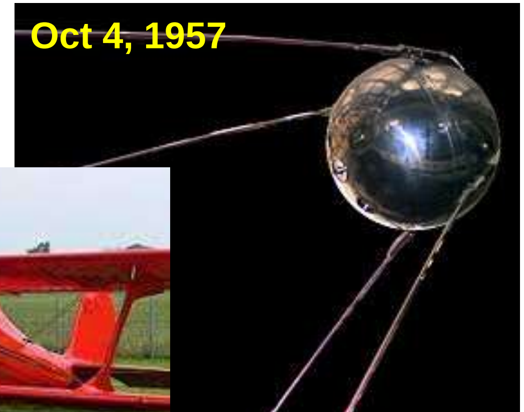
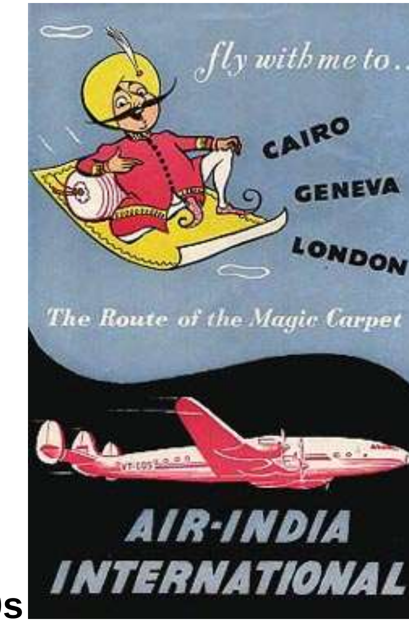
While the World of CFD Was Exploding in '50s &'60s

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

1950s *(Foundational Years)*





Early 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

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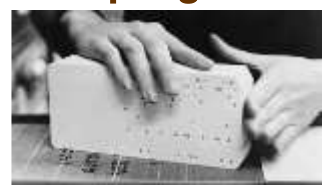
An Aerospace Engineer After All!

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 for computer programs/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 *Journal of Aircraft, 16 (3), 1979*

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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**
  - ✓ ***Wonderful memories of** working with, and learning 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 <u>turbulence models</u> 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

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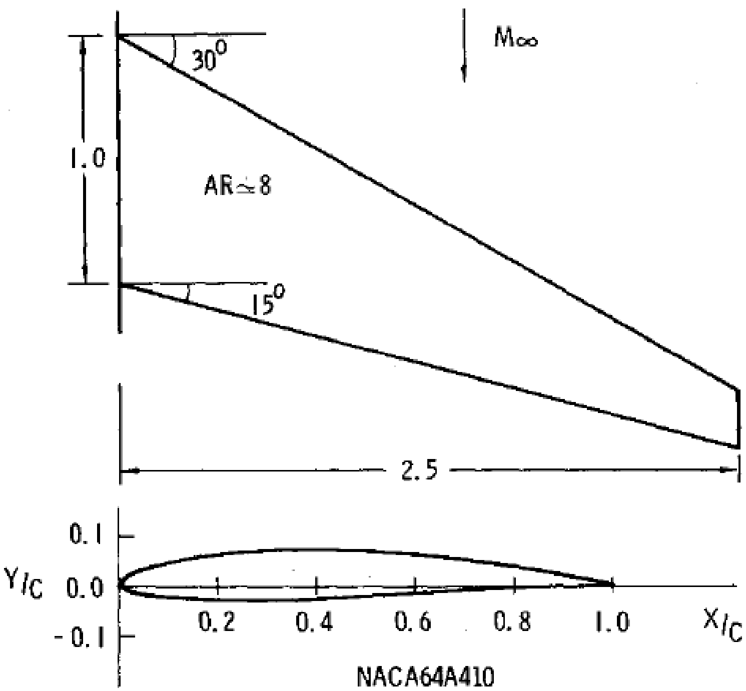
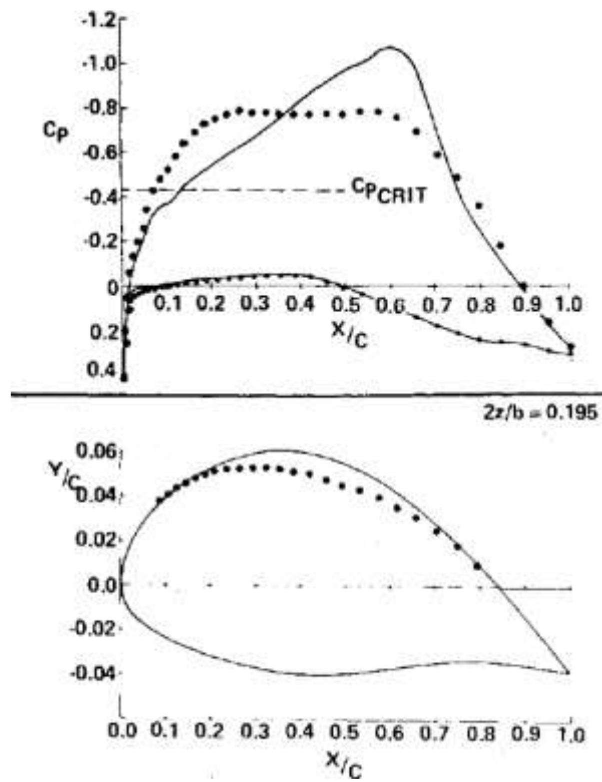
First Day on the Job: *May 1979*

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!

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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 $3\frac{3}{8}$ *(High of $73\frac{7}{8}$ 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

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Image Source: Internet

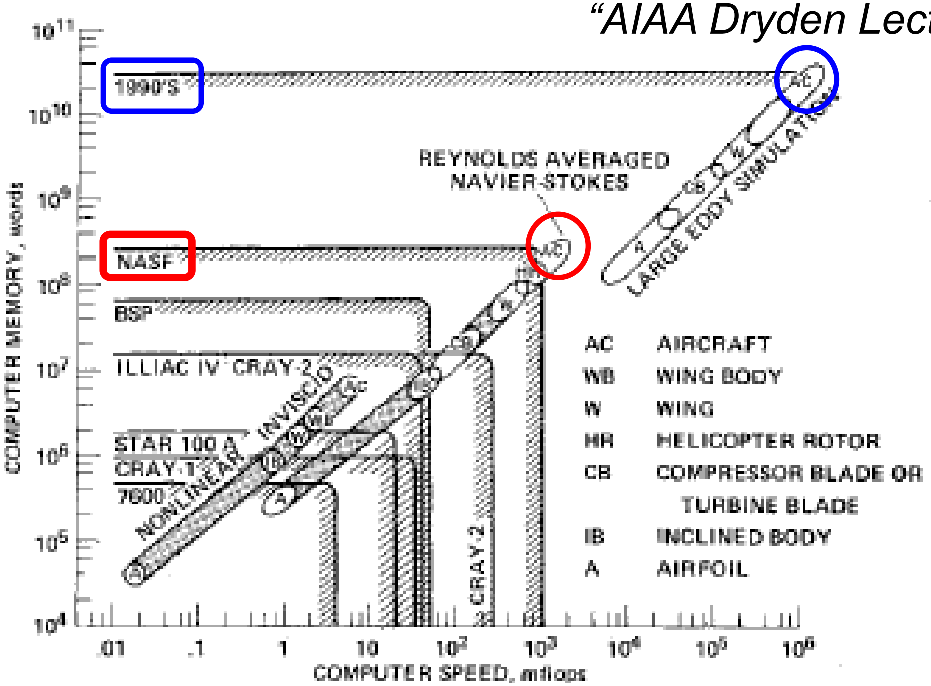
Computational Aerodynamics Outlook
At the End of the 1970s

Computational Aerodynamics Development and Outlook

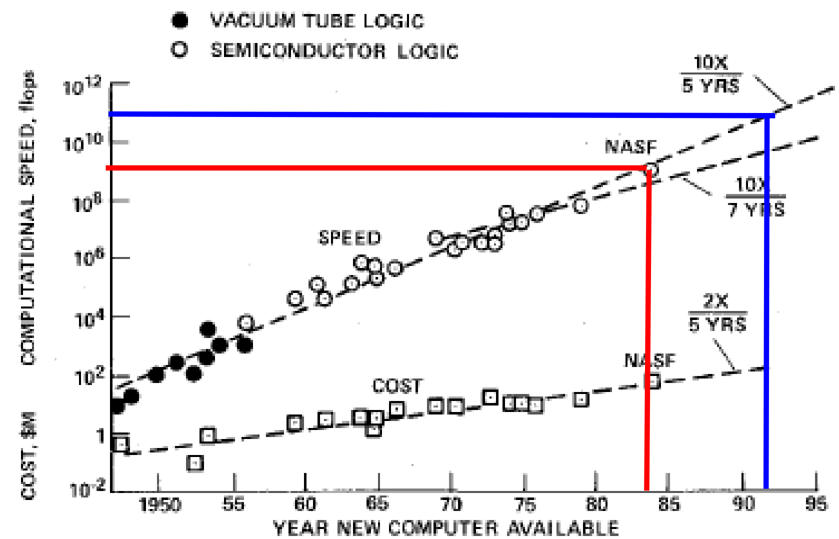
DEAN R. CHAPMAN, Director of Aeronautics,
NASA Ames Research Center, Moffett Field, California

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: <u>1-hour run using 1978 algorithms</u>



Outlook didn't quite pan out!

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

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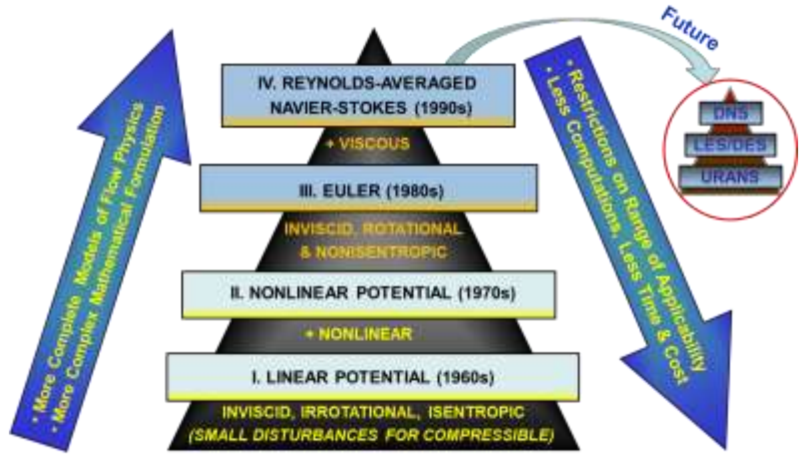
Source: Ref. 5.1.53 & 5.1.54

Section 5.1: Key Takeaways (1 of 2)

- **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, and and aerodynamic design process integration
- **Meeting Transonic Aircraft Design Needs in 1960s--LPMs woefully inadequate**
  - EFD enables peaky airfoils; Area Rule and Supercritical airfoils
- **Nonlinear Potential Methods (NPMs)**
  - Transonic Small Disturbance (TSD) and Full Potential Equation (FPE) Methods: *1970s*
  - *"Supersonic zone and shock waves appear naturally in the course of the solution."*

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Section 5.1: Key Takeaways (2 of 2)

- **1970s: Implications of Neglecting Viscosity in LPMs & NPMs Addressed**
  - Simulation of viscous effects
    - ✓ *Inviscid Potential Flow methods*: Viscous-Inviscid Interaction
      - Direct addition of boundary-layer displacement thickness
      - Transpiration boundary condition
    - ✓ *RANS methods*
      - Active area of research—algorithm development and mostly 2-D applications
      - *"…youthful stage of development"*
  - Phenomenal advancements in digital computers
    - ✓ 10x the speed every 5 years at only 2X the cost!
- **Mid-1970s: "*Adolescent Years with Irrational Exuberance" for CFD***
  - "To displace wind tunnels as the principal source of flow simulations for aircraft design… the required computer capability would be available in the mid-1980s." "…within a decade computers should begin to *supplant* wind tunnels in the aerodynamic design and testing…"
- **Late 1970s: Author got great opportunities to work with CFD pioneers who were excellent mentors; and then joined the ranks of budding "CFDers"**
- **1979: My *'First Day on the Job'* at Lockheed**
  - Computational analysis and design of configurations in transonic flows
  - *"It's about serving the most pressing need of your employer, not about what one might or might not want to do"*
  - *"Your ability to learn, and not just what you know, is a key differentiator"*
- **CFD Outlook at the End of the Seventies**
  - Full aircraft steady simulation in one hour in the 1990s using LES and 1978 algorithms!

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Contents

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ACA Effectiveness Codified: *1980-81*

Unveiled by Luis Miranda in *AIAA 82-0018,* Jan 1982

(later published in 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."

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Source: Ref. 5.2.1

Effectivenss = quality x acceptance
is Broadly Applicable

"I've had to terminate or fire more people for being difficult to work with than being dumb."

Brian Krzanich
Intel CEO (May 2013–June 2018)

For Engineering Team Members

***Quality* Factors**: knowledge and skills

***Acceptance* Factors**: attitude and adaptability

Effectivenss isn't Just for ACA!

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Lockheed ACA 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)*
  - ***Modified Geometry Modeling****: Planform-conforming grid for tapered wings*
  - ***Faster Turnaround****: Multi-grid acceleration*
  - ***Simulation Realism****: Fuselage effects; Viscous effects (interactive boundary layer coupling)*
  - ***Wing Design****: Garabedian-McFadden supercritical wing design technique*
  - ***Documentation:*** *LR 29759; AIAA 83-0262; also Journal of Aircraft, 21(2), 1984*

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

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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 strong shocks and free-vortex flows**

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

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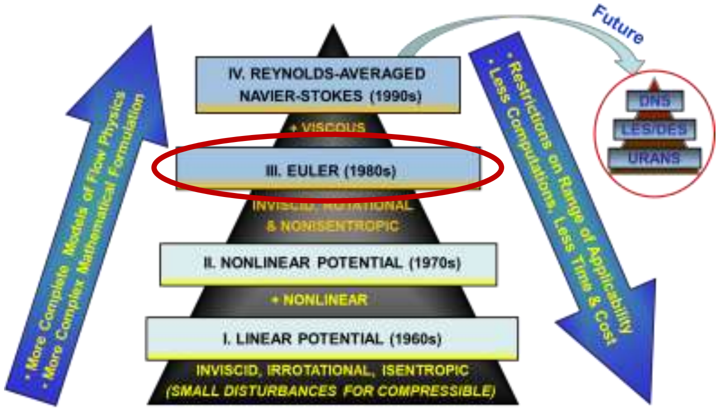
Level III
Euler Methods
1980s - present



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

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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

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Image Source: Internet

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

- **Rizzi and Eriksson (1981)**
  - *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*: 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)**
  - *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)**
  - Embedded mesh solutions on airfoils using a multiple-grid method—***AIAA Paper 83-1946***
- **Benek, Buning and Steger (1985)**
  - A 3-D Chimera grid embedding scheme [hexahedral grids]—***AIAA Paper 85-1523***
- **Löhner, Morgan, Peraire and Zienkiewicz (1985)**
  - Finite-element methods for high speed flows [tetrahedral grids]—***AIAA Paper 85-1531***
- **Jameson, Baker and Weatherill (1986)**
  - Inviscid Transonic Flow over a Complete Aircraft [hexahedral grids]—***AIAA Paper 86-0103***
- **Mavriplis (1988)**
  - Accurate multigrid solutions on unstructured and adaptive meshes—***NASA CR 181679***

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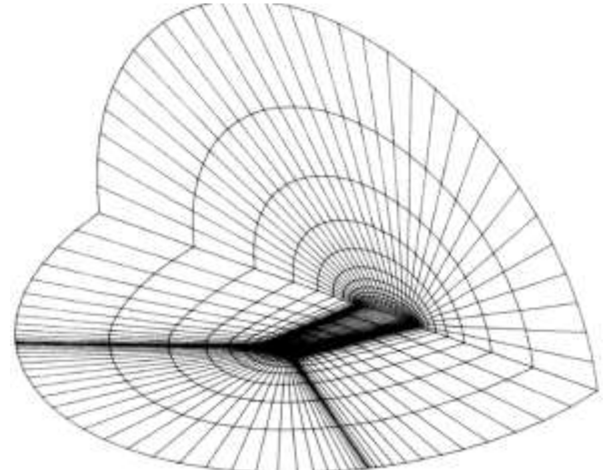
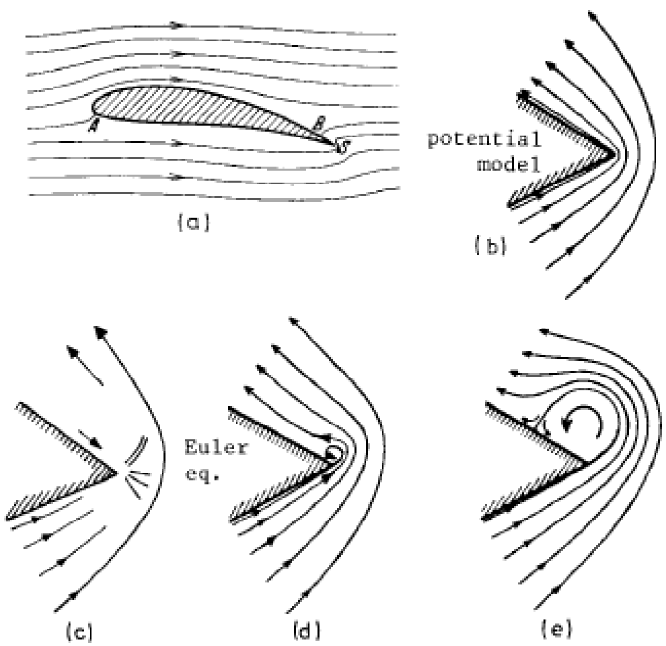
Source: Refs. 5.2.2 – 5.2.9

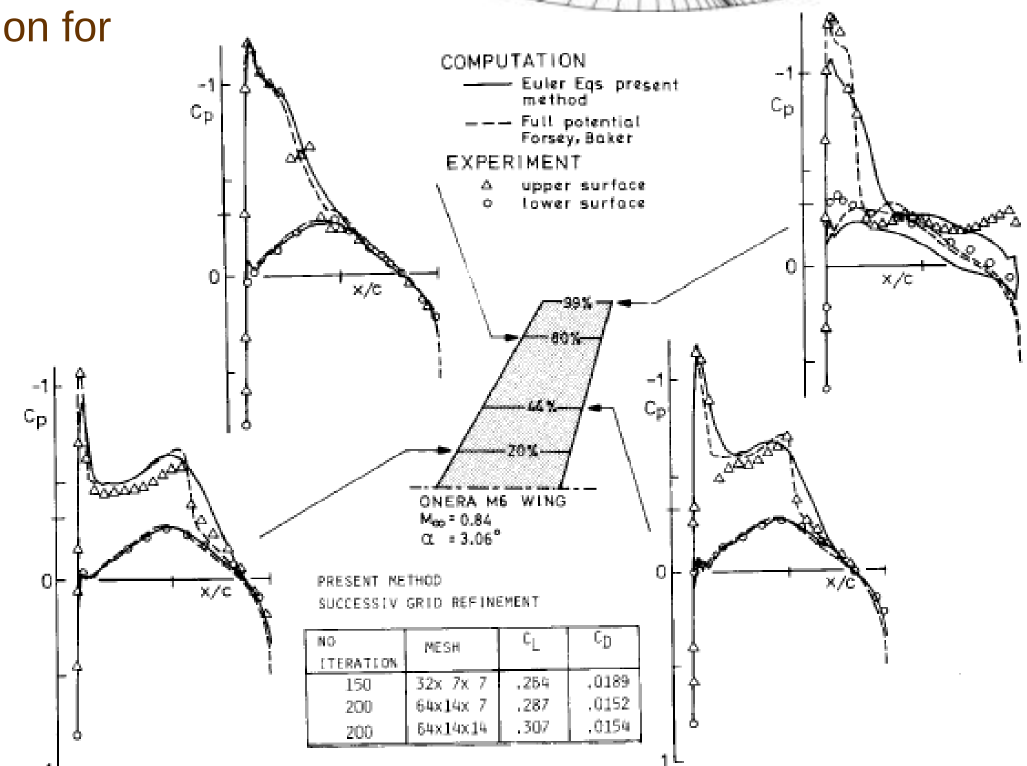
Pioneering Euler Solutions: *1981*

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







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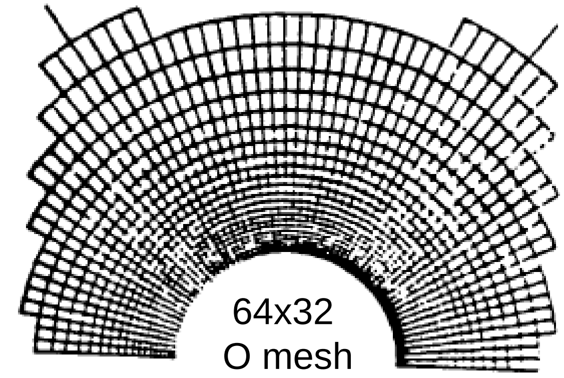
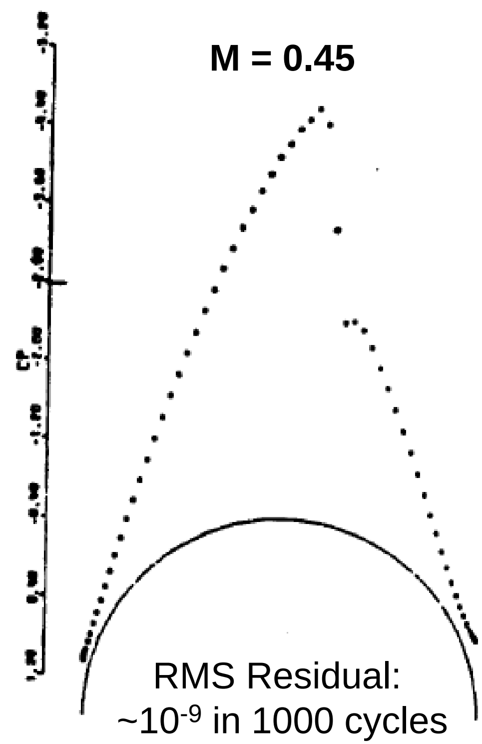
Source: Refs. 5.2.2

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 at the body 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 creates FLO-57 using *JST scheme* for 3-D swept wings soon after**

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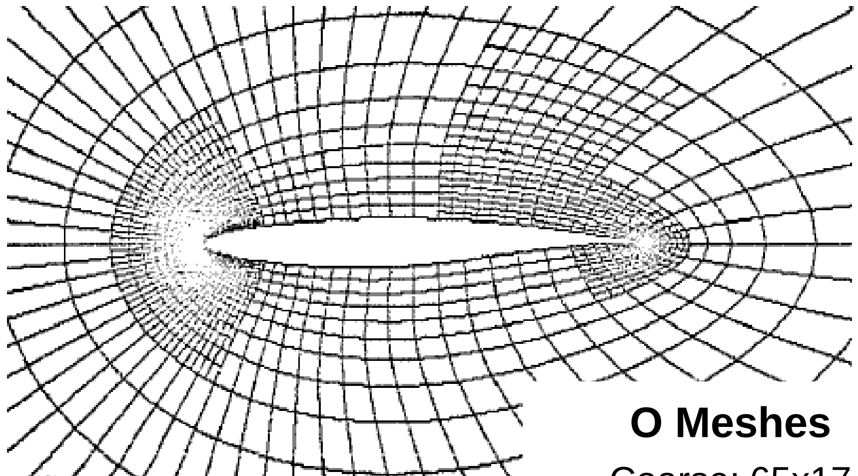
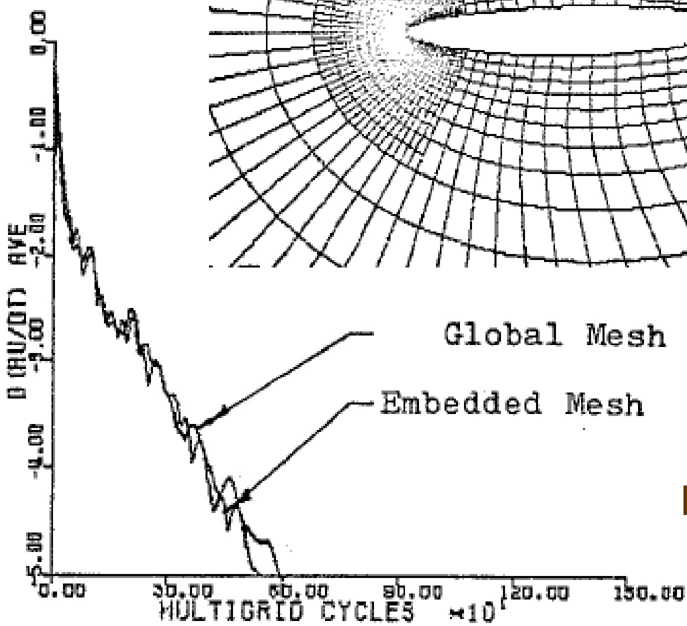
Source: Ref. 5.2.3

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

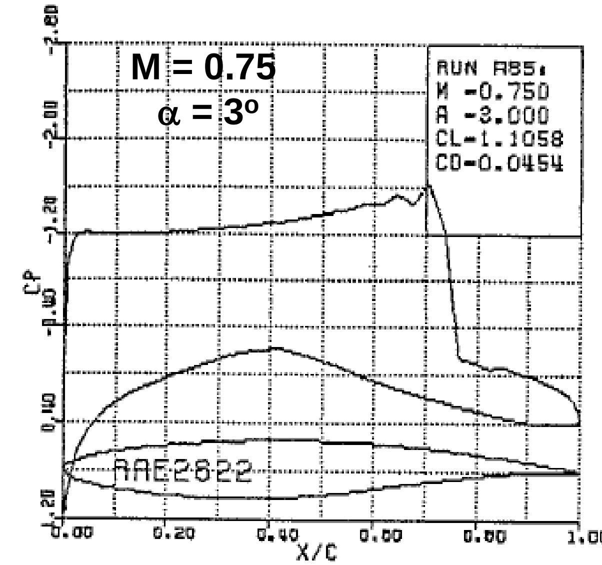


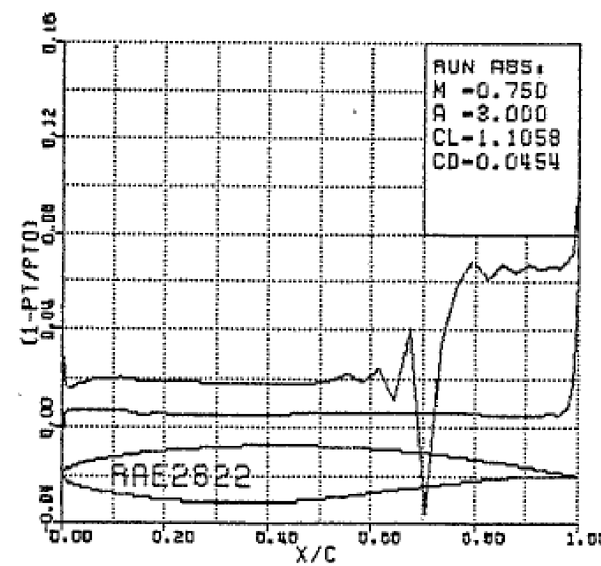


O Meshes

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***

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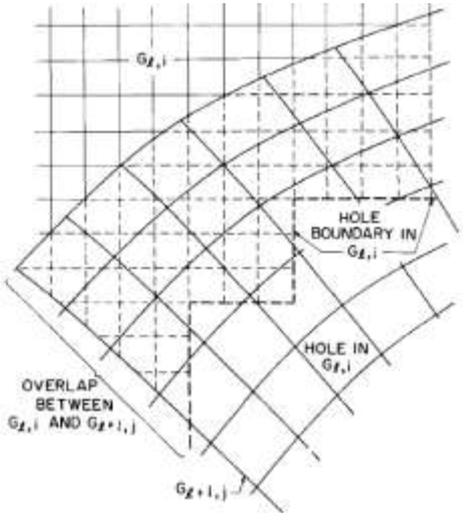
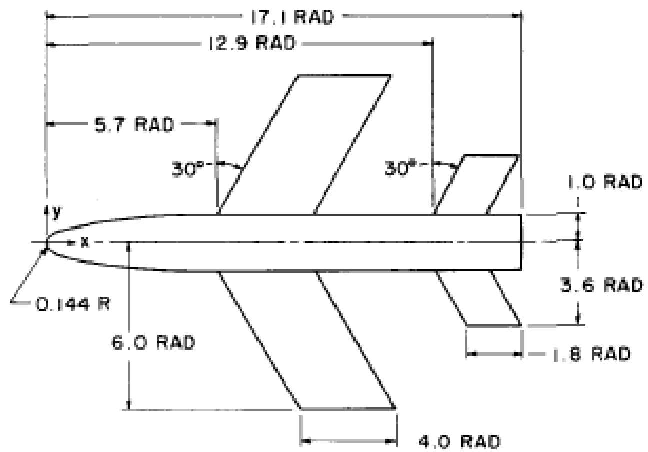
Source: Refs. 5.2.4 & 5.2.5

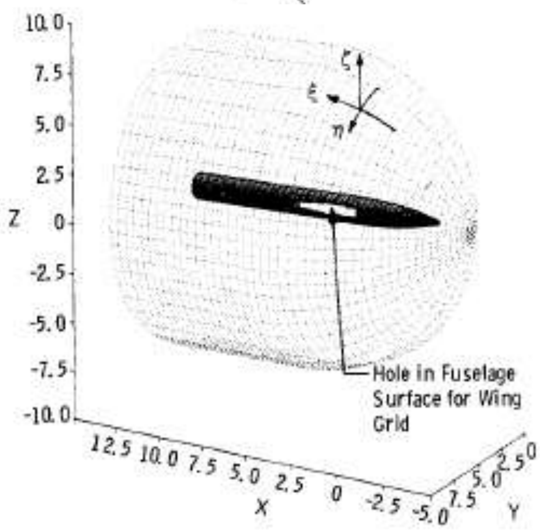
Overlapping Embedded Mesh Scheme for Complex Geometries: *1985*

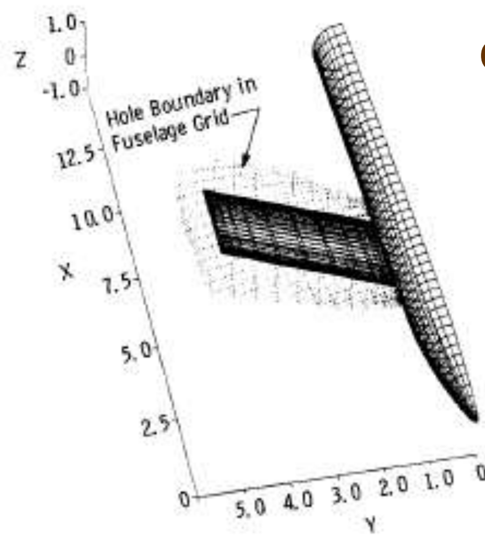
Benek, Buning and Steger (1985)

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





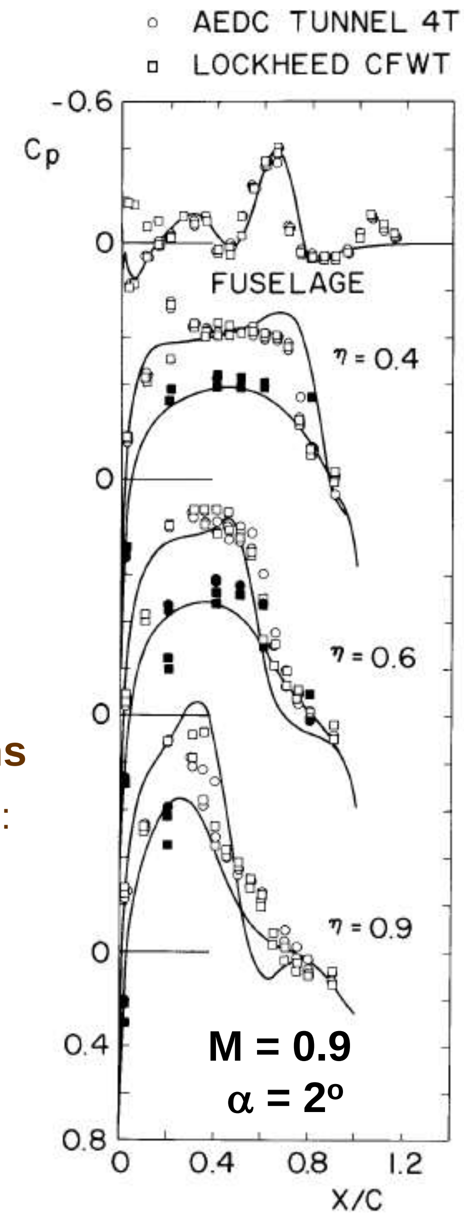




Wing/Body Computations

Fuselage Grid: 47x25x25

Wing Grid: 66x23x11



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Source: Ref. 5.2.6

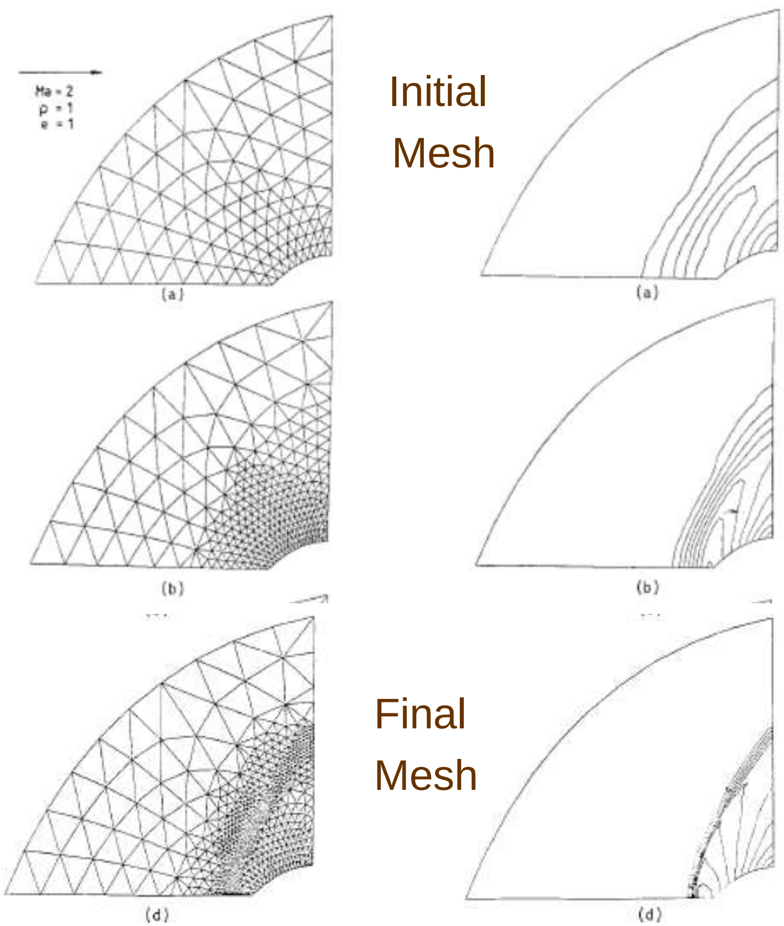
Unstructured-grid Euler Solvers: *1985*

Löhner, Morgan, Peraire and Zienkiewicz (1985)

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

Mach 2 Inviscid Steady Flow past a Simulated Nose Cone Section

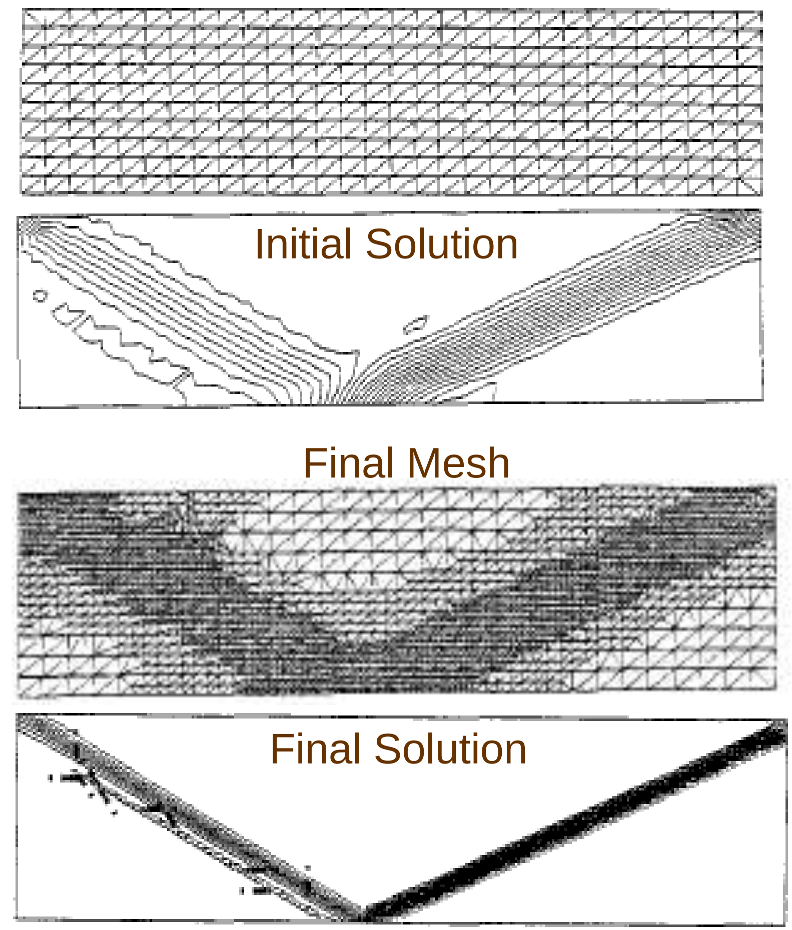
Adaptive Mesh Refinement



Inviscid Shock Reflection off Solid Wall

Adaptive Mesh Refinement

Initial Mesh



Source: Ref. 5.2.7

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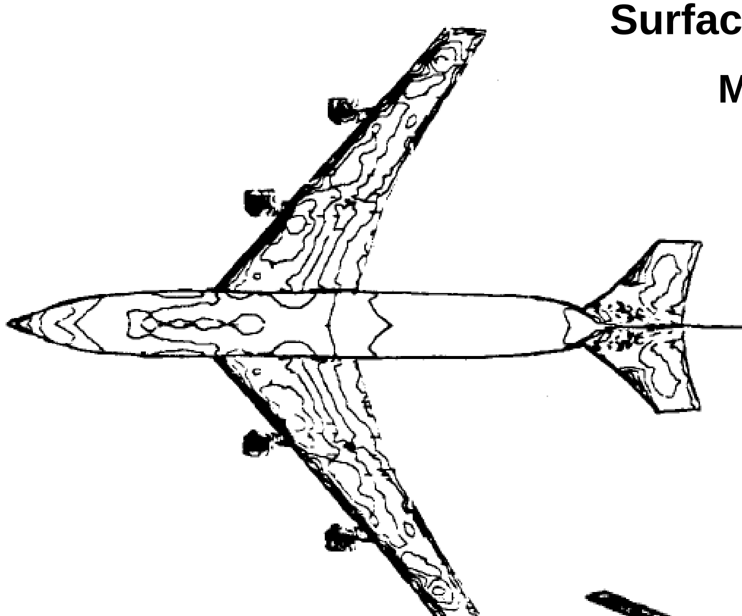
Complete Aircraft Euler Solution: *1986*

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

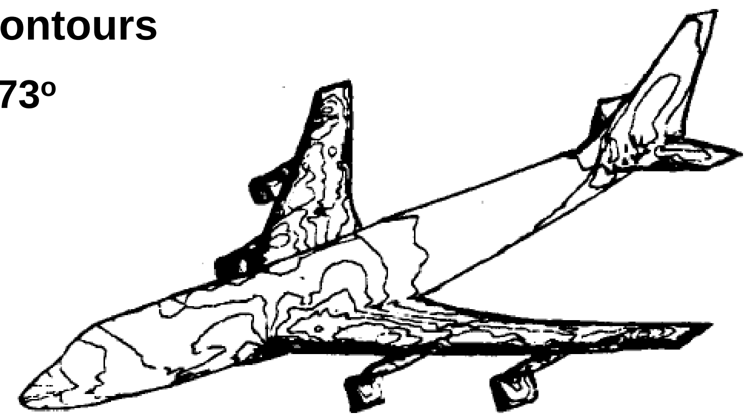
M = 0.84, α = 2.73º

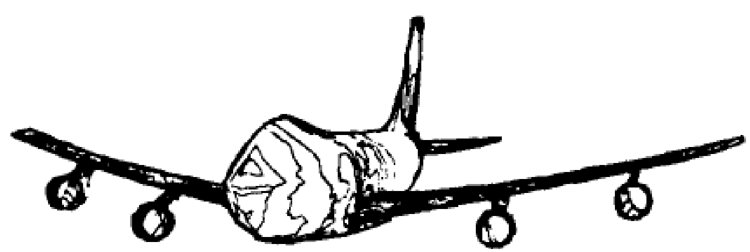


Tetrahedral Mesh

12038 Nodes

57914 Cells





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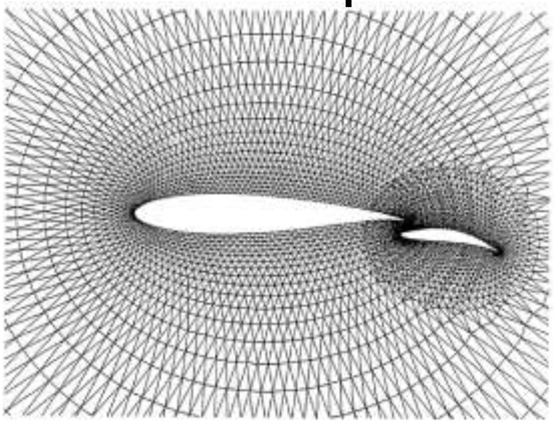
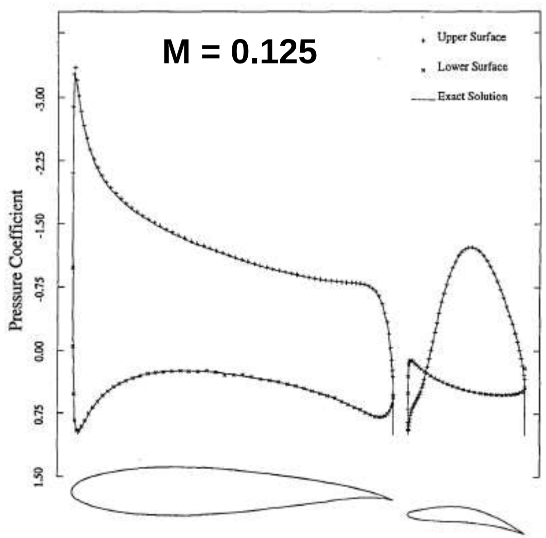
Accurate Euler Solutions on Unstructured Adaptive Meshes: *1988*

Mavriplis (1988)

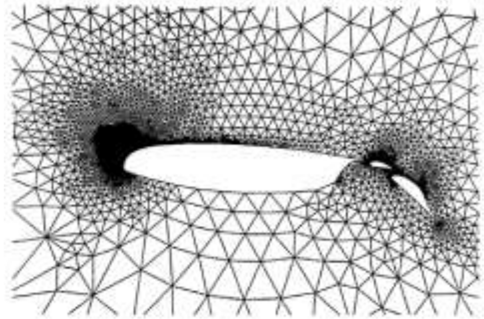
- Accurate multigrid solutions on unstructured and adaptive meshes—***NASA CR 181679***

Karman-Trefftz Airfoil and Flap

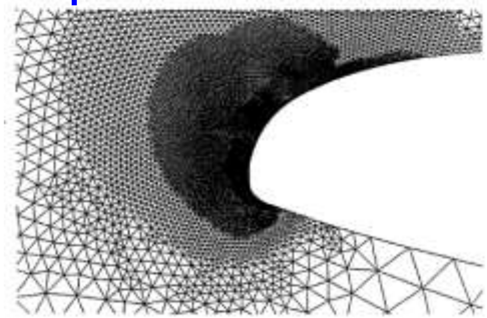




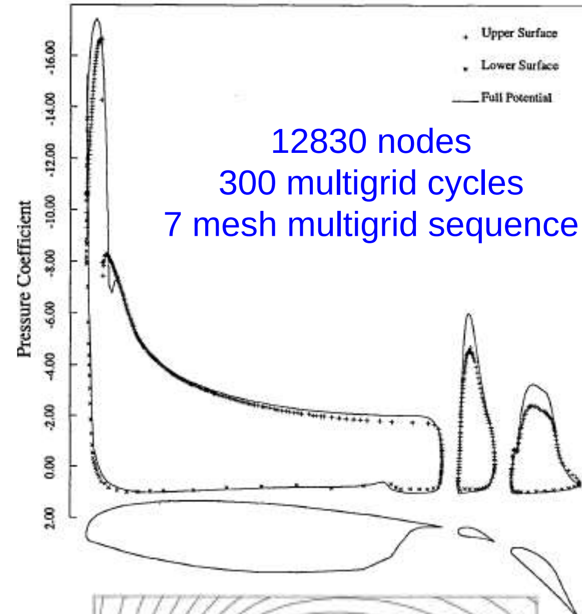
High-lift Three-element Airfoil



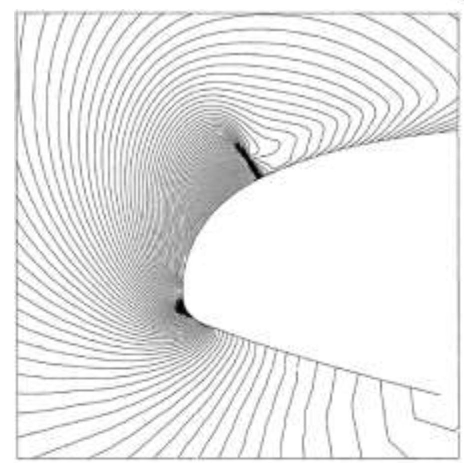
Adaptive Mesh Refinement



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

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

Lockheed Focus in the 1980s

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) contract 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

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Source: Refs. 5.2.10 – 5.2.15

USAF WRDC* Leads the Way

Towards Full Aircraft Computational Simulation Capability (1984)

Contract Requirements

- Aerodynamic analysis of fighter, transport, and flight research configurations with multiple lifting surfaces and flow-through or powered nacelles
- Symmetric or asymmetric flights at subsonic through hypersonic speeds for wide range of attitude angles
- Forces, moments, surface pressures, off-body pressures, velocities, etc.
- Validate code using 10 test cases

Lockheed Team

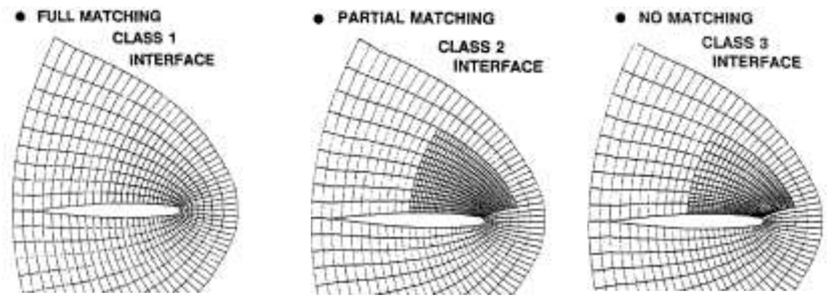
- Raj (Principal Investigator) with Brennan, Keen, Long, Mani, Olling, Sikora, and Singer contributing over five years under Miranda's leadership and supervision

USAF 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 TEAM Code

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

Source: Refs. 5.2.13 – 5.2.15

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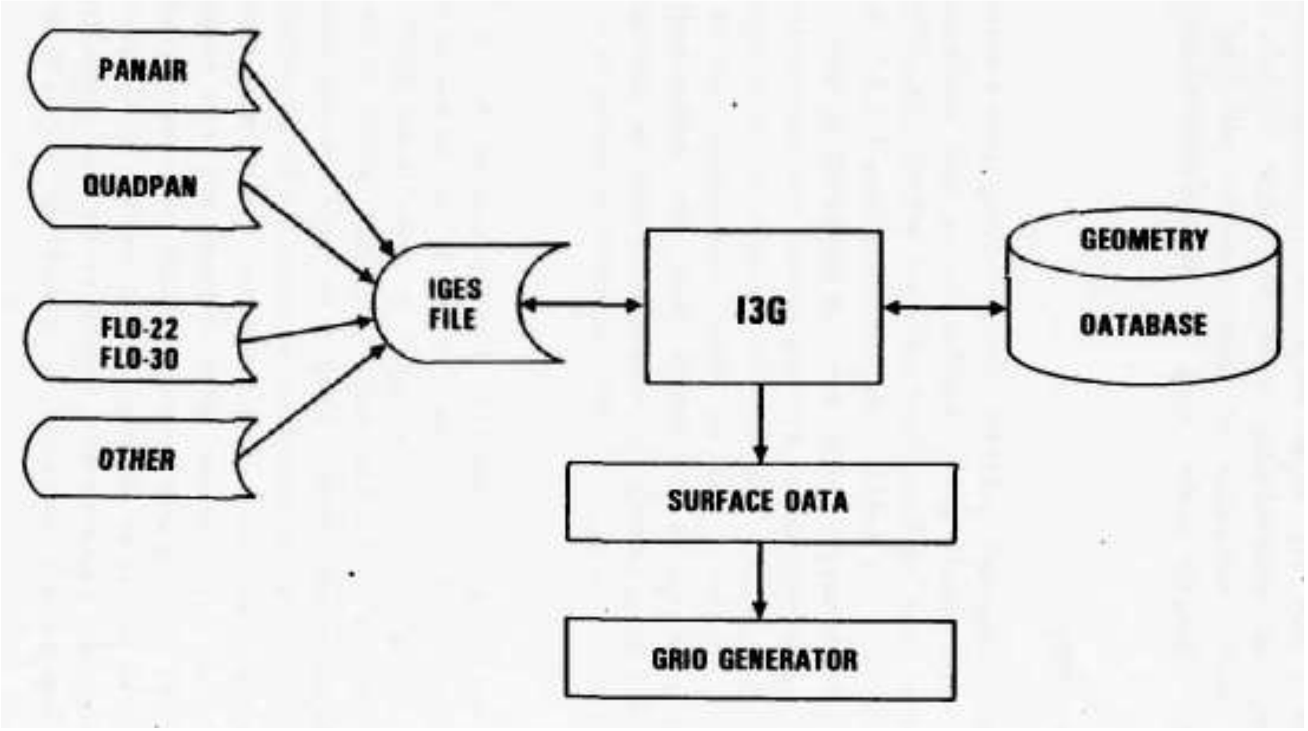
TEAM Preprocessor Module

- **Primary Function: *Construct Suitable Surface Geometry of the Configuration to be Analyzed***
  - Surface grid is the starting point of field grid generation
- **Scope**
  - Depends on the complexity of the configuration, and the field-grid generation method
- **Approach**
  - Use Interactive Graphical Geometry Generation (I3G) in CDMS (Configuration Data Management System)



Source: Ref. 5.2.13

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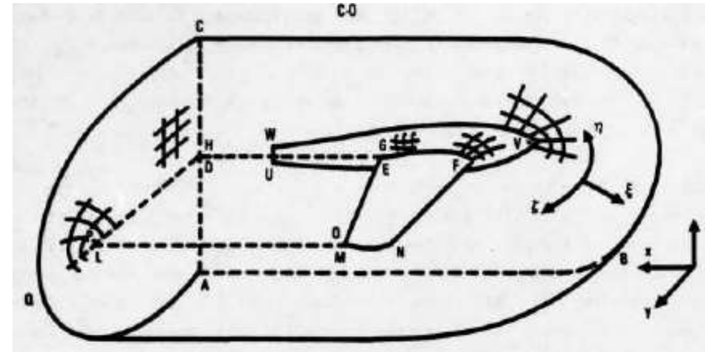
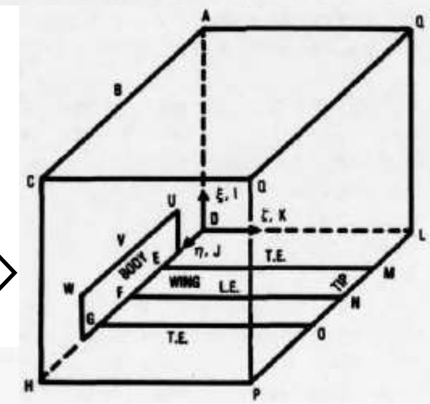
TEAM Grid Generation Module

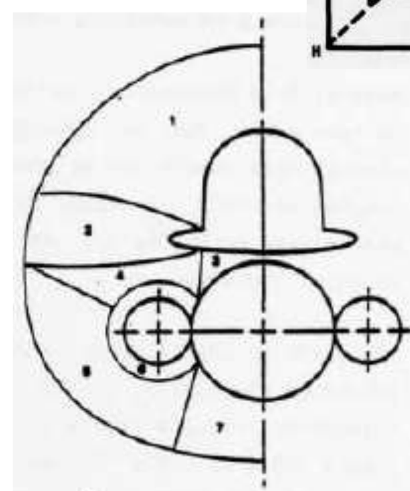
- **Primary Function: *Generate Suitable Structured Grids (Meshes) for Flow Analysis***
  - An ordered set of points at the intersection of coordinate lines in a curvilinear system defined by a mapping of physical domain in Cartesian system to a rectangular box
  - Hexahedral cells in 3D and quadrilateral in 2D
- **TEAM flow solver does *not* require functional description of curvilinear system, only the nodal point coordinates in the physical domain**
  - Both domains must be right handed systems
  - Grids must be boundary conforming, i.e., boundaries of physical domain should map to coordinate surfaces in Curvilinear domain
- **Desirable Grid Characteristics for TEAM Euler solver**
  - Grid lines emanating from the configuration surface should be nearly normal to it
  - Grid lines of same family should not cross each other
  - Grid points should be distributed in a manner conducive to minimizing truncation error
  - Abrupt changes in grid spacing should be avoided
  - Zonal interfaces between grids of different densities should be away from critical flow regions
  - Grid topologies that provide optimum resolution of flow features with minimum number of grid points are preferable



Physical domain

Mapped domain





Zonal interfaces of a patched multi-zone grid

Source: Ref. 5.2.13 & 5.2.14

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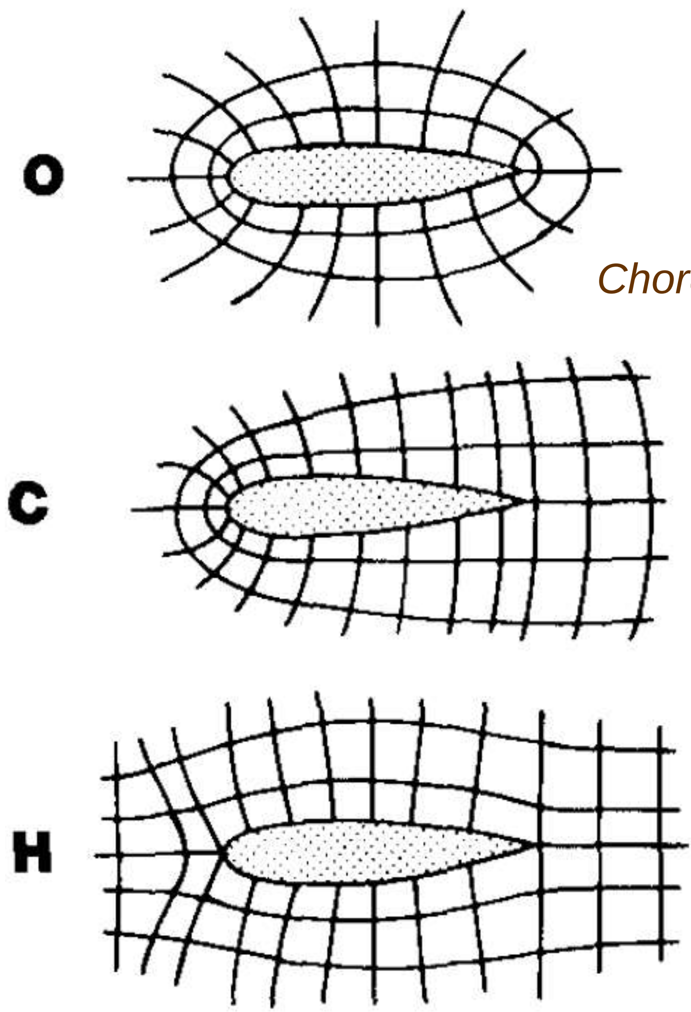
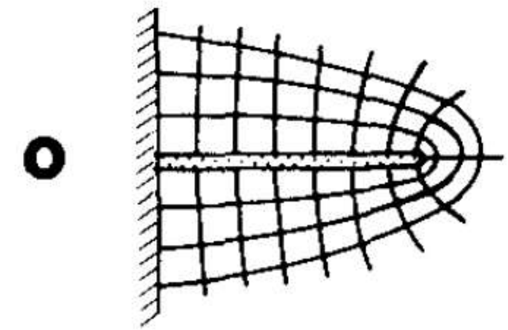
TEAM Structured Grid Topologies

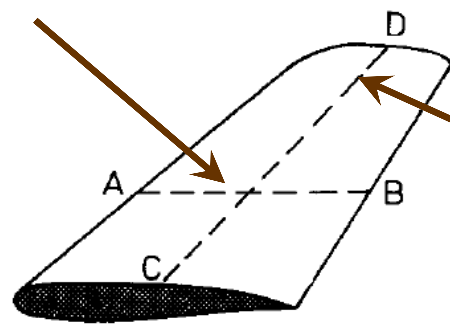
- **Structured Grids consist of an ordered set of quadrilateral (2D) or hexahedral (3D) cells**
- **Cells formed by the intersection of curvilinear coordinate surfaces**



O-O topology: most efficient

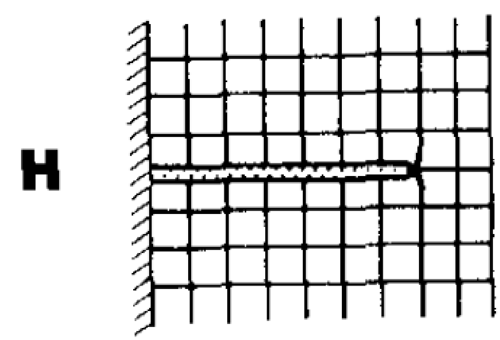


Chordwise Section: AB



Spanwise Section: CD

H-H topology: least efficient



Source: Ref. 5.2.14

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TEAM Grid Generation Module: 5 *Codes*

Codes	***PACMAPS II***	***HYPERGRID***	***BIG***	***TFI3D***	***EAGLE***
Formulation	Parabolic and Conformal Mapping	Hyperbolic PDE	Boundary Integral Grid Generation	Trans-finite Interpolation (Algebraic)	Elliptic PDE
Quality Factors	• Wing & Wing-Body • C-H grids only • Limited grid spacing control • No outer boundary control	• Wing & Wing-Body • Surface grid determines field grid topology • Orthogonal grid lines • Grid spacing control • No outer boundary control	• Wing; Wing-Body; and Wing-Body Tail/Canard • O-O or C-O grids • Orthogonal grid lines • No explicit grid spacing control • No outer boundary control	• Full Aircraft • Explicit grid spacing control • Well-suited for multi-block grids	• Full Aircraft • Grid spacing control
Acceptance Factors	• Automated • Fast and easy to use • Simple input: cross-sections only	• Automated • Only surface grid input • Sensitive to initial data	• Automated but compute-intensive • Easy to use • Only surface grid input	• Extensive user interaction	• Automated but compute-intensive • Needs user interaction

Varying Degrees of Effectiveness–None Satisfactory for Full Aircraft Grid Generation

Source: Ref. 5.2.14

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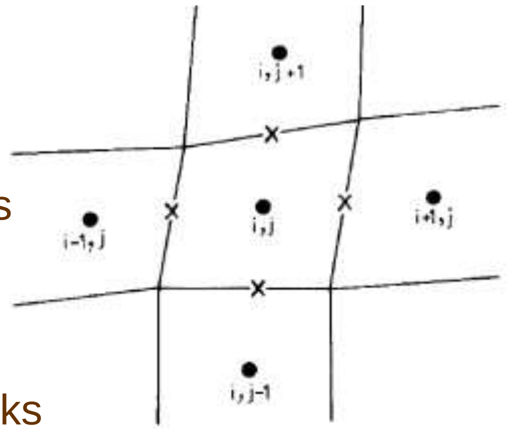
TEAM Flow Solver Module

- **Primary Function: *Solve Time-dependent, Integral Form of Euler (and RANS) Equations***
  - Based on Jameson's finite-volume formulation in FLO-57
- **Cell-centered Spatial Discretization**
  - Flow variables defined at cell centers, fluxes computed at faces
  - Central-difference scheme with 2nd order accuracy on smooth grids
  - Numerical dissipation terms added to (i) suppress odd-even decoupling; (ii) prevent instability; and (iii) cleanly capture shocks
    - Adaptive Dissipation Models
      - ✓ *Standard Adaptive Dissipation:* JST scheme, a blend of 2nd and 4th differences each scaled by user-specified factors; 2nd differences also scaled by normalized magnitude of the 2nd difference of static pressures
      - ✓ *Modified Adaptive Dissipation:* replaced user-specified factor for 2nd differences in each parametric direction by corresponding spectral radii, and bounded to produce locally Total Variation Diminishing (TVD) scheme
      - ✓ *Flux-limited Adaptive Dissipation:* non-oscillatory shock capture (Jameson, MAE Report 1653)
    - Characteristics-based Dissipation Model
      - ✓ Symmetric TVD provides appropriate upwind bias for supersonic and hypersonic flows
- **Multi-stage Time Stepping**
  - Local rather than global minimum time step (pseudo time) for computationally efficient convergence to steady state
  - Enthalpy damping and implicit residual smoothing to further accelerate convergence rate



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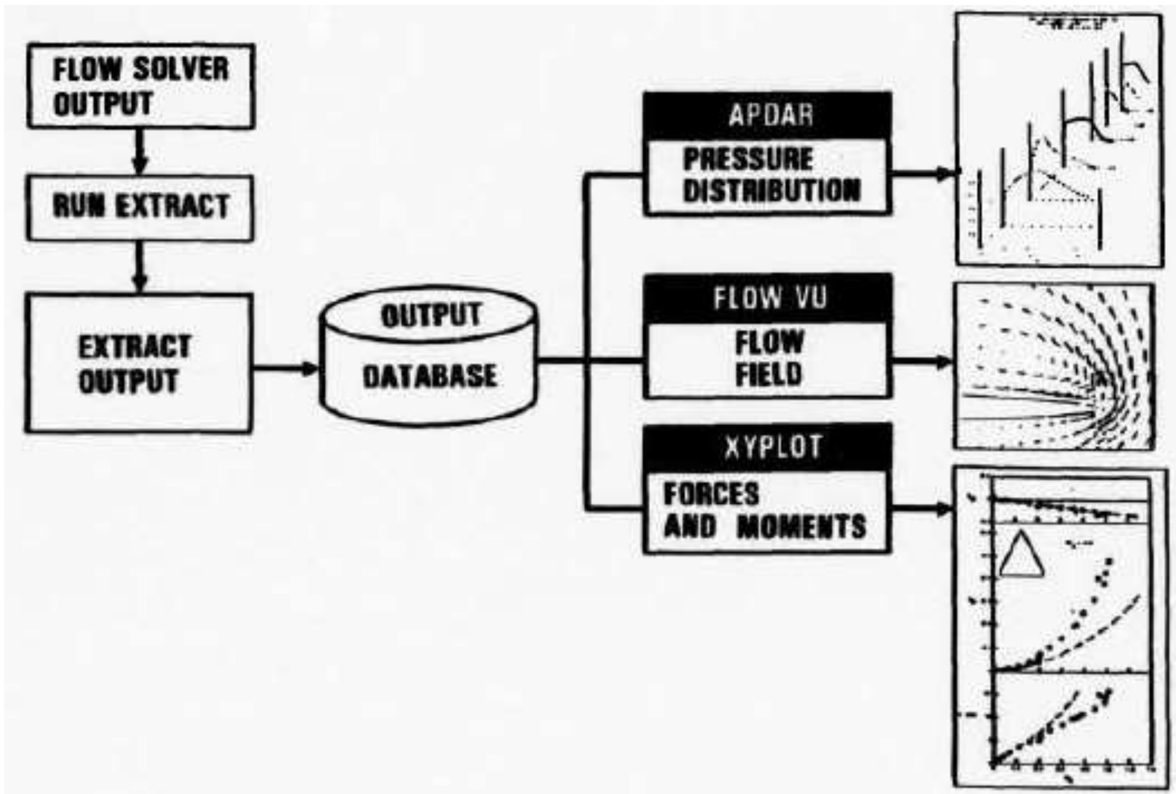
Source: Ref. 5.2.16

TEAM Postprocessor Module

- **Primary Function: *Extract Meaningful Aerodynamic Data from Flow Solver Output Files***
- **Scope**
  - Forces and moments, surface pressure distributions, velocity fields, etc.
  - Display data in graphical form, such as charts, contour plots, etc.
- **Approach**
  - Use CDMS (Configuration Data Management System) capabilities



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Source: Ref. 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*

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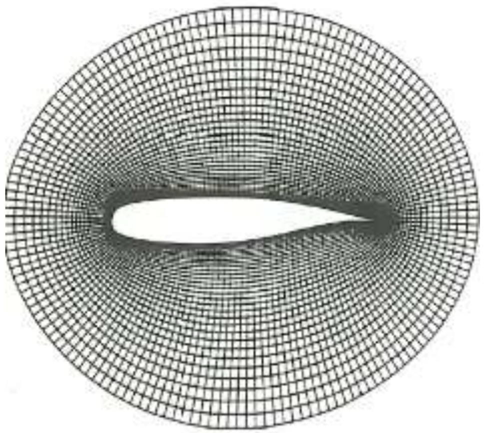
TEAM (Euler) Validation
NLR 7301 Airfoil – *Transonic Flow (2D)*

Comparison with exact shock-free hodograph solution

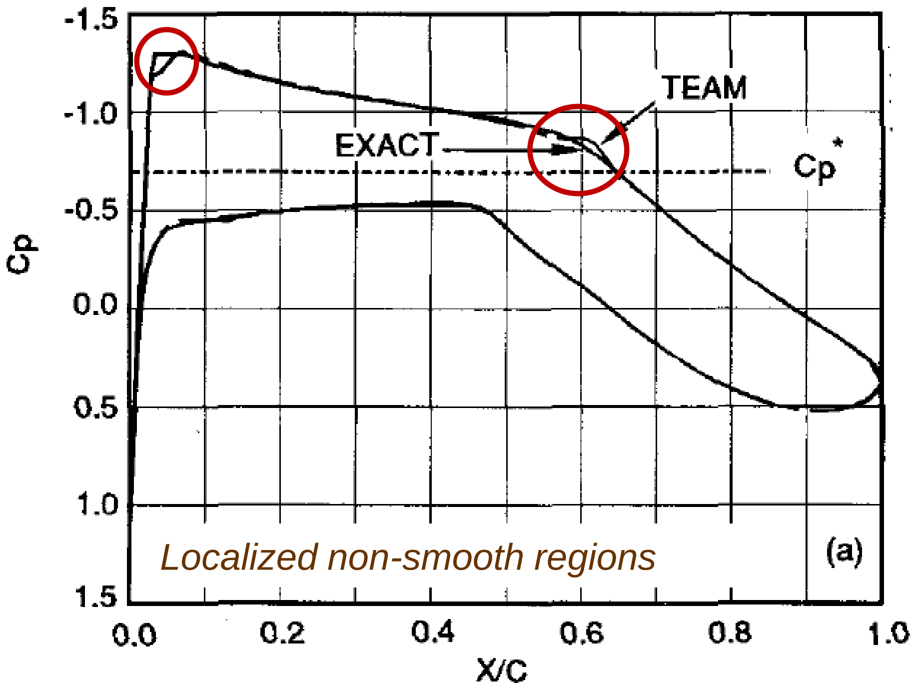
$M_\infty = 0.721, \ \alpha = -0.194^o$



321 x 321 O Grid

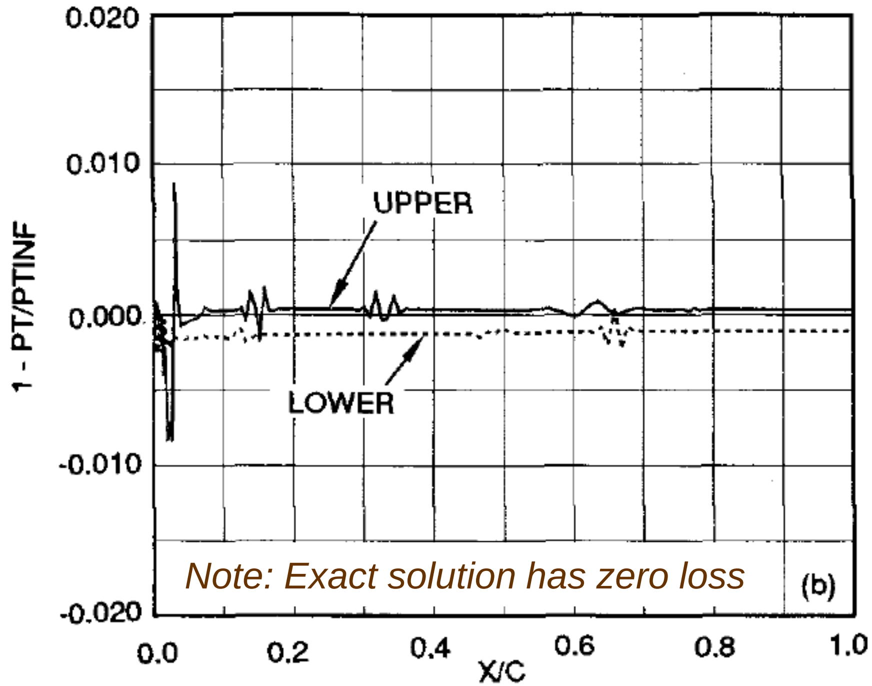
(Far-field boundary 80 chords away)

Surface pressure distribution



Localized non-smooth regions

Surface total pressure loss distribution



Note: Exact solution has zero loss

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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 that was defined by a discrete set of points
  - Computed solutions exhibit "wiggle" in transition from supersonic to subsonic flow
    - amplitude *increases* as grid points in circumferential direction increase from 161 to 241 to 321 for 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" 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 ⇨	49 x 321	81 x 321	161 x 321	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

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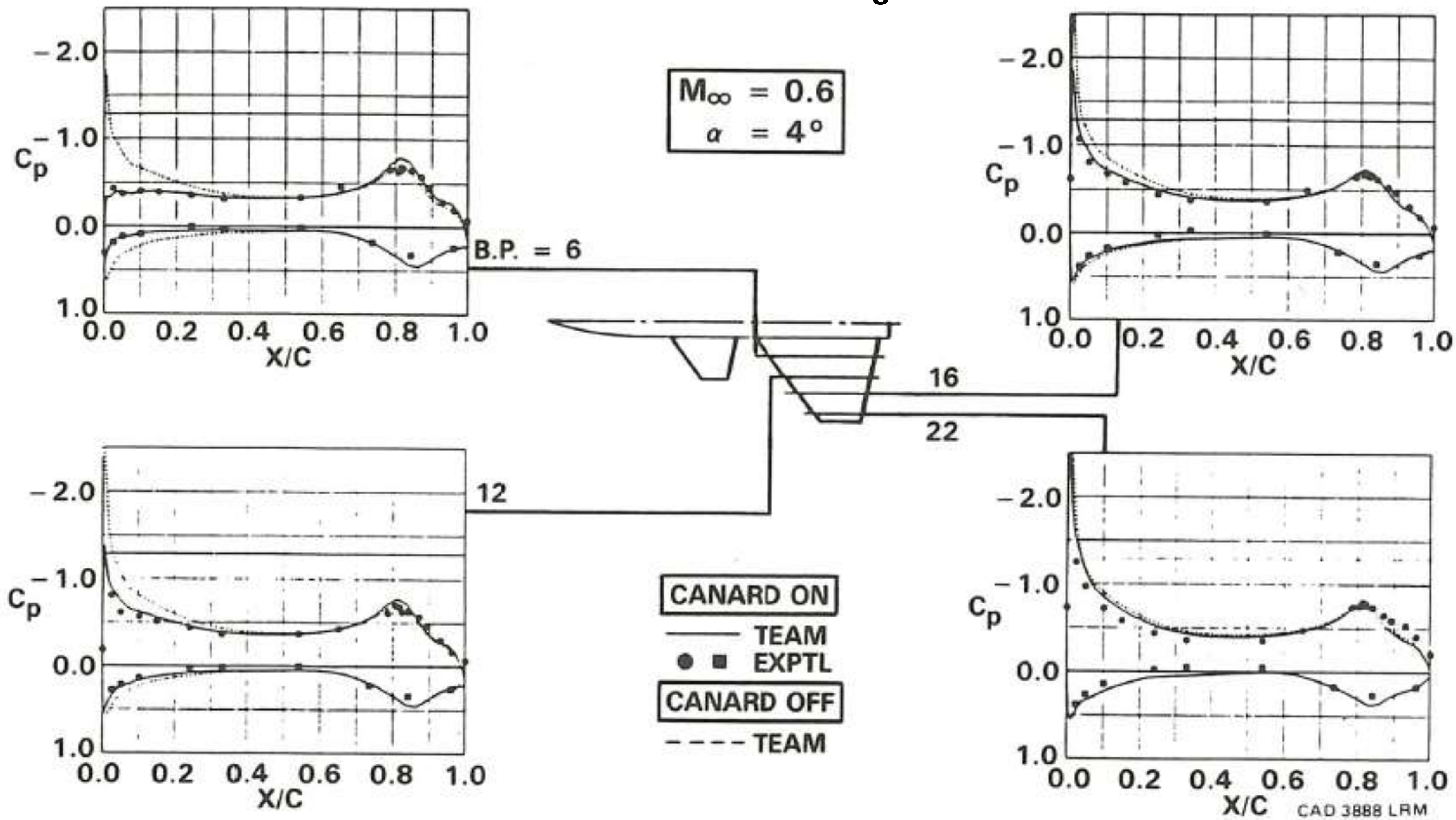
Team (Euler) Validation

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

Canard-Wing Interaction Effect

168 x 84 x 34 H-H grid



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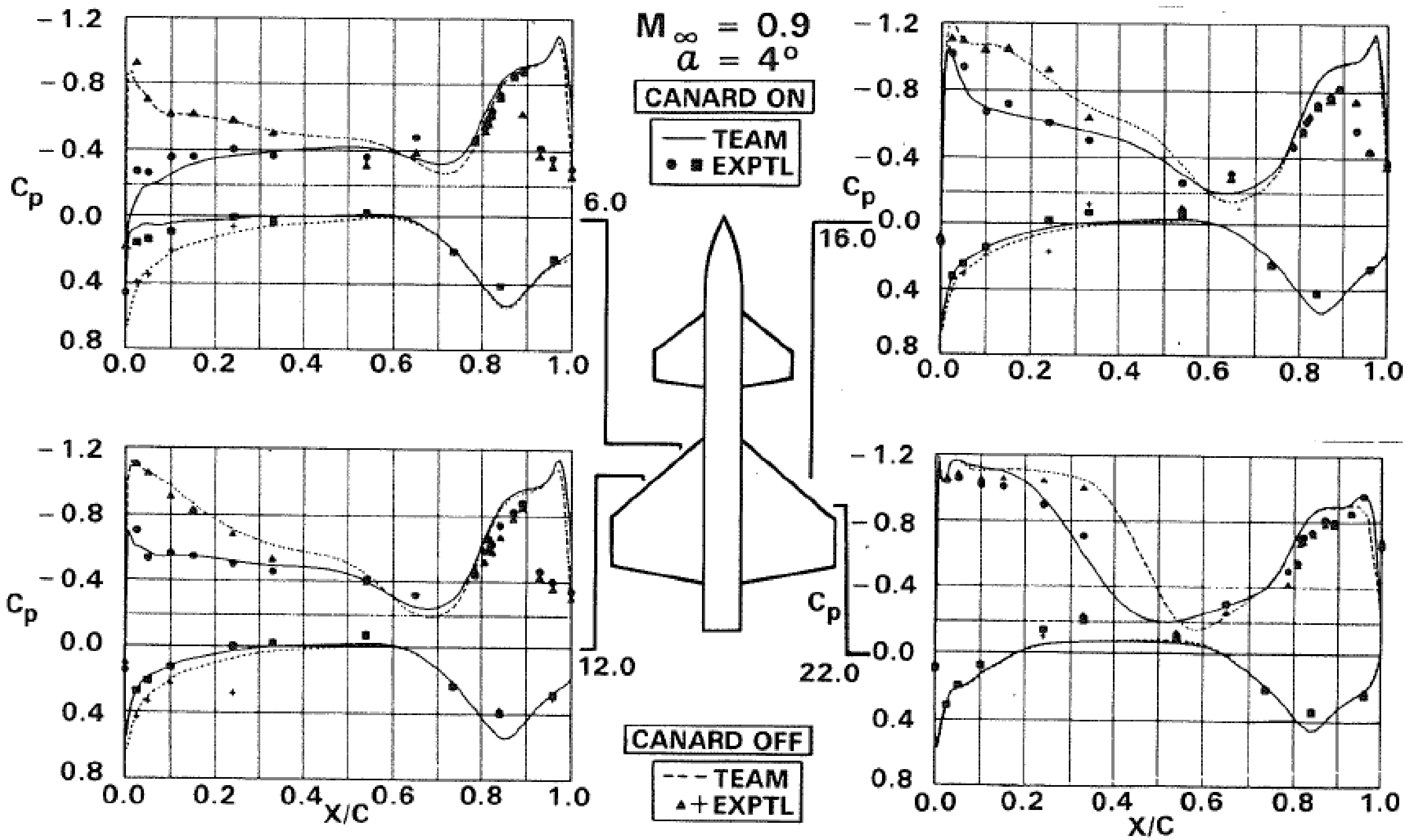
Source: Ref. 5.2.13 & 5.2.16

Team (Euler) Validation

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

Canard-Wing Interaction Effect

168 x 84 x 34 H-H grid



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Source: Ref. 5.2.13 & 5.2.16

TEAM (Euler) Validation

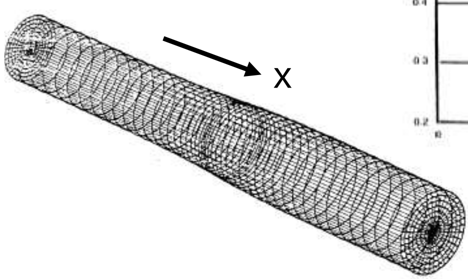
Internal Flow – Three Test Cases

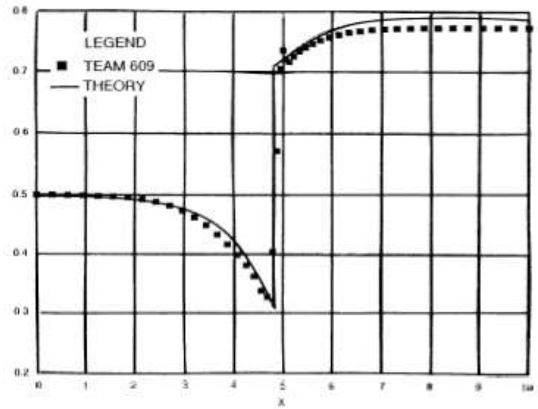
A. Axisymmetric Diverging Nozzle

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

Density

M_∞ = 1.26

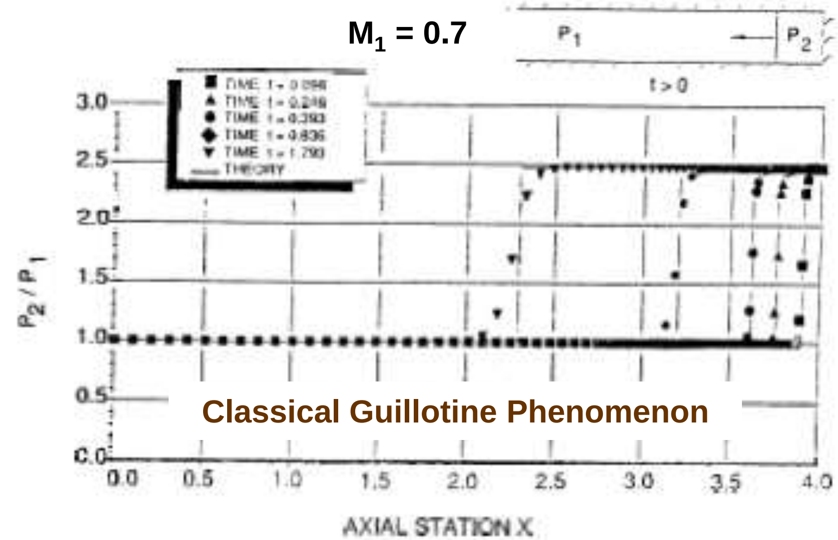




Axial Station X

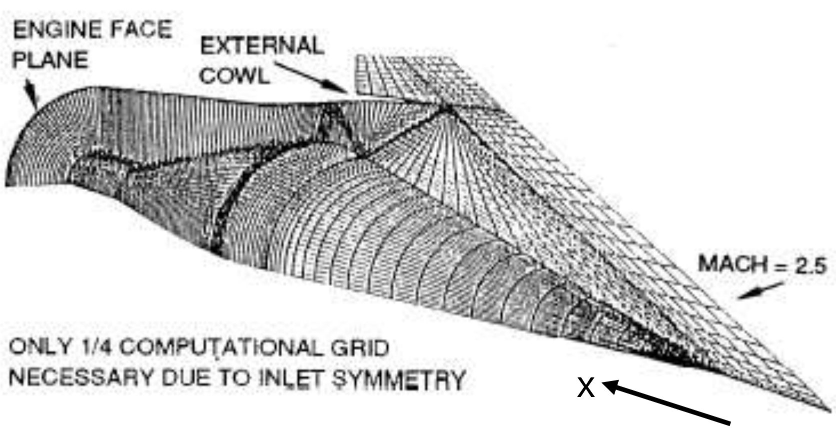
B. 1-D Inlet Duct Hammershock

M_1 = 0.7

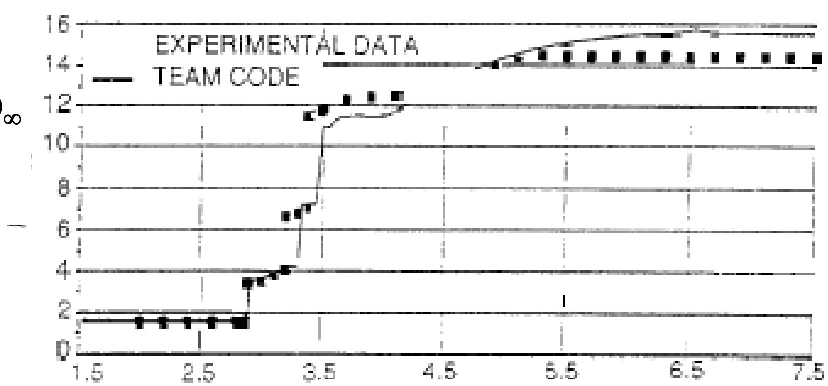


Classical Guillotine Phenomenon

C. External Compression Mach 2.5 Axisymmetric Inlet



p/p_∞



Axial Station x/h_{cowl}

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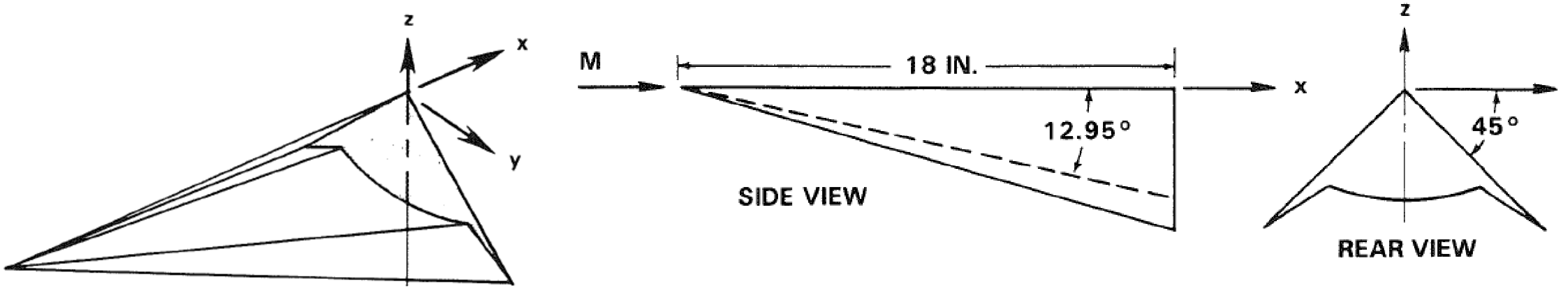
Source: Ref. 5.2.17

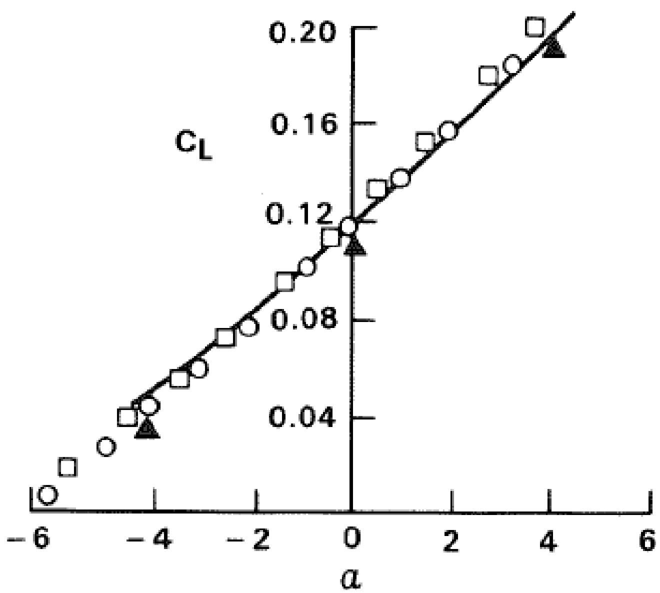
TEAM (Euler) Validation

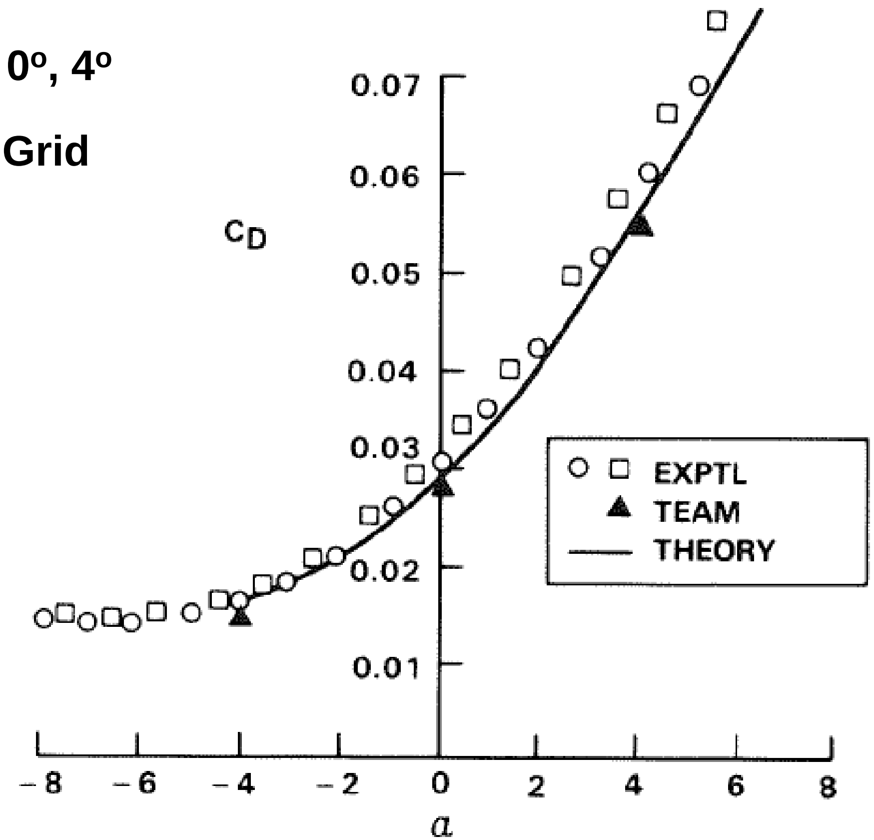
Cone-derived Mach 6 Waverider – *Hypersonic Flow*



$M_\infty = 6$, $\alpha = -4^o, 0^o, 4^o$

45 x 30 x 39 O-H Grid





Source: Ref. 5.2.13 & 5.2.16

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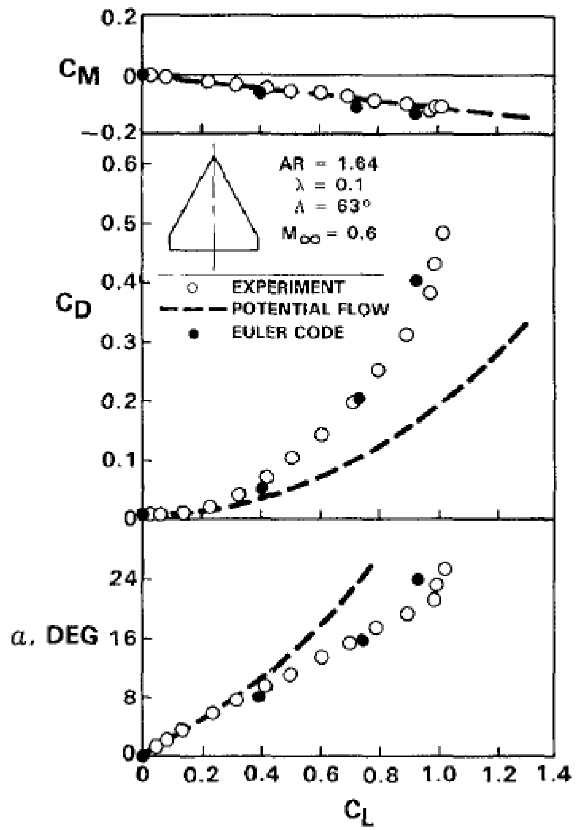
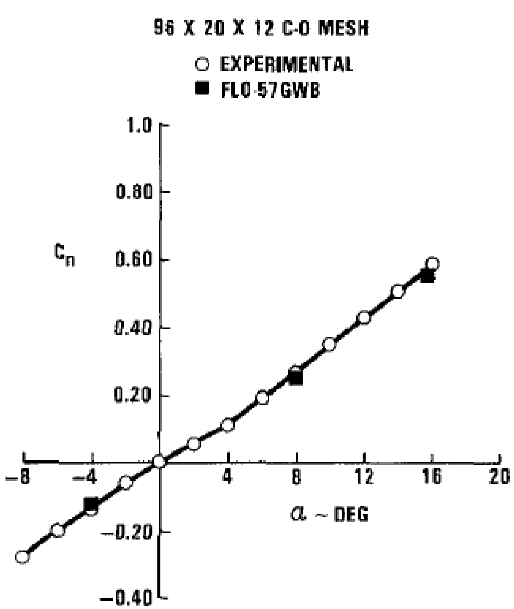
Free-vortex Flow Simulation Using Euler Codes

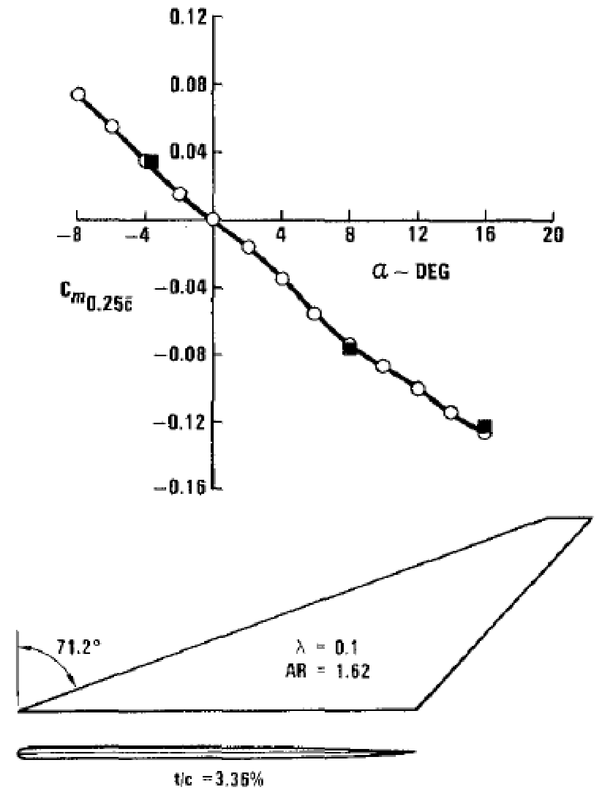
- **Eriksson and Rizzi (1981); Hitzel & Schmidt (1984); Murman & Rizzi (1986)**
  - Euler equation solutions on delta wing at 0.9 and 1.5 Mach numbers and $\alpha = 15^o$; free vortices captured automatically—*1981 IV GAMM Conference*
  - 1984: *Journal of Aircraft*, 21 (10); 1986: *AGARD Symposium*, Aux-Ed-Provence, France
- **Raj and Sikora (1984)—*Recent Encounters with an Euler Code** (FLO-57GWB)***

Sharp-edged cropped delta wing (M = 0.6)



Arrow wing (M = 0.85)





**inspired by Steven Spielberg's Close Encounters of the Third Kind—a 1977 American SciFi classic—he wrote and directed*

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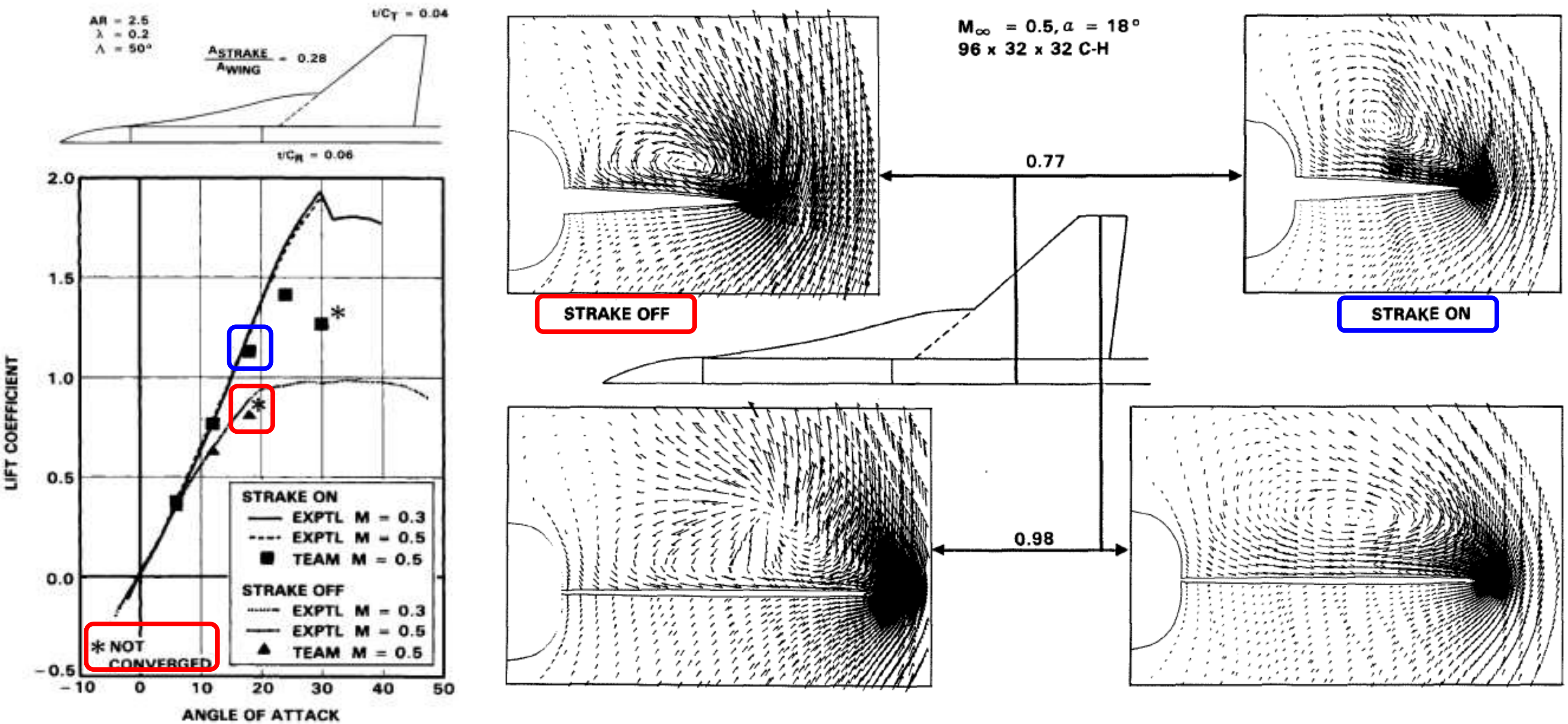
Source: Refs. 5.2.18 – 5.2.25

Team (Euler) Validation

Strake-Wing-Body Configuration – *Free-Vortex Flows*

- **Raj, Sikora and Keen (1986) -** ***ICAS 86-1.5.2***



"…generation of vortices about sharp-edged wings due to the total pressure losses is quite insensitive to the actual magnitude of numerical dissipation, *as long as there is some*."

Euler Codes More Effective Than The-then RANS Codes

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Source: Refs. 5.2.21

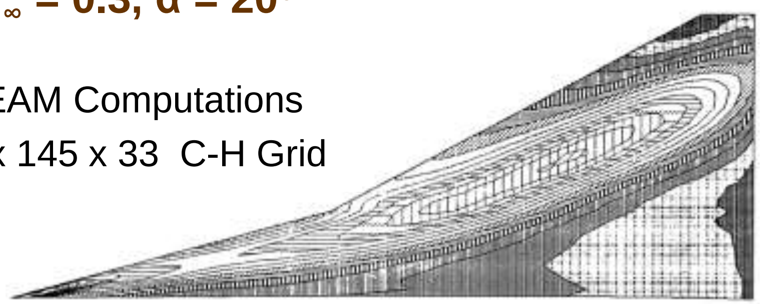
Team (Euler) Validation

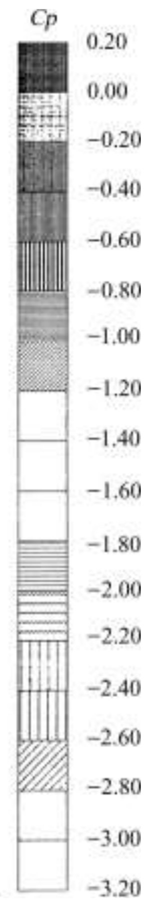
75º/62º Double-Delta Wing Body Configuration - *Free-Vortex Flows*

Raj, Keen, and Singer
AIAA paper 88-2517, 1988

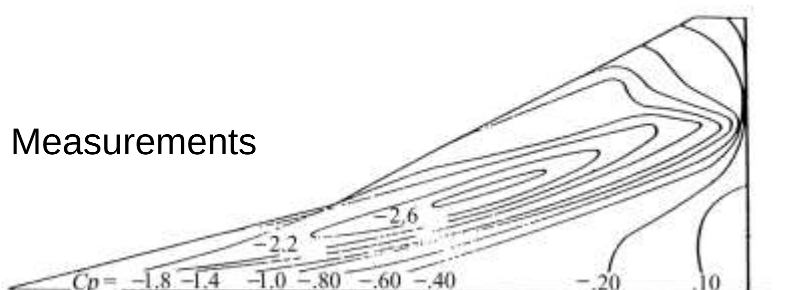
M_∞ = 0.3, α = 20º

TEAM Computations
49 x 145 x 33 C-H Grid





Measurements



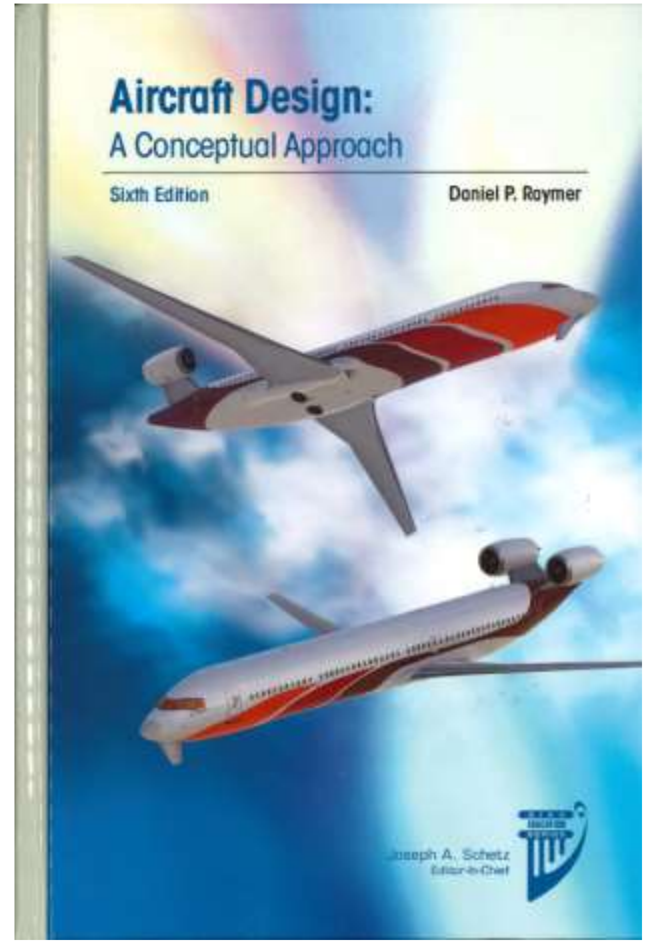


Fig. 12.42 (p 457)

"Recognition" by Aircraft Designer—Doesn't Get Better Than That!

Image Source: Ref. 5.2.23 and Internet

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TEAM Capabilities: *Evolution Summary*

	Configuration Geometry	*Grids*	*Free-stream Mach number*	*Flow Model*
1984	• Wing • Wing-Body	• Single Zone (Block) • C-H, C-O, O-O topologies	Subsonic Transonic Supersonic	Inviscid (Euler)
1986	• Wing • Wing-Body • Wing-Body-Tail/Canard	• Single Zone (Block) • C-H, C-O, O-O • O-H, H-H topologies added	Subsonic Transonic Supersonic	Inviscid (Euler)
1988	• Wing • Wing-Body • Wing-Body-Tail/Canard • Full Aircraft with Inlet and Exhaust Systems	• Single Zone (Block) • Patched Multi-Zone (Multi-Block) • C-H, C-O, O-O, O-H, and H-H topologies	Subsonic Transonic Supersonic Hypersonic	• Inviscid (Euler) • Viscous (RANS with just Baldwin-Lomax Turbulence Model) • Equilibrium Real Gas

USAF/WRDC/Lockheed TEAM Code Offers Full Aircraft Aerodynamic Analysis Capability in 1988 for ATF (Inviscid Euler Much More Effective than Viscous RANS)

Source: Ref. 5.2.13

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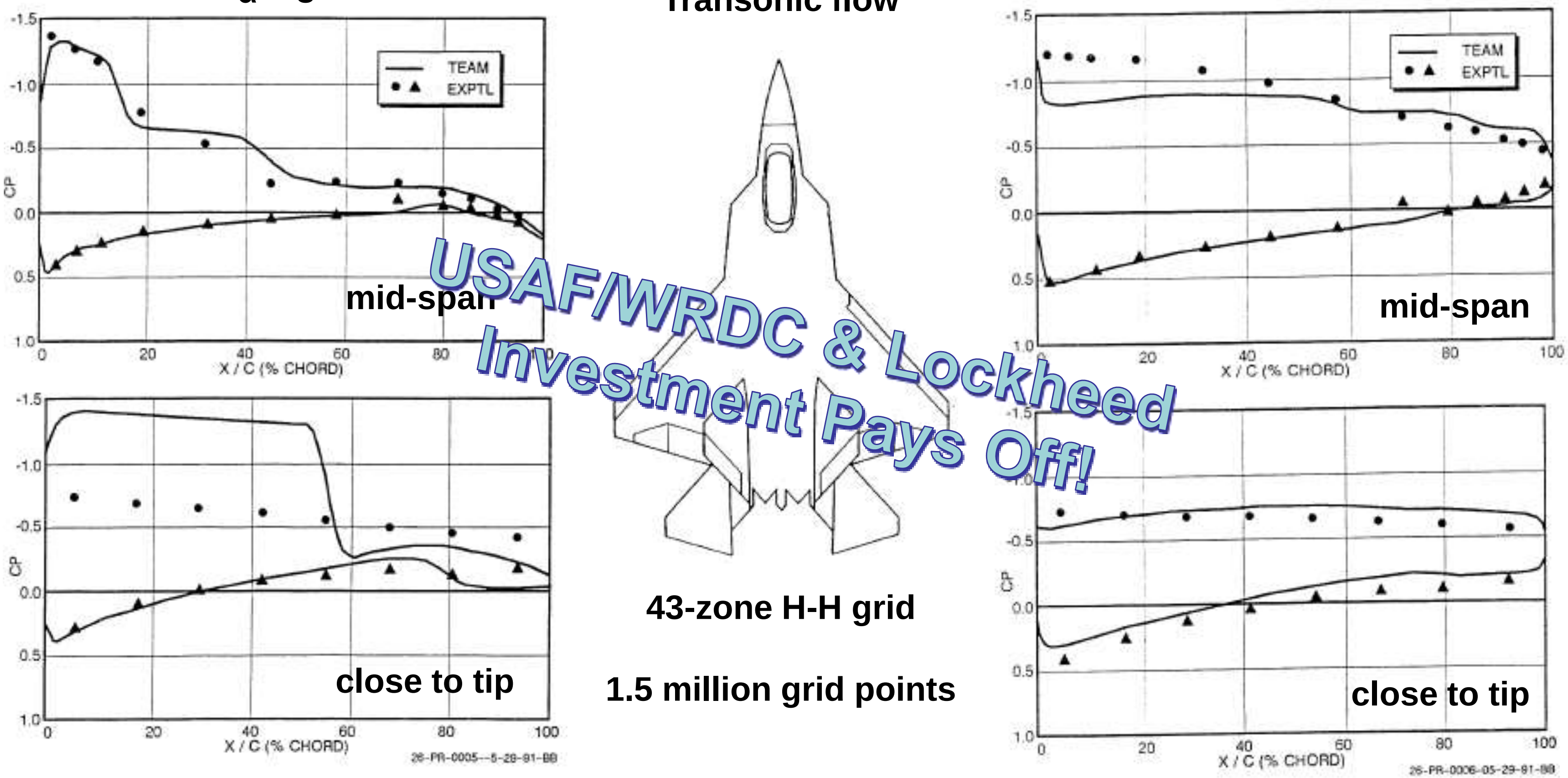
TEAM (Euler) Application: *YF-22 Dem/Val*

1988: Full-aircraft Analysis for Airloads Prediction (Reaser and Singer)

- Several transonic and supersonic Mach numbers
- Symmetric and asymmetric flight conditions
- Flow-through as well as powered nacelles

α = 8°　　Transonic flow　　α = 16°



TEAM results generated *before* wind-tunnel pressure model test

Code used in *predictive mode**; no grid adjustments made for 'better/improved' correlations!

**not necessarily by choice!!!*

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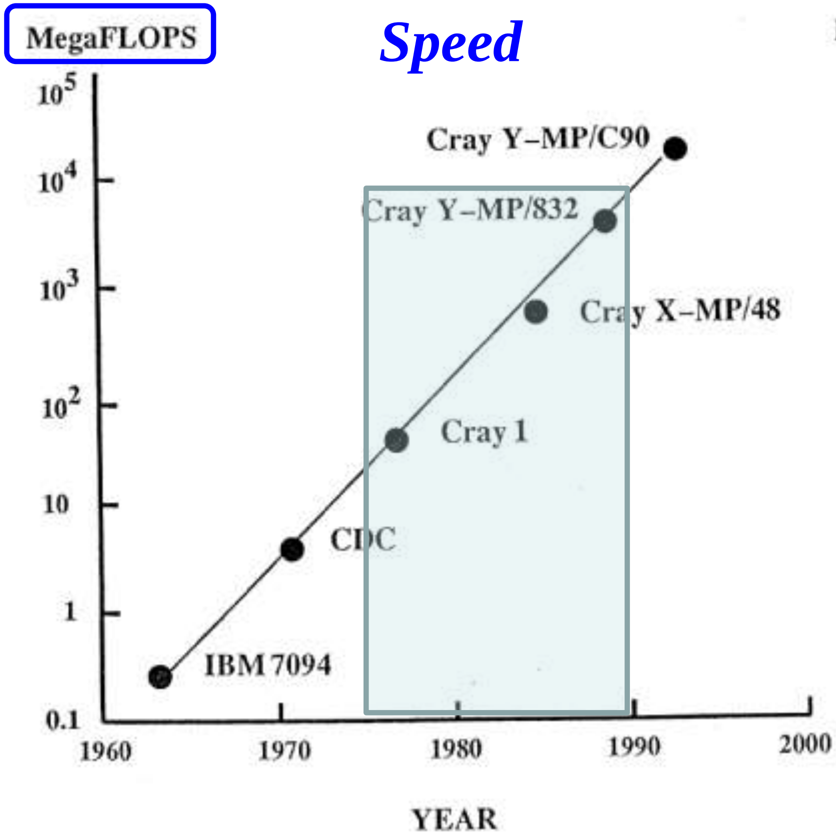
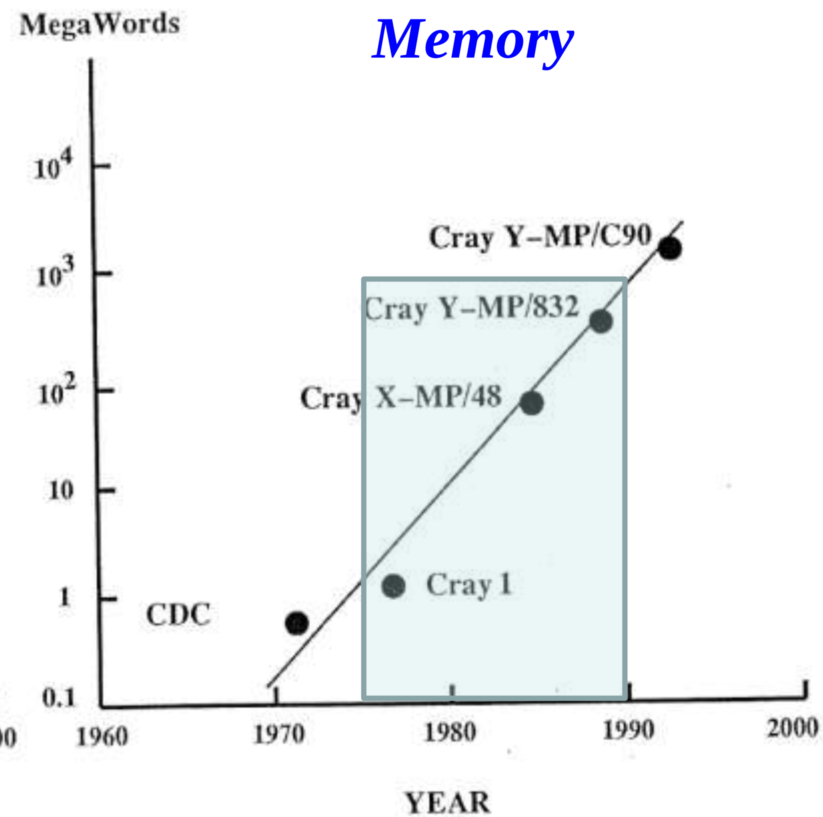
Source: Ref. 5.2.26

Computing Advances: *Key Enablers*

1975-1990: About 3 to 4 orders of magnitude improvement in speed and memory





TEAM Computational Time

Cray Y-MP: 15 to 30 seconds per time step for a million cell grid

TEAM Computational Memory

Cray Y-MP: Approx. 40 times the maximum number of cells

By 1990, Euler Solutions on Million-cell Grid in 6 to 8 Hours…But Weeks of Grid-Generation Time Hampers Effectiveness!

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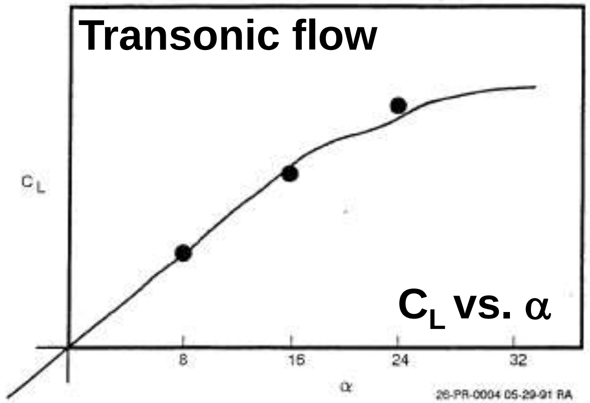
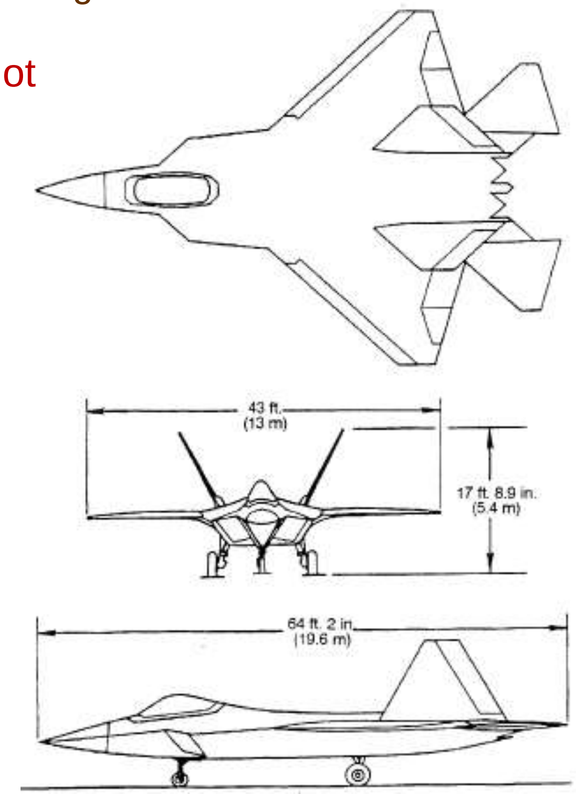
TEAM (Euler) Application: *YF-22 Dem/Val Effectiveness Assessment (1988-1989)*

- ***Long Turnaround Time:*** Tedious and time consuming grid generation
  - Two engineers spent ***few hundred man-hours*** over ***several weeks*** to build a **43-zone H-H topology hexahedral grid** with approximately **1.5 million nodes** for half the configuration
- ***Only Inviscid Drag:*** Program personnel want total drag—not getting it is one of their key complaints

Lift reasonably well predicted for transonic flight conditions





- ***Detailed Surface Pressures Useful:*** for structural design as well as thermodynamics groups
  - ***Structural Design group*** wants force, moment, and surface pressure increments due to control surface deflections

Challenge: ***Too Many Grids, Too Little Time!***

TEAM Run Times 'Reasonable', but Effectiveness Too Low to Meet the Needs of F-22 EMD that Lockheed Hoped to win in 1991

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Efforts to Increase TEAM Effectiveness

1989 – 1991

- **Total (Absolute) Drag:** ***add viscous effects for increased realism***
  - Coupling with integral boundary-layer codes? *Not well suited for fighter analyses*
  - Extend TEAM by adding N-S viscous terms? *In-house TRANSAM efforts initiated in 1986*
- **Grid Generation:** ***make it faster and less labor-intensive***
  - **Multi-block hexahedral grids**
  - **Overlapping grids**
  - **Cartesian grids**
  - **Unstructured tetrahedral grids**
    - **AIRPLANE Code:** Lockheed procured unstructured tetrahedral grid Euler code in 1990 from Jameson's Intelligent Aerodynamics, Inc., Princeton, NJ

AIRPLANE Solution

Key Challenge:

How to develop requisite level of competency and confidence in a brand new code in order to lower the risk enough by early 1991 for F-22 EMD applications?

In 1990, aerospace industry went into depression leading to (a) reduction in the number of qualified engineers, and (b) significant cuts in R&D funding!

- **Interim Path Forward: make maximum use of multi-zone structured grid—*once it's built*—as structured grid generation methodology was the most mature at that time**
  - *Use surface transpiration concept to "simulate" the effect of control surface deflection by appropriately changing the no-normal-flow surface boundary condition*

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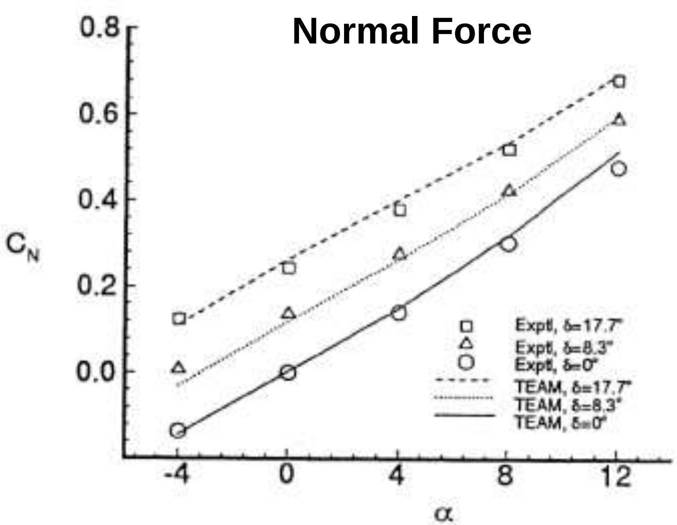
Innovative Approach to Estimating Incremental Loads Due to Control Surfaces

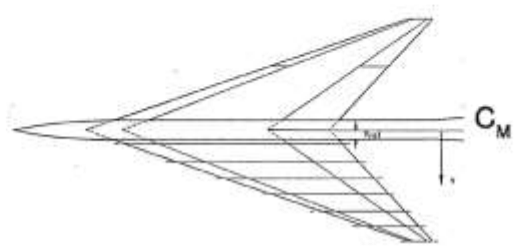
COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

- **Customer's Problem:** Estimate incremental aerodynamic forces, moments, and surface pressures due to control surface deflections for multiple settings and flight conditions to support structural design
- **Solution:** Use *surface transpiration concept* to "simulate" the effect of control surface deflection by appropriately changing the no-normal-flow surface boundary condition
  - NO NEED TO CHANGE THE INITIAL GRID!
  - The concept—originally proposed by Lighthill—had enjoyed great success in simulating the effect of boundary layer on inviscid flow modeled using potential or Euler methods



M_∞ = 0.85

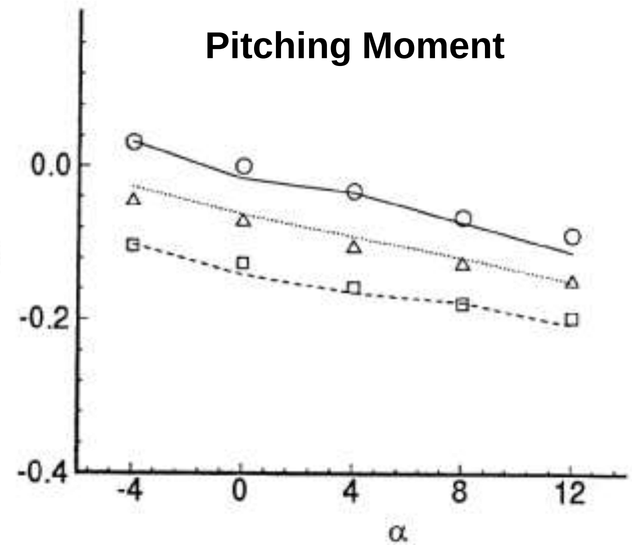
14-zone grid; ~235,000 cells



AR = 1.65

Λ = 71.2°

λ = 0.1



Solution developed and implemented in 1989-90; published in 1993, AIAA Paper 93-3506

Results Improved Confidence in Meeting Customer Needs

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Source: Ref. 5.2.32

The Exciting Eighties!

- **April 12, 1981: Launch of the First Space Shuttle Mission**
  - Mission Commander **John Young** had already flown in space four times, including a walk on the Moon in 1972
  - **Bob Crippen**, the pilot, was a Navy test pilot who would go on to command three future shuttle missions

- **June 1981: USAF ATF Request for Information (RFI)**
- **September 26, 1981: Boeing 767 First Flight**
  - September 8, 1982: original 767-200 entered service with United Airlines
  - October 1986: 767-300 followed by 767-300ER in 1988

- **February 19, 1982: Boeing 757 First Flight**
  - January 1, 1983: original 757-200 entered service with Eastern Airlines
  - Compared with 707 and 727, it consumed approx. 40% less fuel per seat, on typical medium-haul flights

- **December 14, 1984: Grumman X-29 First Flight**
  - Experimental aircraft that tested forward-swept wing, canard control surfaces, and other novel technologies

- **September 1985: USAF ATF Request for Proposal (RFP)**
- **October 1986: Lockheed and Northrop Awarded 50-month Prototype Dem/Val Contracts**
  - First Flights: YF-22 (29 Sep 1990); YF-23 (27 Aug 1990)

- **February 22, 1987: Airbus 320 First Flight**
  - 18 April 1988: entered service with Air France

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The Exciting Eighties (for the Author!)

Personal

1980

- **Granted US Permanent Resident status**
- **And…**

1981
1st son

1985
2nd son

1985
Naturalized US Citizen

Professional

- **AIAA & SAE**
  - AIAA ASM: St. Louis (1981), Reno (1983, 1984, 1987)
  - AIAA APA: Danvers (1983), Williamsburg (1988)
  - AIAA Euler Solvers Workshop: Monterey (1987)
  - SAE Aerospace Tech Conf. & Expo: Anaheim (1988)
  - Two AIAA Technical Committees: *Fluid Dynamics (1985-88)* and *Applied Aerodynamics (1988-91)*
- **ICAS* Congress**
  - Toulouse (1984), London (1986), Stockholm (1990)
- **3rd Intl. Congress of Fluid Mech., Egypt** (1990)
- **After-hours teaching** *(1985-1990)*
  - Lockheed Employee Edu. Pgm. (*Aerodynamics for Designers*)
  - UCLA Continuing Education (*Introduction to Aerodynamics*)
  - Lockheed Tech Institute (*Computational Fluid Dynamics*)
- ***Lockheed consolidation*** *(1987)*
  - ***Three companies into one: Lockheed Aeronautical Systems Company (LASC) headquartered in Burbank, California***
  - *Loss of CFD and ACA talent and expertise in Georgia*
- **Appointed *Comp Aero Technical Lead*** *(1989)*
  - Represented LASC on Corporate Task Force on Advanced Computing Methods (ACM)

*International Council of the Aeronautical Sciences

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The Exciting Eighties (for the Free World)

Final Collapse of the USSR & Emergence of the New World Order

A Pivotal Event in World History: November 9, 1989

Fall of Berlin Wall Created New Geo-political Realities

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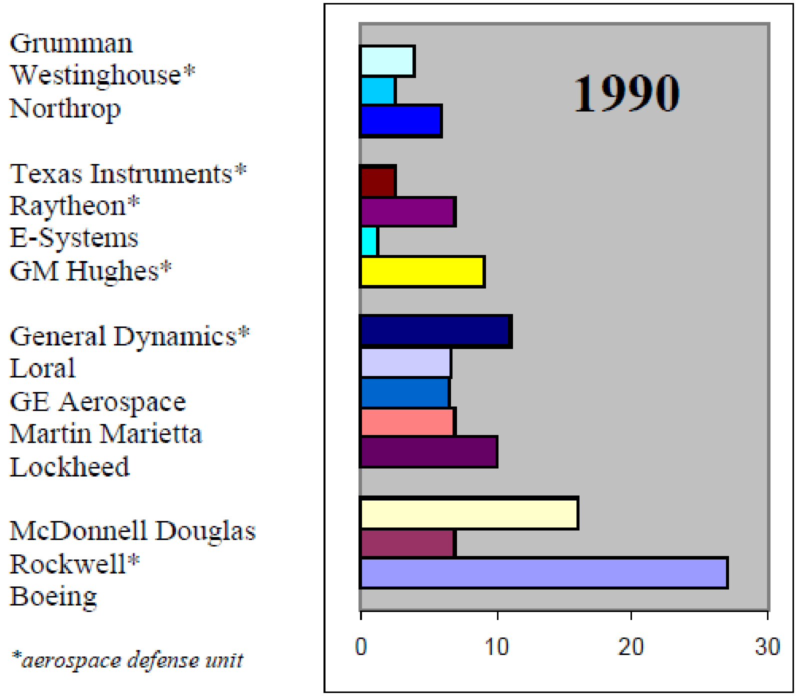
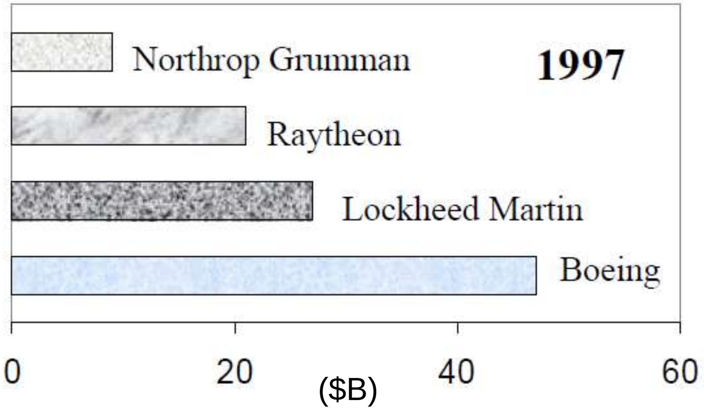
The Nasty Nineties Followed the Exciting Eighties!

- **"Peace Dividend"—*Major Contributor to Depression in US Aerospace Industry***
  - Loss of 495,000 people (37% of workforce) in just five years (1990-1994)
  - Overall sales down 9% in 1994 after single-year 10% drop in 1993
  - Dramatic reductions in Research & Development funding in aerospace industry
- **Consolidations, Mergers, and Reorganizations—*To Reduce Capacity & Cost***
  - Dec 1992: *Lockheed acquires General Dynamics military aircraft division*
  - Mar 1995: *Lockheed and Martin Marietta formally merge*
  - Dec 1996: *Boeing and McDonnell Douglas announce merger*



(size of the bar represents sales volume)



- Reduce Excess Capacity
- Reduce Overhead Costs

15 down to 4 in 7 years!

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Source: Ref. 1.3

New Opportunities: *Early 1990s*

- **May 1990: Lockheed Reorganization—*one company into two!***
  - Decides to vacate Burbank—split operations between Palmdale and Marietta
    - Lockheed Advanced Development Company (LADC), Palmdale, California
    - Lockheed Aeronautical Systems Company (LASC), Marietta, Georgia
- **23 April 1991: *YF-22 is the winner!***
  - Secretary of the US Air Force Donald Rice announced Lockheed's **YF-22** as the **winner**
  - LASC to work the F-22 Engineering and Manufacturing Development (EMD) contract in Georgia
  - ***Raj relocates to Georgia in August 1991***

- **13 December 1991: *LASC selects two Technical Fellows in the inaugural year***
  - **Chellman (Structures)** & **Raj (CFD)**
  - Most Senior Rank in Technical Track
  - Increased Emphasis on Mentoring and Technical Leadership
  - **Key Challenge:** *Rebuild Capabilities in Georgia*

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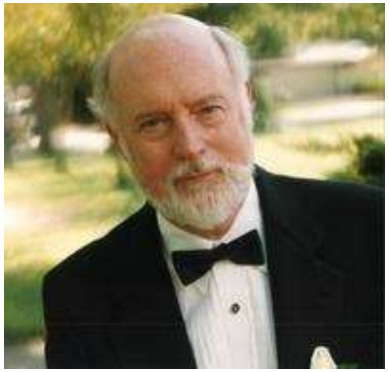
Raj's Tech Fellow Mission
Spurred by "A Jolt of Reality"

- **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

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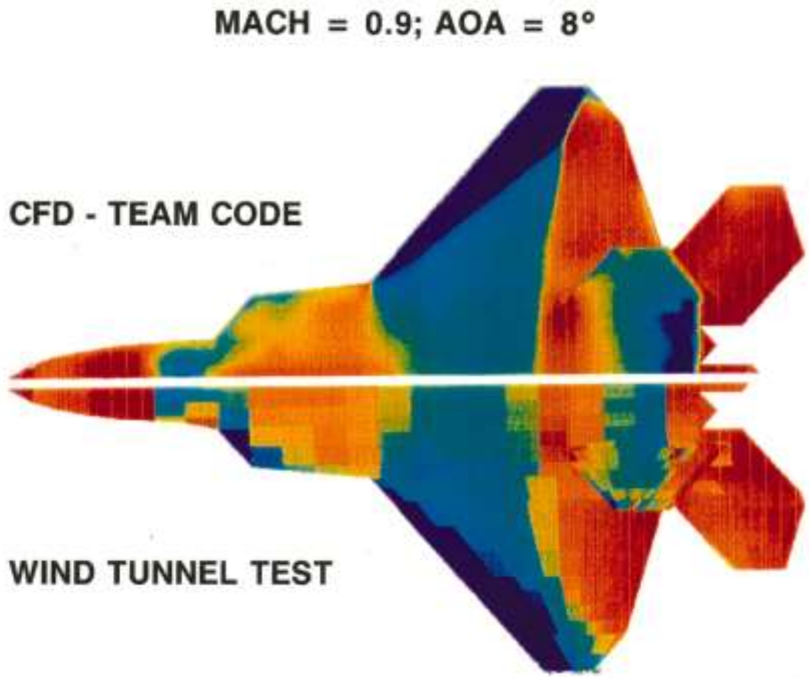
Source: Ref. 1.1 – 1.3

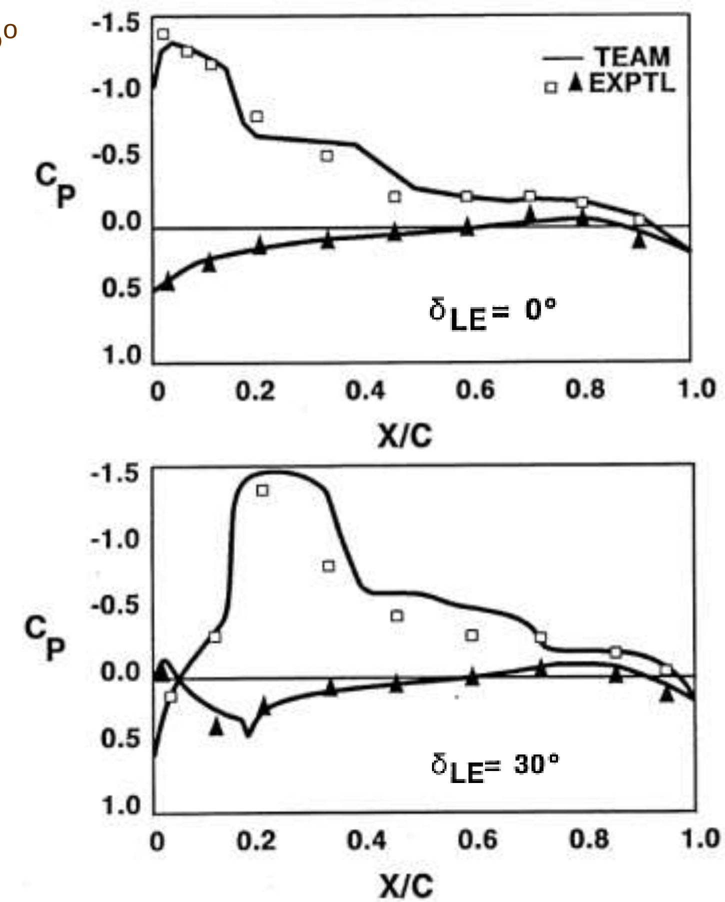
TEAM (Euler) Application: F-22 EMD *(1991)*

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



Transonic flow



$40M Estimated Cost Avoidance

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

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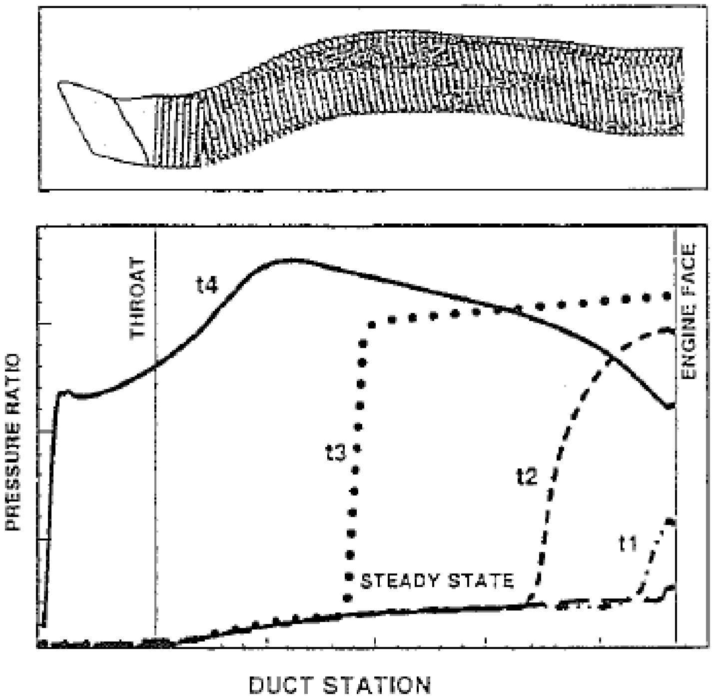
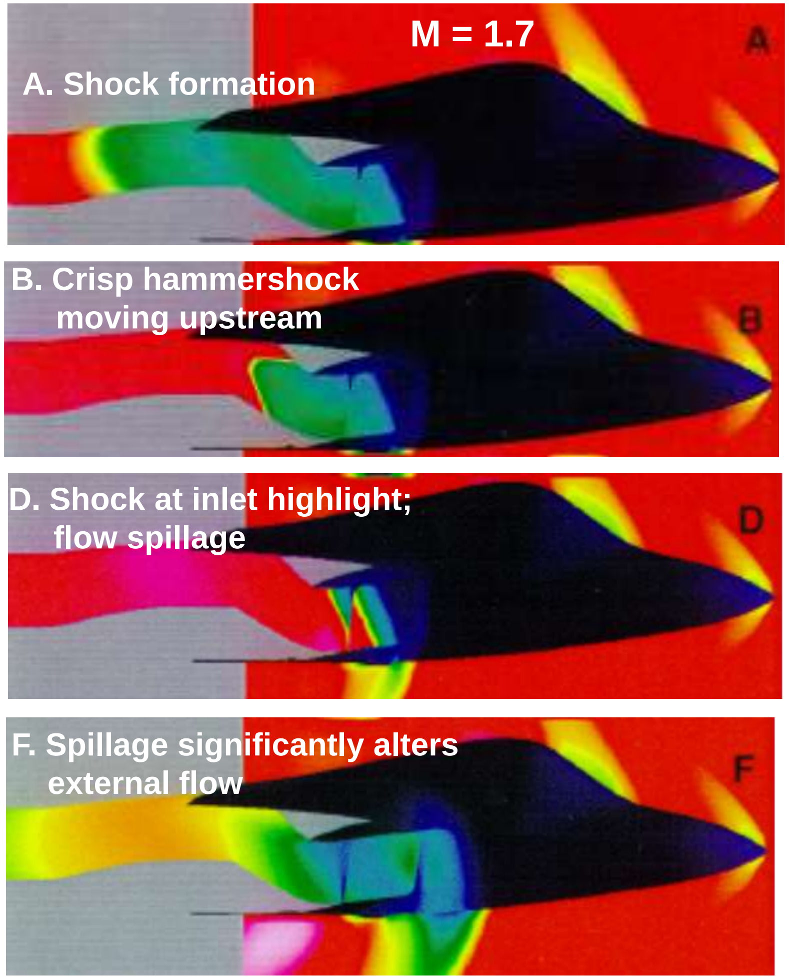
Source: Ref. 5.2.33 & 5.2.29

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

Inlet Hammershock Simulation

- **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 <u>1.7</u>
- **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

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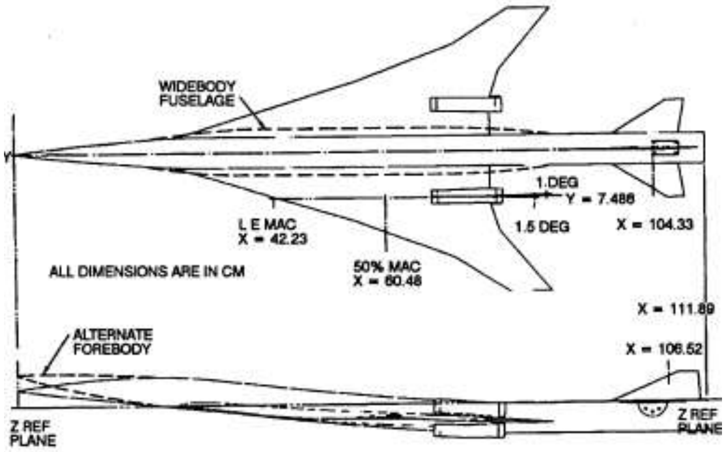
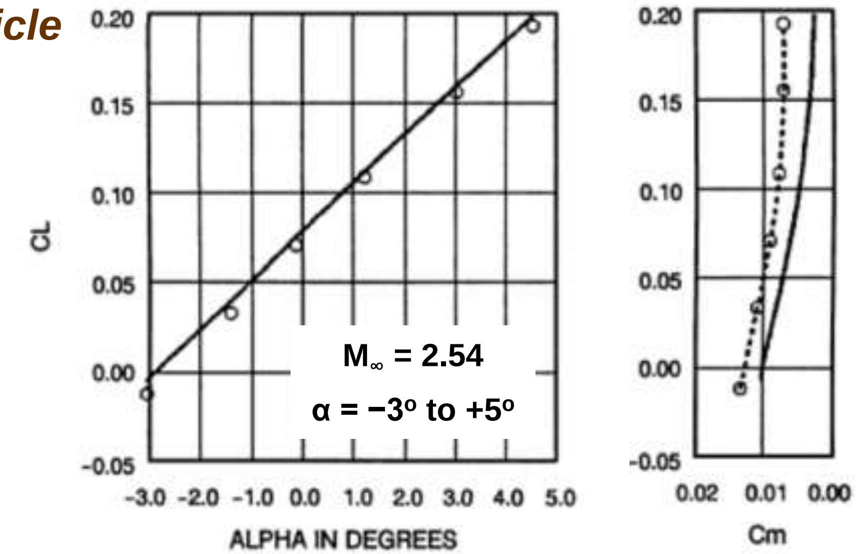
Source: Ref. 5.2.34

TEAM (Euler): *Mature Capabilities by Early 1990s*

Demonstrated for Wide Range of Geometries & Flow Conditions

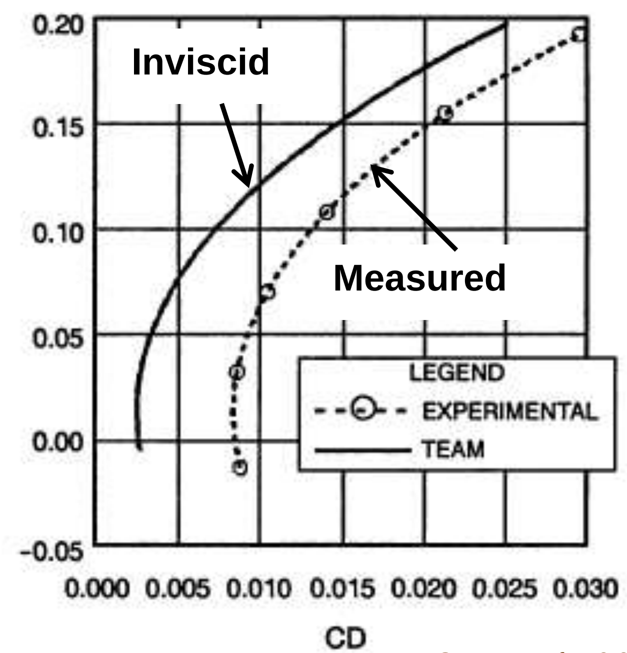
Typical Example: Supersonic-Cruise Vehicle with Over/Under Engine Arrangement





Grid: 10-Zone 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: Long Grid Generation Times and Lack of Viscous Effects

Source: Ref. 5.2.26

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Lockheed Addresses Grid Generation Issue

1990s

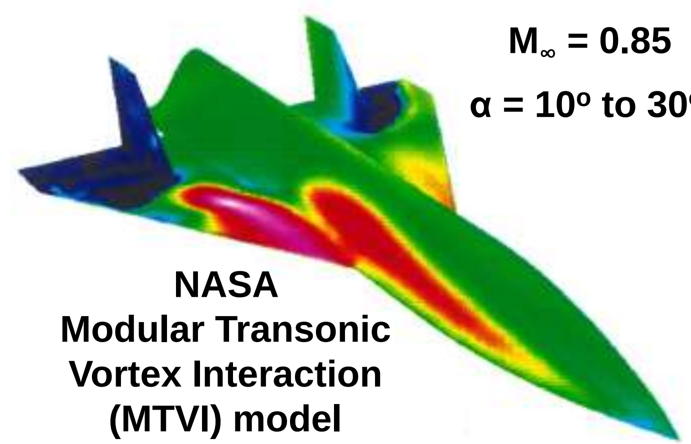
Explore potential benefits of unstructured grids by participating in studies sponsored by Dr. Jim Luckring, NASA-LaRC (1993-1996)

- **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

All Unstructured Grid Methods More Effective than TEAM!



NASA Modular Transonic Vortex Interaction (MTVI) model

Source: Refs. 5.2.35 – 5.2.37

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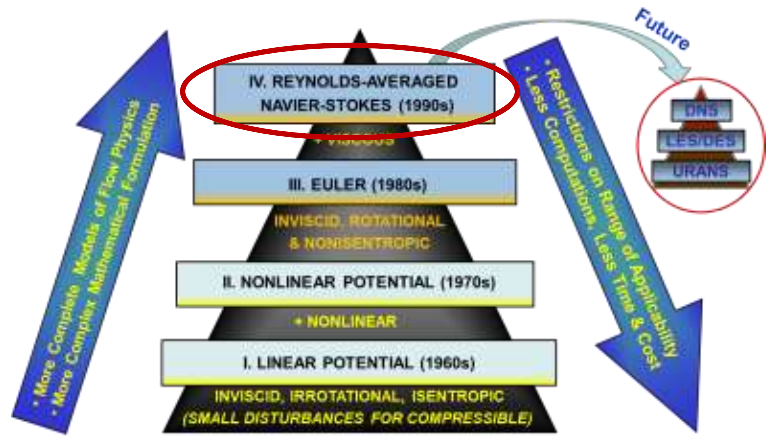
Level IV

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

Applicability

- All Mach numbers and all flow configurations

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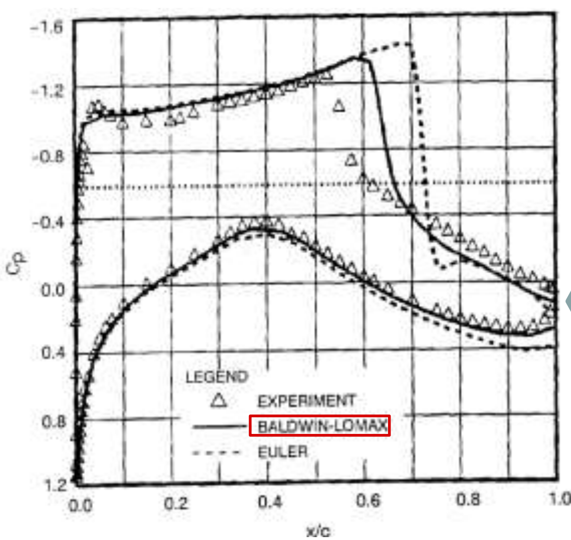
Lockheed Addresses Viscous Effects Issue

- **Olling, Raj, and Miranda (1986)**
  - Initiated **TRANSAM*** *(Three-dimensional Reynolds-Averaged Navier-Stokes Aerodynamic Method)* development by extending TEAM Euler solver to RANS equations; TRANSAM served 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)

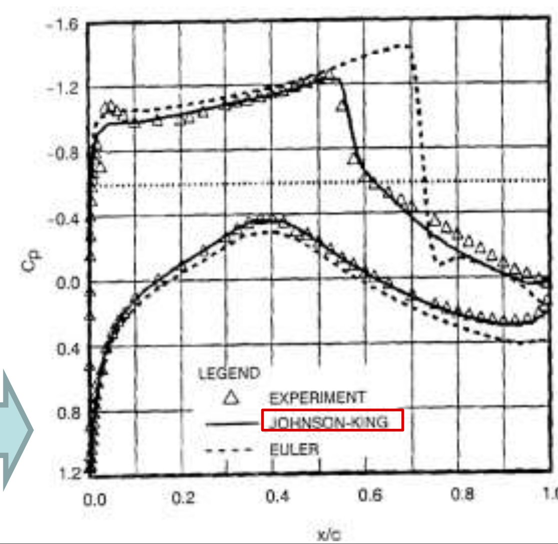
$M_\infty = 0.75$, $\alpha_{corrected} = 2.81^o$

$Re = 6.2 \times 10^6$

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

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Source: Refs. 5.2.38 – 5.2.42

TEAM (RANS) Validation

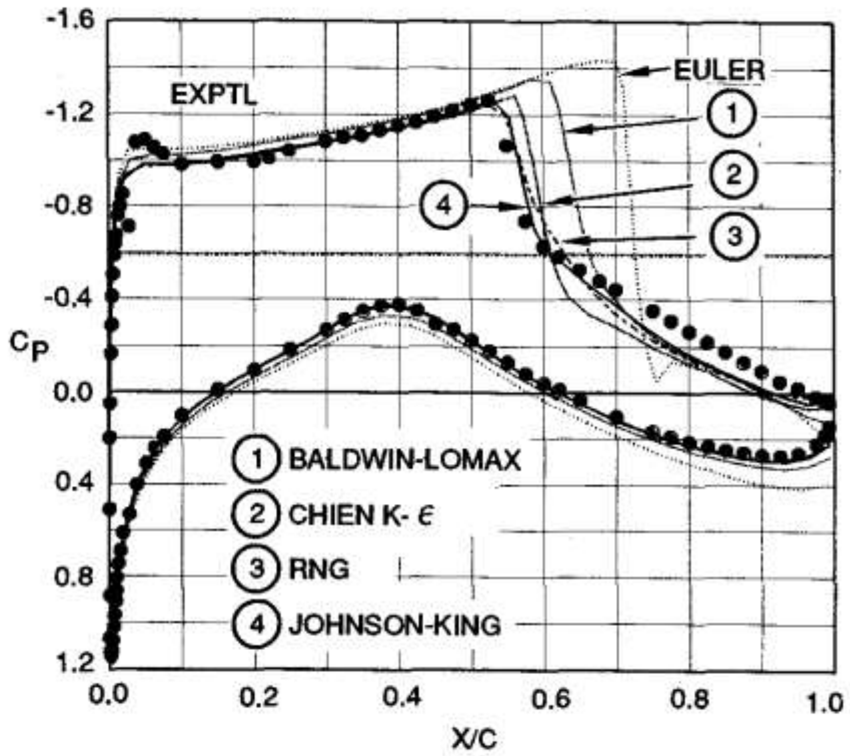
Transonic Flow (2D)

AGARD Test Case 10: *RAE 2822 Airfoil*

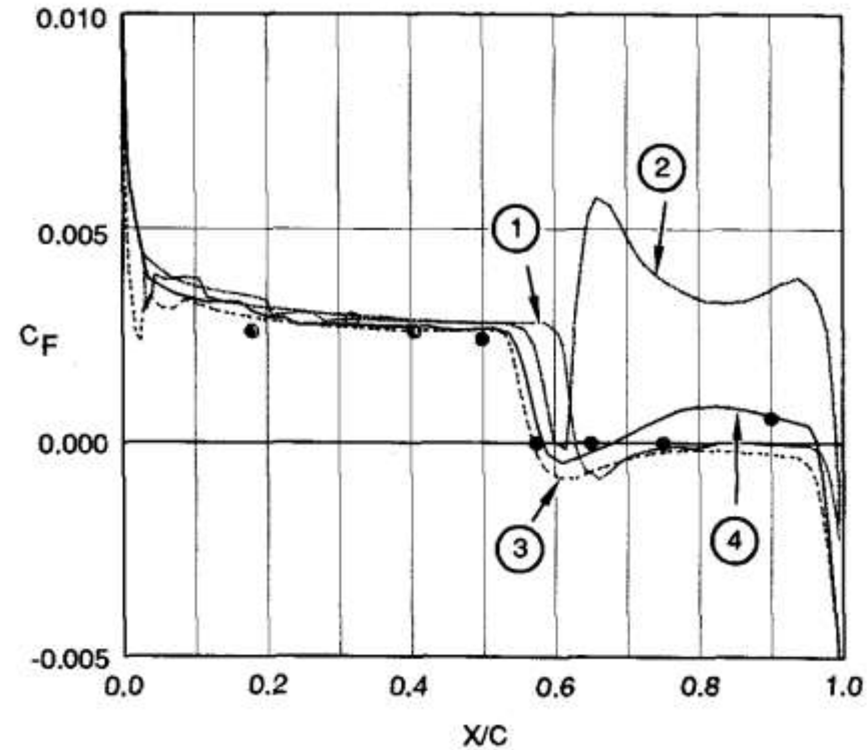
$M_\infty = 0.75$, $\alpha = 2.8^o$, $Re_c = 6.2x10^6$

129 x 257 C Grid **$y^+ < 1$ in cells next to the surface**

Surface pressure distribution



Skin friction coefficient distribution



Solution Exhibits Sensitivity to Turbulence Models

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Source: Ref. 5.2.38

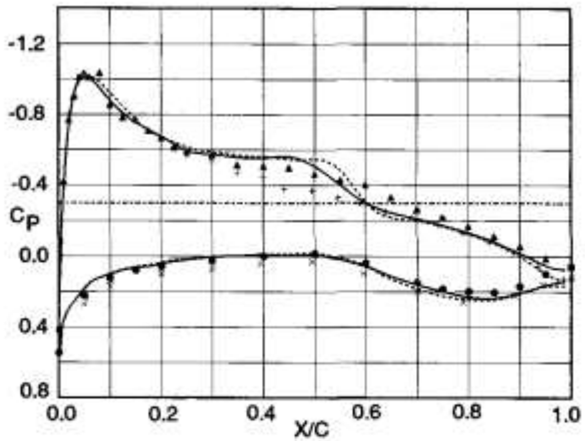
TEAM (RANS) Validation

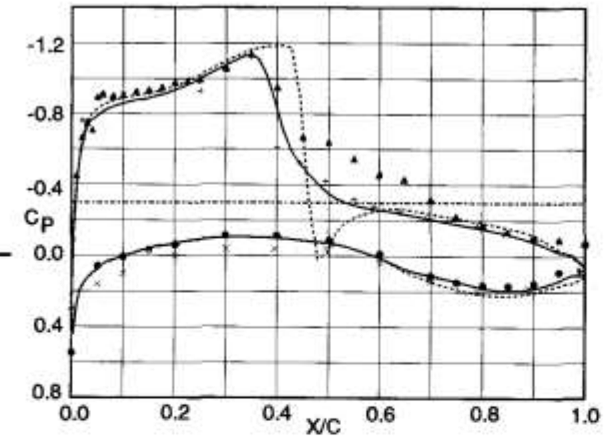
Transonic Flow (3D)

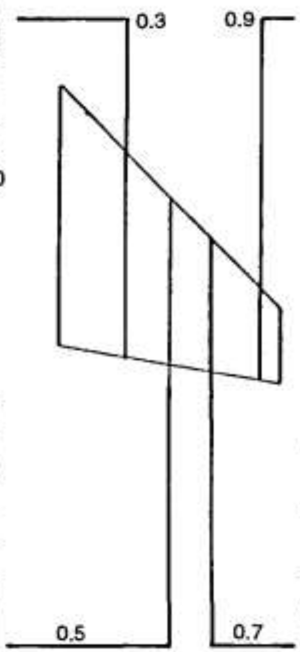
AFOSR-Lockheed Wing C: *Surface Pressure Comparisons*

7 zone C-O grid (51 x 257 x 35) **Baldwin-Lomax turbulence model**

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





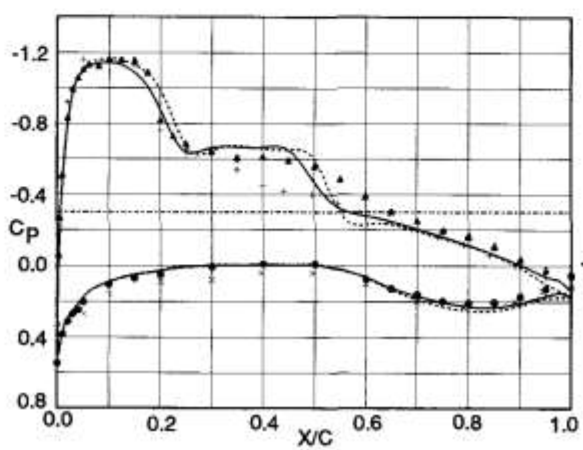


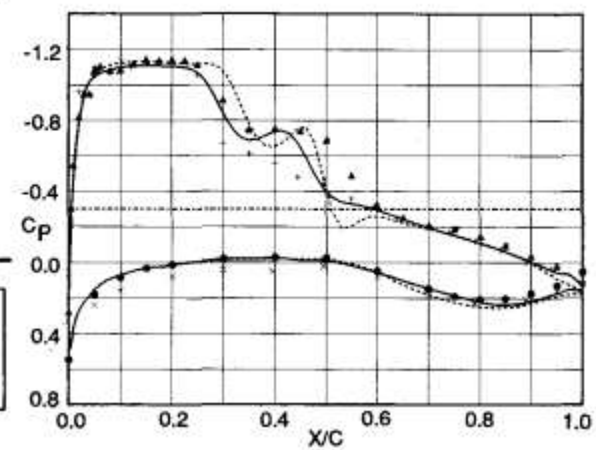
Viscous (RANS) analysis: 6 inner zones

Inviscid (Euler) analysis: 1 outer zone

▲ ● Large-scale test

+ × Small-scale test





Source: Ref. 5.2.38

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TEAM (RANS) Effectiveness *(early 1990s)*

In spite of improved 'quality' of simulated results, achieving high levels of Effectiveness for the RANS version of TEAM remained elusive due to

(a) labor-intensive and time-consuming process for structured grid generation about full aircraft configurations, and

(b) the use of expensive high performance computing for acceptable turnaround times.

Goal *(set in early 1990s)*

Less than 24 hour RANS aero analysis turnaround without increased cost by 2000!

Strategy

- ***Automated grid generation***
- ***Affordable high performance computing***

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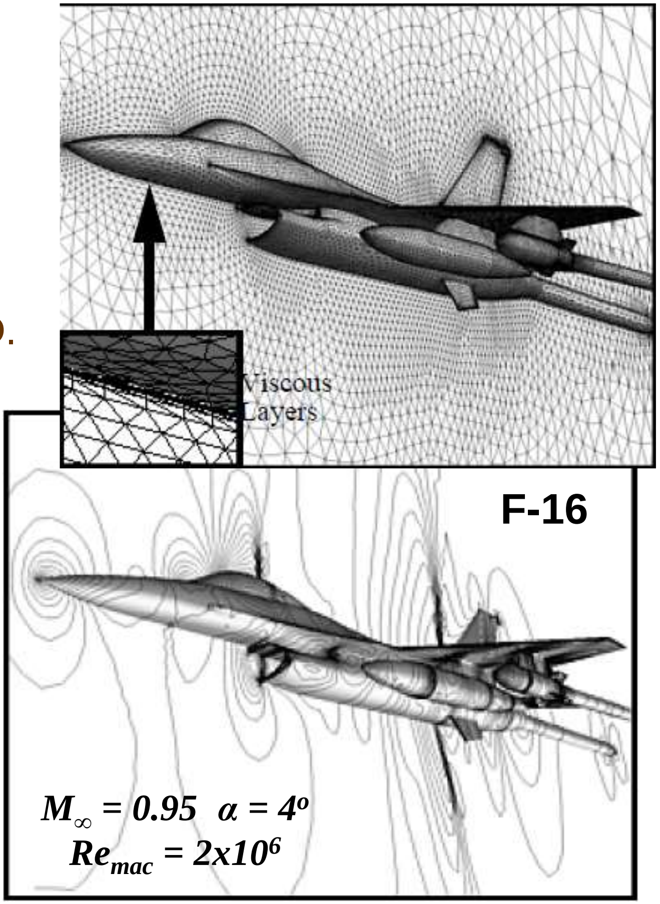
Out with TEAM, In with TetrUSS!

(Later half of 1990s)

- **TetrUSS Software: A Modular System Developed by NASA-LaRC**
  - GridTool—Graphical User Interface (GUI) for surface definition
  - VGRID/ VGRIDns—advancing front method to generate tetrahedral grids
  - USM3D/ USM3Dns—cell-centered finite-volume upwind flow solver
  - 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

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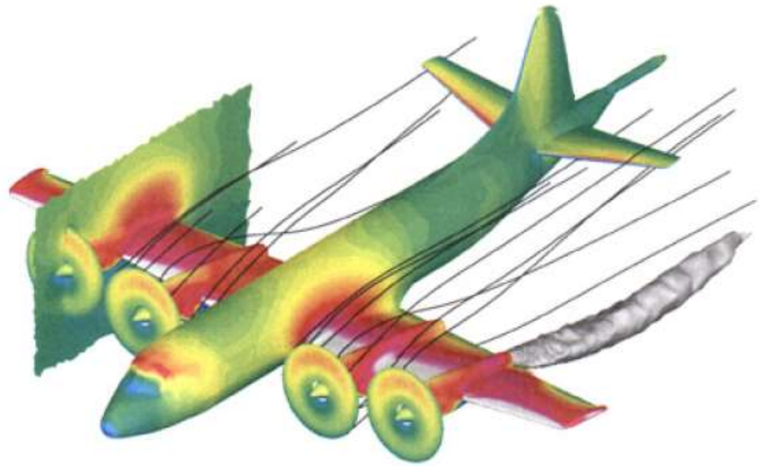
Source: Ref. 5.2.43 and 5.2.44

Y2K: *Mission Accomplished!*

Goal of less than 24-hour turnaround time of full aircraft RANS simulation, set in early ’90s, was achieved using TetrUSS

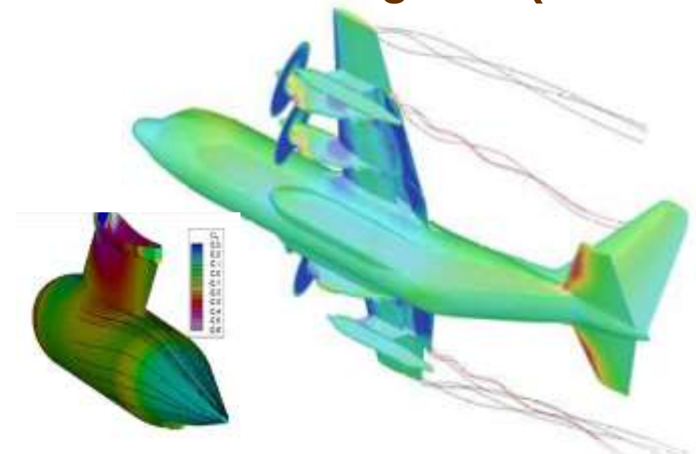
(Thanks to the hard work and dedication of the ACA team in Georgia)

- **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!

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Source: Refs. 5.2.45 & 5.2.46

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

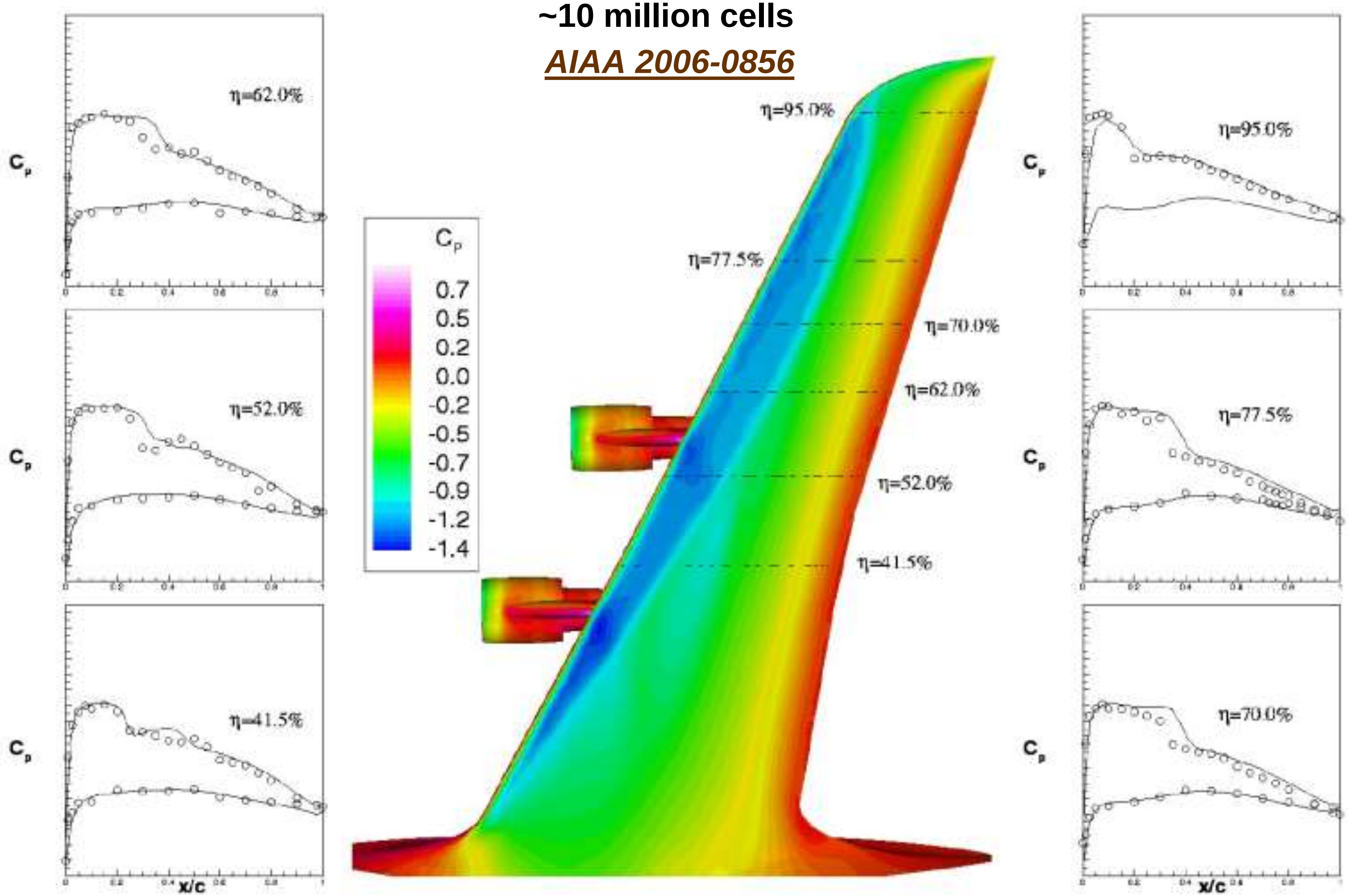
RANS-based ACA: *Full Aircraft Analysis*

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

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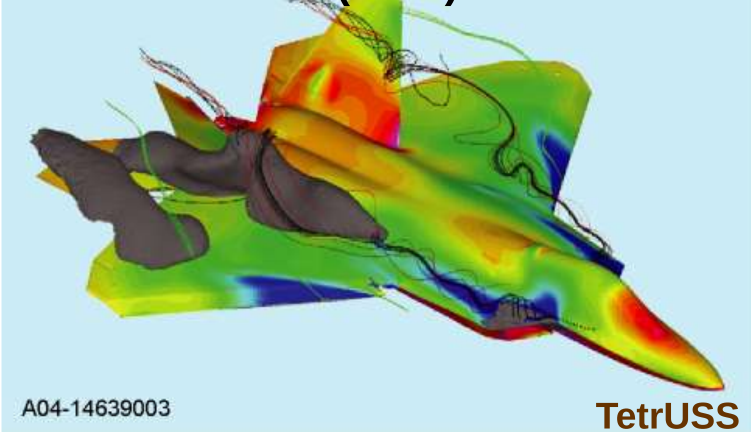
Source: Ref. 1.18

RANS-based ACA

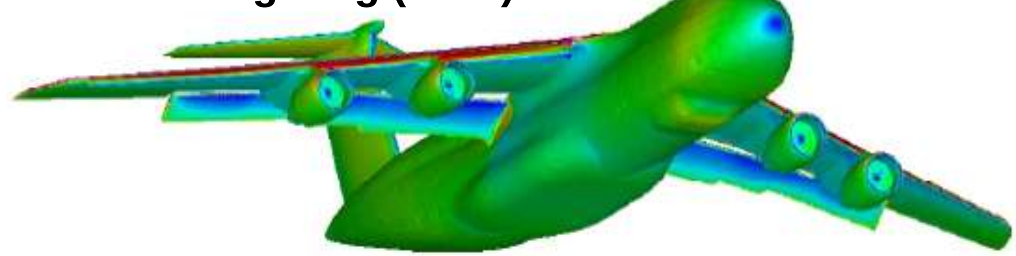
Impressive Capabilities Demonstrated throughout the 2000s

F-22 Tail Buffet (2005)



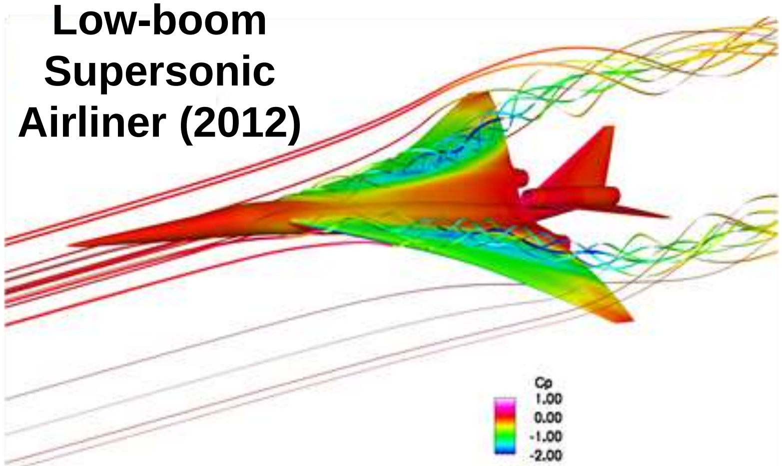
TetrUSS

C-5M Re-engining (2006)



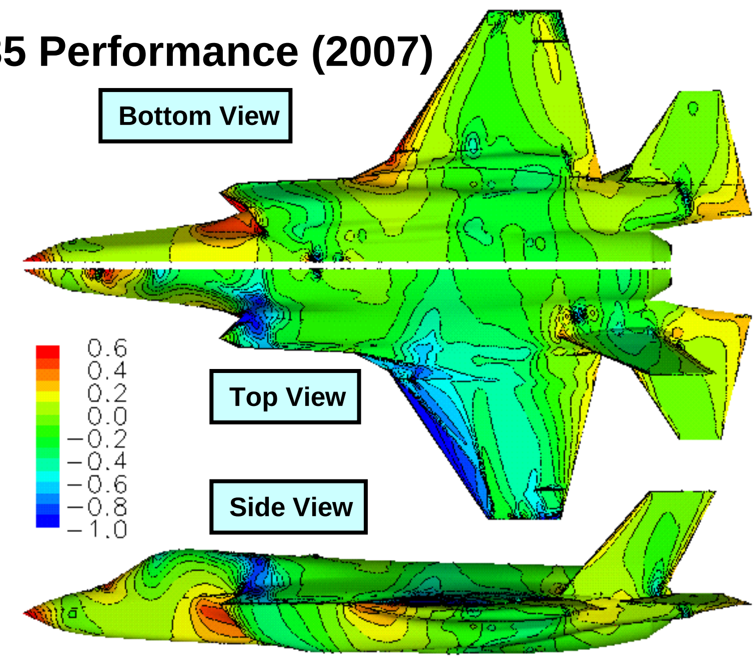
TetrUSS

Low-boom Supersonic Airliner (2012)



CFD++

F-35 Performance (2007)



Falcon

Reasonably Quick and Affordable Flow Simulations for a Wide Variety of Full Aircraft Configurations

Source: Refs. 5.2.47 – 5.2.50

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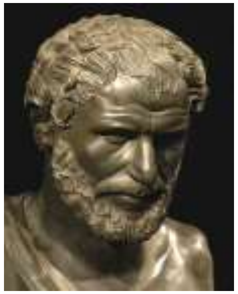
An Unexpected Turn in the Road
As the 1990s Wind Down

- **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

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Source: Wikipedia

Section 5.2: Key Takeaways (1 of 3)

- **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 evolved structured hexahedral and unstructured tetrahedral grids
    - **Euler solver**—*solve the unsteady form of Euler equations using a code with 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 Needs *(flows with strong shocks and with free-vortices or leading-edge vortices)***
    - Development of **TEAM** code (**T**hree-dimensional **E**uler/Navier-Stokes **A**erodynamic **M**ethod) under a USAF, WRDC (Wright Research & Development Center) contract (1984-1989)
    - 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 Jameson-Schmidt-Turkel (JST) adaptive dissipation
        - Multistage pseudo time stepping to steady state

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Section 5.2: Key Takeaways (2 of 3)

- **Team validation using many configurations and a range of flow conditions**
- **1988: TEAM (Euler) analysis of full YF-22 Dem/Val configuration**
- **1988-1989: Assessment of TEAM (Euler) Effectiveness based on YF-22 Dem/Val Application**
  - **Grid Generation**: Tedious and time consuming
  - **Extensive Validation**: Limited value (***Lesson Learned: must be done for geometries and flow conditions that aren't substantially different from the intended application***)
  - **Total Drag**: Unable to predict using inviscid Euler code
  - **Surface Pressures**: Deemed useful for structural design…but increments for deflected control surfaces would be really useful
- **Many promising technologies to increase Effectiveness, but none mature enough to meet the anticipated needs of F-22 EMD effort in 1991 time frame**
- **Interim Path Forward**
  - **Make maximum use of the multi-zone grid for the baseline configuration—once it is built**
- **1990: Innovative Approach to estimation of incremental loads due to control surface deflections for multiple settings**
  - **Surface transpiration concept** incorporated in TEAM to simulate control surface deflections

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Section 5.2: Key Takeaways (3 of 3)

- **The Exciting Eighties**
  - Launch of the 1st Space Shuttle *(April 12, 1981)*
  - USAF Advanced Tactical Fighter (ATF): *RFI (Jun 1981); RFP (Sep 1985); 50-month Dem/Val contract award to Lockheed and Northrop (Oct 1986)*
  - Boeing: *767 first flight (Sept 26, 1981); 757 first flight (Feb 26, 1982)*
  - Grumman X-29 First Flight *(Dec 14, 1984)*
  - Airbus First Flight (Feb 22, 1987)
- **The Nasty Nineties**
  - "Peace Dividend" contributed to US aerospace industry depression resulting in mergers and consolidations: 15 down to 4 in 7 years!
- **Feb 1991: Realization [by author] that higher level CFD (Euler/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 ever since 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 2/16
  - ***But…NO TOTAL DRAG! ACA wasn't ready. F-22 Program relied on wind-tunnel testing***
- **Throughout 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!**
- ***"The only constant in life is change"***

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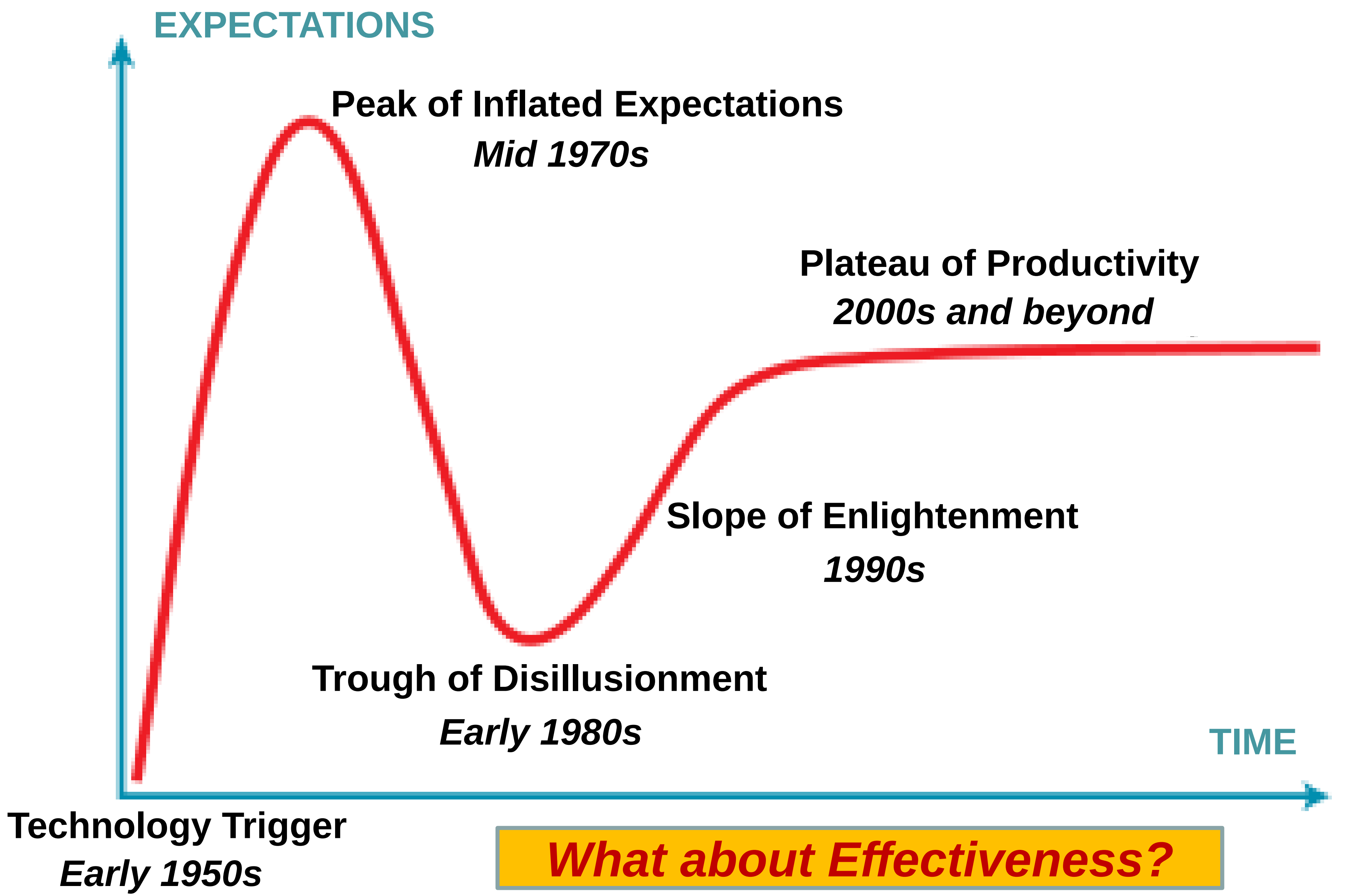
ACA Evolution Has Paralleled *Gartner Hype Cycle* of CFD Technology!



What about Effectiveness?

Source: https://en.wikipedia.org/wiki/Hype_cycle

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Status of ACA Effectiveness

In this section, we more closely examine

(a) the status of the effectiveness of RANS-based ACA since the 2000s when RANS CFD methods were finding widespread use as their productivity had reached an acceptable level, and

(b) barriers to achieving fully effective ACA.

Maximizing Effectiveness Has Been the "North Star" of Author's ACA Efforts Since the Inception of **"Miranda's Law"** ***in 1980***

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Assessment of ACA Effectiveness

Degree of ACA Effectiveness Depends on the Ability to Provide Credible Solutions (that Replicate Reality) While Meeting Cost & Schedule Constraints

- **Qualitative Approach**
  - This is the approach proposed by Miranda
  - Assessment is based on engineer's judgment about 'quality' and 'acceptance' factors
- **Quantitative Approach**
  - A simple *quasi*-quantitative approach is devised and proposed by the author
  - It uses an "effectiveness index" as a composite of a "quality index" and an "acceptance index" (See Appendix A)

Design Teams, in Collaboration with ACA Practitioners, Are Best Suited to Assess ACA Effectiveness, Not the Developers

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Source: https://en.wikipedia.org/wiki/Hype_cycle

Author's Assessment of the Effectiveness of RANS-based ACA *(ca early 2000s)*

Although RANS simulations of full aircraft configurations are [acceptably?] quick and affordable, predictions of aerodynamic characteristics aren't always credible* *especially for complex flows dominated by separation and free vortices!*

***credible:** *how faithfully do the predictions imitate reality*

Dilemma when designing novel configurations in a simulation based design environment

- If RANS simulations predict flow separation or free vortices, are the data credible enough to invest additional time and effort for configuration redesign?
- If expensive and time-consuming wind-tunnel tests must be done for validating RANS predictions—doesn't it defeat the purpose of using RANS in the first place?

ACA Effectiveness: Less Than Satisfactory!

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Boeing Assessment of RANS CFD for Aircraft Design Applications *(2005)*

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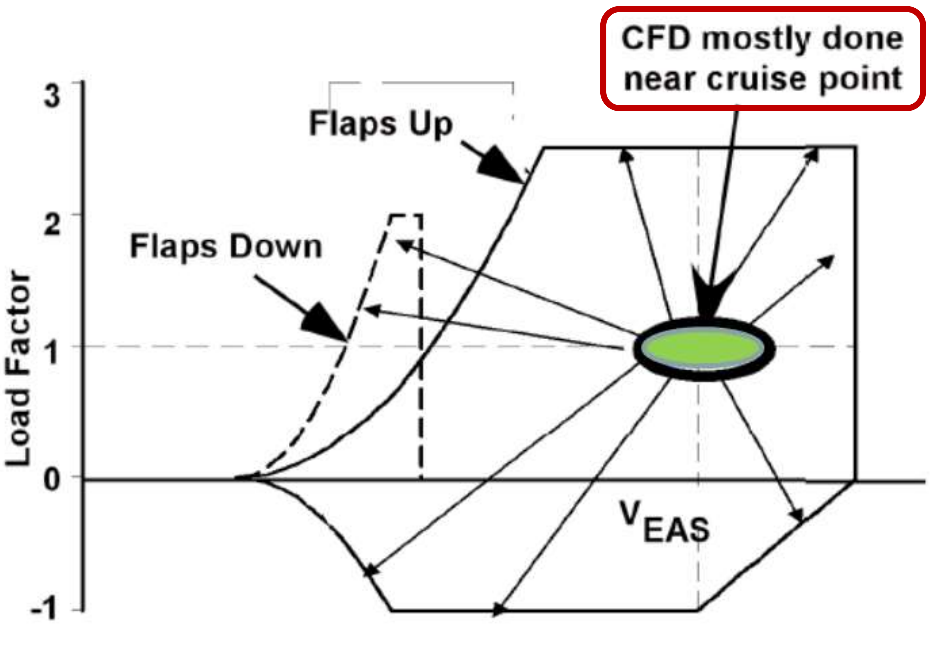

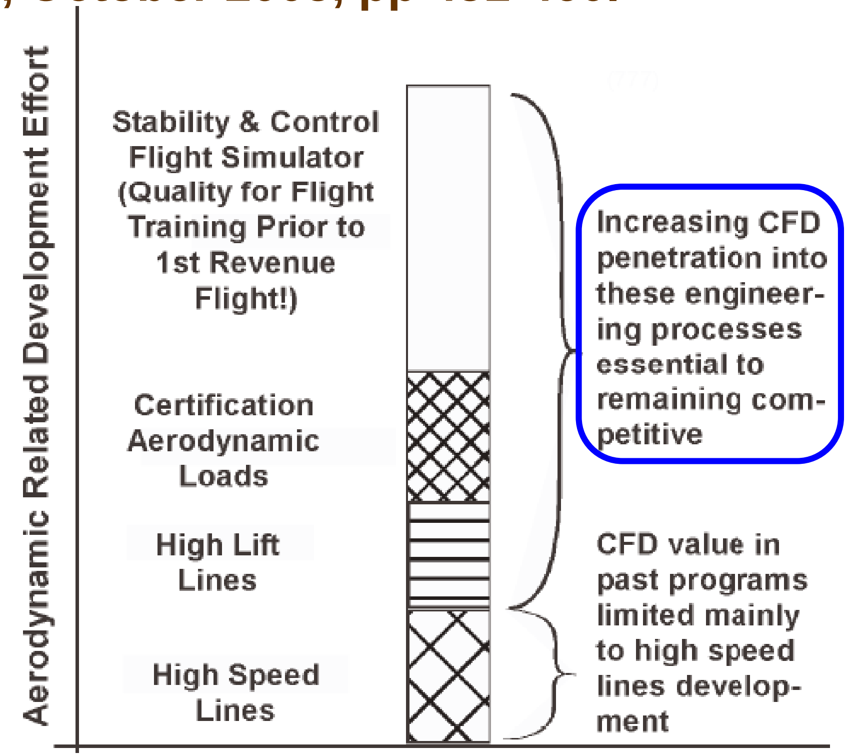

"The major impact of CFD, delivered to date at Boeing, has mainly been related to its application to *high speed cruise*."

Severely Limited Scope of Applications

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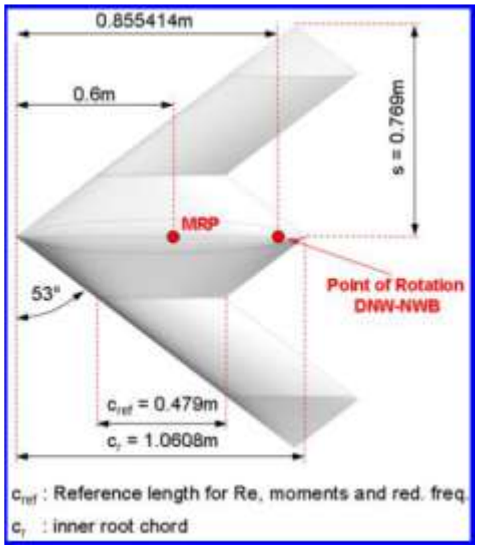
Source: Refs. 6.1.1

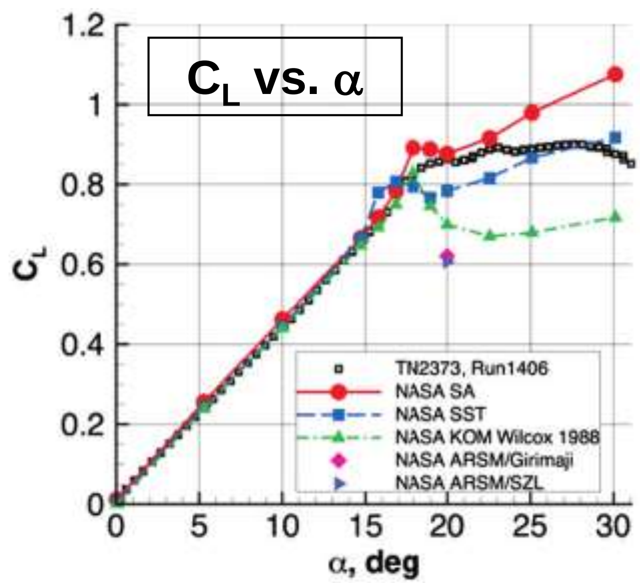
NATO RTO Assessment of RANS CFD *(2012)*

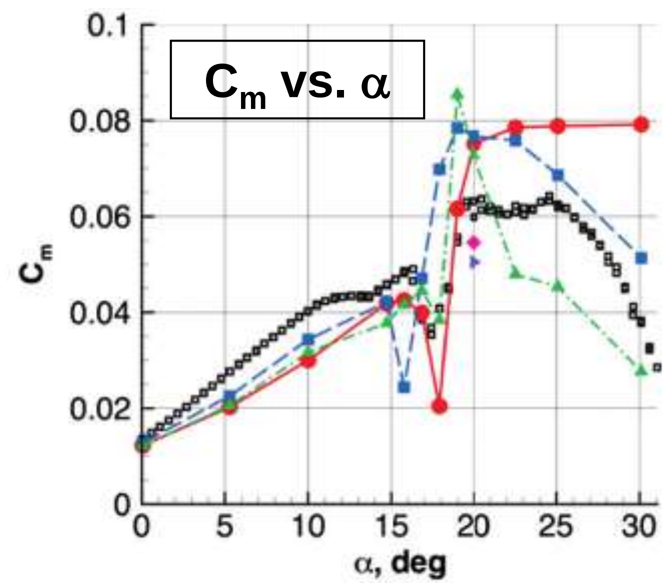
TetrUSS simulations by Frink et al, *AIAA Journal of Aircraft, 2012*

NATO RTO AVT-161: **S**tability **A**nd **C**ontrol **CON**figuration (SACCON)

M = 0.149; α = 0° to 30°; Re = 1.6x10⁶







Wide variation in data among state-of-the-art turbulence models!

Laminar-to-turbulent transition modeling: yet another challenge!

Predictions are NOT Credible for Flows with Separation and/or Free Vortices

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Source: Ref. 6.1.2

RANS-based ACA:
The Overarching Challenge

PRODUCING CREDIBLE SOLUTIONS

Assessing and Overcoming this Challenge
Has Been a Constant Focus of
the ACA Community Ever Since the Early 2000s

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Assessment of RANS Predictions: *Absolute (Total) Drag*

AIAA CFD Drag Prediction Workshops (DPWs)

- **Formally initiated in 2000**; seven (7) workshops to date: 2001, 2003, 2006, 2009, 2012, 2016, and 2022; numerous publications
- **Primary Goal:** *Assess state-of-the-art CFD methods as practical aerodynamic tools for the prediction of forces and moments on industry-relevant geometries, with a focus on absolute drag.*
- **Test Cases:** *Variants of commercial transport wing-body configurations; transonic flows; many meshes and flow-solvers; multiple turbulence models*

Importance of Accurate Prediction Cannot Be Over Emphasized!

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Source: Ref. 6.1.3

Importance of Accurate Drag Estimation

C-141 Cruise Drag (early 1960s)

- **Total Drag predicted based on wind-tunnel tests was within *One Count (0.0001) of flight data…***

  …but good agreement was due to Compensating Errors!
  - Minimum Profile Drag: *underpredicted*
  - Compressibility Drag: *overpredicted*

- **DoD Aeronautical Test Facilities Assessment Team (1997)**
  - *Question*: **Can we do better with improved wind-tunnel test techniques combined with CFD?**
  - *Answer*: **Cruise drag would be underpredicted by 3.5%**
    - *Considering only Reynolds Number Scaling*
      - *Minimum Profile Drag Underprediction—about eight (8) counts*
      - *Compressibility Drag Overprediction—eliminated*

Erroneous Predictions would Increase Fuel Cost by $688M (FY96 dollars) for Entire Fleet over Service Life

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Source: Ref. 6.1.4

Importance of Accurate Drag Estimation

C-5 Cruise Drag (mid 1960s)

- **Total drag overpredicted by 2.5% based on wind-tunnel tests**
  - Minimum Profile Drag*: underpredicted by one scale-up method and correctly predicted by another*
  - Compressibility Drag*: overpredicted*
- **DoD Aeronautical Test Facilities Assessment Team (1997)**
  - *Question*: **Can we do better with improved wind-tunnel test techniques combined with CFD?**
  - *Answer:* **Cruise drag would be underpredicted by 1.5%**
    - *Considering only Reynolds Number Scaling*
      - Minimum Profile Drag Underprediction—*1% to 3%*
      - Compressibility Drag Overprediction—*eliminated*

Erroneous Predictions would Increase Fuel Cost by $153M (FY96 dollars) for Entire Fleet over Service Life!

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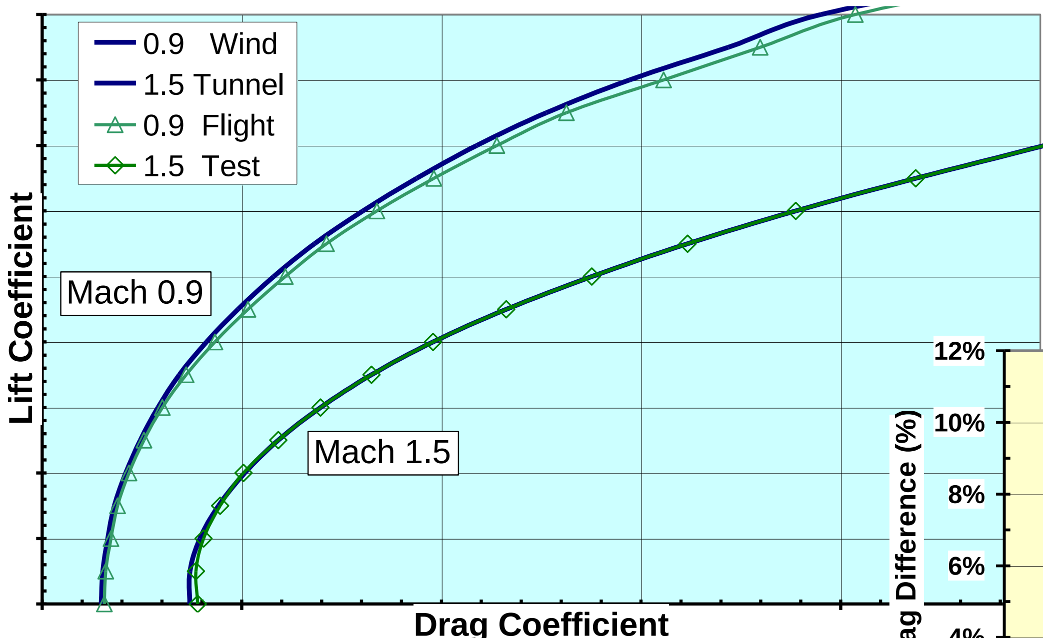
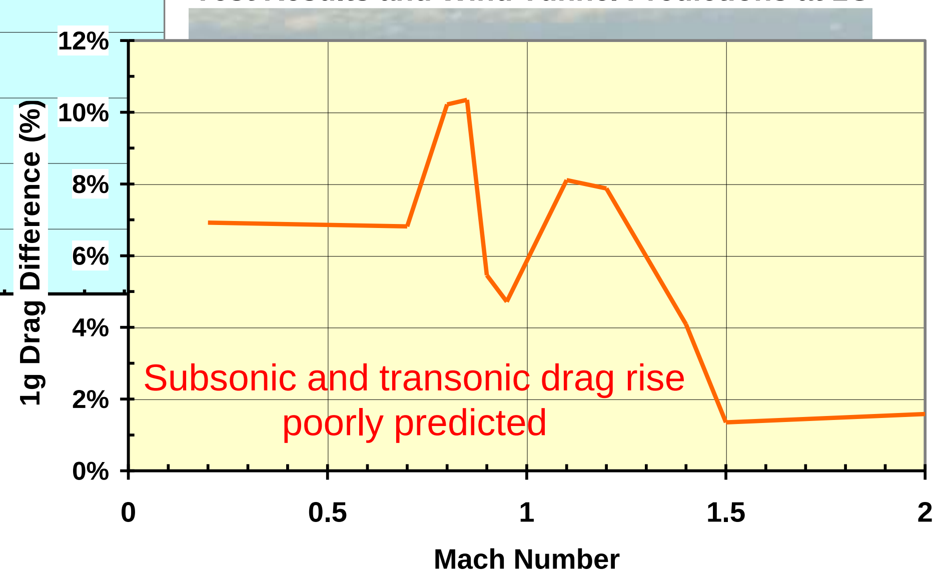
Source: Ref. 6.1.4

Importance of Accurate Drag Estimation

F-22 Cruise Drag Example (1990s)



Percent Drag Difference between Preliminary Flight Test Results and Wind Tunnel Predictions at 1G



- **Drag predicted using wind-tunnel tests matched well with flight test data for Mach 0.9 and 1.5**

- **Differences may be due to a combination of interpolated pieces**
  - Thrust effects, auxiliary inlet and vents, control surface scheduling

Poor Drag Predictions Impacted Accelerations, Decelerations, Cruise and Loiter Performance

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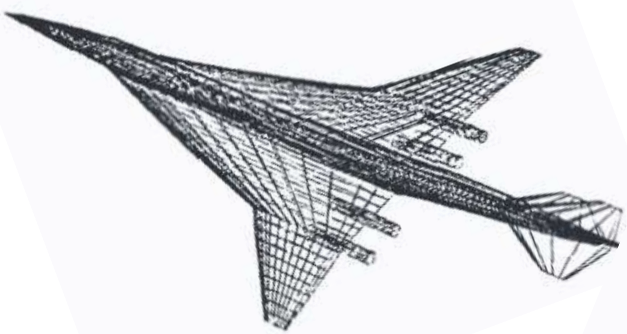
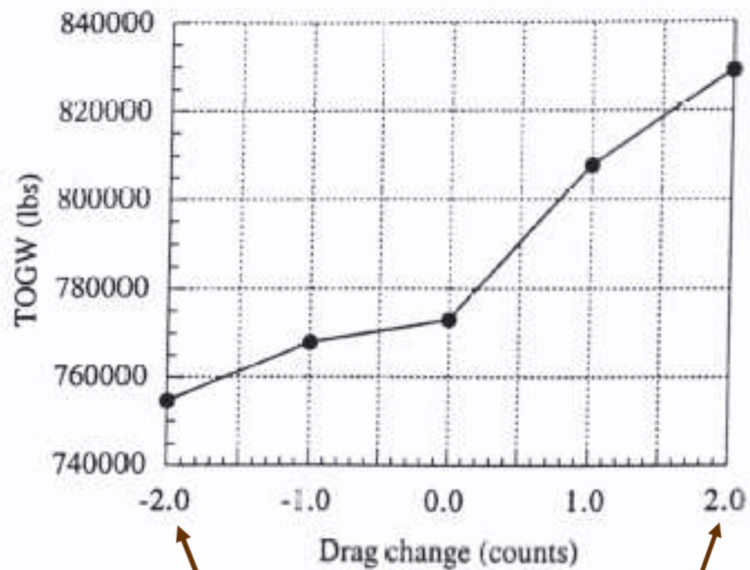
Source: Ref. 6.1.5

Importance of Accurate Drag Estimation

HSCT Conceptual Design MDO Study (mid 1990s)

- **High Speed Civil Transport**
  - *Cruise Mach Number: 2.4*
  - *Range: 5,500 nm*
  - *Payload: 250 passengers*





- TOGW = 772,907 lbs.
- Fuel Weight Fraction = 0.52
- Empty Weight Fraction = 0.39
- Aspect Ratio = 2
- $(L/D)_{max}$ = 9.16

TOGW = 754,560 lbs.

TOGW = 829,100 lbs.

Just Two-count Cruise Drag Overestimation Increases Take-Off Gross Weight by More Than 7%!

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Source: Ref. 6.1.6

AIAA 6th CFD DPW (2016)

Some Interesting Findings: Tinoco et al, *Journal of Aircraft, 55 (4), 2018*

- **NASA Common Research Model (CRM) Wing-Body (WB)**
  - M = 0.85; Re = 40 million; C_L = 0.5
  - 54 datasets; multiple turbulence models
  - *Solutions exhibited "tighter" convergence of total drag with a spread of less than 10 counts [1 count = 0.0001]*

- **NASA CRM WB Static Aeroelastic Effect**
  - *Higher lift predicted at a given angle of attack, and more negative (nose down) pitching moment at a given lift coefficient than observed in test data.*
- **NASA CRM Wing-Body-Nacelle-Pylon**
  - *Drag increment predicted within the uncertainty of the test data… this is of significant importance to industry design processes*

"One must ask if steady RANS is adequate for modeling this flow regime [with shocks and uffet]. Will URANS be adequate, or must one go to an eddy resolving method such as detached Eddy simulation to accurately simulate this flow regime?"

Source: Ref.6.1.7

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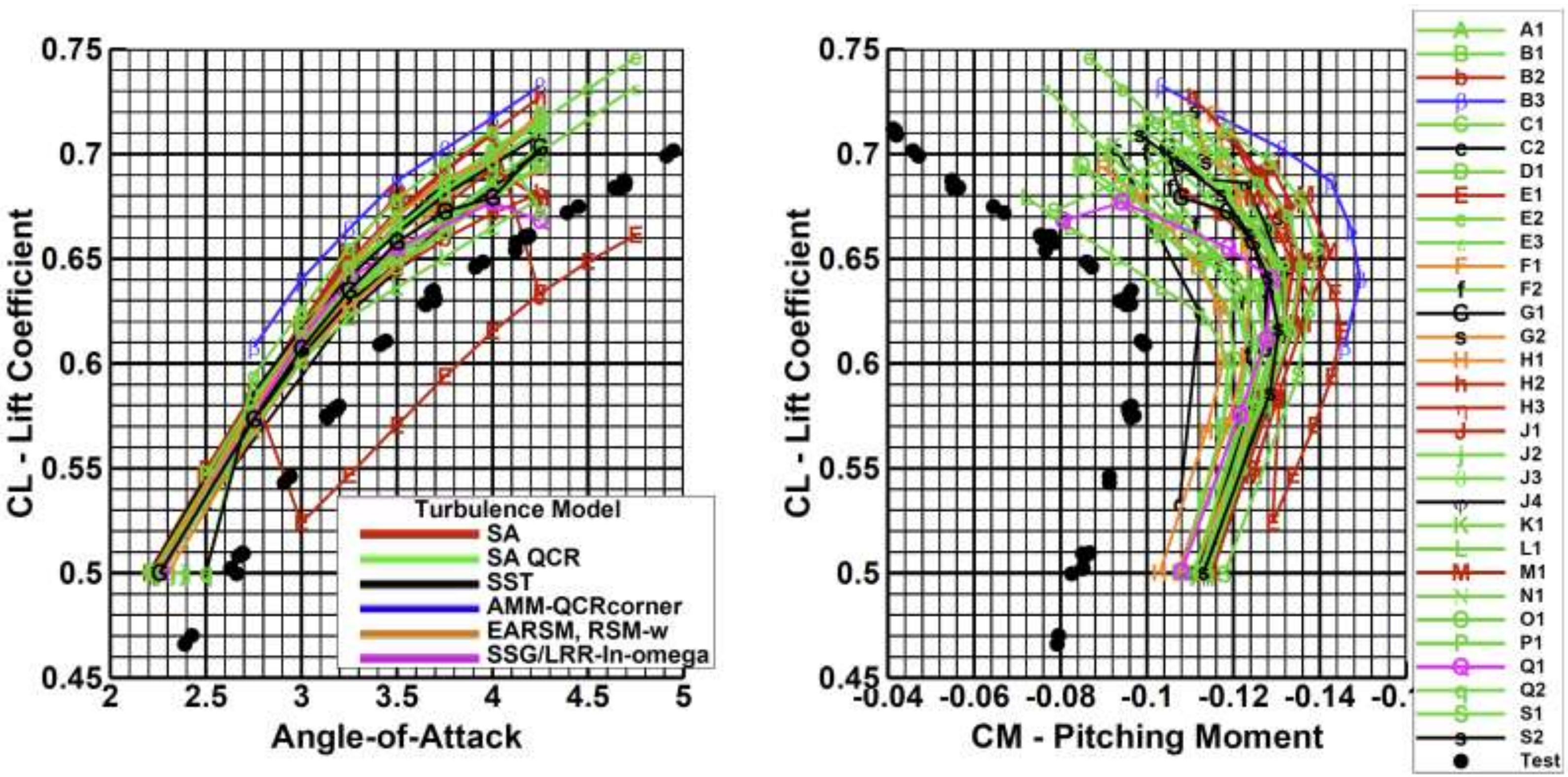
AIAA 7th CFD DPW (2022): *Case 2a*

- **Wing-Body static aeroelastic/buffet study**
  - ***Investigate CFD predictions where significant flow separation is expected [around $\alpha = 4^o$]***
  - **M = 0.85; Re = 20 million; α sweep, 2.50^o to 4.25^o in 0.25^o increments**
  - **29 datasets; six turbulence models**

NASA Common Research Model (CRM)



Source: Ref. 6.1.8

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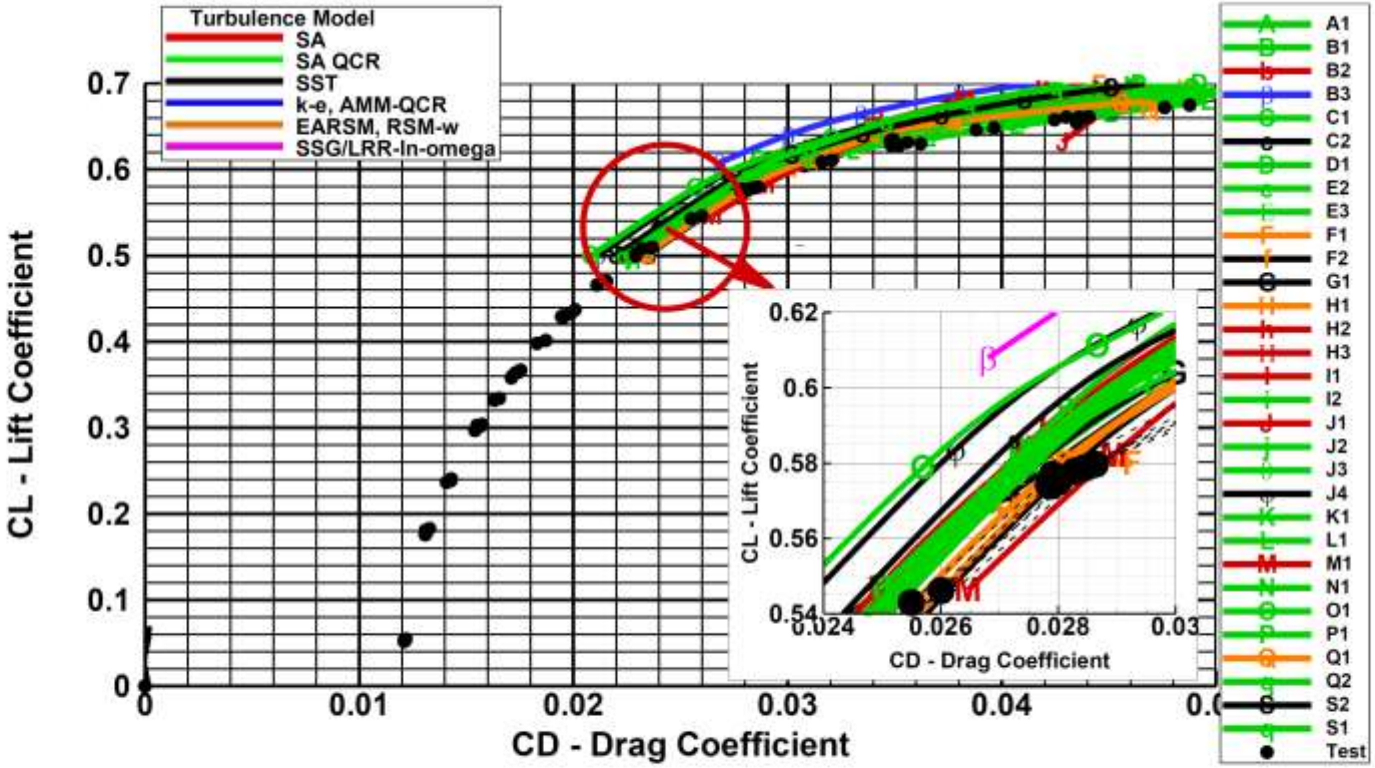
AIAA 7th CFD DPW (2022): *Case 2a*

- **Wing-Body static aeroelastic/buffet study:**
  - **M = 0.85; Re = 20 million; Alpha sweep, 2.50º to 4.25º in 0.25º increments**
- ***Investigate CFD predictions where significant flow separation is expected***
  - **29 datasets; six turbulence models**

NASA Common Research Model (CRM)



Drag characteristics plotted in terms of idealized profile drag: $C_{DP} = C_D - C_L^2/(\pi\ AR)$

Source: Ref. 6.1.8

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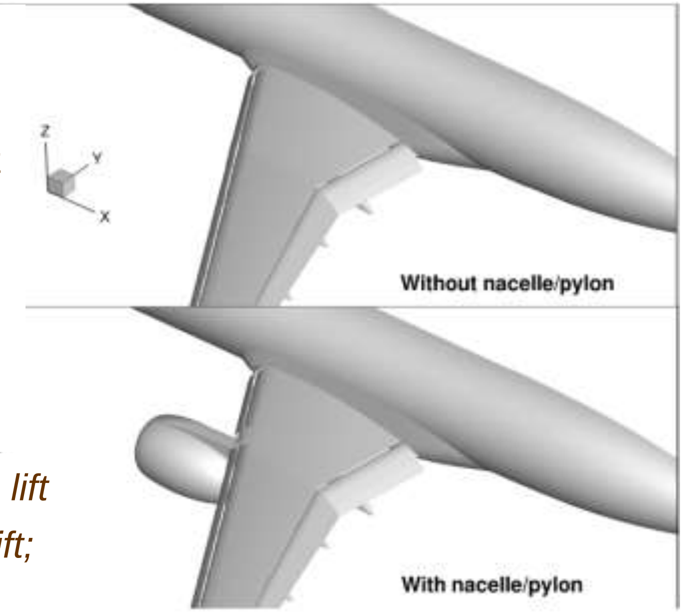
Assessment of RANS Predictions: *High-Lift Configurations*

AIAA High Lift Prediction Workshops (HLPWs)

- **Formally initiated in 2009**; four (4) workshops to date: 2010, 2013, 2017, 2022; numerous publications
- **Primary Goal:** *Assess the numerical prediction capability (mesh, numerics, turbulence modeling, high-performance computing requirements, etc.) of current-generation CFD technology for swept, medium/high-aspect ratio wings in landing/takeoff (high lift) configurations.*
- **Test Cases:** *Variants of commercial transport configurations; subsonic flows; variety of grid systems and flow solvers; multiple turbulence models*
- **Interesting Findings from 3rd HiLiftPW**: Rumsey et al, *AIAA 2018-1258*
  - JAXA Standard Model High-lift Configuration with and without Pylon/Nacelle
    - ✓ *Fairly tight clustering of results in the linear lift-curve range, and very large scatter in results near maximum lift*
    - ✓ *Differences between nacelle/pylon on and off were well predicted in general*
    - ✓ *Significant influence of grid for the solutions near maximum lift*
    - ✓ *Transition model results were inconsistent near maximum lift; reasonable results for the wrong reasons!*



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Source: Ref. 6.1.9

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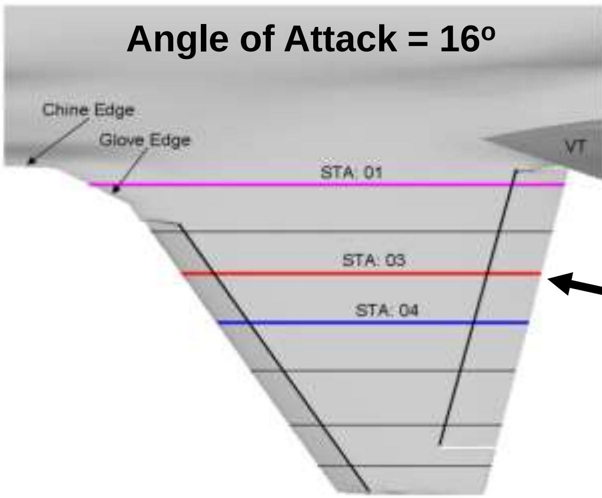
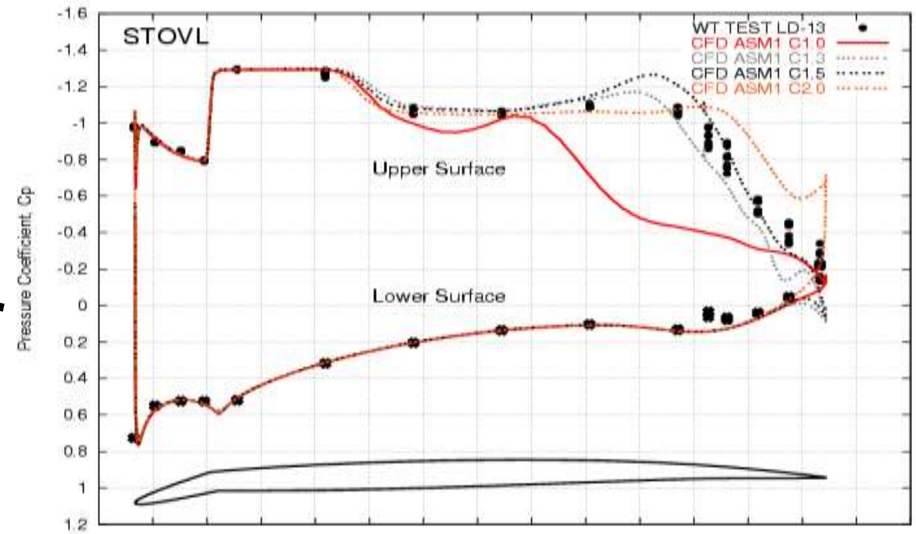
Two Key Factors Hamper Credibility of RANS Predictions

1. Numerical Models



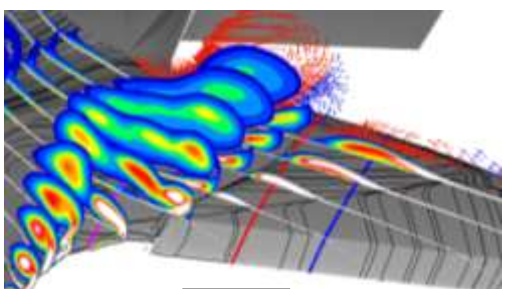
Example: *Solution sensitivity to compression factor in limiter function in MUSCL* scheme of Falcon V3.4 code*



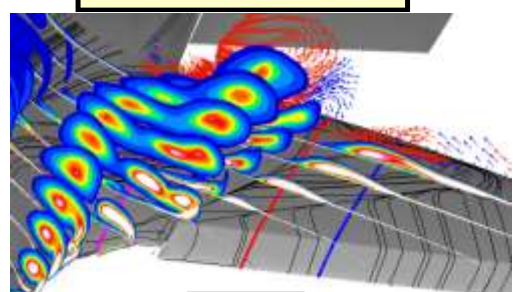
2. Turbulence Models

Example: Solution Sensitivity to Turbulence Modeling

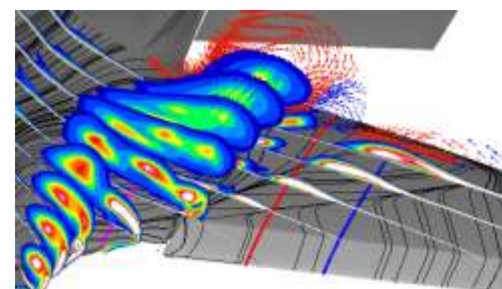
VORTICITY MAGNITUDE



K-KL



ASM1



ASM2

"All Models are Wrong, But Some Models are Useful!" -- George Box, 1997

ASM - Algebraic Stress Model

**M*onotonic *U*pstream-centered *S*cheme for *C*onservation *L*aws

Source: Ref. 6.1.10

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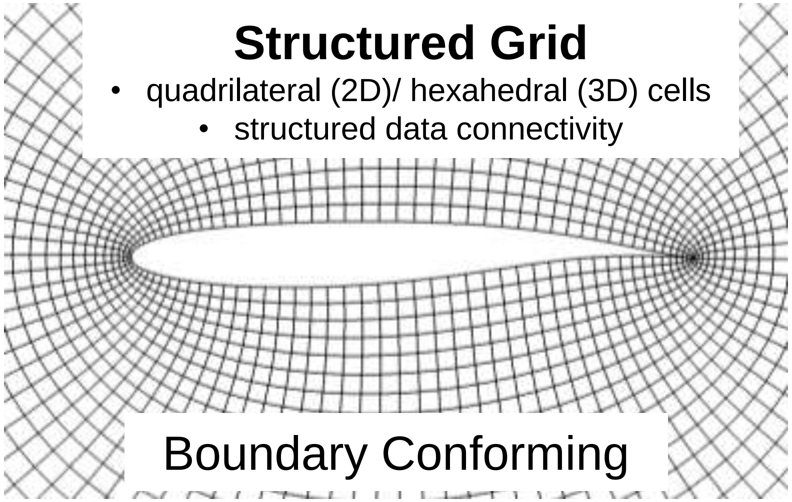
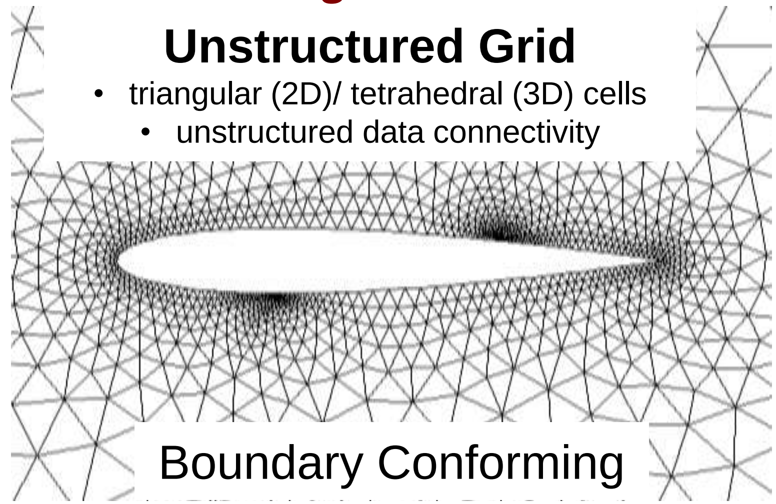
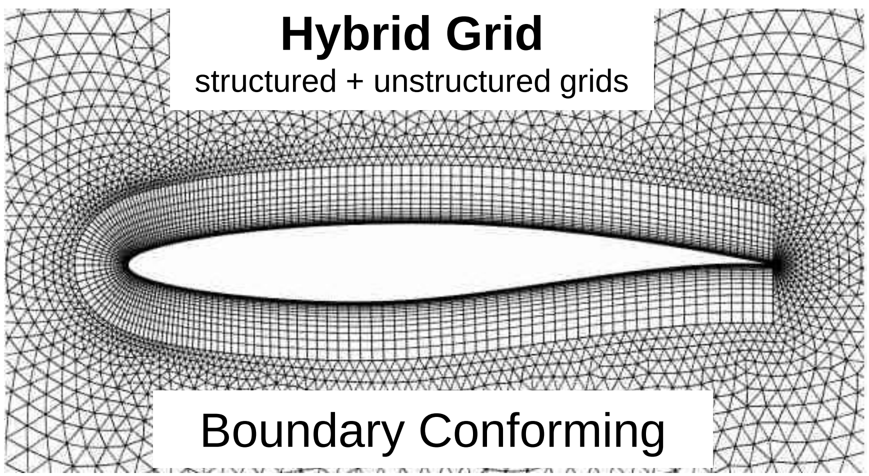
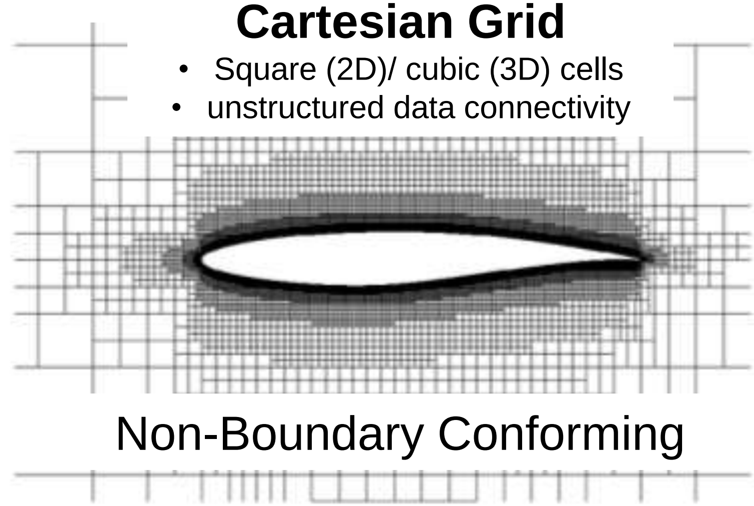
No Shortage of Grid Types

To Discretize the Spatial Domain for Numerical Modeling of Euler/RANS PDEs









***Discretization errors** contribute to differences between computed and exact solutions*

Difficult to Assess Errors: Exact Solution Not Known a Priori

Image Source: Internet; also Ref. 6.1.11

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No Shortage of Numerical Algorithms

For solving Euler & RANS PDEs on Different Types of Grids!

Year	Developer(s)	Scheme
1969	MacCormack	Two stage scheme for hyperbolic equations
1973	Boris & Book	Flux Corrected Transport (FCT) oscillation control via slope limiters
1974	Van Leer	Higher-order Godunov scheme - MUSCL
1981	Steger & Warming	Flux splitting
1981	Jameson, Schmidt, Turkel	Shock capturing via controlled diffusion – full convergence to steady state
1981	Ni	Multigrid Euler solver
1983	Roe	Approximate Riemann solver
1983	Harten	Theory of Total Variation Diminishing (TVD) schemes
1983	Jameson	Agglomeration multigrid full approximation storage (FAS) scheme for Euler equations
1985-86	Jameson, Baker, Weatherill	Airplane Code: 3D Euler equations on unstructured mesh – edge based data structure
1986-88	Yoon-Jameson	Lower-Upper Symmetric Gauss Seidel (LU-SGS) scheme
1987	Harten, Engquist, Osher, Chakravarthy	Essentially Non-Oscillatory (ENO) scheme
1990	Cockburn & Shu	Local Discontinuous Galerkin (LDG) method
1991	Jameson	Multigrid dual time stepping scheme for unsteady flow
1993	Liou	Advection Upstream Splitting Method (AUSM) scheme
1994	Jameson	Theory of Local Extremum Diminishing (LED) scheme
1994-96	Liu, Osher, Chan, Shu	Weighted ENO (WENO) scheme
2001	Jameson-Caughey	Nonlinear Symmetric Gauss-Seidel (SGS) multigrid scheme

Minimize Truncation, Dispersive, and Dissipation Errors

Source: Ref. 6.1.12

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No Shortage of Turbulence Models

For RANS Equations

- **Zero-equation models**
  - Cebeci-Smith (1967) and Baldwin-Lomax (1978): *two layer, algebraic*
- **Half-equation models**
  - Johnson-King (1985): *ODE to specify shear stress level*
- **One-equation models**
  - Baldwin-Barth (1990) and Spalart-Allmaras (1992): *turbulent kinetic energy*
- **Two-equation models**
  - Jones-Launder (1972): k-ε (*turbulent kinetic energy and turbulent dissipation)*
  - Wilcox (1988): k-ω; Smith (1990): k-$k\ell$; Menter (1993): SST* k-ω
- **Explicit Algebraic Reynolds Stress Models (EARSM or ASM)**
  - Gatzki-Speziale (1993); Girimaji (1996)
- **Reynolds Stress Transport Models (RSTM or RSM)**
  - Speziale-Sarkar-Gatski (1991)

"It is quite clear that no model is universal, giving good results for all flows of interest."

Peter Bradshaw, FRS, Imperial College & Stanford, 1999

*Shear Stress Transport

Source: Ref. 6.1.13

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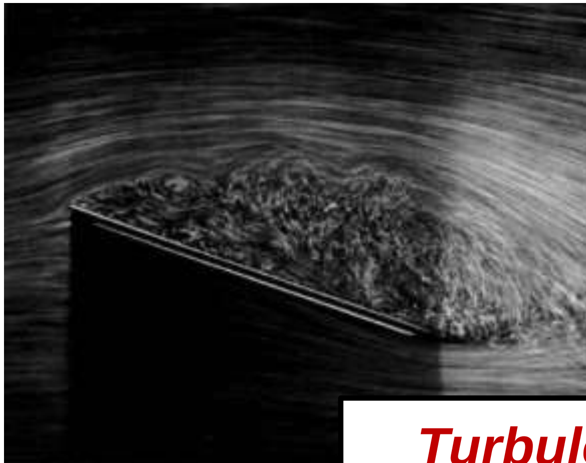
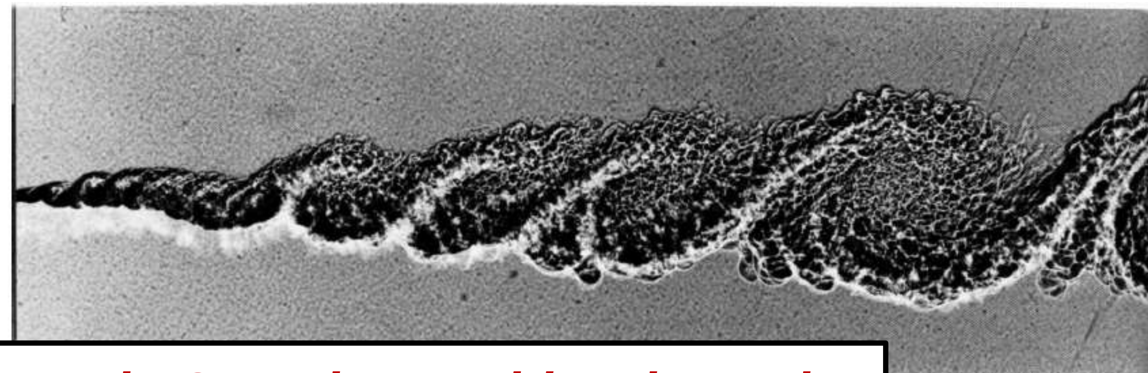
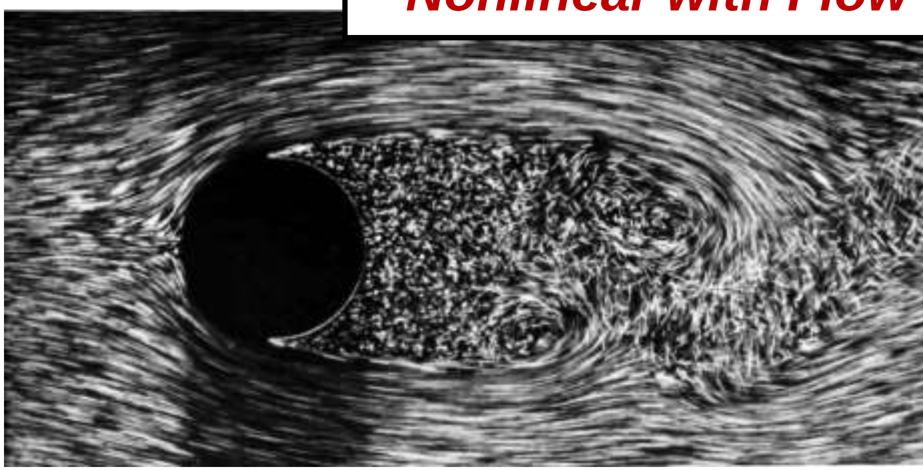
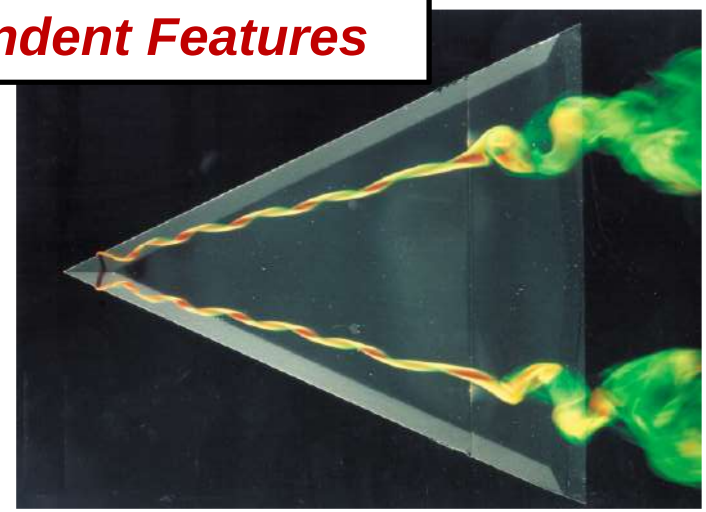
Why Turbulence Modeling is a Huge Challenge?





Turbulence is Complex, Multiscale, and Nonlinear with Flow-dependent Features





Accurate Modeling of <u>Complex, Multiscale, Nonlinear</u> Phenomena with a Few Free Parameters is an <u>Extremely Long Shot Indeed</u>

Source: Ref 6.1.14

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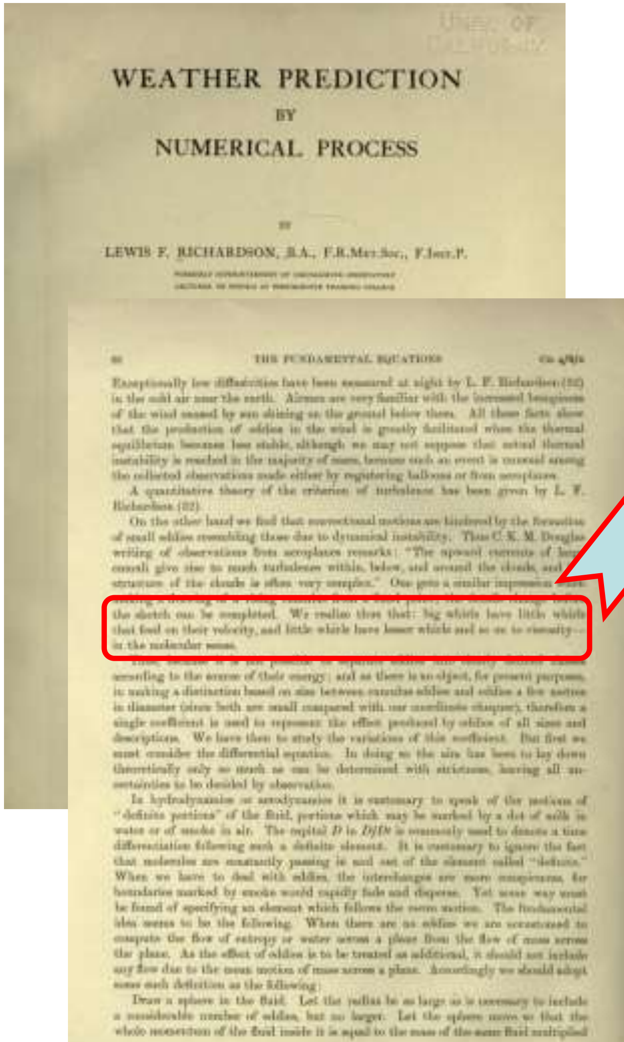
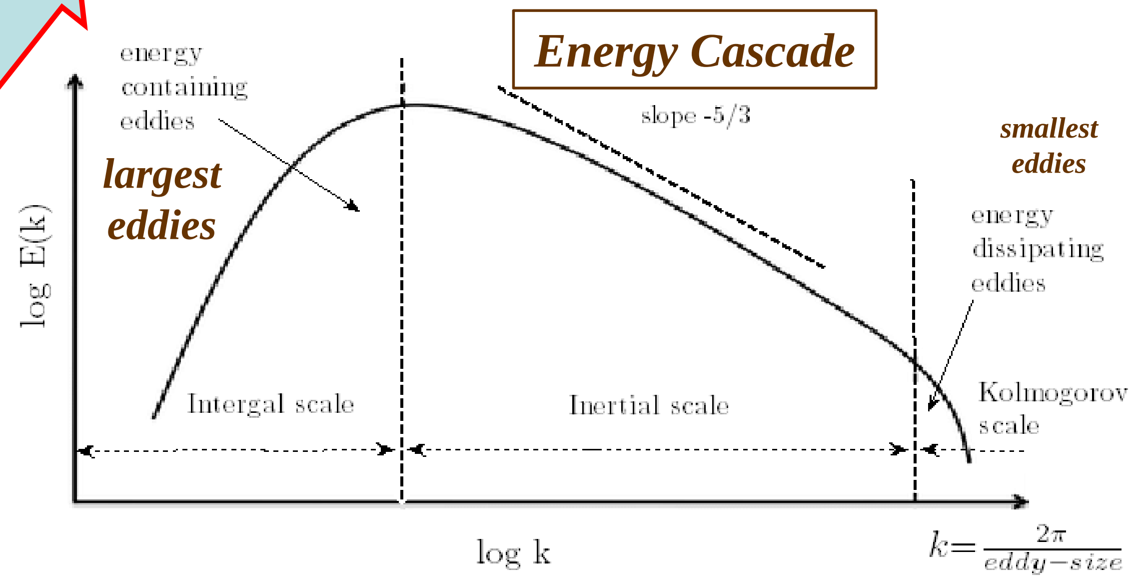
Fundamental Nature of Turbulence



"big whirls have little whirls
that feed on their velocity,
and little whirls have lesser whirls
and so on to viscosity"

Lewis F. Richardson, 1922



Multiscale in Space and Time!

Ratio of the Largest to Smallest Length Scale in Turbulent Flows is ~ $Re^{3/4}$
(Re based on the largest eddy)

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Source: Ref. 6.1.15 and 6.1.16

How Complex is Turbulence?

"I am an old man now, and when I die and go to Heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am really rather optimistic."

Sir Horace Lamb
Address to British Association for the Advancement of Science
London, U.K., 1932

27 Nov 1849 – 4 Dec 1934

Turbulence Has Been the Bane of Fluid Dynamicist's Existence—Seemingly Forever!

Leonardo da Vinci, Flow behind obstacle, **ca. 1510 – 1513**, (from Royal Collection Trust, London, UK)

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Source: Ref. 4.4

What's the Dominant Contributor to Error in RANS Solutions?

Is it the Mesh, the Solver, or the Turbulence Model?

Ollivier-Gooch, *AIAA 2019-1334*

Interesting Findings from ["Crude"] Statistical Analysis

- ***Approach:*** 39 datasets from Third High-Lift Prediction Workshop (2017) and 31 datasets from Fifth Drag Prediction Workshop (2016) matched into groups based on three primary variables: mesh, flow solver, and turbulence model.
- ***"Crude" statistical analysis*** due to sparse amount of data in each group.
- ***Qualitative Conclusions***
  - **Mesh and turbulence model appear to have about equally large impacts on outputs**.
    - ✓ Results of different mesh sets with the same flow solver and turbulence model differed about as much as the average results for the three groups varied from each other!
  - Even with relatively fine meshes used, there are still **flow features resolved by some meshes and not others.**
  - **Flow solver is at least as big a difference as other factors.**
    - ✓ Community needs to do a better job of *verification* of numerical model and turbulence model implementations.
  - **User selected input parameters can cause significant variation in output values**.
    - ✓ Improved user training can help.

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Source: Ref. 6.1.17

Author's Assessment of the Effectiveness of RANS-based ACA

RANS-based ACA is Unlikely to be Fully Effective Anytime Soon, If Ever!

With Advances in High Performance Computing (HPC) and Numerical Modeling, Effectiveness of RANS-based ACA Will Steadily Increase, But RANS Will Not Produce Credible Data Due to Turbulence [and Transition] Modeling Deficiencies.

"It is the mark of an educated man to look for precision in each class of things just so far as the nature of the subject admits." – Aristotle

Source: Internet for image and quote

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An Expert's Assessment

"…the state of aeronautical CFD makes difficult to evade the conclusion that a decisive improvement in turbulence accuracy must be achieved before CFD becomes general."

"…the author [Spalart] deems it unlikely that a RANS model, even complex and costly [RSTM], will provide the accuracy needed in the variety of separated and vortical flows we need to predict."

Philippe R. Spalart

Senior Technical Fellow
Boeing Commercial Airplanes

"…it is more than plausible that Reynolds averaging suppresses too much information, and that the only recourse is to renounce it to some extent, which means calculating at least the largest eddies simply for their nonlinear interaction with the mean flow."

Source: Ref. 6.1.18

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Section 6.1
Overarching Takeaways

"What We Simulate is Not Reality Itself, But Reality Determined by Our Models"

Prediction of Aerodynamic Characteristics Isn't That Hard…Making Credible Prediction Is!

And It's Really Hard Under Stringent Cost and Schedule Constraints!

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Section 6.1: Key Takeaways (1 or 2)

- **Impressive RANS-based ACA capability demonstrations in the 2000s, but effectiveness '*Less Than Satisfactory*'**
- **Reliable use of RANS limited to cruise part of flight envelope—hence less than satisfactory effectiveness (Boeing Assessment, 2005)**
- **RANS predictions not always credible, especially for complex flows dominated by separation and free-vortices (NATO RTO Assessment, 2012)**
- **Overarching challenge for RANS-based ACA: PRODUCING CREDIBLE SOLUTIONS**
- **Aerospace Professional Community initiatives to systematically assess RANS CFD capabilities and shortcomings**
  - AIAA CFD Drag Prediction Workshops—the first one in 2001
    - *Accurate prediction of drag is of critical importance to design teams*
  - AIAA High Lift Prediction Workshops—the first one in 2009
- **Two factors hamper credibility of solutions:**
  - (1) Numerical Models; and (2) Turbulence Models
- **Numerical Models—No shortage of options for grids to discretize spatial domain, and for numerical algorithms to solve Euler/RANS PDEs on the various types of grids**
  - *Solution of discretized equations is not necessarily a solution of the differential equation!*

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Section 6.1: Key Takeaways (2 of 2)

- **Turbulence Modeling**
  - No shortage of turbulence models ranging from simple algebraic to complicated Reynolds stress transport (RSTM)
  - Accurate modeling of Complex, Multiscale, Nonlinear turbulence using a few free parameters is an extremely long shot indeed
- **RANS-based ACA is Unlikely to be Fully Effective Anytime Soon, If Ever!**
  - *"…[Spalart] deems it unlikely that a RANS model, even complex and costly [RSTM], will provide the accuracy needed in the variety of separated and vortical flows we need to predict."*

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So what are the Prospects for

Fully Effective ACA?

We address this question in the next section.

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Contents

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Future Prospects of Effective CFD

If RANS cannot provide credible solutions, what are the other options that could possibly be used to computationally simulate turbulent flows?

Typical Commercial Transport Aircraft Wing

AR = 12, Re_x = 50 million

	RANS (Reynolds-Averaged Navier-Stokes)	DES (Detached Eddy Simulation)	LES (Large Eddy Simulation)	DNS (Direct Numerical Simulation)
Level of Empiricism	**High**	**Medium**	**Low**	**None**
Unsteady Flows	**No**	**Yes**	**Yes**	**Yes**
# of Grid Points	**10^7**	**10^7 to 10^8**	**10^{11}**	**10^{20}**
Feasibility Demonstration	**1995**	**2010**	**2045***	**2080***

*Estimated feasibility demonstration time frame assuming Moore's Law will still hold!

Note: Dense grids also need extra time steps—hence *much more computational time*!

DNS, With No Empiricism, Is the Only Option for Fully Effective CFD

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DNS and LES Grid Requirements

- **DNS**: Grids must be fine enough to accurately resolve small-scale eddies

  DNS computational domain for flat plate turbulent boundary layer $L_x \times \delta \times L_z$

  # of grid points: $N_{DNS} = 0.000153 \frac{L_z}{L_x} Re_{L_x}^{37/14} \left[1 - \left(\frac{Re_{x_0}}{Re_{L_x}} \right)^{23/14} \right]$

  x_0 is streamwise location beyond which flow is turbulent

- **WR-LES** (Wall Resolved LES): small-scale eddies near the wall accounted for by inherent numerical dissipation [aka implicit LES or ILES]
- **WM-LES** (Wall Modeled LES): small scale eddies near the wall modeled using sub-grid-scale (SGS) models

Airfoil: *LES computational domain for turbulent boundary layer, no separation*

Aspect Ratio 4, $Re_{x0} = 5 \times 10^5$

Re_c	N_{wm}	N_{wr}
10^6	3.63×10^7	5.23×10^7
10^7	8.20×10^8	7.76×10^9
10^8	9.09×10^9	5.98×10^{11}
10^9	9.26×10^{10}	4.34×10^{13}

Haecheon Choi and Parviz Moin, *"Grid-point requirements for large eddy simulation: Chapman's estimates revisited" Physics of Fluid*, 24, Jan 2012

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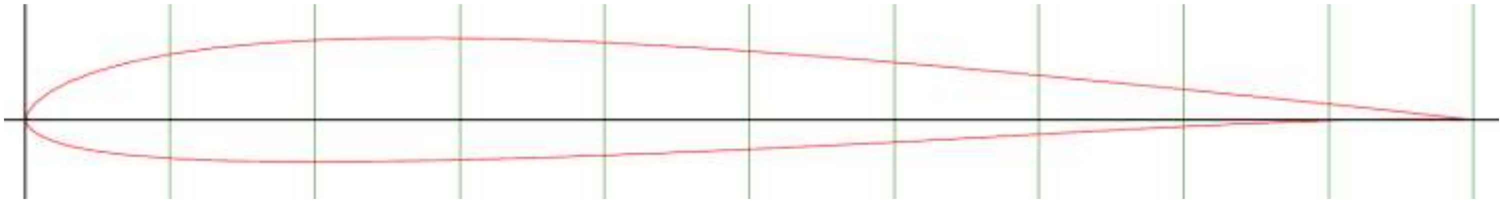
DNS and LES of Flow Past an Airfoil:
An Example

Selig/Donovan SD7003 Low Reynolds Number Airfoil

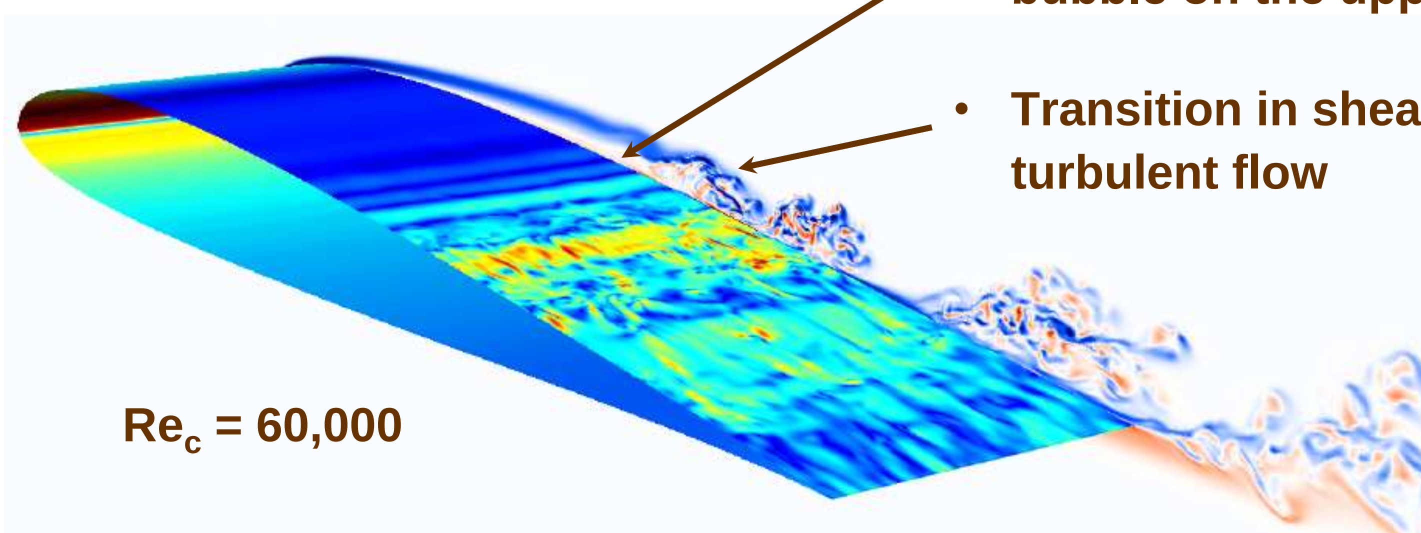


Max thickness 8.5% at 24.4% chord Max camber 1.2% at 38.3% chord
Source: UIUC Airfoil Coordinates Database

Typical Flow Features

M = 0.1 $\alpha = 4^{o}$

- **Fairly stable laminar separation bubble on the upper surface**
- **Transition in shear layer leads to turbulent flow**



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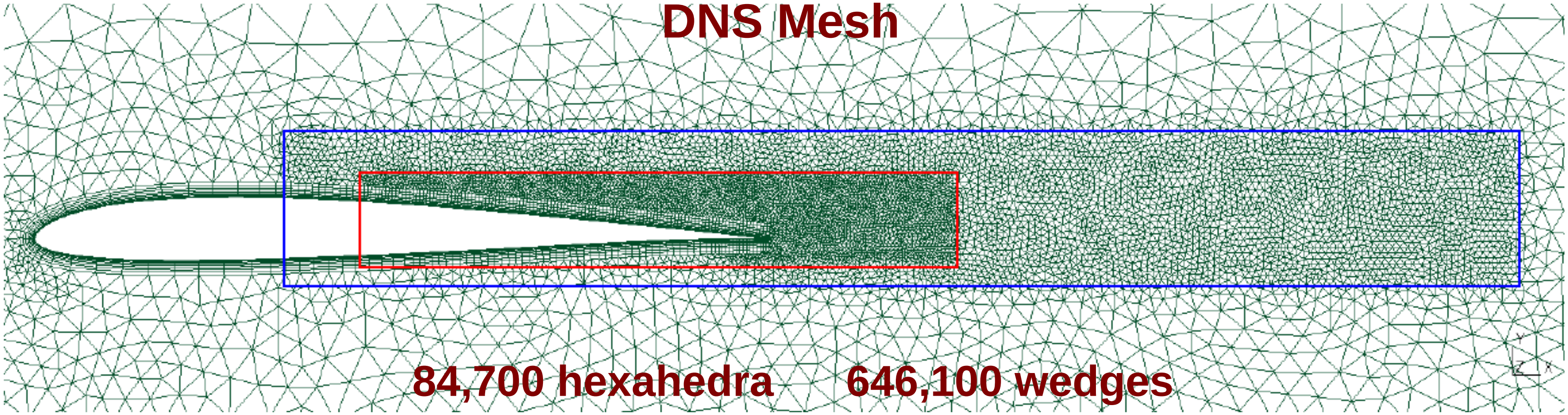
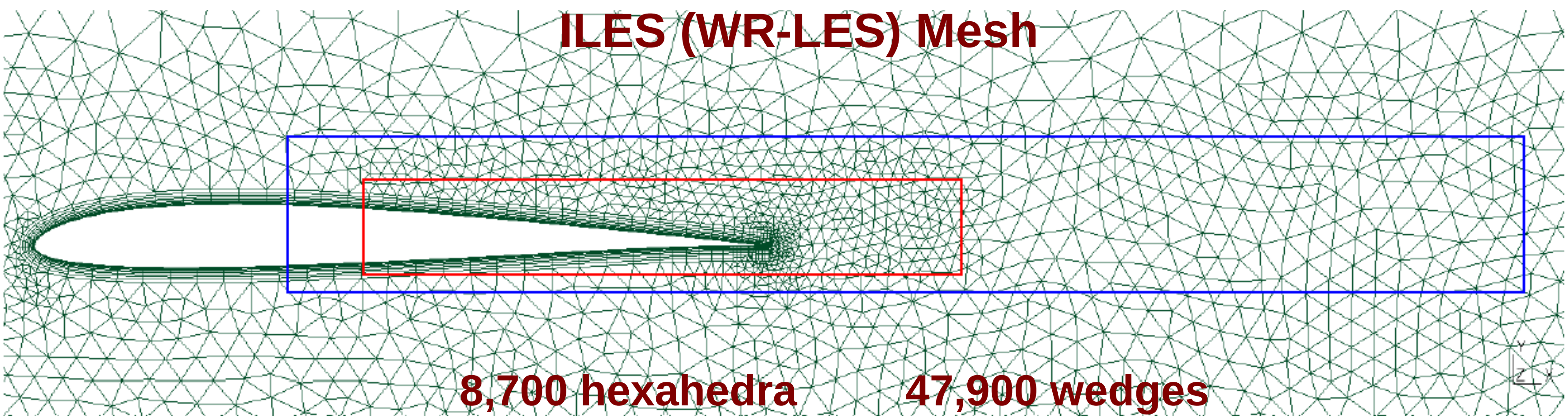
DNS and LES of Flow Past an Airfoil

SD7003 Low Reynolds Number Airfoil **$M = 0.1$, $\alpha = 4^o$, $Re_c = 60{,}000$**

AR = 0.2 **Far-field boundary at 100 chords**



DNS requires much denser grids than LES!



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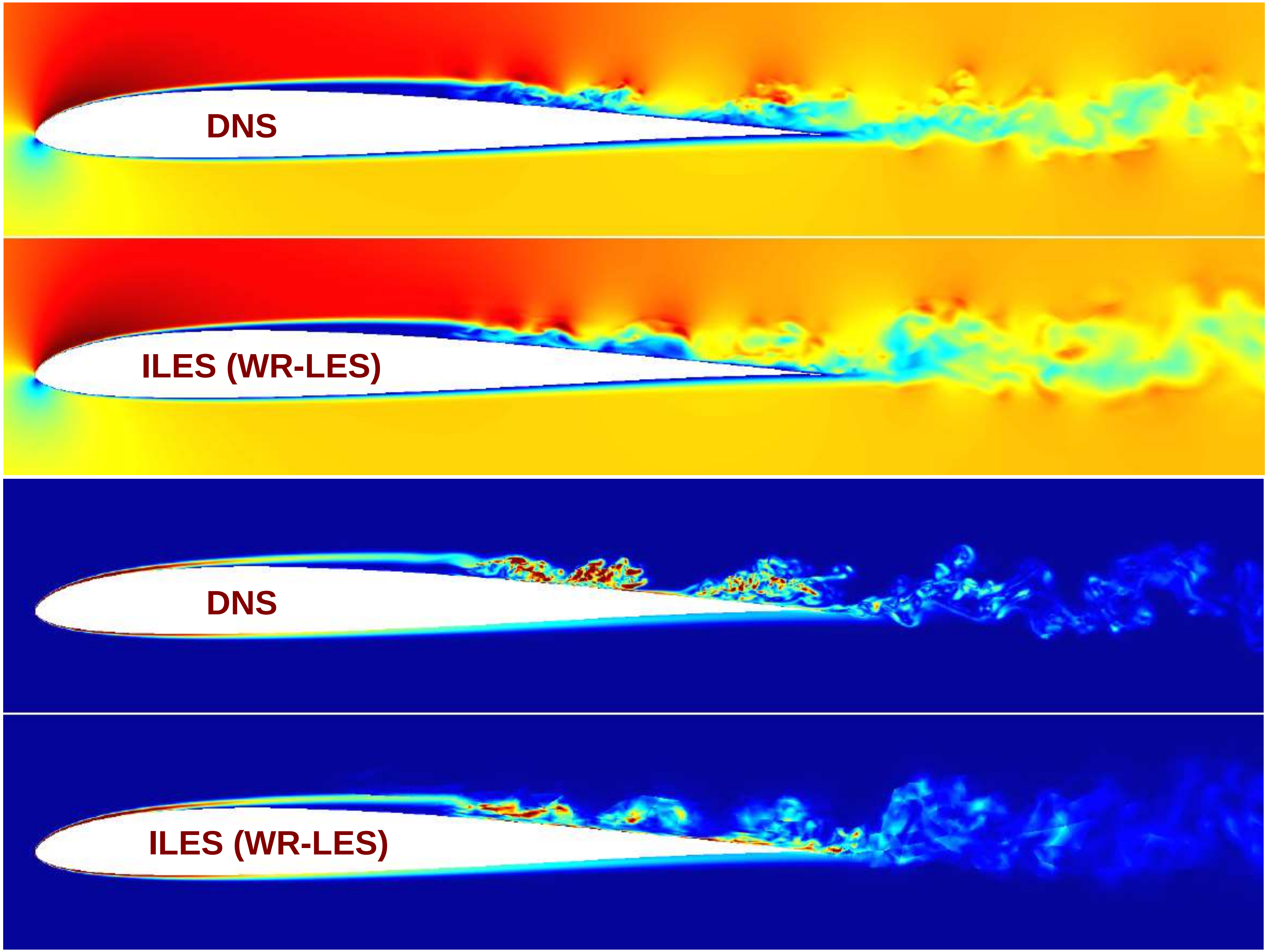
DNS and LES of Flow Past an Airfoil

SD7003 Low Reynolds Number Airfoil **M = 0.1, α = 4°, Re_c = 60,000**

Snapshot of **Velocity** norm

Snapshot of **Vorticity** norm



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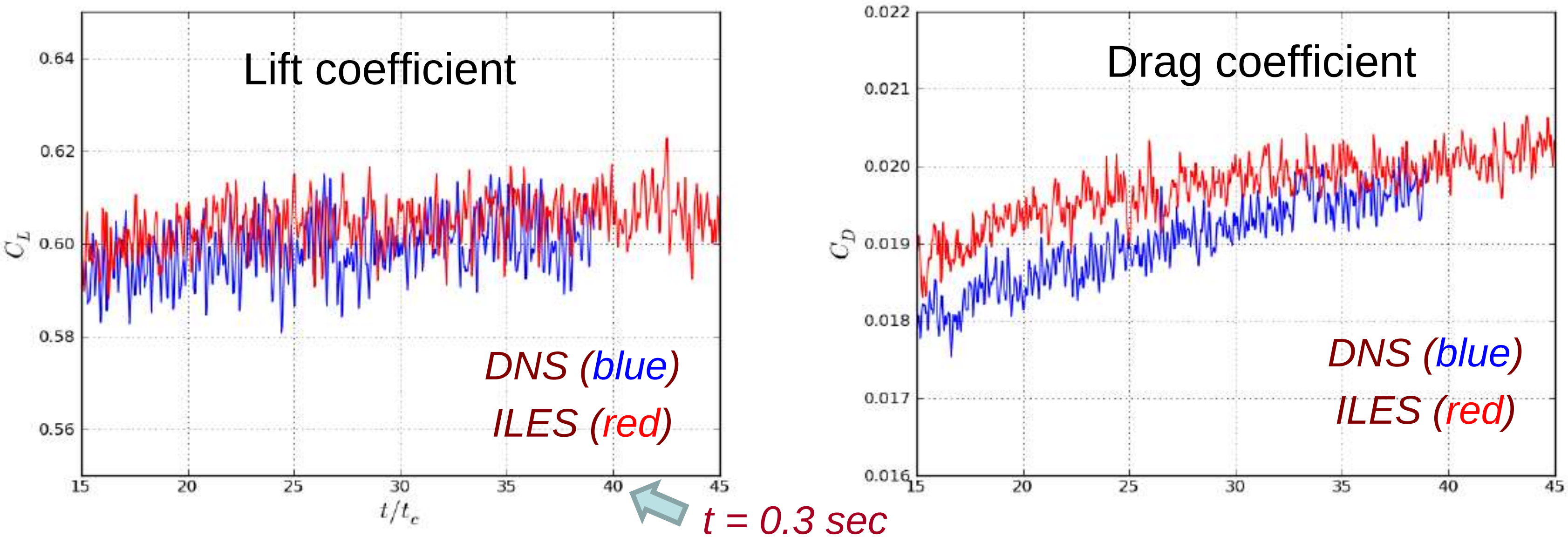
DNS and LES of Flow Past an Airfoil

SD7003 Low Reynolds Number Airfoil $M = 0.1, \alpha = 4^o, Re_c = 60,000$

Temporal evolution of lift and drag coefficients



t = 0.3 sec

	DNS	ILES	XFoil	Expt. (TU-BS)	Expt. (AFRL)
Freestream Turbulence	0	0	*(N_{crit} = 7.5)*	0.08%	~ 0.1%
C_L *(mean)*	0.602	0.607	0.583	-	
C_D *(mean)*	0.0196	0.020	0.0181	-	
Separation (x_{sep}/c)	0.209	0.207	0.26	0.30	0.18
Reattachment (x_r/c)	0.654	0.647	0.57	0.62	0.58
CPU-Hrs* for one t_c	**11,001**	**415**	-	-	

Note: $t_c = c/U_\infty$ is convective time; $t_c = 7.6\text{x}10^{-4}$ sec (est.)

DNS took 25X more CPU time than ILES for one t_c

*16,000 CPUs on "Jugene" (https://en.wikipedia.org/wiki/JUGENE)

Source: Ref. 6.2.4 & 6.2.5

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DNS can produce credible solutions but it will require incredible reduction in turnaround time and total cost for DNS to be fully effective in meeting aircraft design needs.

Both "A - Acceptance" and "Q - Quality" factors in $E = Q \times A$ need to be simultaneously maximized for Fully Effective ACA based on DNS

Since DNS is not expected to be feasible—even for a wing—until around 2080, how do we improve ACA effectiveness?

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NASA CFD Vision 2030

Motivation

"…the last decade has seen stagnation in the capabilities used in aerodynamic simulation within the aerospace industry, with RANS methods having become the high fidelity method of choice…"

"…the <u>well-known limitations of RANS methods for separated flows have confined reliable use of CFD to a small region of the flight envelope</u> …"

NASA/CR–2014-218178

(Published in 2014)

CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences

Jeffrey Slotnick and Abdollah Khodadoust
Boeing Research & Technology, Huntington Beach, California

Juan Alonso
Stanford University, Stanford, California

David Darmofal
Massachusetts Institute of Technology, Cambridge, Massachusetts

William Gropp
National Center for Supercomputing Applications, Urbana, Illinois

Elizabeth Lurie
Pratt & Whitney, United Technologies Corporation, East Hartford, Connecticut

Dimitri Mavriplis
University of Wyoming, Laramie, Wyoming

A Clarion Call to the Community

Source: Refs. 6.2.8

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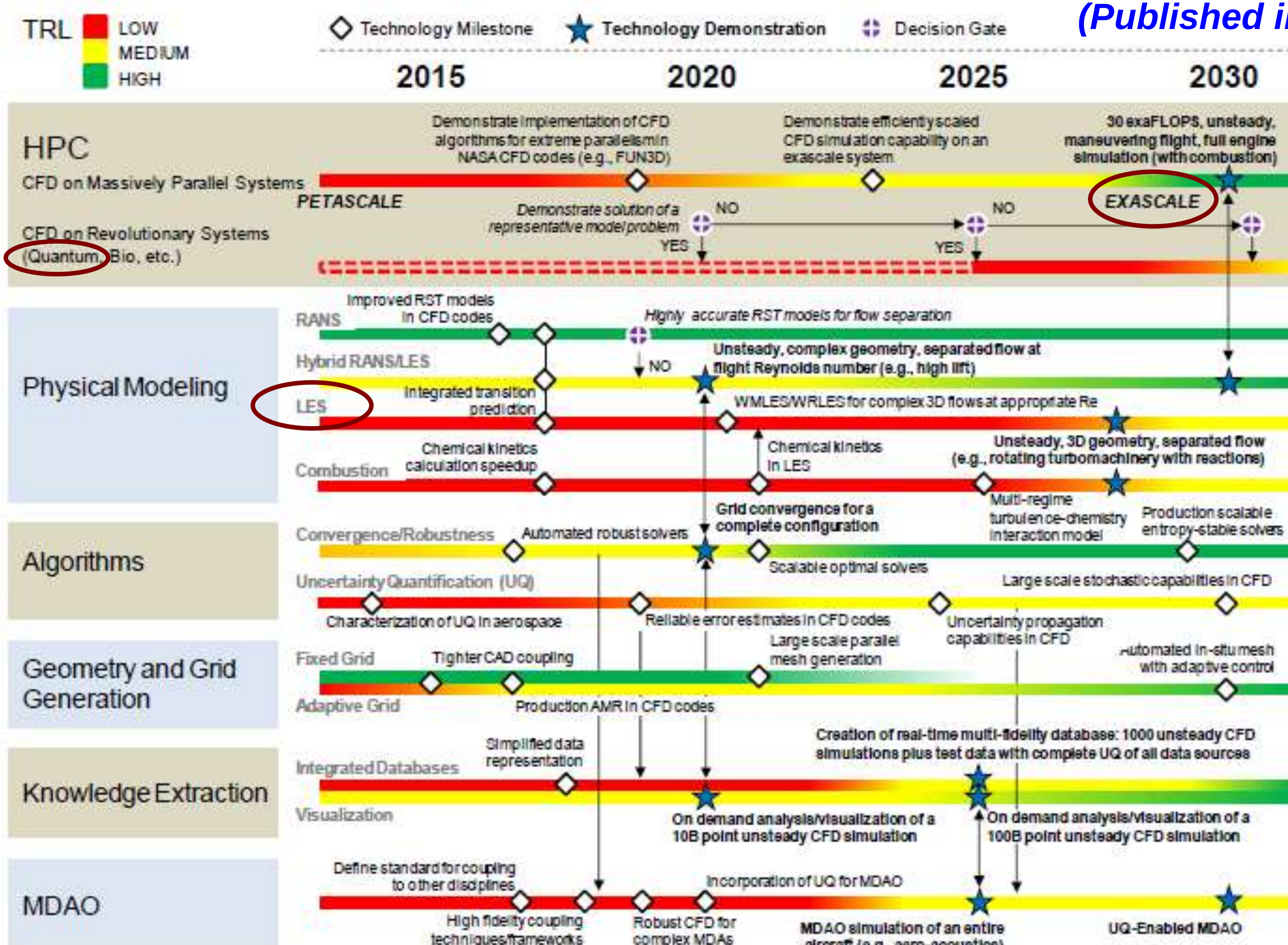
NASA CFD Vision 2030: *Roadmap*

(Published in 2014)



A Comprehensive Plan That Could Significantly Increase ACA Effectiveness by 2050(?)

Source: Ref. 6.2.8

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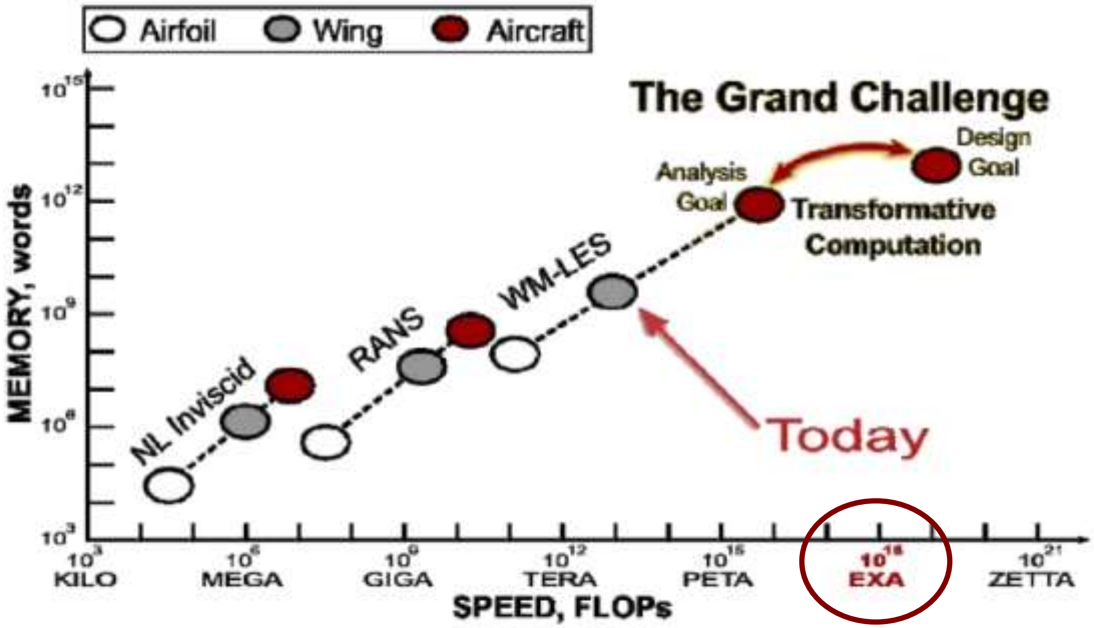
LES for Increased ACA Effectiveness

Pace of progress closely tied to advances in many key areas

- **Grids:** Methods for rapidly generating very fine, *truly* boundary-conforming grids
- **Models**: Advanced near-wall sub-grid-scale (SGS) models for WM-LES
- **Algorithms:** Higher-order numerical methods that minimize numerical dissipation
- **Software:** Development and implementation of effective strategies for designing computer software that exploits *emerging computer hardware architectures*
- **V&V:** Effective approaches for verification and validation of complex software, and for uncertainty quantification
- **Data Management:** Cost-effective approaches for efficiently managing large amounts of data, and for fast processing of extremely large datasets to extract information of value for ACA engineers
- **Etc., etc.**

- **Computer Requirements**



A Midterm Strategy (2050+) At Best

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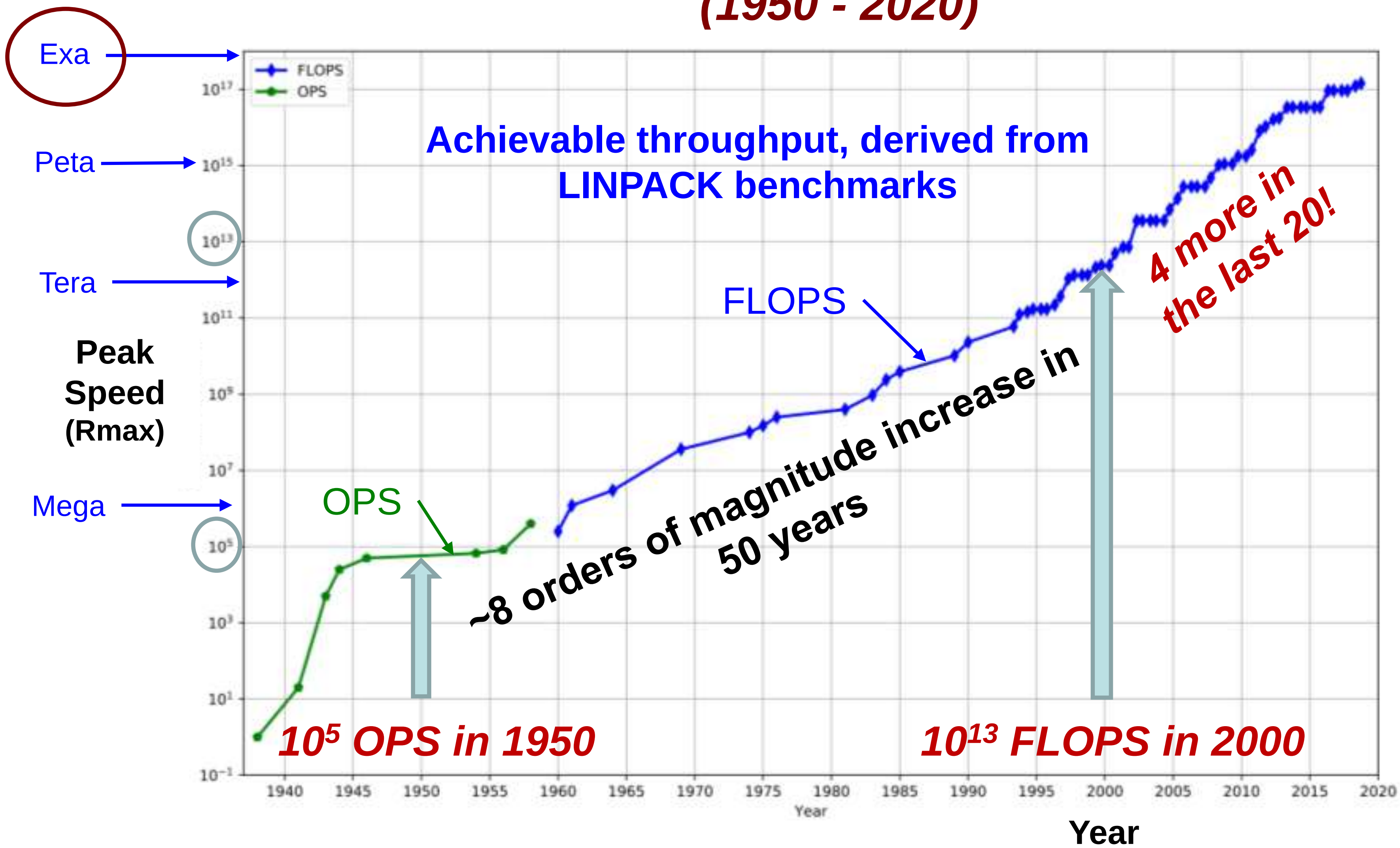
Source: Ref. 6.2.6 & 6.2.7

Increase in Digital Computer Peak Speed
(1950 - 2020)



ExaFLOPS Peak Speed is Within Reach—BUT We Need Sustained Speeds at this Level for Practical LES Applications

Source: https://en.wikipedia.org/wiki/Supercomputer

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Current Status of LES

2023

Turbomachinery Flow

Large Eddy Simulation (LES)

Unstructured grid: 1.69 x 10^9 elements

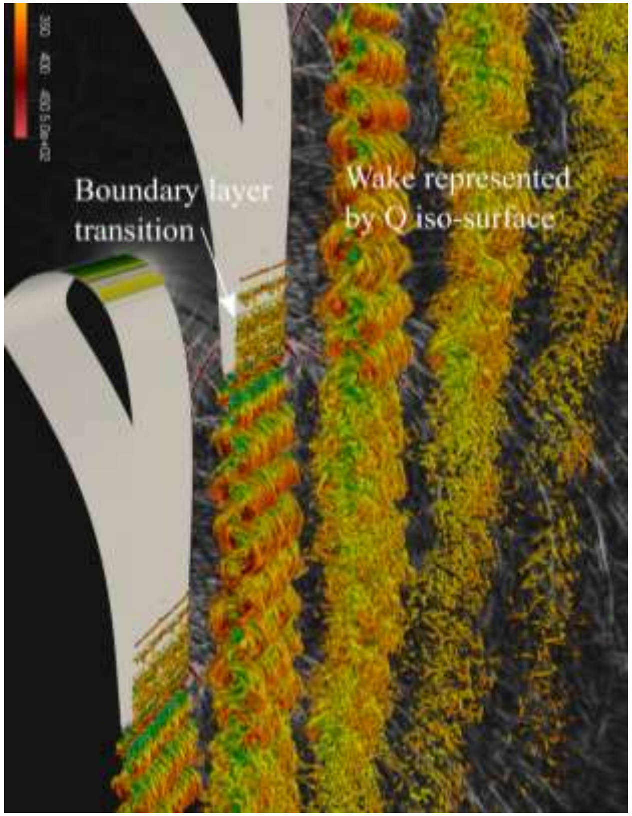
High order solver: up to 8^{th} order

HPC cores: 19.2 million

HPC performance: 115.8 PetaFLOPS (DP)

Y. Fu, W. Shen, J. Cui, Y. Zheng, et al, Towards Exascale Computation for Turbomachinery Flows, SC'23, November 12-17, 2023, Denver, CO

Gordon Bell Prize nominee



Challenge: *Full Aircraft DNS*

Full Aircraft

Direct Numerical Simulation (DNS)

Unstructured grid: > 10^{20} elements

HPC cores: ???

HPC performance: ???

How Do We Get There From Here?

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Quantum Computing (QC)
Offers A Ray of Hope!

- **Ongoing Revolutionary Research**
  - We can perform 2^N computations simultaneously on a quantum computer of N qubits (*qubits are quantum entities manipulated to act like computer bits*)
  - A grid of 2^N elements requires a quantum computer with N qubits

Problem	CFD	Timeframe	HPC cores	QC qubits
Turbomachinery	LES	2023 (now)	19.2 million	30
Full Aircraft	DNS	??? (future)	???	57

- **Quantum-inspired, Hybrid Quantum-Classical, and Quantum Algorithms**
  - An order of magnitude faster and cost-effective simulations using quantum algorithms than classical algorithms on today's HPC have been demonstrated
  - Quantum algorithms running on simulation platform of HPCs and quantum computers could reduce time and cost by nearly three orders of magnitude!

Potential for DNS of Full Aircraft Using QC Much Sooner Than The 2080s!

Source: **Personal Communication, Abhishek Chopra, Founder and CEO, BosonQ Psi (https://www.bosonqpsi.com/)**

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Conundrum for Today's Engineers

RANS is Here to Stay!

"…engineering calculations will have to be done by Reynolds-averaged methods for the foreseeable future…"

"…computer simulations of eddy motion can and will provide the detailed statistics—above all, the pressure fluctuation statistics—that cannot be adequately measured."

"…***we cannot calculate all flows of engineering interest to engineering accuracy. However, the best modern methods allow almost all flows to be calculated to higher accuracy than the best-informed guess***, which means that **the methods are genuinely useful** even if they cannot replace experiments."

Excerpts from TURBULENT SECONDARY FLOWS by Peter Bradshaw
Annual Review of Fluid Mechanics, Vol 19, 1987, pp 53-74

Author's Take: "Glass is half full"

Despite relatively low effectiveness for simulating complex flows, RANS methods can, and do, add value if used wisely

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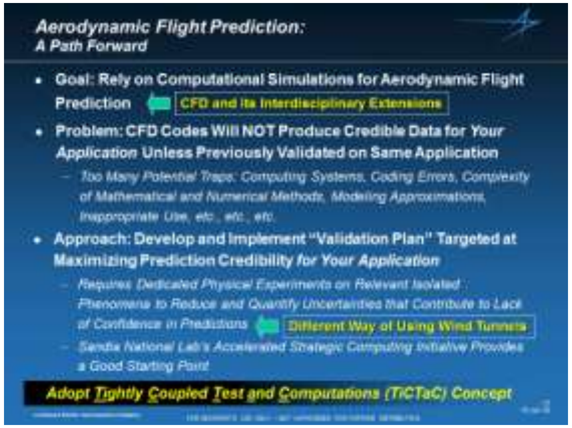
The TiCTaC Paradigm for Improving RANS-based ACA Effectiveness

Tightly Coupled Tests and Computations

Devise the best way of *judiciously* coupling wind tunnel testing (WTT) with RANS CFD to deliver credible aerodynamic data—rapidly and affordably

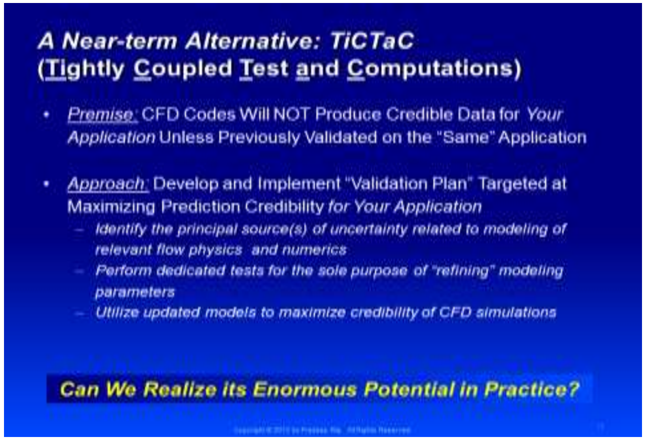
2002: First proposed (Raj)

NASA/DOD Workshop on Aerodynamic Flight Predictions, Williamsburg, VA, USA, Nov 19-21, 2002



2012: Revisited (Raj)

5th Symposium on Integrating CFD and Experiments in Aerodynamics, JAXA, Tokyo, Japan, Oct 3-5, 2012



2014 & 2016: An updated approach (Raj et al) *Applied Aero Conference, Bristol, UK*

- Develop and implement *TiCTaC*: leverage complementary strengths of CFD and EFD by exploiting ongoing technological advances in both WTT and CFD
  - ✓ WTT (*Additive Manufacturing, Rapid Prototype Testing, Measurement Techniques*)
  - ✓ CFD (*Grid Adaption, High Performance Computing, Uncertainty Quantification*)

A Near Term "Stopgap" Strategy

Source: Refs. 6.2.9 thru 6.2.12

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No Shortage of CFD Software!

Commercial Codes for Viscous Flow Simulation

A New Paradigm Emerged in the 1980s as an Alternative to Aerospace Industry's Proprietary CFD Development

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": $1.75B Revenue in 2019 with Compound Annual Growth Rate (CAGR) of 9%!

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"Free" CFD Software!

An Alternative to Proprietary and Commercial CFD

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!

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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 Value to the Customers 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)

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Source: Ref. 1.2 & 1.3

ACA Engineers Should Use/Choose CFD Codes Wisely Based on Effectiveness

1. **Understand the Customer's Problem**
   - Develop a *comprehensive* understanding of the scope of customer needs (potential impact of solution, desired level of accuracy, type and amount of data, etc.) and constraints (cost and schedule)
2. **Devise a Practical Approach to Solving the Problem**
   - Examine <u>all four levels</u> of available CFD codes for solving the problem with effectiveness as the key measure of merit
   - Choose a code based on customer need and constraints [the type, amount and quality of aerodynamic data required to meet customer needs subject to the specified constraints]
3. **Deliver a *Best Solution* that Adds Value**
   - Provide a solution that *best* meets customer needs while satisfying all constraints

Don't Use a Hammer When You Need a Screwdriver!

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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…"

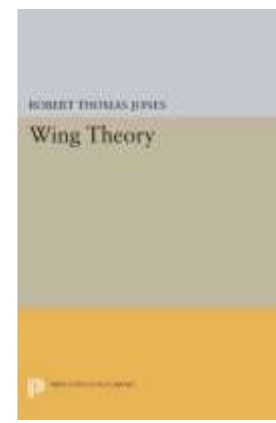
Robert T. "RT" Jones

Premier Aeronautical Engineer
28 May 1910 – 11 Aug 1999

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



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

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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

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Section 6.2
Overarching Takeaways

It's the aerodynamics, stupid!*

A Talented Engineer Can Do Wonders Even with a Poor Tool!

It's the airplane, not the tools, stupid!*

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

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Section 6.2: Key Takeaways

- ***DNS is Seemingly the Only Path to Fully Effective ACA!***
  - Incredible reductions in turnaround times and total cost are required to produce ***credible*** solutions using DNS
  - Achieving high enough 'Acceptance' factors keep the effectiveness of DNS quite low in spite of its extremely high 'Quality' factor
  - Since DNS is not expected to be feasible—*even for a wing*—until around 2080, LES is probably a more promising option to explore for improving ACA effectiveness
- **LES for Improved Effectiveness—A Promising Midterm Strategy (2050+)**
  - Pace of progress closely tied to advances in grid generation; SGS models; algorithms; integrated software/hardware development; V&V; data management; etc.
- ***RANS is here to stay! — A* Conundrum for Today's ACA Engineers**
  - "*the best modern methods allow almost all flows to be calculated to higher accuracy than the best-informed guess,* which means that the methods are genuinely useful…" Peter Bradshaw
  - TiCTaC—A Near Term Stopgap Strategy: Devise the best way of judiciously coupling wind-tunnel testing (WTT) with RANS CFD to deliver credible aerodynamic data—rapidly and affordably
  - No shortage of software suites: Commercial as well as "Free" Open Source
- **Not all codes are created equal—choose and use wisely!**

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6 ACA Effectiveness: Status and Prospects *(2000-20xx)*

6.2 Prospects for Fully Effective ACA (2020–20xx)

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6.2.2 Richardson, L.F., "Weather Prediction by Numerical Process," The University Press, Cambridge, UK, 1922, p. 66.

6.2.3 Sinha, N., "Towards RANS Parameterization of Vertical Mixing by Langmuir Turbulence in Shallow Coastal Shelves," Ph.D. Dissertation, Nov. 2013. DOI: 10.13140/RG.2.2.26443.90404

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Pursuit of Effective Applied Computational Aerodynamics (ACA) Started Long Ago…

"Both for engineering and for many of the less exact sciences, such as biology, there is a demand for ***rapid methods, easy to be understood*** *and* ***applicable to unusual equations and irregular bodies****. If they can be* ***accurate****, so much the better; but* ***1 per cent, would suffice*** *for many purposes."* ***– Richardson, 1910***

"Prospective users…rarely interested in whether or not an accurate solution of an idealized problem can be obtained, but are concerned with ***how well the calculated flow agrees with the real flow****."* ***– Hess and Smith, 1967***

"The ***effectiveness*** *of computational aerodynamics* ***depends not only on the accuracy*** *of the codes* ***but*** *to a very large degree—perhaps more than is generally appreciated—****on their robustness, ease and economy of use****."* ***– Miranda, 1982***

…and Continues Today!

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Source: Refs. 5.1.9, 5.2.1

ACA Effectiveness:

Summary Status (circa 2020) and Prospects

RANS-based ACA is Unlikely to be Fully Effective Anytime Soon, If Ever!

DNS-based ACA May Lead to Fully Effective Capability in the Long Term (2080+)
Many Decades Hence—A Bridge Too Far?

LES-based ACA Offers a Promising Alternative in the Mid-term (2050+)

TiCTaC (Judicious Coupling of Wind Tunnel Testing and RANS CFD) Offers a Near-term "Stopgap" Option

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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*): *Fast Pace of Progress***
  - ***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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Top Ten Takeaways

From My Journey on a Long and Winding Road

1. ACA is an engineering discipline that is enabled by CFD

- ACA adds value by meeting customer's most pressing needs—on time, on budget by delivering *credible solutions*
- *CFD is to ACA as airplane is to air transportation*

2. ACA and CFD aren't synonymous

- CFD produces data, ACA produces solutions *— don't confuse data with solution!*

3. EFD remains the best source of data to assess CFD 'goodness'

- If CFD and EFD data don't match, ask why? If they do, *most definitely ask why*?

4. Effectiveness is the best Measure of Merit for Assessing ACA

- Effectiveness = quality x acceptance*:* $E = Q \times A$
- *ACA Effectiveness is ultimately assessed by design teams (who initiate the "Value Chain"), not by CFD code developers, in collaboration with ACA engineers*

5. Predicting aerodynamic characteristics isn't that hard

- Generating credible predictions is—*and it's REALLY HARD!*

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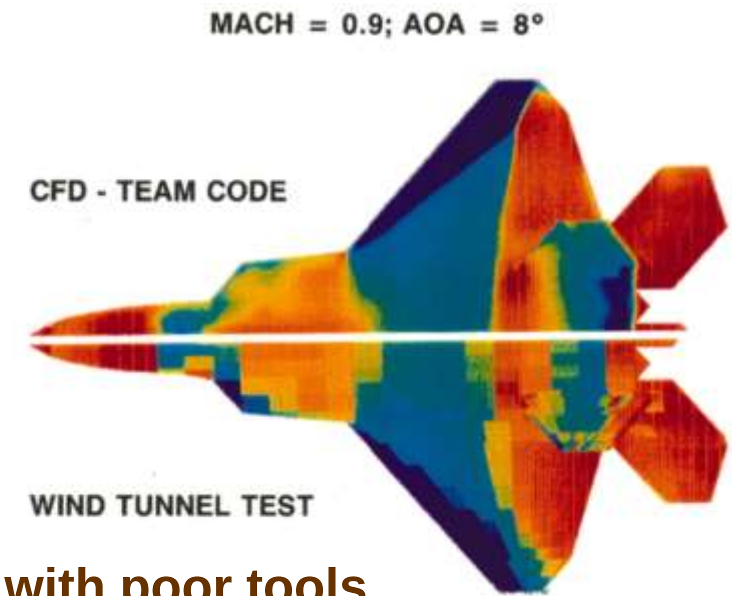
Top Ten Takeaways (contd.)

From My Journey on a Long and Winding Road

6. **Converting a basic research concept into an *effective* capability is a long and arduous process marked by *invention, initiative, and innovation…and lots of patience!***



7. **Success requires communication & collaboration across <u>all</u> stakeholders to *simultaneously* improve quality of results and productivity of processes**
8. **A *talented engineer* can do wonders even with poor tools**
   - Talent trumps tools, any day of the week! Talent with tools—makes the impossible possible! *It's the airplane, not the tools, stupid!*
   - CFD competency is necessary but not sufficient to an effective ACA engineer. *It's the aerodynamics, stupid!*
9. **Nothing—*absolutely nothing*—is worth compromising your integrity**
10. **Life is akin to an unsteady system with unsteady boundary conditions, *don't expect a steady solution***
    - *Don't underestimate the role of luck!*

Lewis, Michael, "Don't Eat Fortune's Cookie," Princeton University's 2012 Baccalaureate Remarks
https://www.princeton.edu/news/2012/06/03/princeton-universitys-2012-baccalaureate-remarks

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Be Mindful of Four "Immutable" Laws and Principles!

Murphy's Law

"If anything can go wrong, it will."

Parkinson's Law

"Work expands so as to fill the time available for its completion."

The Peter Principle

"In a hierarchy, every employee tends to rise to his level of incompetence."

The Dilbert Principle

"Companies tend to systematically promote their least-competent employees to management (generally middle management) in order to limit the amount of damage they are capable of doing."

You will never be disappointed in your professional life!

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"Look ahead where the horizons are absolutely unlimited"

Robert E. Gross

Entrepreneur, Industrialist

Founder, Lockheed Aircraft Corporation (now Lockheed Martin)

Enshrinee, The National Aviation Hall of Fame

11 May 1897 – 3 Sep 1961

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DEDICATED TO LUIS R. MIRANDA

Father of $E = Q \times A$

My mentor, adviser, coach

Aerodynamics Engineer par excellence

A consummate professional and a model leader

(Carlsbad, California, January 2016)

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Appendix A

An Approach for ACA Effectiveness Assessment

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Source: https://en.wikipedia.org/wiki/Hype_cycle

A Quasi-quantitative Approach for Assessing ACA Effectiveness

The proposed quasi-quantitative approach defines an *effectiveness index (E)* as a composite of *quality index (Q)* and *acceptance index (A)*

$$E = Q \times A$$

- ***Effectiveness index (E)*** **is the outcome/result of effectiveness assessment**
- ***Quality index (Q)*** **represents the level of 'credibility' of data generated by the computational simulations *for a target application***
  - 'Credibility' of data is a function of two factors: *Accuracy* and *Realism*
    - *Accuracy*—the degree to which the results of numerical simulations match the *correct* or *exact* values (*verification*)
    - *Realism*—the degree to which computational results represent *reality* *(validation)*
- ***Acceptance index (A) represents the level of*** **'acceptability' of a simulation by users and customers for a target application**
  - 'Acceptability' is a function of four factors: *applicability*, *usability*, *affordability*, and *responsiveness*
    - *Applicability*—the degree to which a procedure is applicable to the problem at hand
    - *Usability*—how easy the procedure is for ['non-expert'] users to use
    - *Affordability*—lower the cost [labor + computer], higher the affordability of simulations
    - *Responsiveness*—lower the turnaround time [elapsed time from go-ahead to data delivery], higher the responsiveness to customer needs

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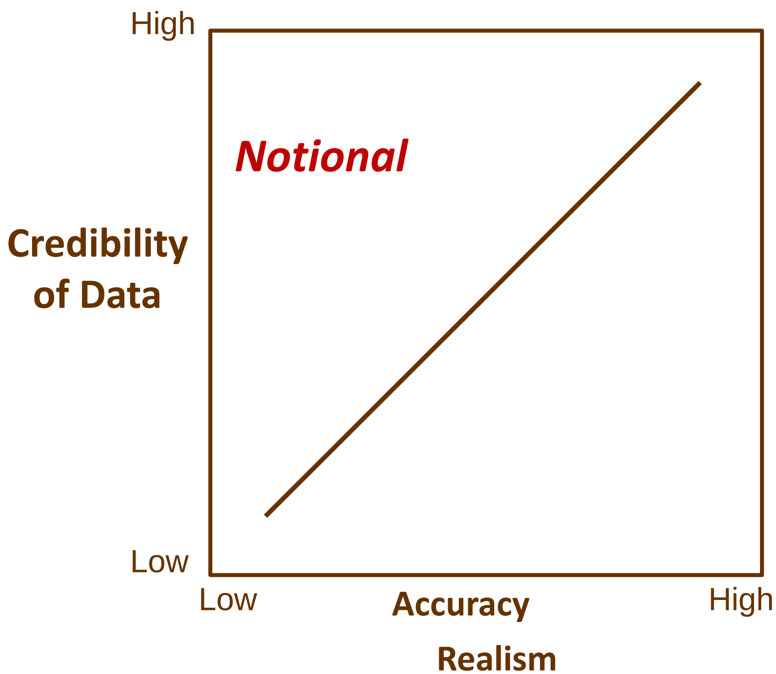
Source: Ref. 5.2.1

Quality Index (Q) Estimation

Quality index (Q) **represents the level of 'credibility' of a computational simulation** ***for a target application*** **which is a function of** ***Accuracy*** **and** ***Realism***

- *Accuracy*—the degree to which numerical results match the correct value
- *Realism*—the degree to which computational results represent reality



Higher the credibility, higher the Q

Quality Index, $$Q = \sum_{i=1}^{2} W_i S_i$$

Factors	Weights (W_i)	Score (S_i)
1. Accuracy		
2. Realism		

Weight Scheme (W_i)

$$0 \leq W_i \leq 1$$

$$\sum_{i=1}^{N} W_i = 1$$

Scoring Scheme (S_i)

Low	0 – 0.4
Medium	0.4 – 0.7
High	0.7 – 1.0

Users selects relative weights and assigns scores for the two factors

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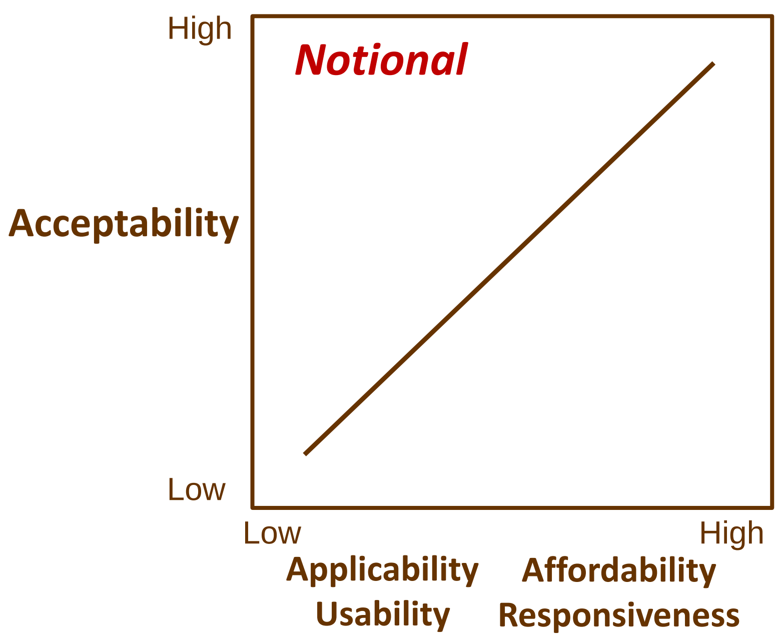
Acceptance Index (A) Estimation

Acceptance index (A) represents the level of* 'acceptability' of computational simulation by users and customers for a target application, and is a function of *applicability*, *usability*, *affordability*, and *responsiveness

- *Applicability*—the degree to which a method is suitable for the problem at hand
- *Usability*—how easy a computational procedure is for ['non-expert'] users to use
- *Affordability*—lower the cost (labor + computer), higher the affordability
- *Responsiveness*—lower the turnaround time (elapsed time from go-ahead to data delivery), higher the responsiveness



Users selects relative weights and assigns scores for the four factors

Higher the acceptability, higher the A

Acceptance Index, $A = \sum_{i=1}^{4} W_i S_i$

Factors	Weight (W_i)	Score (S_i)
1. Applicability		
2. Usability		
3. Affordability		
4. Responsiveness		

Weight Scheme (W_i)

$$0 \leq W_i \leq 1$$

$$\sum_{i=1}^{N} W_i = 1$$

Scoring Scheme (S_i)

Low	0 – 0.4
Medium	0.4 – 0.7
High	0.7 – 1.0

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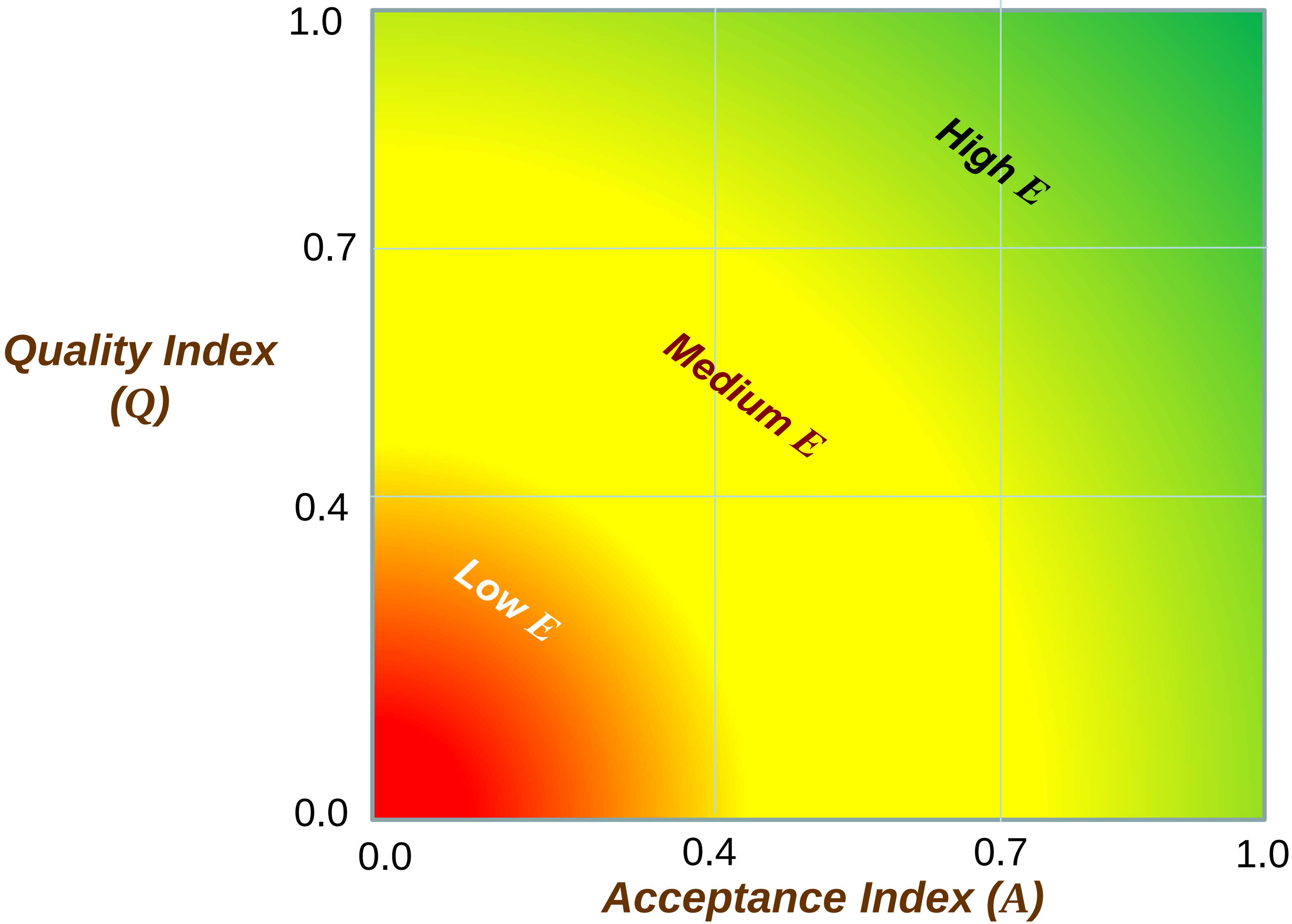
Effectiveness Index (*E*)

$$E = Q \times A$$



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VITA

Pradeep Raj is currently a collegiate professor emeritus in the Kevin T. Crofton Department of Aerospace and Ocean Engineering at Virginia Tech in Blacksburg, Virginia, USA. Since 2012 through 2024, his primary responsibilities at VT included (a) teaching the AOE undergraduate Capstone Aircraft Design courses, and (b) pursuing collaborative research in multidisciplinary analysis, design, and optimization (MADO) tools and processes, with emphasis on applied aerodynamics, to enable simulation based design of affordable flight vehicles.

Raj joined VT in 2012 after a 32-year career with Lockheed Martin. Starting out in 1979 as a Senior Aerodynamics Engineer at the Lockheed-California Company in Burbank, he assumed positions of increasing responsibility before retiring in 2011 as a Director from Advanced Development Programs, Palmdale, California, commonly known as the Skunk Works® and widely recognized for creating breakthrough technologies and landmark aircraft. For the first 20 years, including 8 as Technical Fellow (1991-1999), Pradeep was instrumental in enhancing the effectiveness of applied computational aerodynamics for aircraft design through several research, development, and application campaigns.

Prior to joining LM, Raj spent one year (1978-79) as an assistant professor at the University of Missouri-Rolla (now Missouri Science & Technology University), and two years (1976-78) as a research assistant professor at the Iowa State University, Ames, Iowa. Pradeep earned his Ph.D. in Aerospace Engineering from Georgia Tech in 1976. Before going to GT, he earned a Master of Engineering (with Distinction) in Aeronautical Engineering in 1972, and a Bachelor of Engineering (with Distinction) in Electrical Technology in 1970, both from the Indian Institute of Science, Bangalore, India. He received a Bachelor of Science (with Honors) from Meerut University in 1967.

Pradeep Raj is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA), of the Royal Aeronautical Society (RAeS), and of the Institute for the Advancement of Engineering (IAE).

https://www.aoe.vt.edu/people/emeritus/raj/personal-page/curriculum_vitae.html

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