The Future of Fluid Mechanics in Aircraft Design

Re-engineering Engineering

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OUTLINE

- *Aerodynamic design of aircraft*
  - *classical theory, wind tunnels, and numerical prediction*
- *Numerical optimization and automatic design*
- *Revolutionizing the engineering process in an integrated multidisciplinary environment*

BACKGROUND

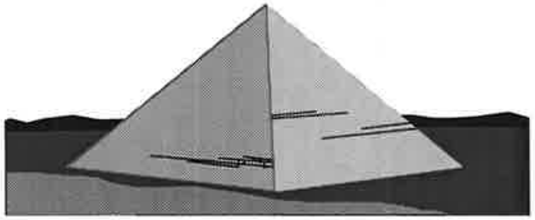
Why is Fluid Mechanics different?

- Structural analysis is routinely performed by commercial software such as MSC NASTRAN, ANSYS, PATRAN, ELFINI.
- COMPUTATIONAL FLUID DYNAMICS (CFD) remains the subject of intense development in NASA, Los Alamos, Livermore, and universities. Most aerospace companies continue to devote large resources to develop their own in-house software.

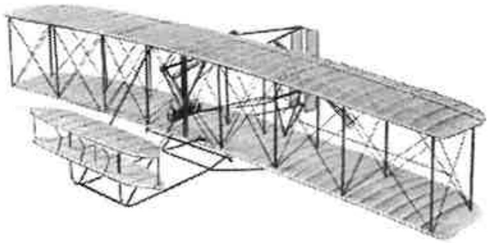
– Boeing	Tranair
– Lockheed	TEAM, Splitflow
– Rockwell	USA

BACKGROUND - *Cont'd*

- *Fluid flow is generally more complex than the behaviour of solids*
- *Impressive structures were built 5,000 years before the first flight of aircraft.*



Pyramids of Egypt



Wright Flyer

- *Fluid mechanics is inherently NONLINEAR, and allows CHAOTIC phenomena such as TURBULENCE.*

COMPLEX FEATURES OF FLUID FLOW

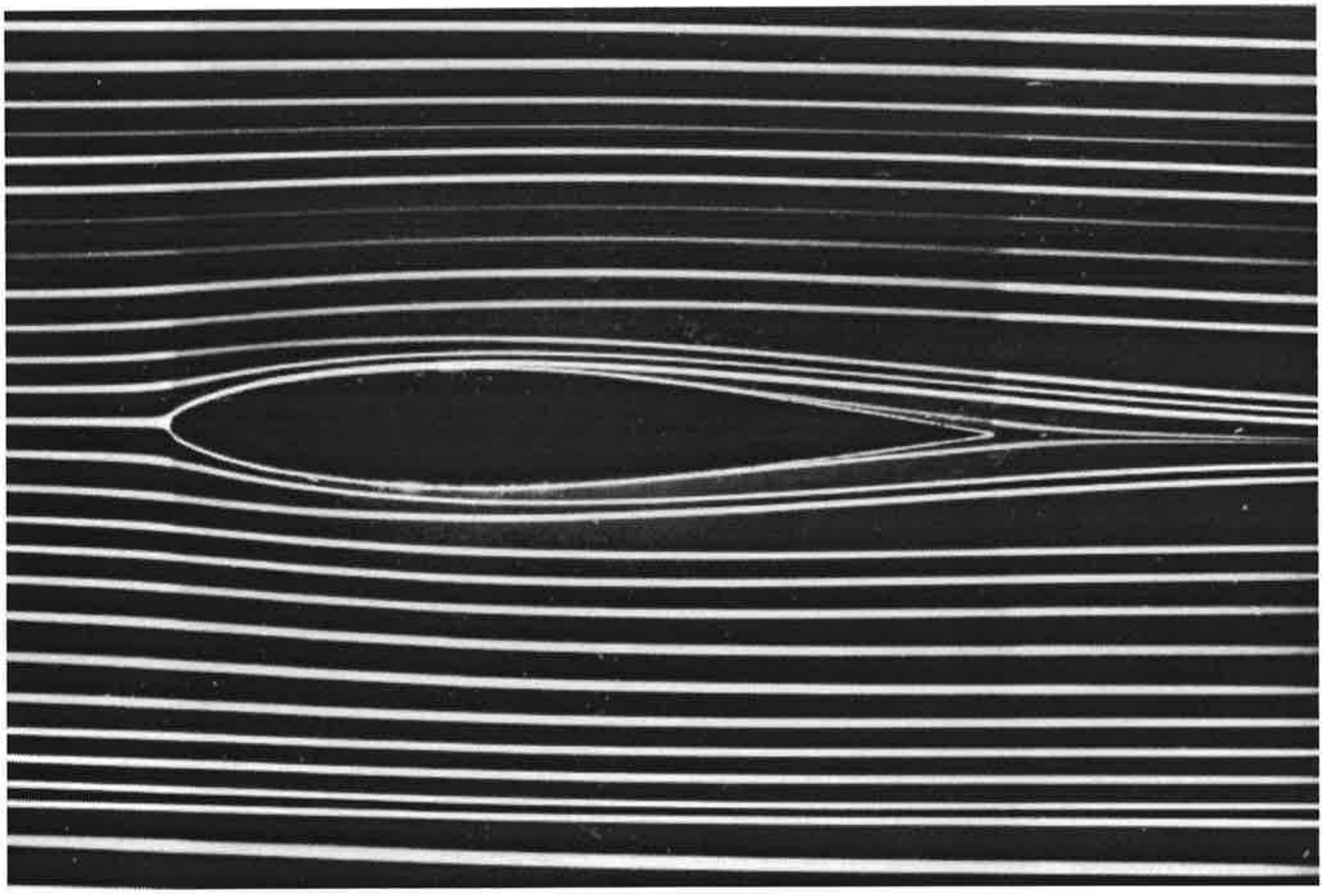
- *Flow induced by viscosity and compressibility*
- *Viscous boundary layers and separation (stall)*
- *Unsteady vortex shedding (Karman vortex street)*
- *Turbulence*
- *Shock waves, contact discontinuities and expansion fans*

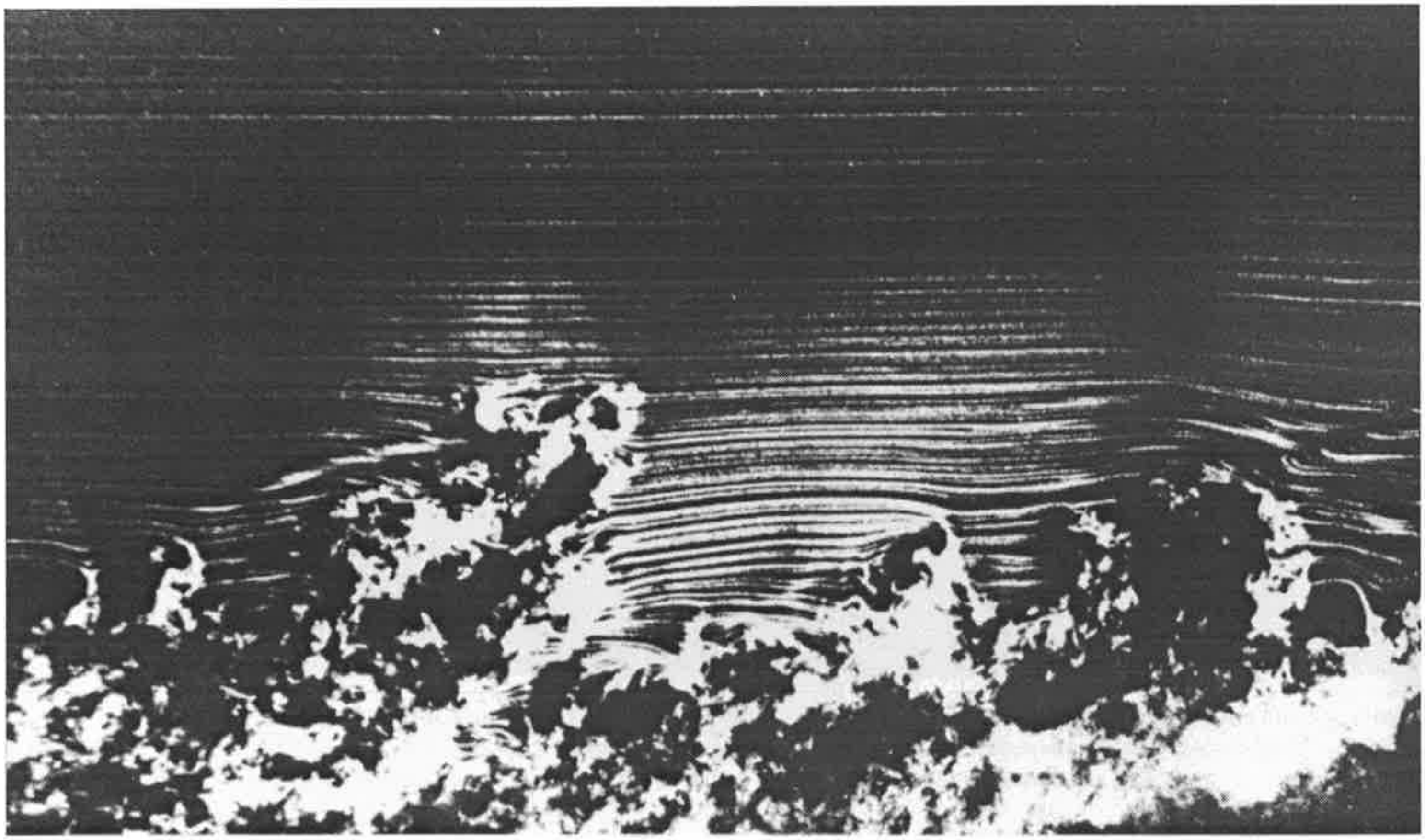
Examples of Complex Flows

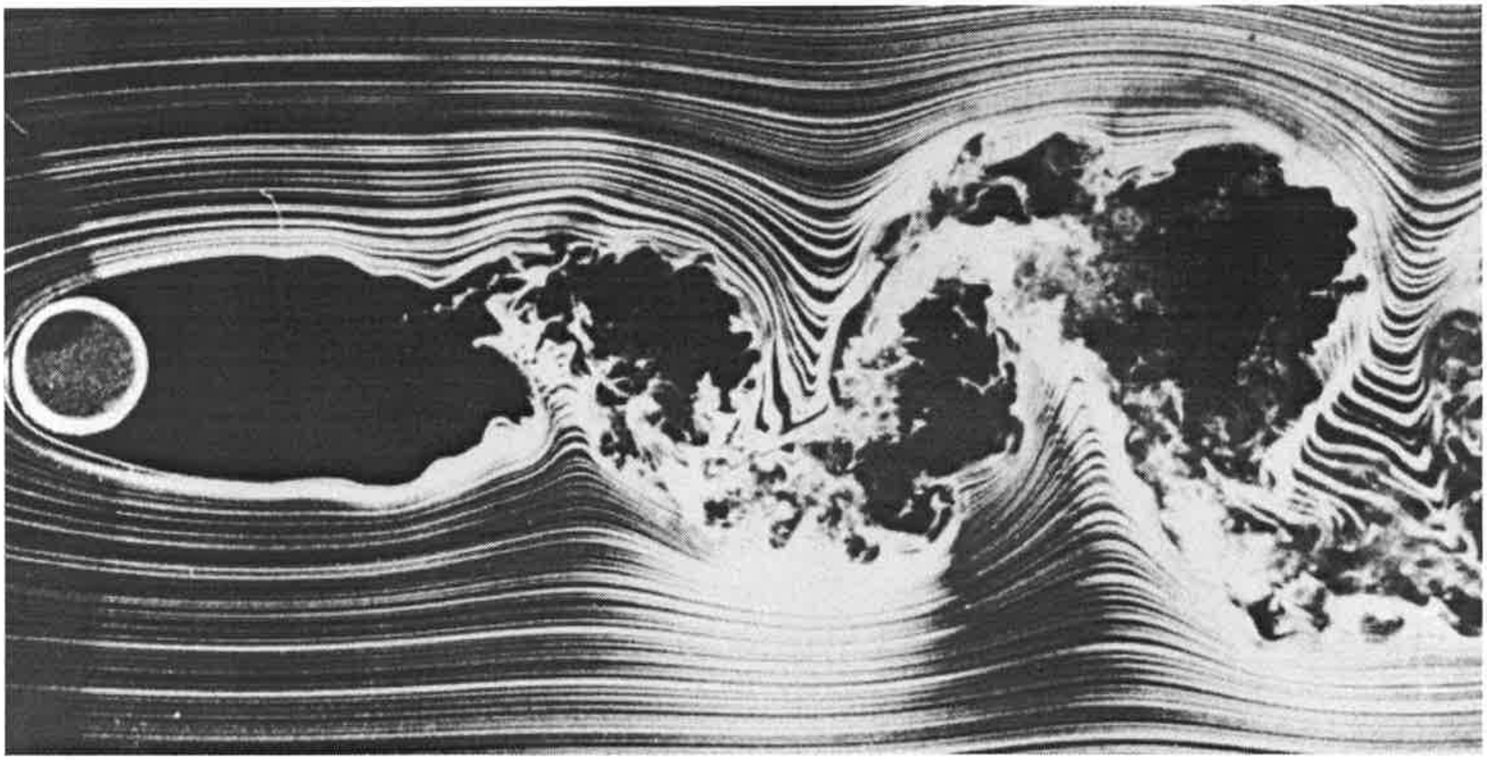
from

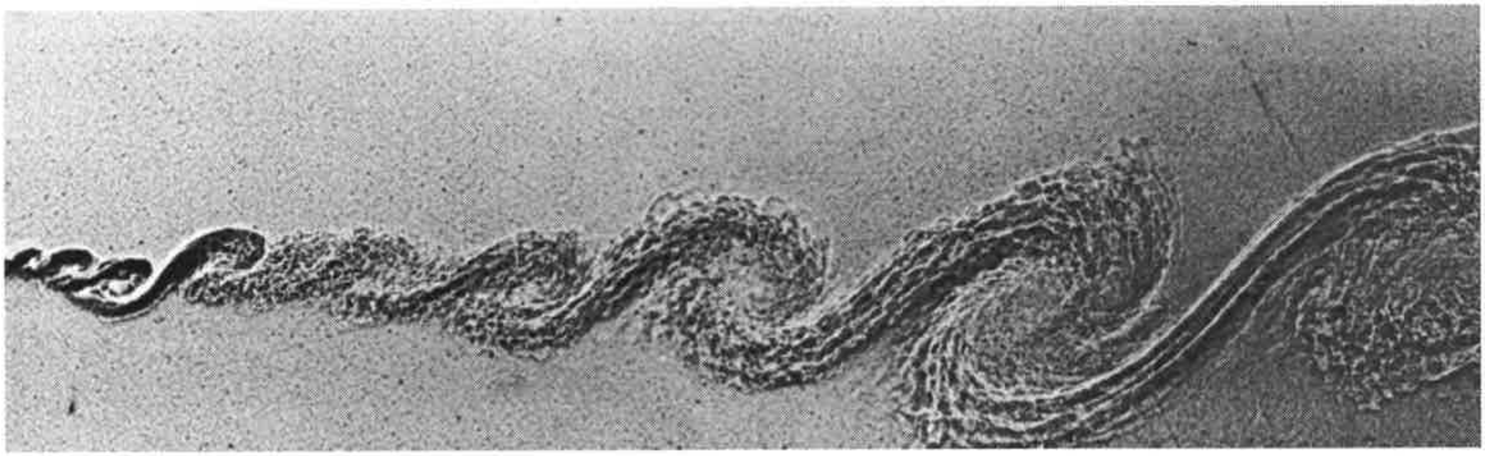
An Album of Fluid Motion

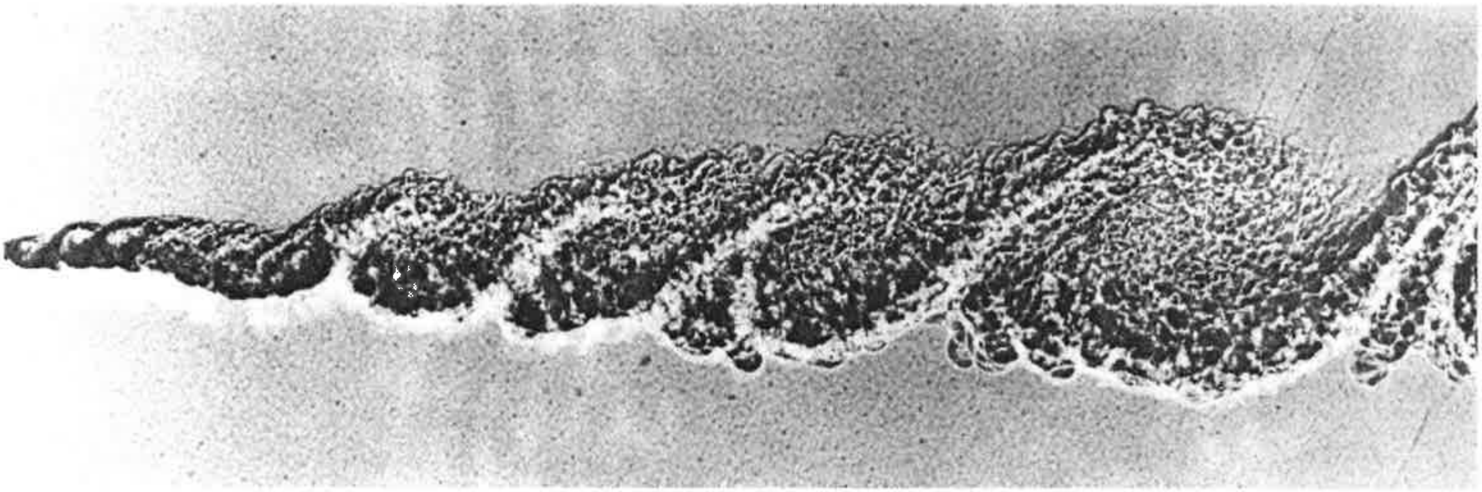
Milton Van Dyke

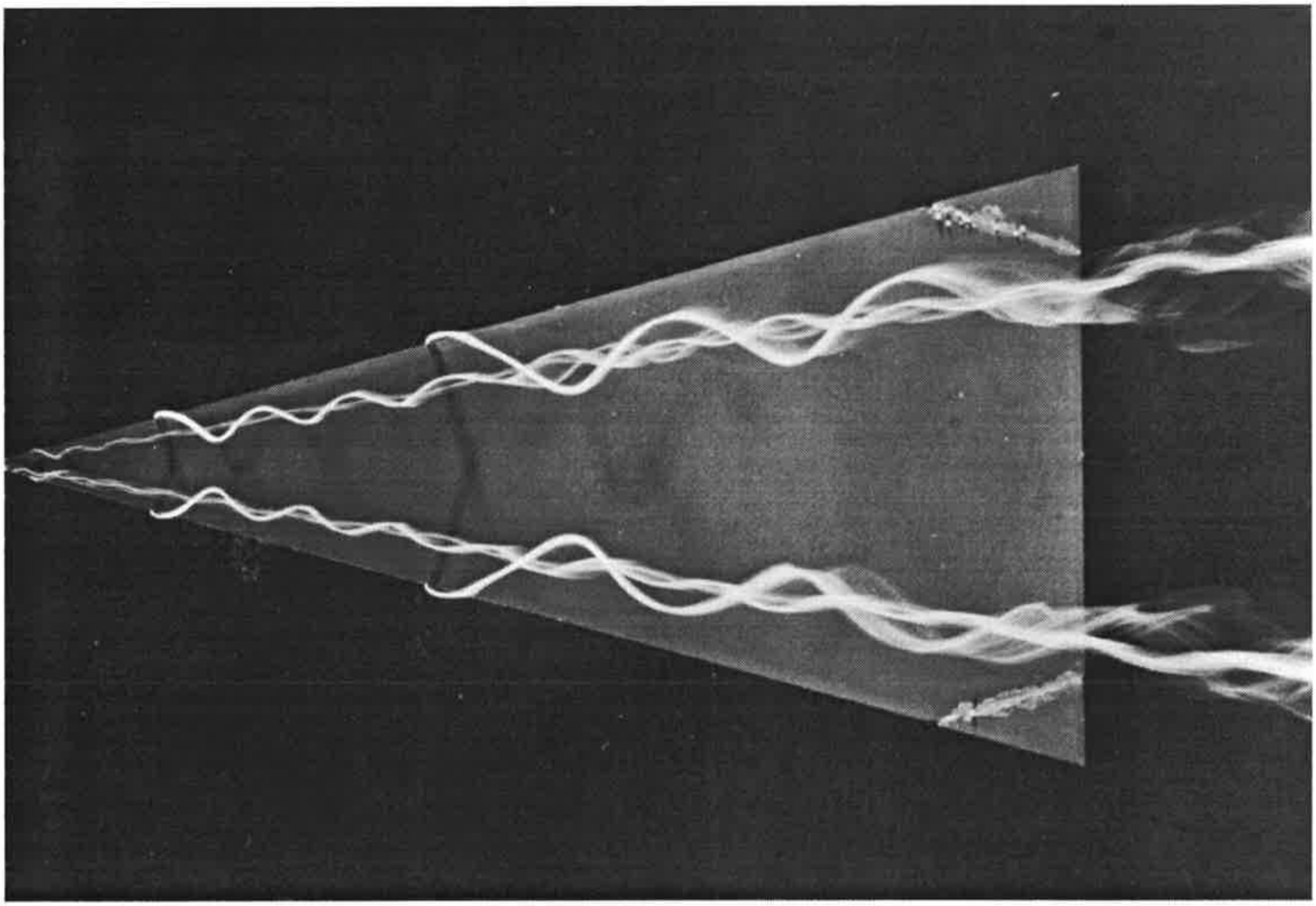


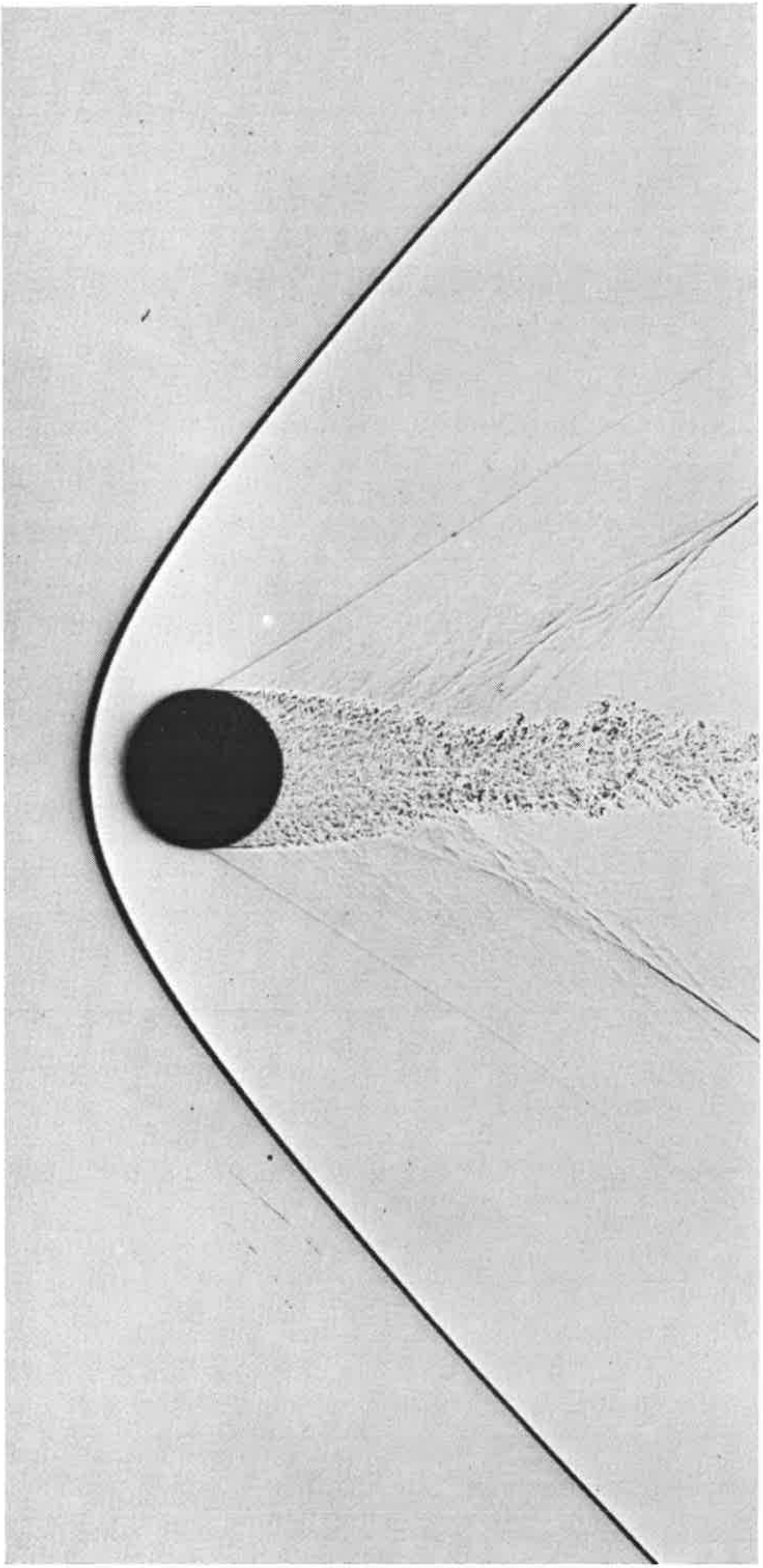


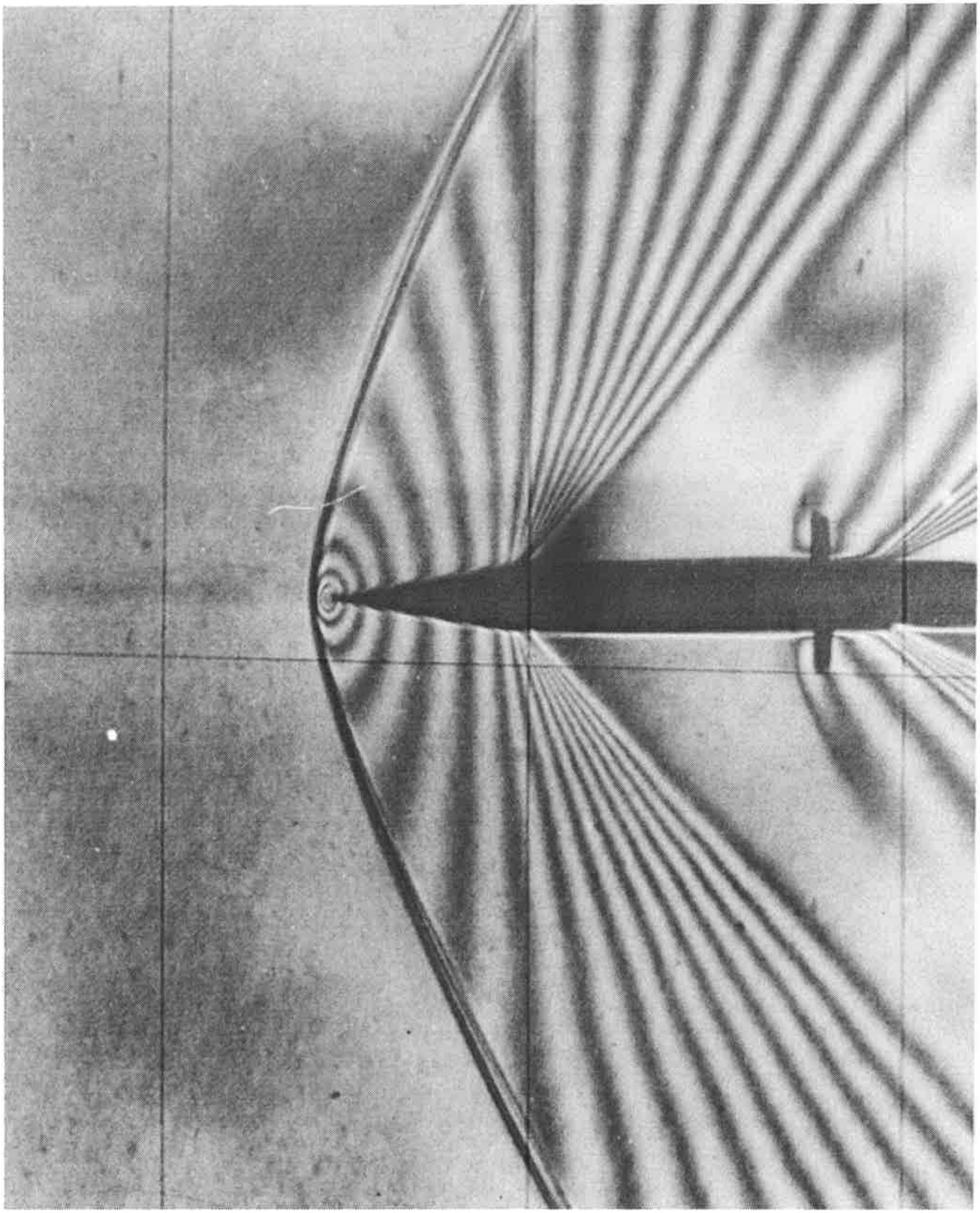


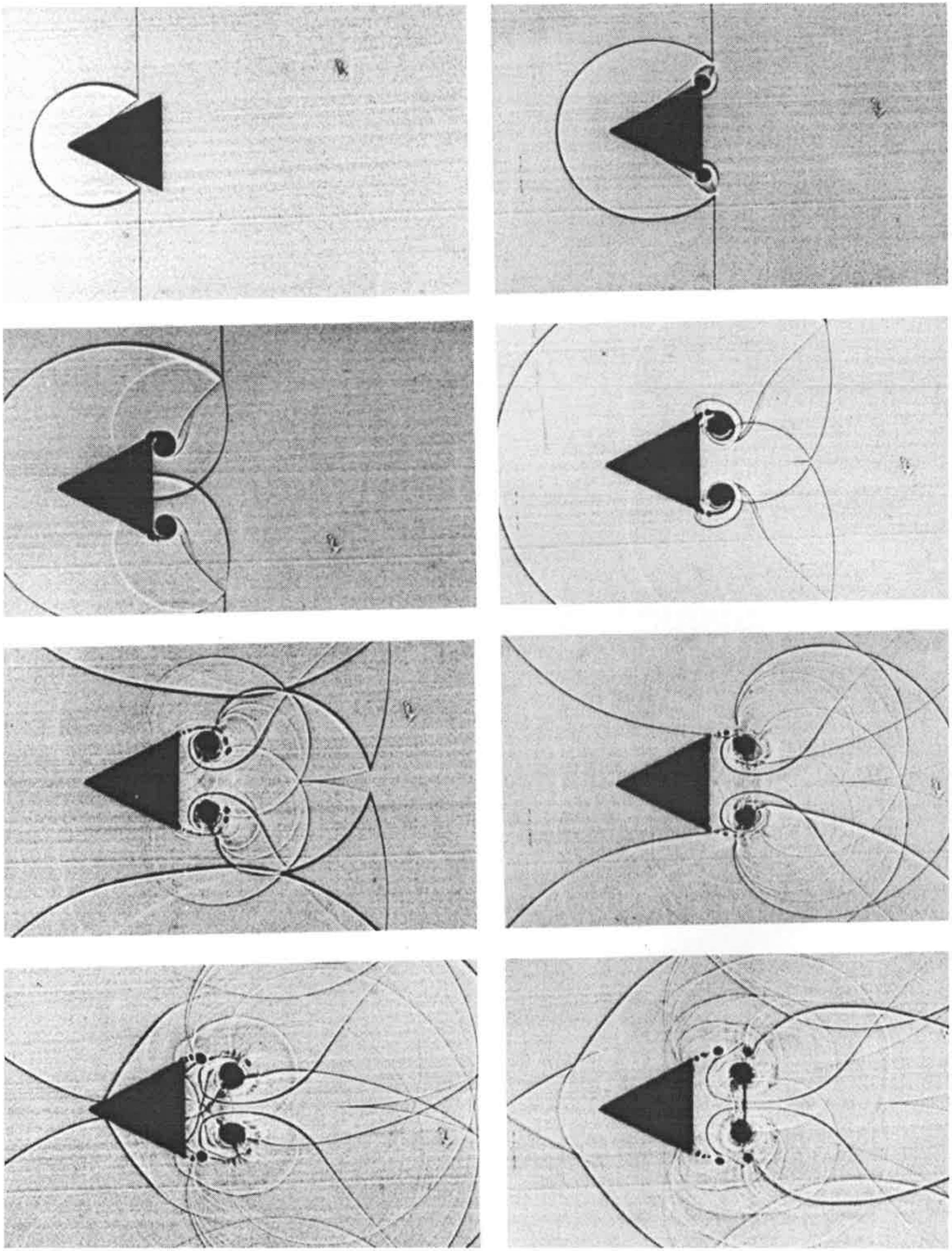












FLUID MECHANICS AND AIRCRAFT DESIGN

- *Because of the complexity of fluid flow, analytical theories could only be developed by drastic simplification.*
- *CLASSICAL FLUID MECHANICS of "PERFECT FLUIDS" eliminates:*
  - *viscosity*
  - *compressibility*
- *Then, the flow is IRROTATIONAL and one can set:*
  - $\mathbf{q} = \nabla \phi$ *(vel. vector)*
  - $\mathrm{div}\,\mathbf{q} = \nabla^2 \phi = 0$ *(Laplace's eqn.)*

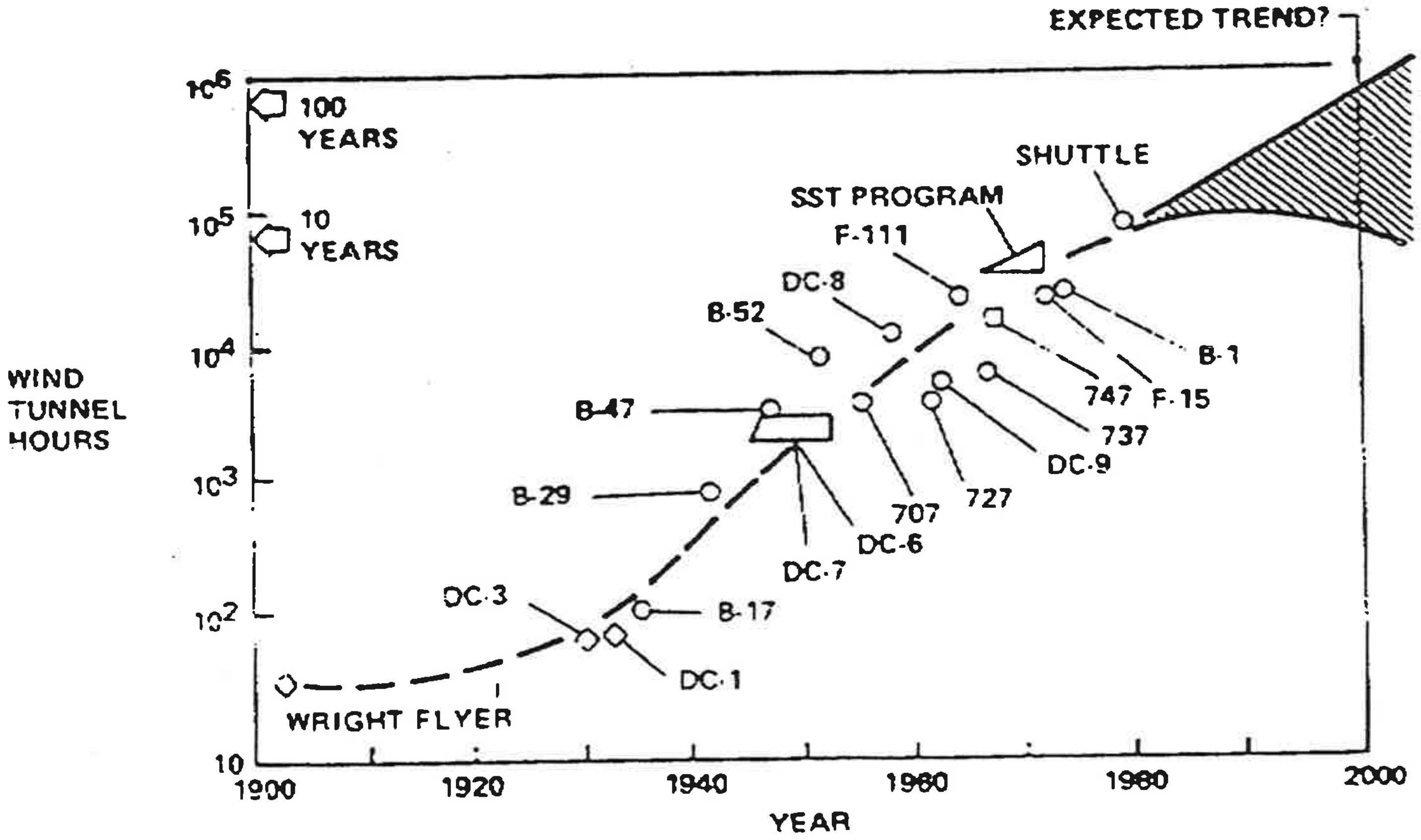
FLUID MECHANICS AND AIRCRAFT DESIGN

- *This made possible the development of WING THEORY (Jowkowsky, Lanchester, Prandtl)*
- *Viscous effects could be estimated by BOUNDARY LAYER THEORY (Prandtl, Schlichting)*
- *CLASSICAL FLUID MECHANICS provided the INSIGHTS for RATIONAL QUALITATIVE DESIGN.*
- *This lead to the emergence of aircraft such as the DC3, SPITFIRE, P38, P51, Me262*
- *QUANTITATIVE ANALYSIS was impossible for complete configurations.*

FLUID MECHANICS AND AIRCRAFT DESIGN

- *Therefore aerodynamic design of aircraft from the WRIGHT FLYER to the BOEING 747 and F16 relied on WIND TUNNEL TESTING for detailed evaluation (the Wright brothers built a wind tunnel)*
- *Wind tunnel testing exceeded 25,000 hours for both the B747 and the F16*

Wind Tunnel Usage to Develop Major Aircraft



THE PRESENT SITUATION

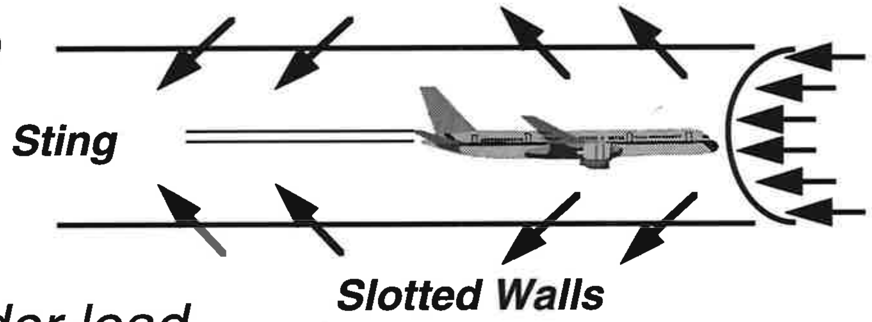
Aerodynamic design is performed using:

- *Computational Fluid Dynamics (CFD)*
- *Wind Tunnel testing*

as complementary tools

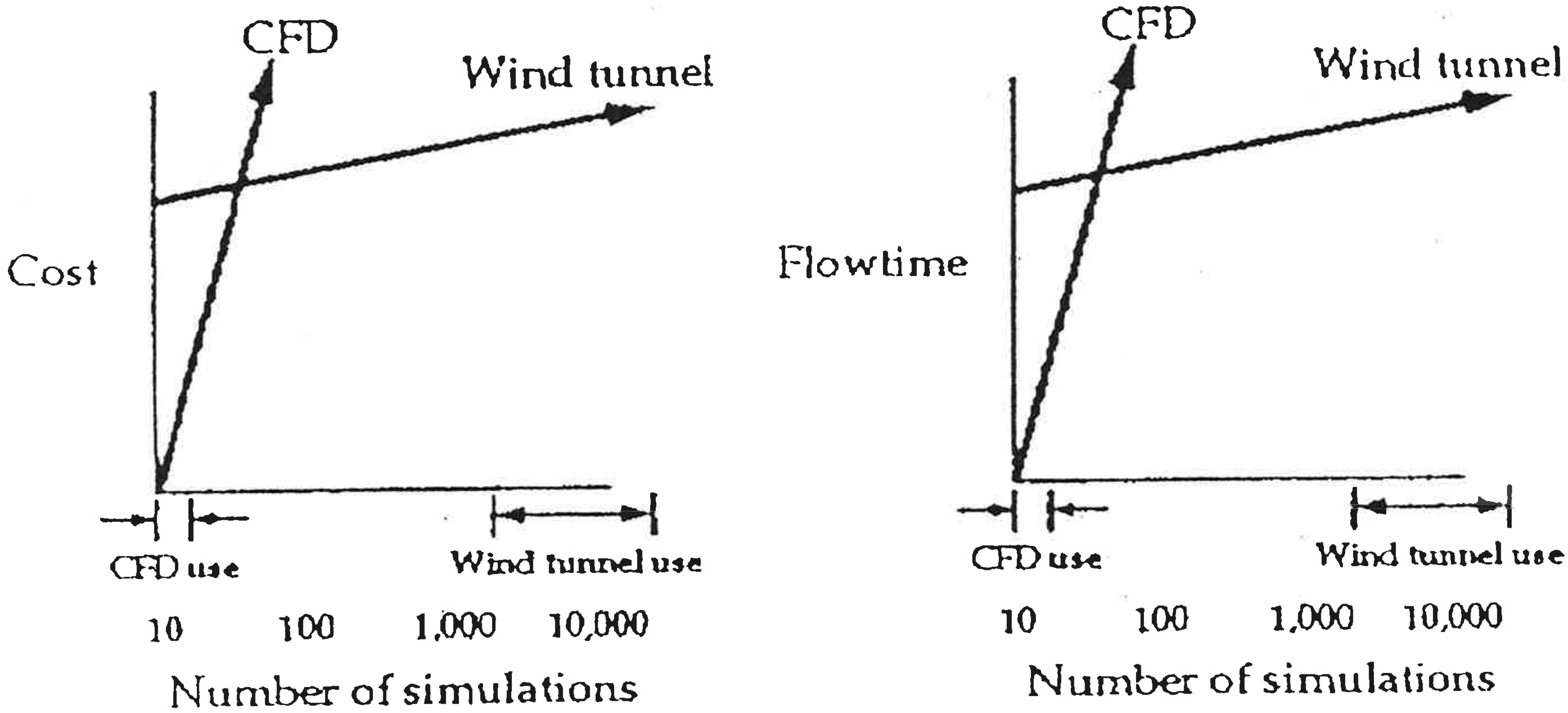
LIMITATIONS OF WIND TUNNEL TESTING

- *Non uniform flow*
- *Interference from slotted walls*
- *Support interference*



- *Model imperfections*
- *Model deflections under load*
- *Scale effects*
- *Reynolds no.* $\frac{\rho UL}{\mu}$ *= 100 million (B747), 5 million (wind tunnel)*
- *Flow can be drastically different (shock location, separation)*

Paul Rubbert "CFD and the Changing World Of Airplane Design
AIAA Wright Brothers Lecture, Sept. 1994



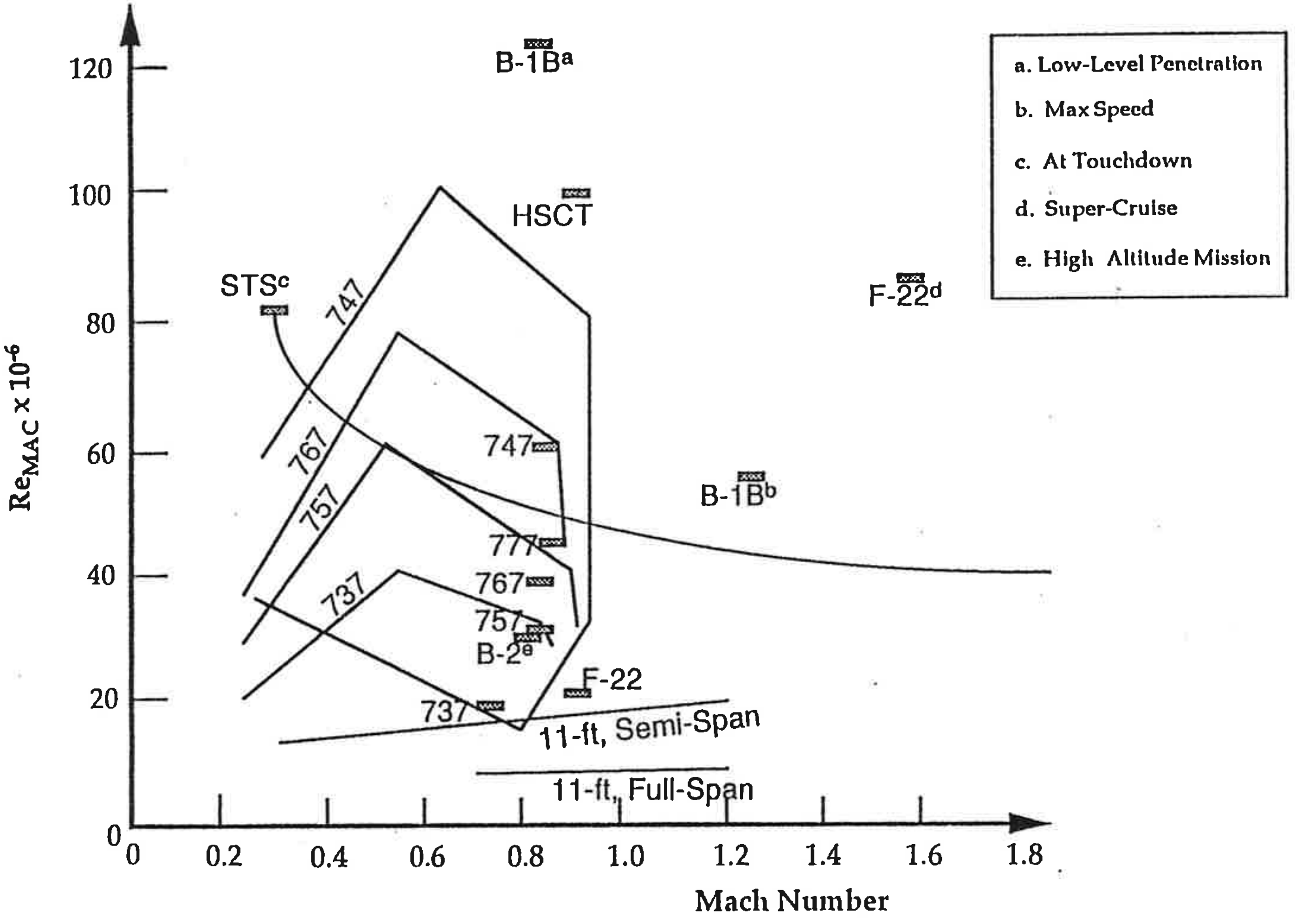
Note: One complete airplane development requires about 2.5 million aerodynamic simulations.

Figure 18. Cost and Flowtime Characteristics of Wind Tunnels and CFD

TRANSONIC TESTING REQUIREMENTS

REYNOLDS NUMBER

- Large subsonic transports require 65 million for cruise simulation



COMPUTATIONAL FLUID DYNAMICS (CFD)

- *Computational methods offer QUANTITATIVE PREDICTIONS of complex flows which previously could only be measured in WIND TUNNELS. They can treat both:*
    - *COMPLEX GEOMETRY*
    - *COMPLEX NONLINEAR EQUATIONS*
- *PANEL METHODS for solving the classical equations for a perfect fluid (Laplace's equation) on ARBITRARILY COMPLEX GEOMETRY appeared in 1965*
- *Computational methods for solving the NONLINEAR flow models ranging up to the full NAVIER-STOKES equations have become available since 1970*
- *The aircraft designer has to trade-off:*

ACCURACY	*vs.*	*COST*
TRUST LEVEL		*TURN AROUND TIME*

in comparison with wind tunnel data

REQUIREMENTS FOR EFFECTIVE AERODYNAMIC SIMULATION

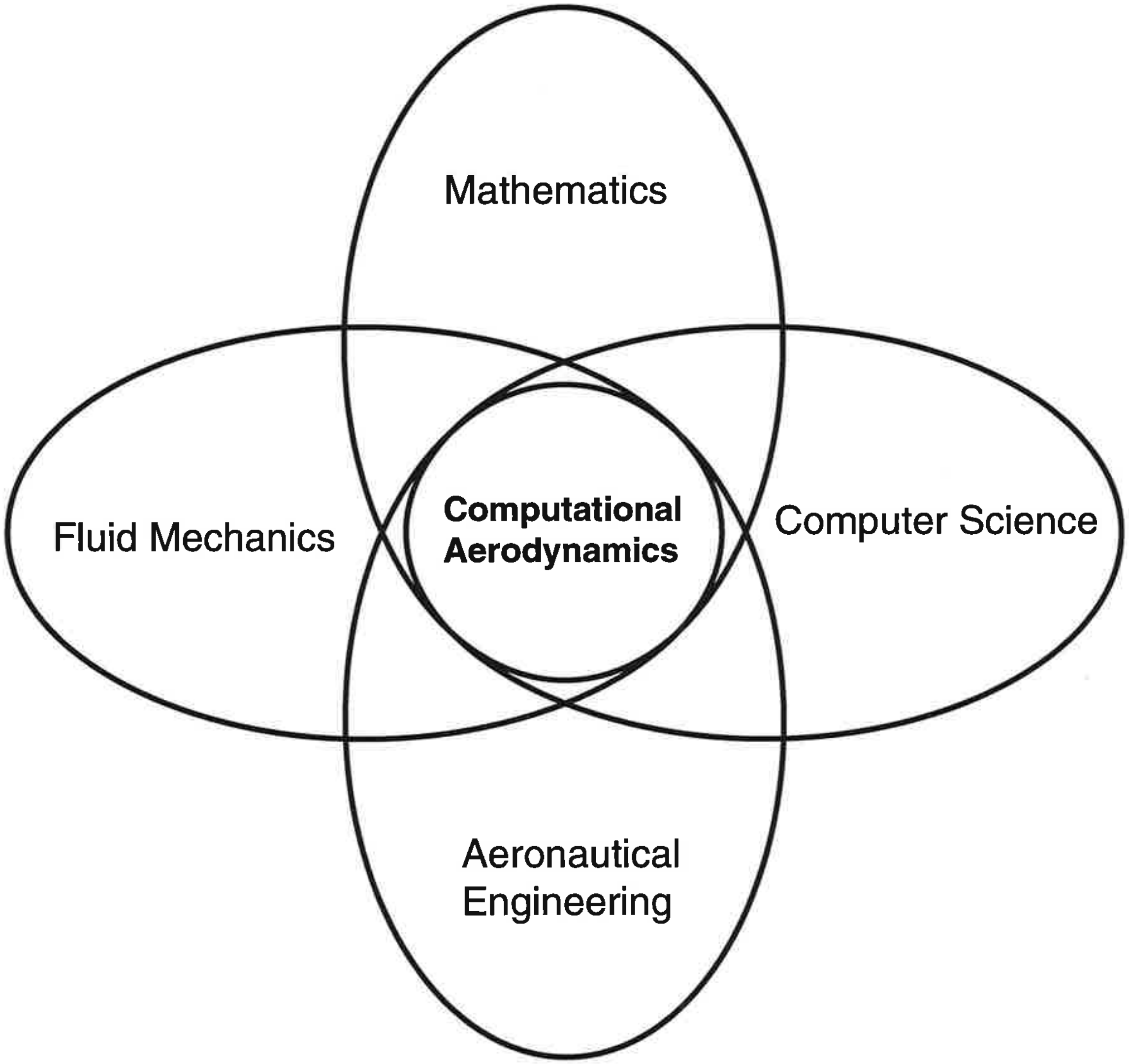
- *Sufficient and known level of accuracy*
- *Acceptable computational and manpower costs*
- *Fast turn-around time*

ACCURACY REQUIREMENTS

- *For aircraft design accuracy is crucial and should be in the range of 0.5%*
- *The drag coefficient of the B747 is in the range of 0.0275 (depending on the lift). The drag coefficient of current SST designs is in the range of 0.0150*
- *Thus one needs an accuracy for Cd of 0.0001 (1 count)*

- *Manufacturers have to guarantee performance*
- *Errors are very expensive in: redesign, penalty payments, and lost orders*
- *The MD11 was initially 7% high in fuel comsumption (5% due to the engines) and lost orders*

MULTIDISCIPLINARY NATURE OF CFD



Mathematics

Fluid Mechanics

Computational Aerodynamics

Computer Science

Aeronautical Engineering

CHOICE OF MATHEMATICAL MODEL

***Must** take into account:*

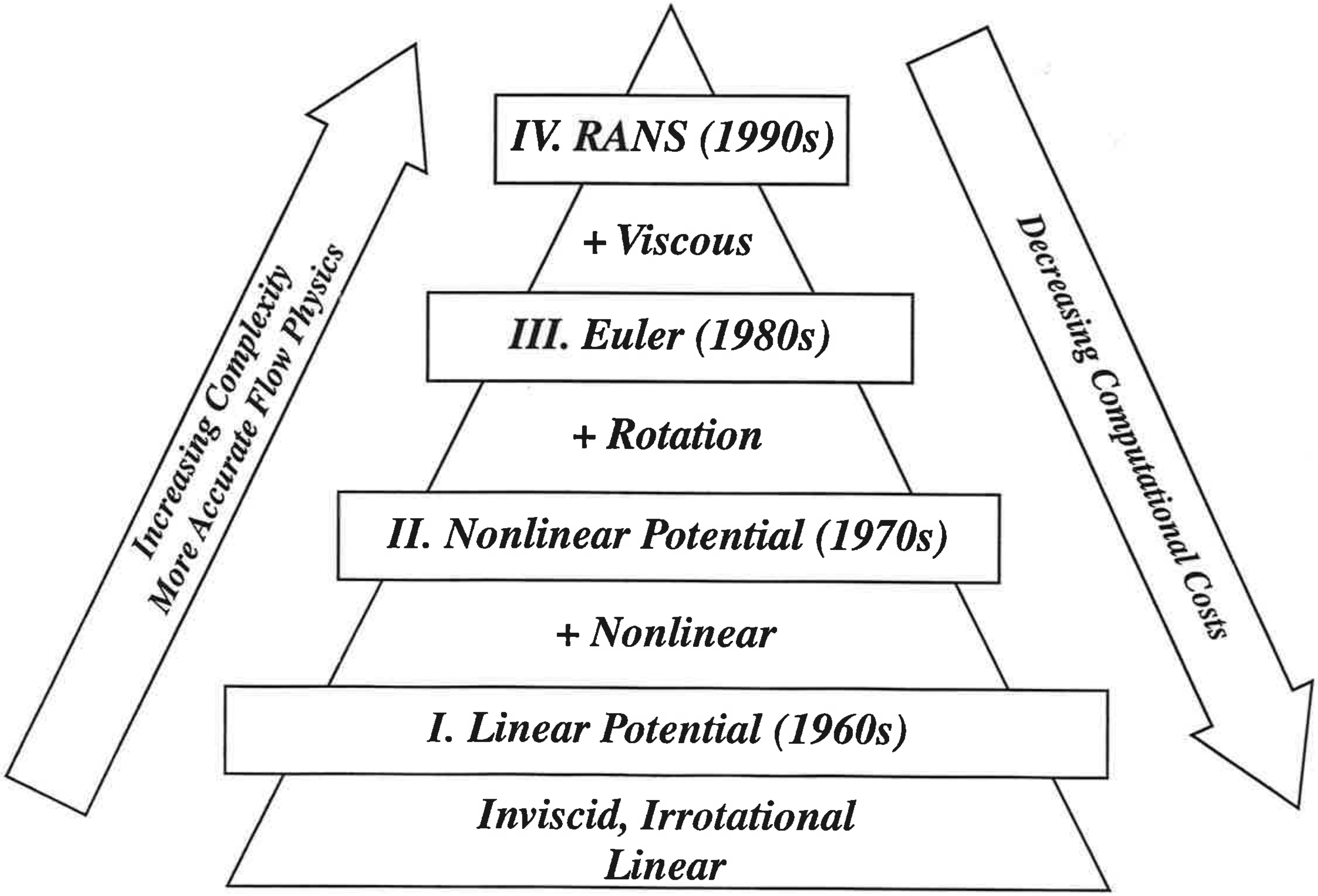
- *The suitability of the model for simulation of the expected type of flow (e.g., attached, separated, presence of strong shock waves)*
- *Available computing power*

NAVIER-STOKES EQUATIONS

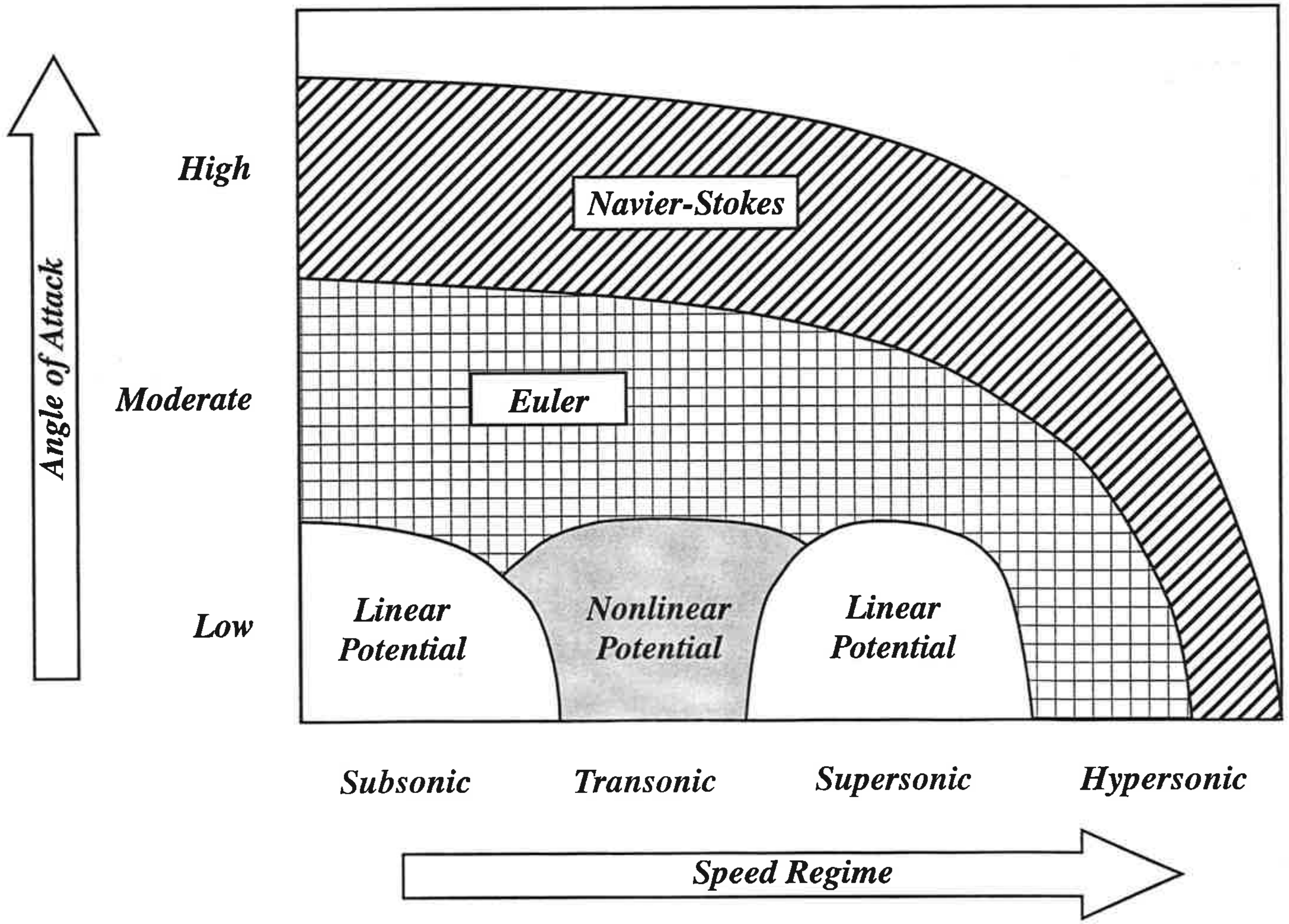
$$\frac{\partial w}{\partial t}+\frac{\partial F_j}{\partial x_j}=0$$

Mass equation	$w=\rho, F_j=\rho u_j$
i-momentum equation	$w_i=\rho u_i, F_{ij}=\rho u_i u_j+p\delta_{ij}-\sigma_{ij}$
Energy equation	$w=\rho E, F_j=(\rho E+p)u_j-\sigma_{jk}u_k-\kappa\frac{\partial T}{\partial x_j}$
Equation of state	$p=(\gamma-1)\rho(E-\frac{1}{2}u_i u_i)$
Stess tensor	$\sigma_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)+\lambda\delta_{ij}\left(\frac{\partial u_k}{\partial x_k}\right)$

HIERARCHY OF FLUID FLOW MODELS



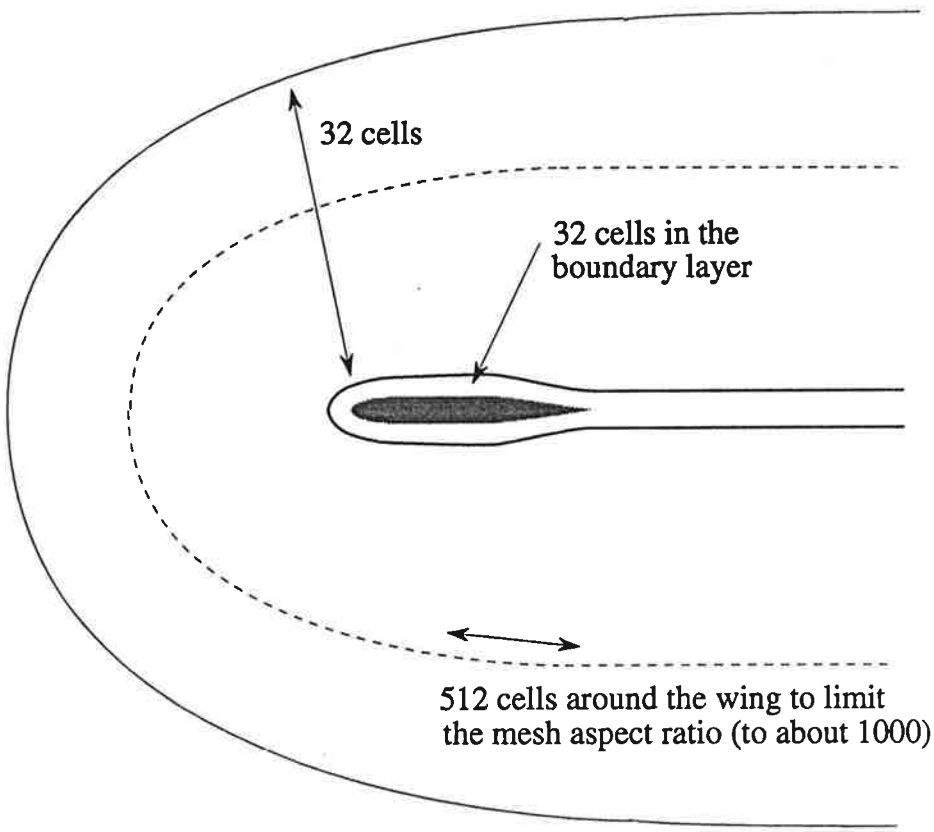
RANGE OF APPLICABILITY OF DIFFERENT FLOW MODELS



COMPLEXITY OF FLUID FLOW CALCULATIONS

- *At high Reynolds numbers (Re) the smallest scales of turbulence are proportional to $Re^{3/4}$(Kolmogorov) Complexity to resolve space and time in a full Direct Navier-Stokes (DNS) calculation ~ Re^3 For a Boeing 747 Re ~ 10^8, complexity ~ 10^{24}*
- *Inviscid flow past a complete aircraft ~ 1/2 million mesh cells*
- *Viscous flow simulation with turbulence modeling ~ 10 million mesh cells to fully resolve boundary layers*
- *Large Eddy Simulation (LES) with subgrid scale (SGS) modeling ~ 10 billion mesh cells (W. H. Jou, chief of CFD research at Boeing)*

Mesh Requirement for 3D Viscous Calculation

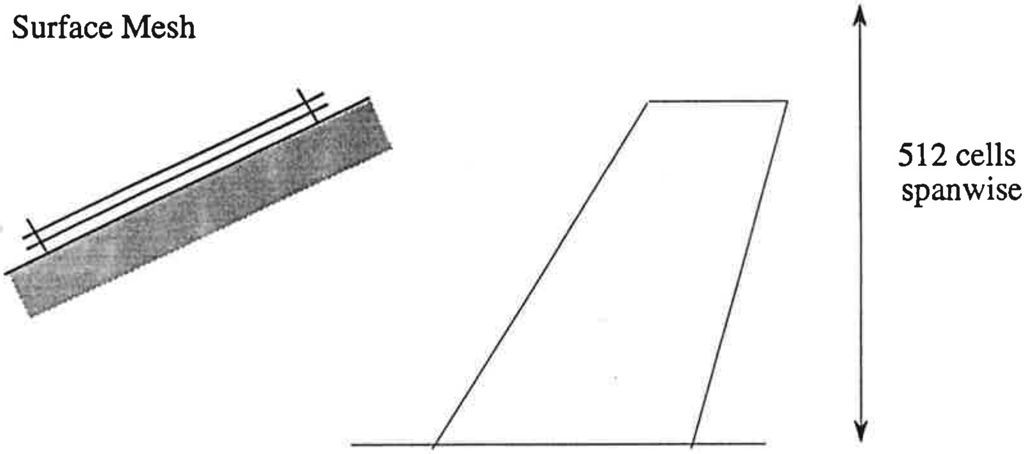


32 cells

32 cells in the boundary layer

512 cells around the wing to limit the mesh aspect ratio (to about 1000)

Surface Mesh



512 cells spanwise

Total: 512 x 64 x 512 = 16 777 216 cells

COMPLEXITY ESTIMATE FOR LES

(Due to W.H. Jou, Boeing)

- *Resolve eddies 1/5 of the boundary layer thickness*
  - *10 points per eddy = 50 intervals in the b.l.*
- *Eddies are roughly isotropic*
- *If b.l. thickness is 0.01 of the chord*
  - *5,000 intervals chordwise*
- *Aspect ratio = 10*
  - *50,000 intervals spanwise*
- *Total ~ 12.5 billion cells in the boundary layer*

REVIEW OF ALGORITHMS

NUMERICAL METHODS FOR COMPRESSIBLE FLOW

*In order to **resolve** the complex features of compressible flow such as **shock waves**, **contact discontinuities**, and **slip lines** it has been necessary to develop entirely new numerical methods which reflect the **mathematical theory of shock waves** due to P.D. Lax*

FINITE VOLUME SCHEMES

Subdivide *the domain into small* ***hexahedral*** *or* ***tetrahedral cells***

Satisfy the ***conservation laws*** *in* ***integral form***

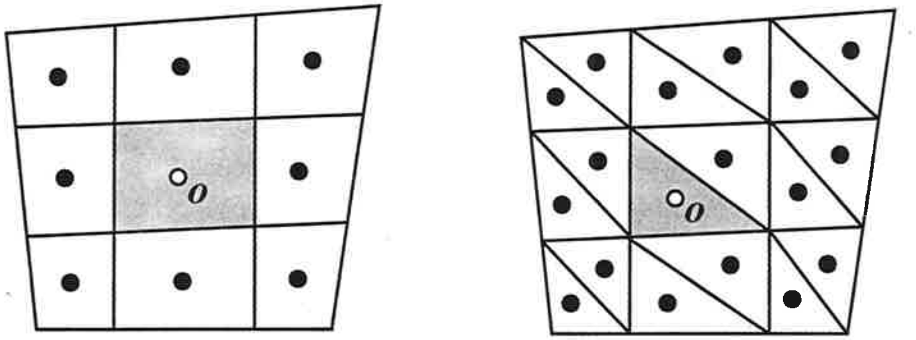
$$\frac{\partial}{\partial t}\int_{\Omega} w\,dv + \int_{\partial\Omega} \boldsymbol{F} \bullet d\boldsymbol{S} = 0$$

for each cell, giving the ***semi-discrete scheme***

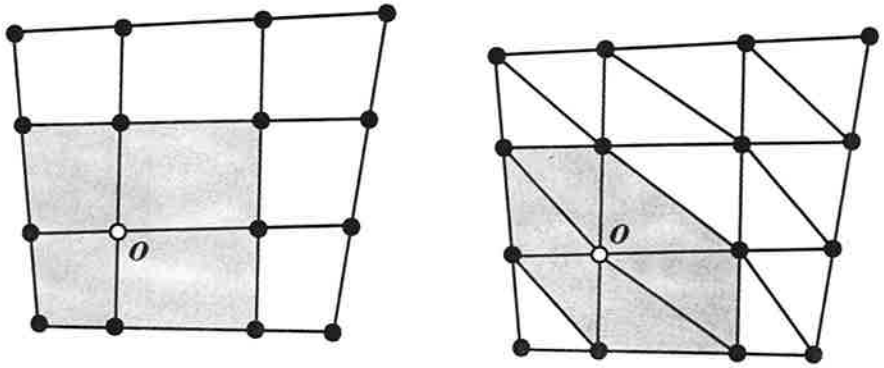
$$\frac{d}{dt}(wV) + \sum_{faces} \boldsymbol{F} \bullet \boldsymbol{S} = 0$$

valid in the presence of ***shock waves*** *and* ***slip lines***

STRUCTURED AND UNSTRUCTURED DISCRETIZATIONS



Cell Centered Scheme



Cell-vertex Scheme

LOCAL EXTREMUM DIMINISHING (LED) SCHEMES

Central difference schemes produce spurious **oscillations** in the solution and **overshoots** in the vincinity of shock waves

Oscillations can be eliminated by the use of **local extremum diminishing (LED)** schemes which prevent maxima from increasing and minima from decreasing. A general **semi-discrete** scheme in the form

$$\frac{dv_j}{dt} = \sum_{k \neq j} c_{kj}(v_k - v_j)$$

is **LED** if $c_{jk} \geq 0$, and $c_{jk} = 0$ if the mesh points j and k are not neighbors. This property can be enforced by **upwind biasing** of the difference formulas

HIGH RESOLUTION FLUX SPLIT SCHEMES

*The **system of equations** for **gas dynamics** allows **waves** travelling at the speeds u, u+c, u-c where u is the fluid velocity and c is the speed of sound.*

*To construct properly **upwind biased** schemes the **fluxes** may be **split** into differences of **characteristic variables** corresponding to the **different waves**. Alternatively the **convective** and **pressure** terms may be separated to produce a Convective Upwind and Split Pressure (CUSP) scheme*

*Both **characteristic** and **CUSP** schemes can be formulated to produce **stationary discrete shocks** with a structure containing a **single interior point***

TIME STEPPING SCHEMES

*The **semi-discrete scheme** which results from the **space discretization** can be written as a set of ordinary differential equations*

$$\frac{dw}{dt} + R(w) = 0$$

*where w is the vector of the flow variables at the mesh points, and R(w) is the vector of **residuals** defined by the **flux balances***

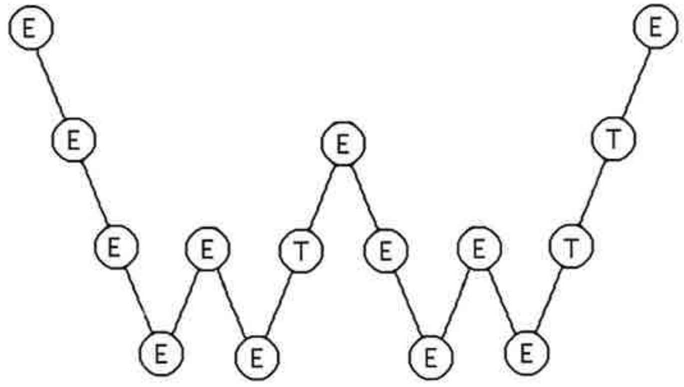
***Implicit schemes** of the form*

$$\omega^{n+1} = \omega^{n} - \Delta t \left\{ (1-\mu) R(\omega^{n}) + \mu R(\omega^{n+1}) \right\}$$

*allow **large time steps** at the expense of the complexity of solving coupled equations at each time step. The **time step** of an **explicit multistage scheme** is limited by a **stability restriction**, but the **computational** cost of the time step is **reduced**, and the scheme is **easily parallelized***

MULTIGRID ACCELERATION

*Very rapid **convergence** to a **steady state** can be achieved by calculating corrections on a **sequence** of **successively coarser meshes** which are applied to the **fine mesh** solution, following a complex cycle*



4 Levels

Ⓔ = Evaluate the change in the solution

Ⓣ = Transfer the data without updating the solution

*With the aid of this technique **equilibrium** can be **simultaneously established** at **all scales** from **local** to **global***

*The multigrid procedure can be used as an efficient method of solving the coupled equations of an **implicit time stepping** scheme*

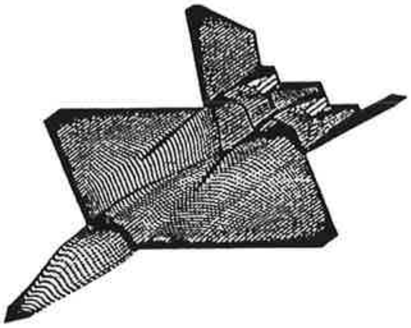
REFERENCES

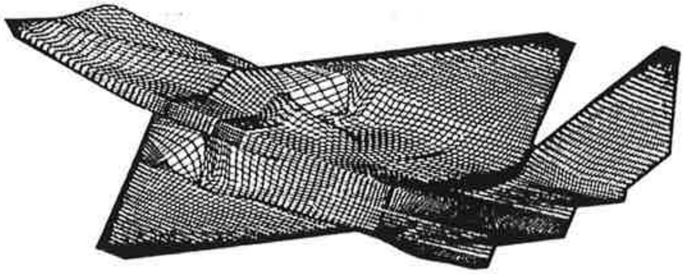
A more detailed discussion of numerical algorithms for CFD can be found in the follwing:

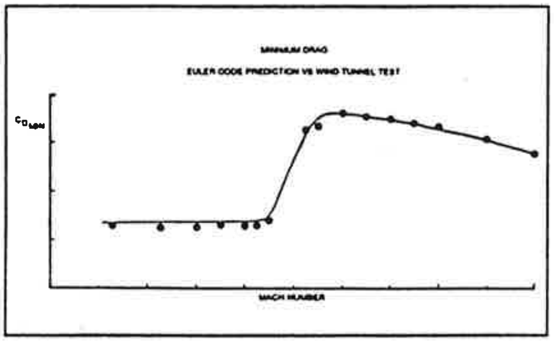
- *A. Jameson, Analysis and Design of Numerical Schemes for Gas Dynamics 1 Artificial Diffusion, Upwind Biasing, Limiters and their Effect on Accuracy and Multigrid Convergence. To appear in International Journal of Computational Fluid Dynamics.*
- *A. Jameson, Analysis and Design of Numerical Schemes for Gas Dynamics 2 Artificial Diffusion and Discrete Shock Structure. To appear in International Journal of Computational Fluid Dynamics.*
- *S. Tatsumi, L. Martinelli, and A. Jameson, A New High Resolution Scheme for Compressible Viscous Flow with Shocks, AIAA 33rd Aerospace Sciences Meeting, AIAA Paper 95-0466, Reno, NV, January 1995.*
- *J.J. Alonso, L. Martinelli, and A. Jameson, Multigrid Unsteady Navier-Stokes Calculations with Aeroelastic Applications, AIAA 33rd Aerospace Sciences Meeting, AIAA Paper 95-0048, Reno, NV, January 1995.*
- *A. Jameson, Aerodynamic Design Methods. CERCA International Workshop on Solution Techniques for Large Scale CFD Problems, Montreal, September 1994.*
- *A. Jameson, Requirements and Trends of Computational Fluid Dynamics as a Tool for Aircraft Design, Proceedings of the 12th NAL Symposium on Aircraft Computational Aerodynamics, Tokyo, June 1994.*

EXAMPLES OF FLOW CALCULATIONS

- *Euler Equations*
  - *F23*
  - *SST*
  - *MD11*
- *Viscous flows with turbulence modelling*
  - *RAE 2822 Airfoil*
  - *F18*
  - *Transport Wing*
- *Unsteady Flow*
  - *Pitching airfoil*







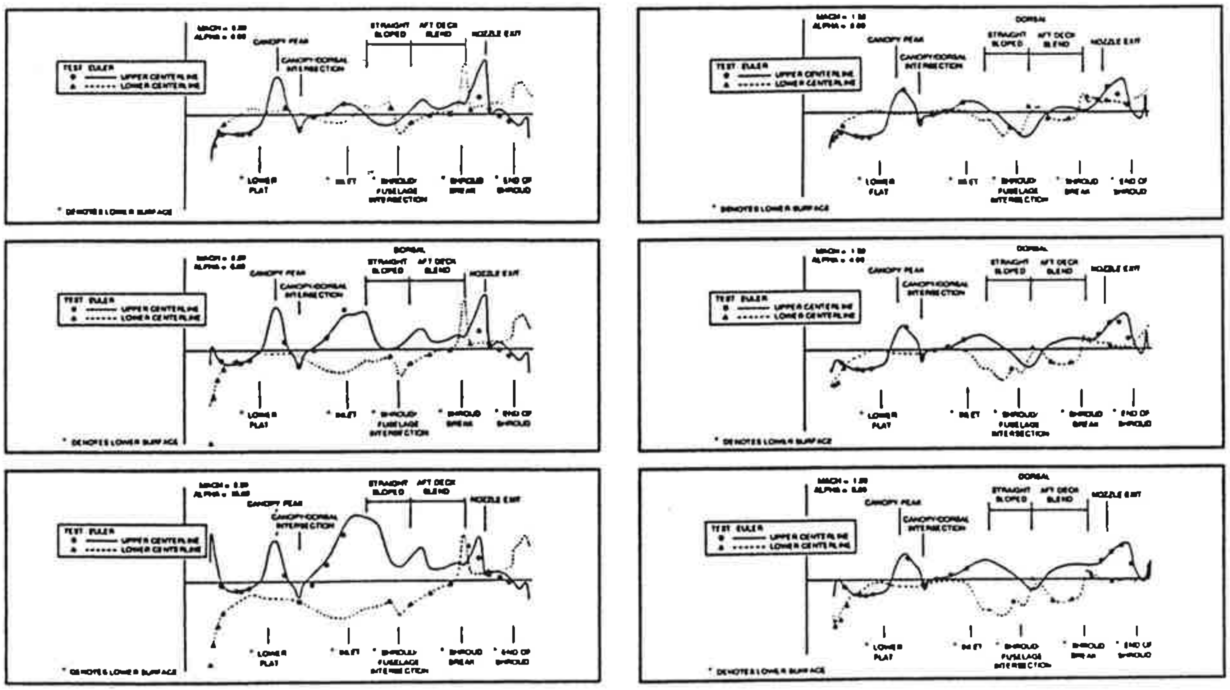
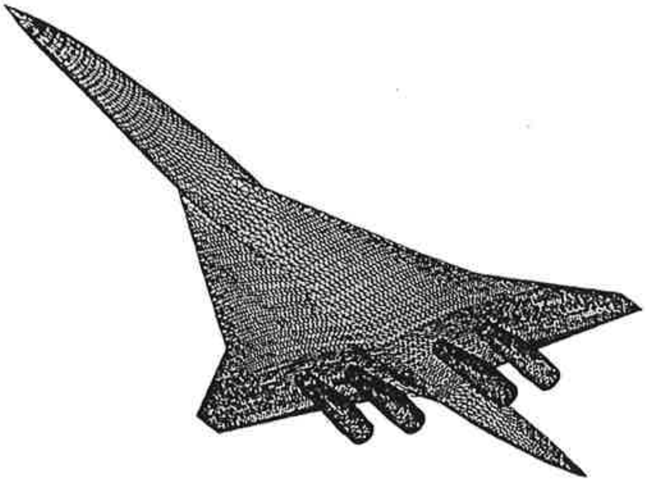
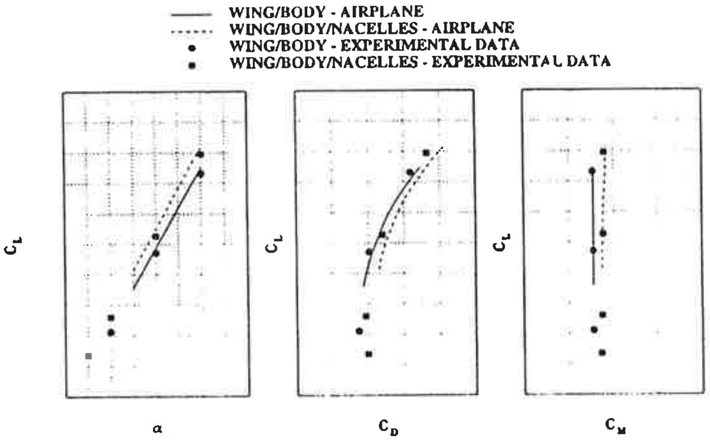
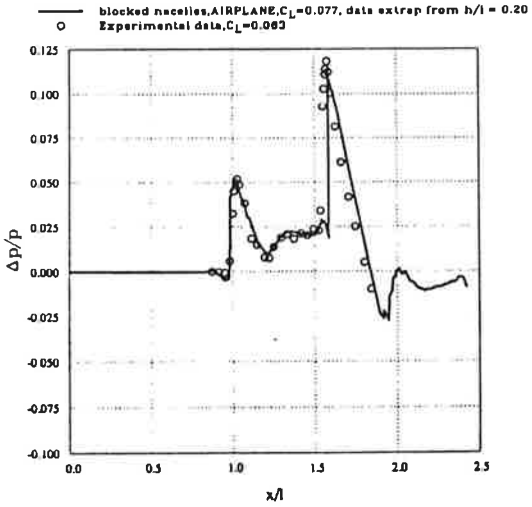


Plate 1: Northrop YF-23.
Supplied by R.J. Busch, Jr.





3a: Force Coefficients, Mach 2.1.



3b: Sonic Boom Prediction, Mach 2.5.

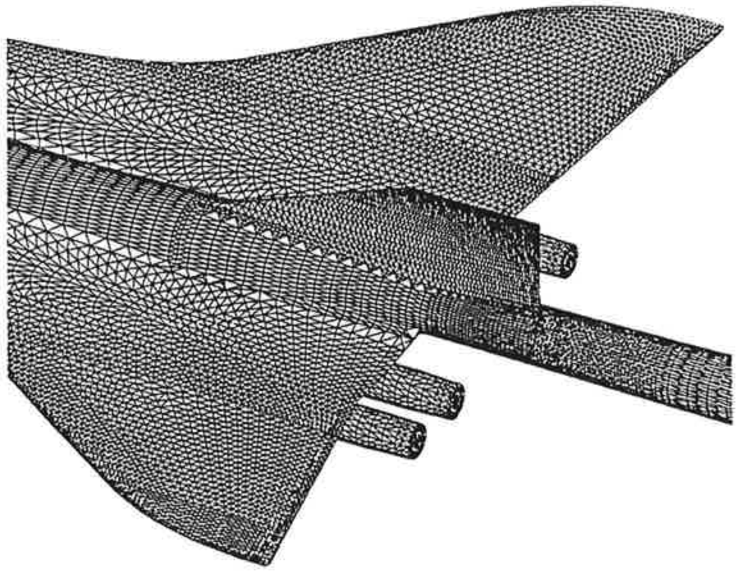
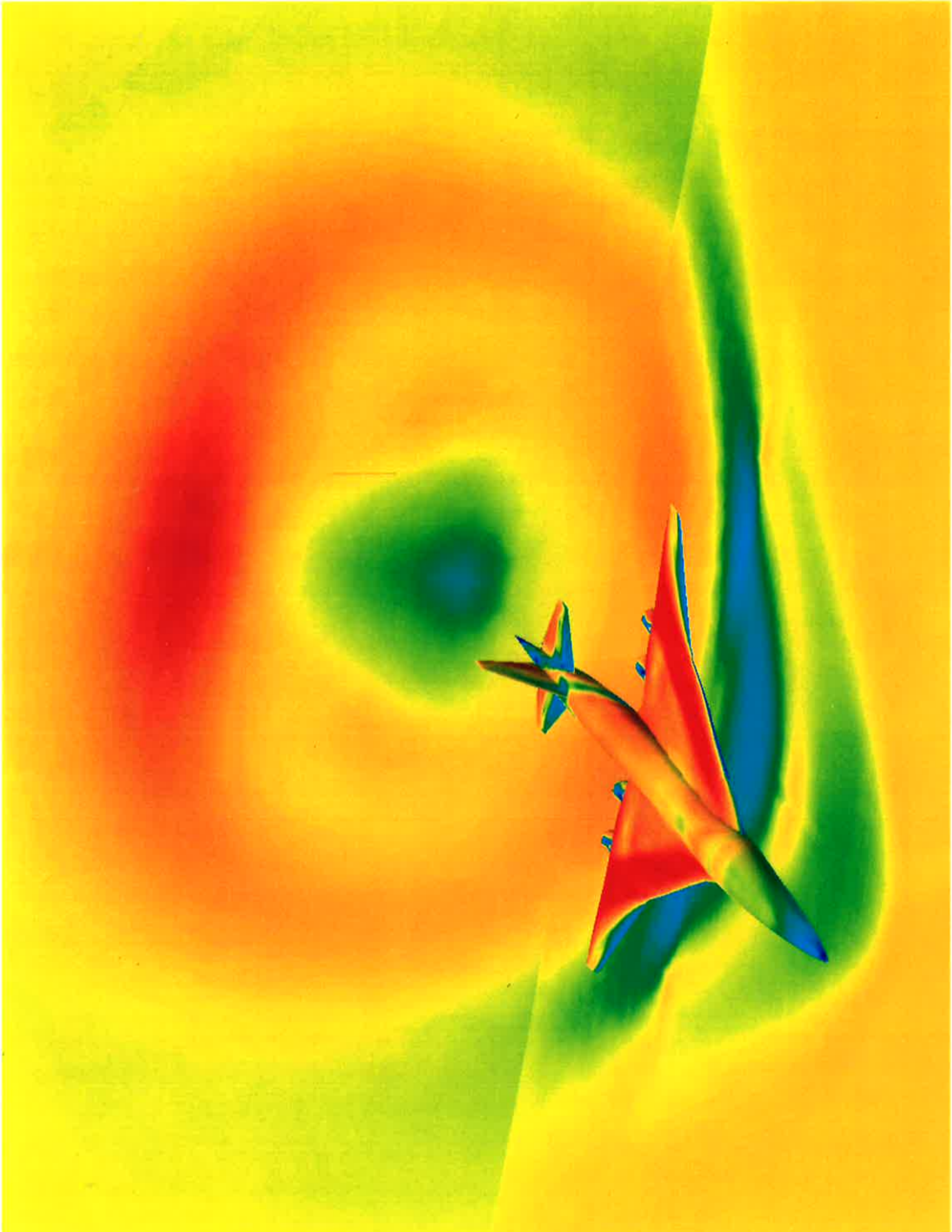
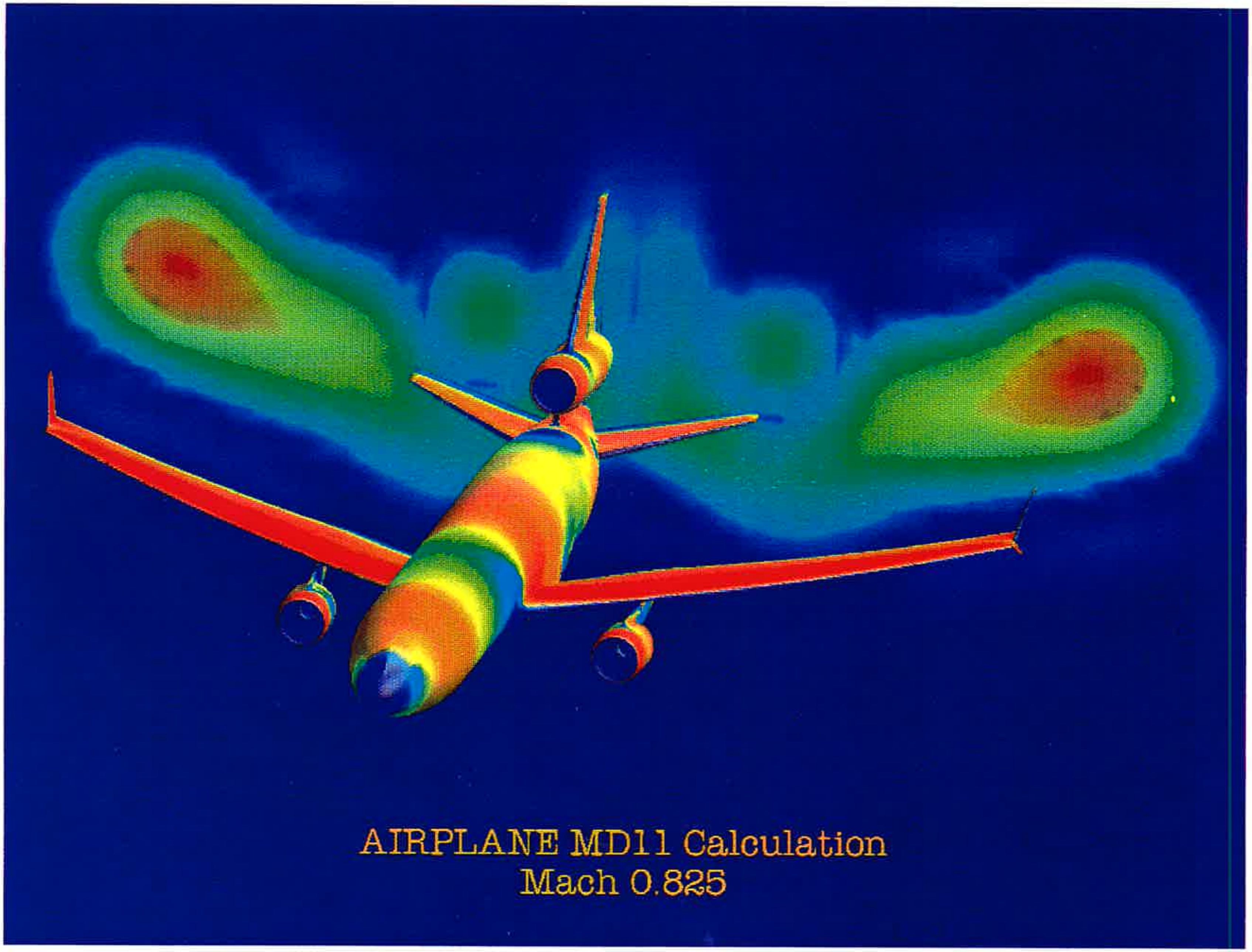


Plate 3: Supersonic Transport Calculations.
AIRPLANE code (A. Jameson and T.J. Baker).





AIRPLANE MD11 Calculation
Mach 0.825

CALCULATIONS OF COMPLETE AIRCRAFT USING UNSTRUCTURED TETRAHEDRAL MESHES

Benefits:

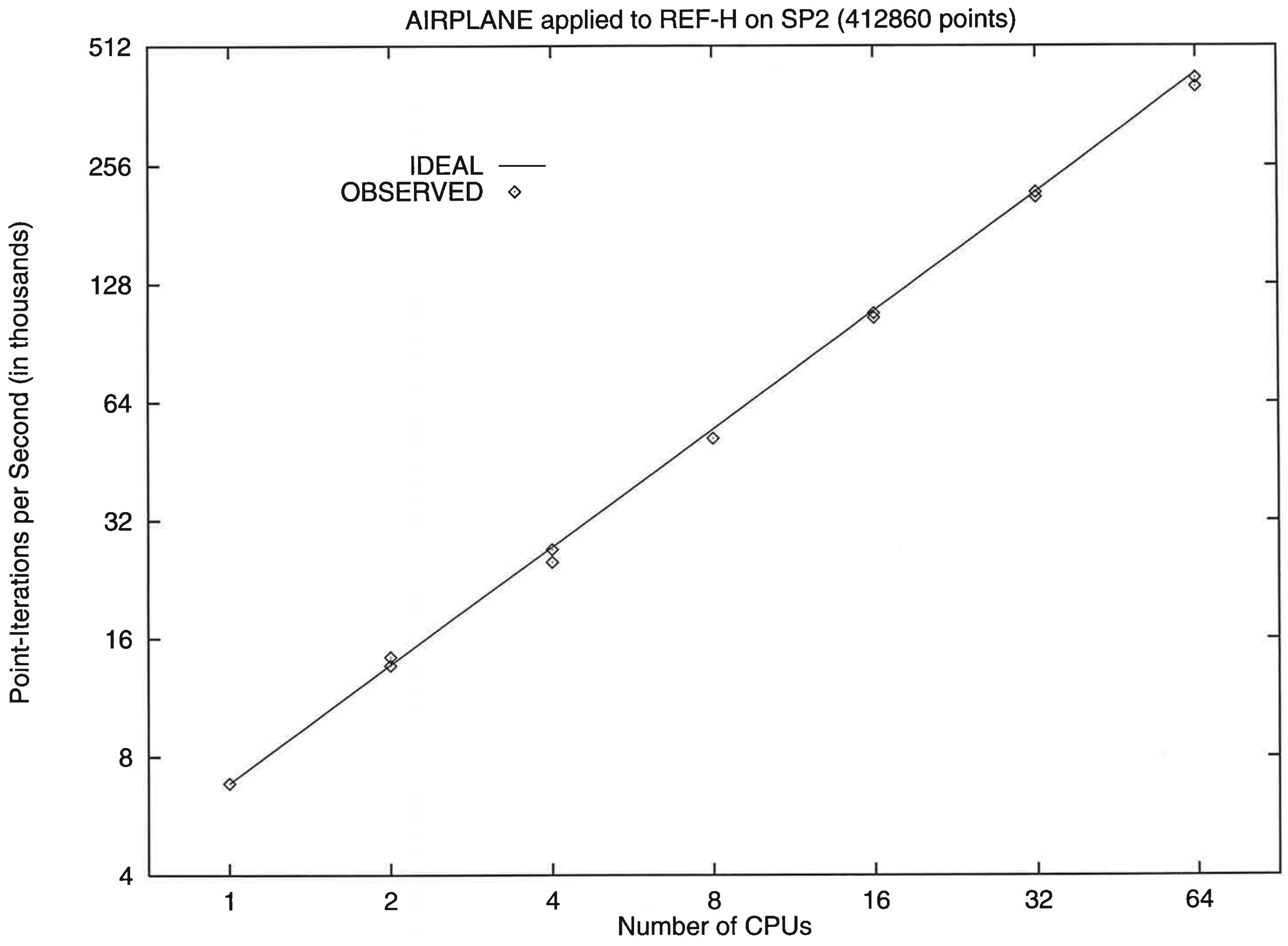
- *Fast turn-around and reduced cost of mesh generation for arbitrarily complex configurations*
- *Easy to concentrate additional mesh points where needed for improved resolution*
- *Computing times for MD11, 350,000 mesh points, 2.1 Million tetrahedra:*
  - *4.0 hours on IBM RS6000/590*
  - *16 minutes on IBM SP2 (16 Processors)*

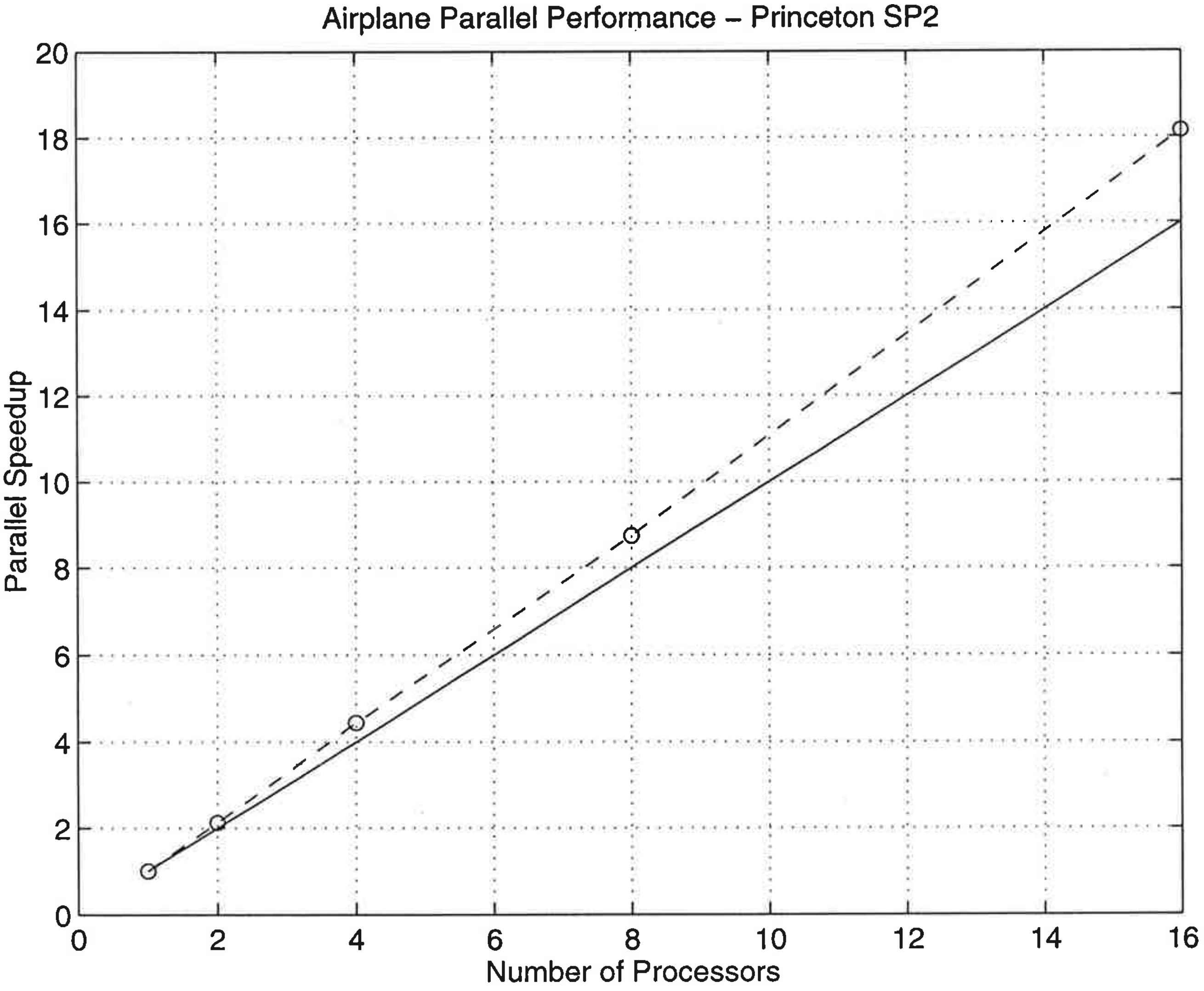
***Table** AIRPLANE Performance on the SP2, Mc Donnell Douglas MD11 Model*

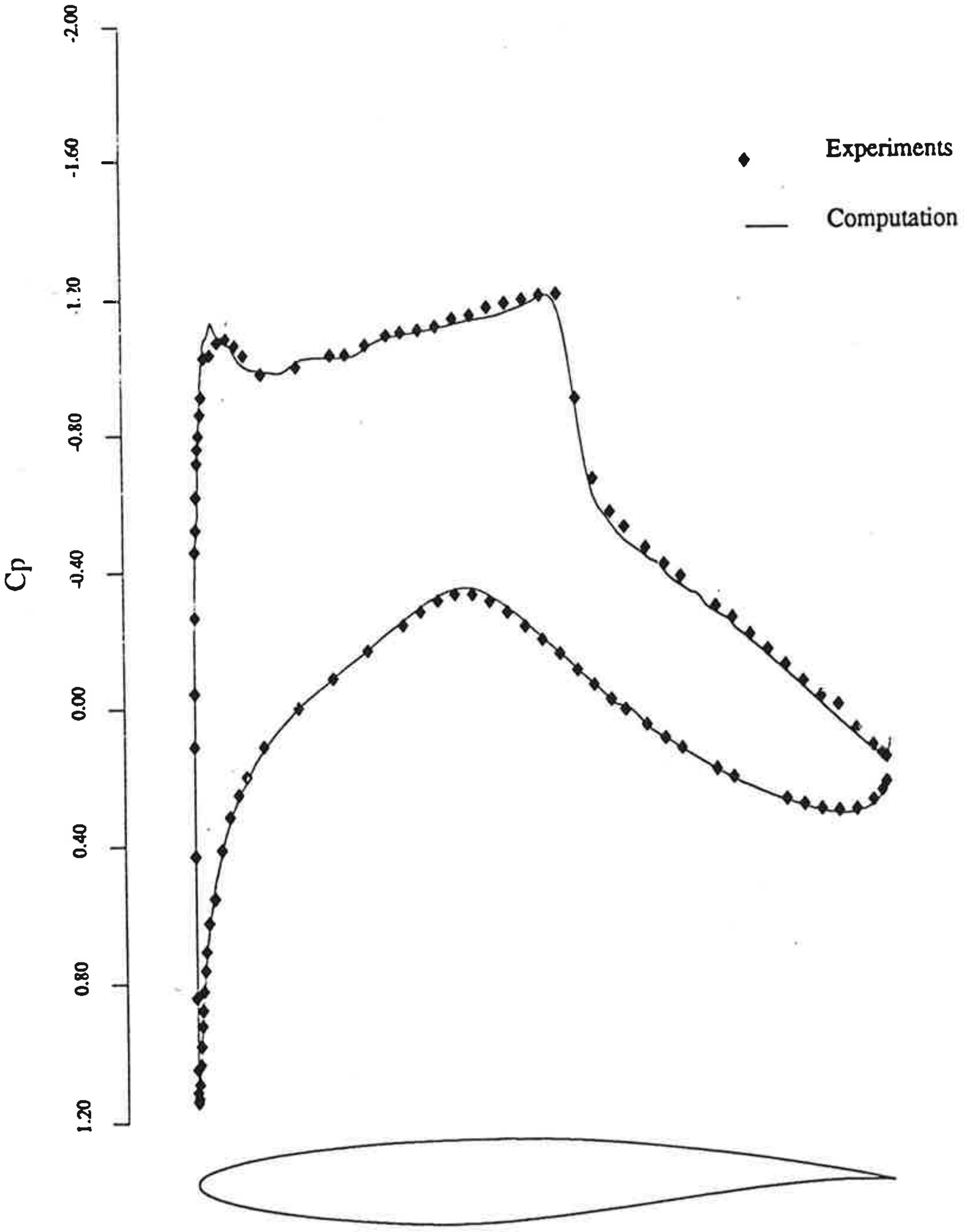
# Nodes	*"Wide" Node Performance (seconds/cycle)*	*Speedup*
1	*36.03*	*1.00*
2	*18.11*	*1.99*
4	*9.11*	*3.96*
8	*4.66*	*7.73*
16	*2.39*	*15.08*

Note: MD11 (Using local psmooth to reduce message passing):

Total 348,407 nodes, 2,100,466 tetrahedral elements, 75,518 faces, and 2,486,640 edges. Four stages with smoop = 1


AIRPLANE applied to REF-H on SP2 (412860 points)
IDEAL
OBSERVED
Point-Iterations per Second (in thousands)
512
256
128
64
32
16
8
4
1
2
4
8
16
32
64
Number of CPUs


Airplane Parallel Performance – Princeton SP2
Parallel Speedup
Number of Processors
0
2
4
6
8
10
12
14
16
18
20
0
2
4
6
8
10
12
14
16



RAE2822 6 .225

MACH 0.729 ALPHA 2.310

CL 0.7283 CD 0.0071 CM -0.0911

GRID 512X64 NCYC 75 RES0.000E+00

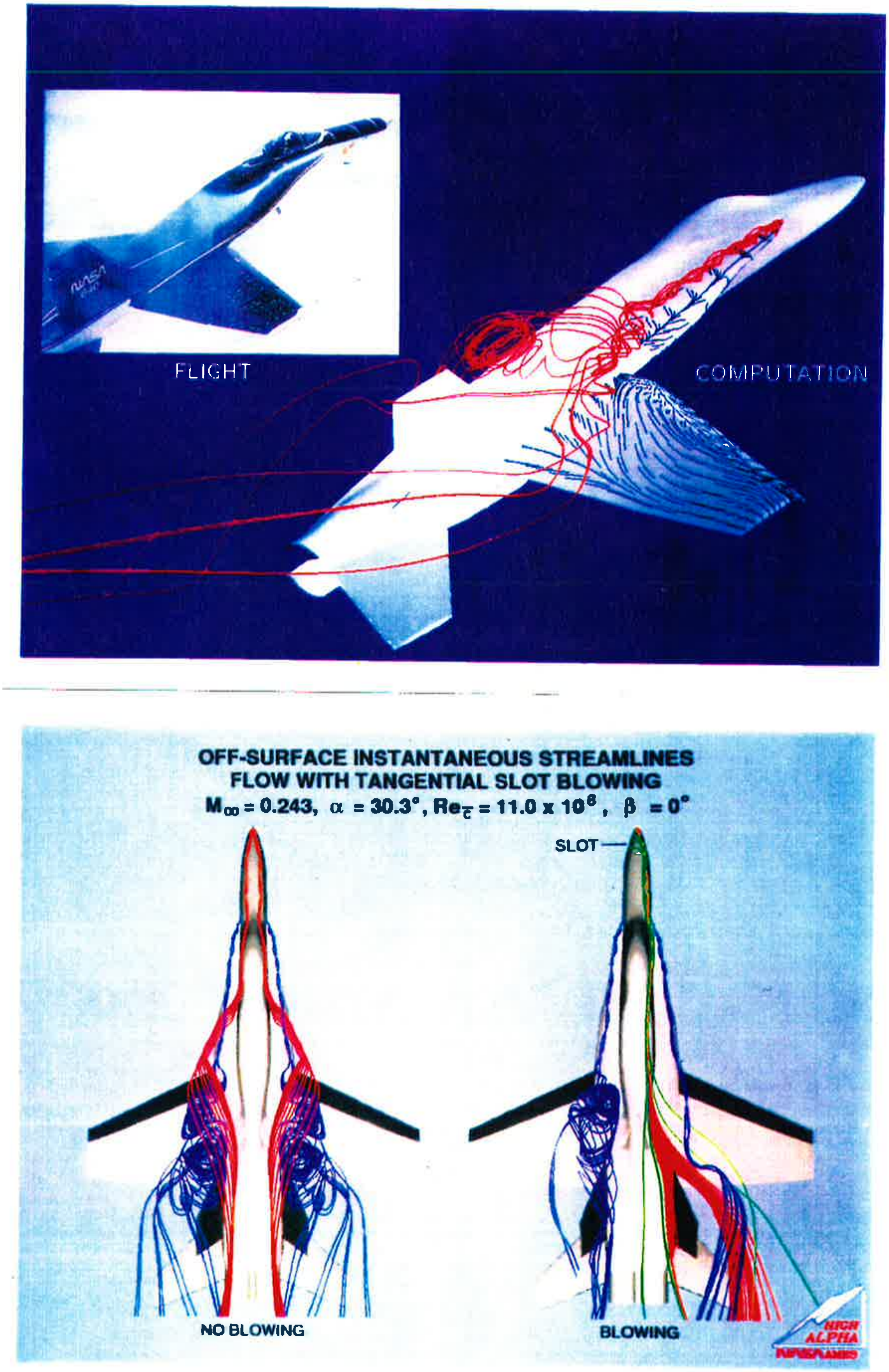
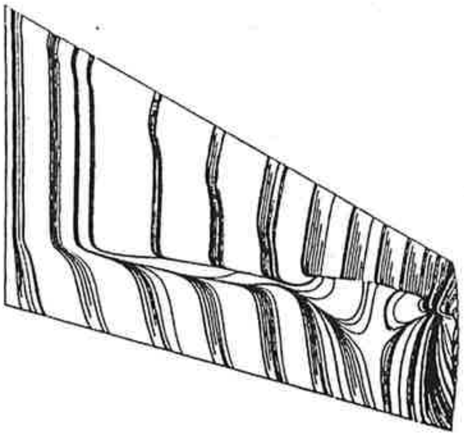
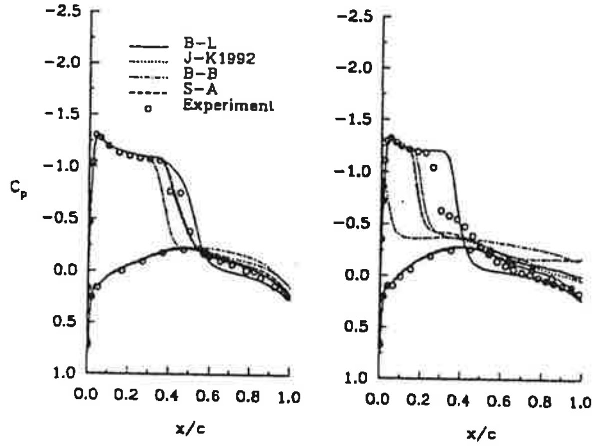


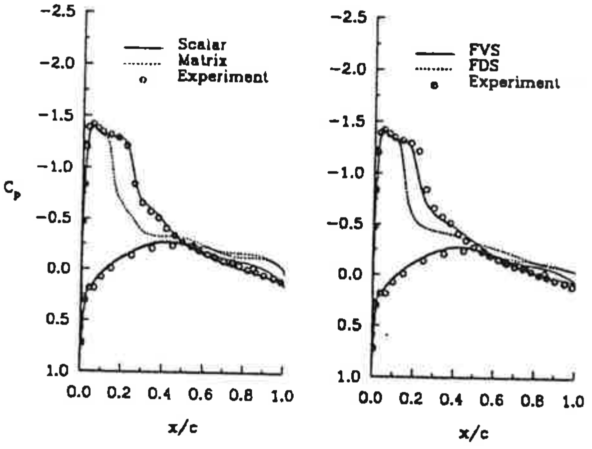
Plate 7: Navier-Stokes Predictions for the F-18 Wing-Fuselage at Large Incidence.
Supplied by R.M. Cummings, Y.M. Rizk, L.B. Schiff, and N.M. Chaderjian.





a) 2y/B = 0.65

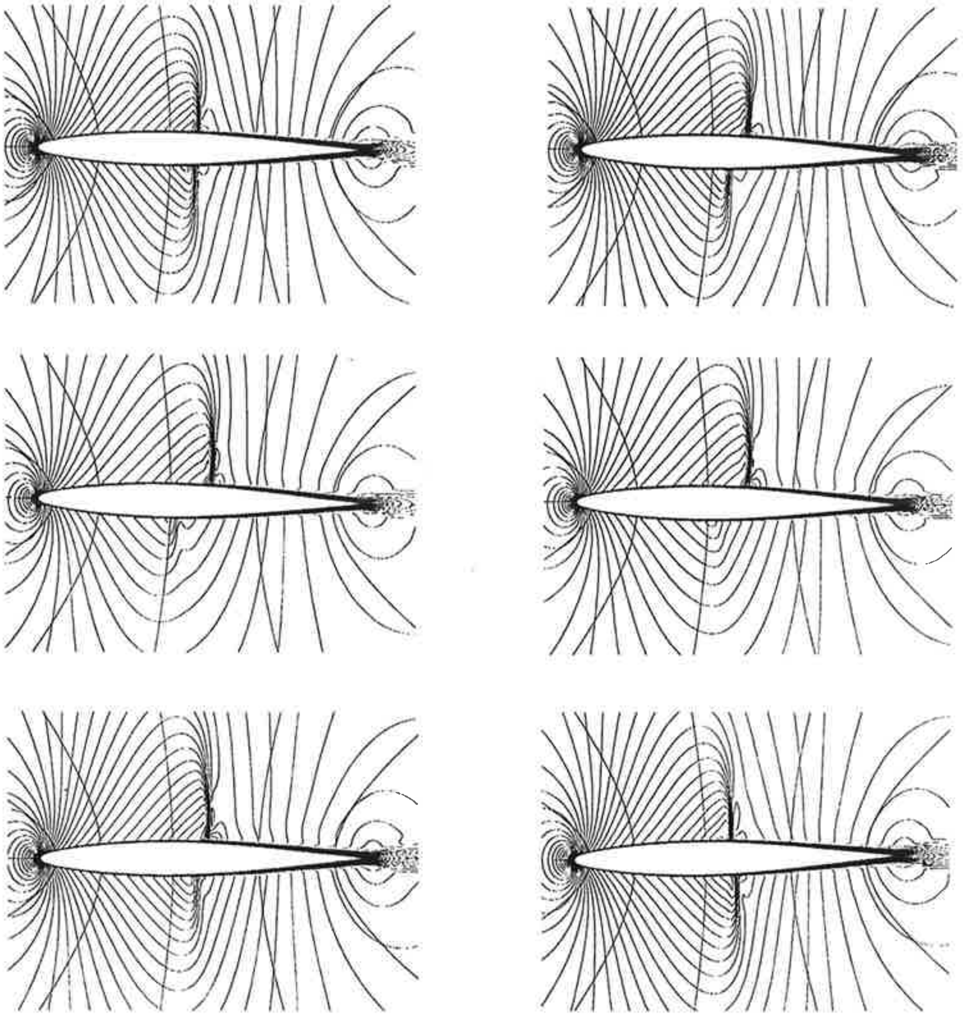
b) 2y/B = 0.90



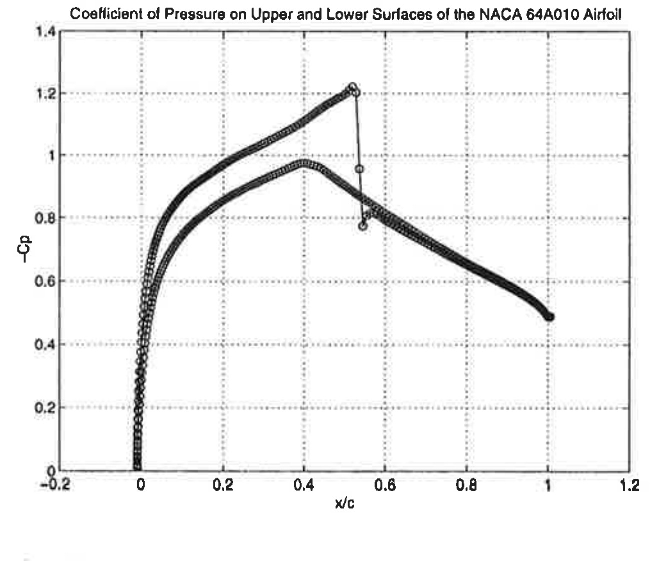
a) TLNS3D

b) CFL3D

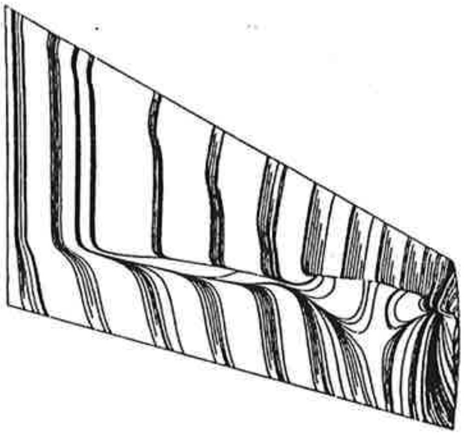
Plate 9: Navier-Stokes Solutions for the ONERA M6 Wing using TLNS3D and CFL3D with Different Turbulence Models.
Supplied by C.L. Rumsey and V.N. Vatsa.

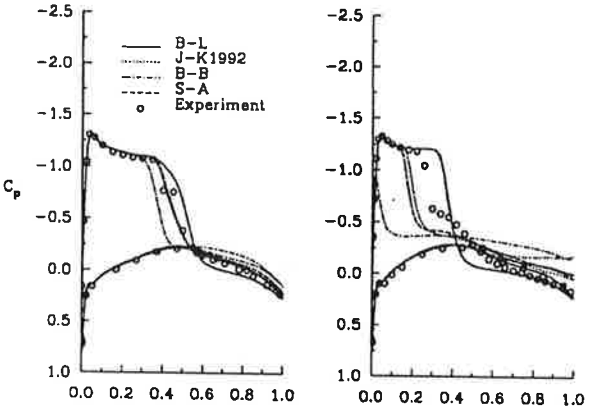


Mach Number Contours. Pitching Airfoil Case. $Re = 1.0 \times 10^6$, $M_\infty = 0.796$, $K_c = 0.202$.



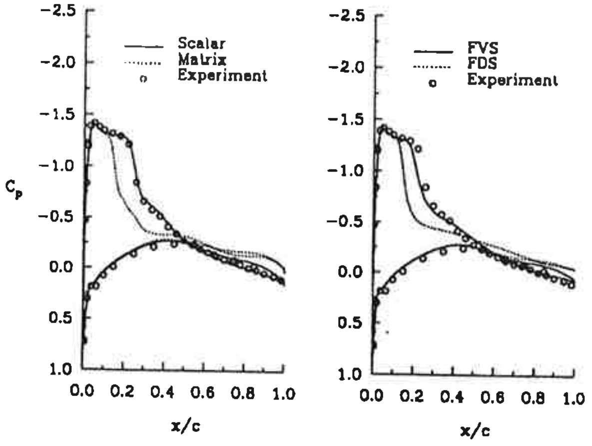
Coefficient of Pressure on a Grid Line Just Outside of the Boundary Layer.





a) 2y/B = 0.65

b) 2y/B = 0.90



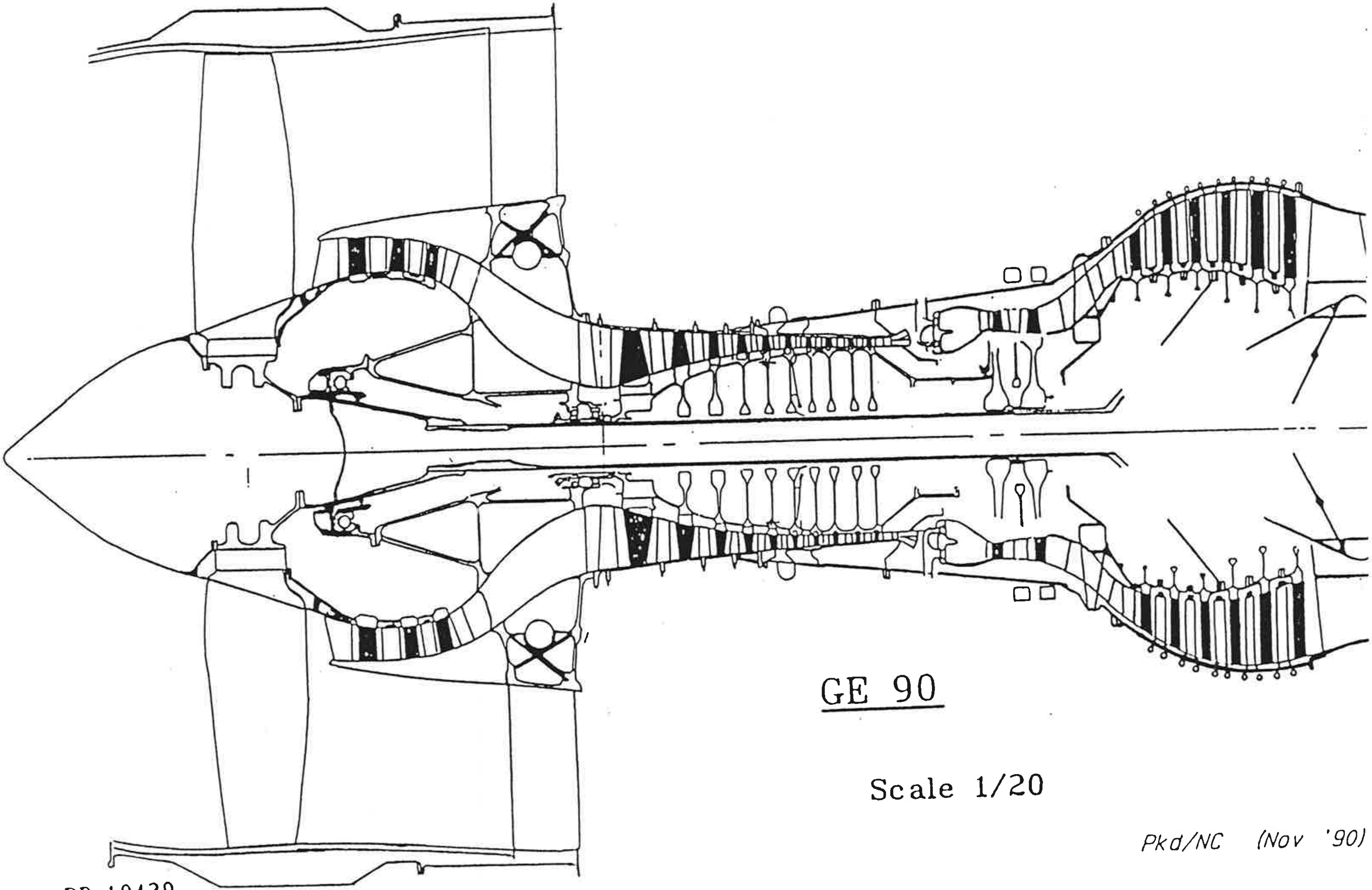
a) TLNS3D

b) CFL3D

Plate 9: Navier-Stokes Solutions for the ONERA M6 Wing using TLNS3D and CFL3D with Different Turbulence Models.
Supplied by C.L. Rumsey and V.N. Vatsa.

ADVANCED CALCULATIONS OF COMPLEX VISCOUS FLOWS

- *Currently not accessible tools for industrial use*
  - *Accuracy is uncertain*
    - *Turbulence modelling*
    - *Mesh resolution*
  - *Too expensive*
    - *Parallel computing*
  - *Turn-around too slow*
    - *Data handling*
    - *Geometry modelling*
    - *Mesh generation*



GE 90

Scale 1/20

Pkd/NC (Nov '90)

PD 10439

Calculations of Ship Hull Wave and Friction Resistance

- Naval Vessels
- Sailing Yachts

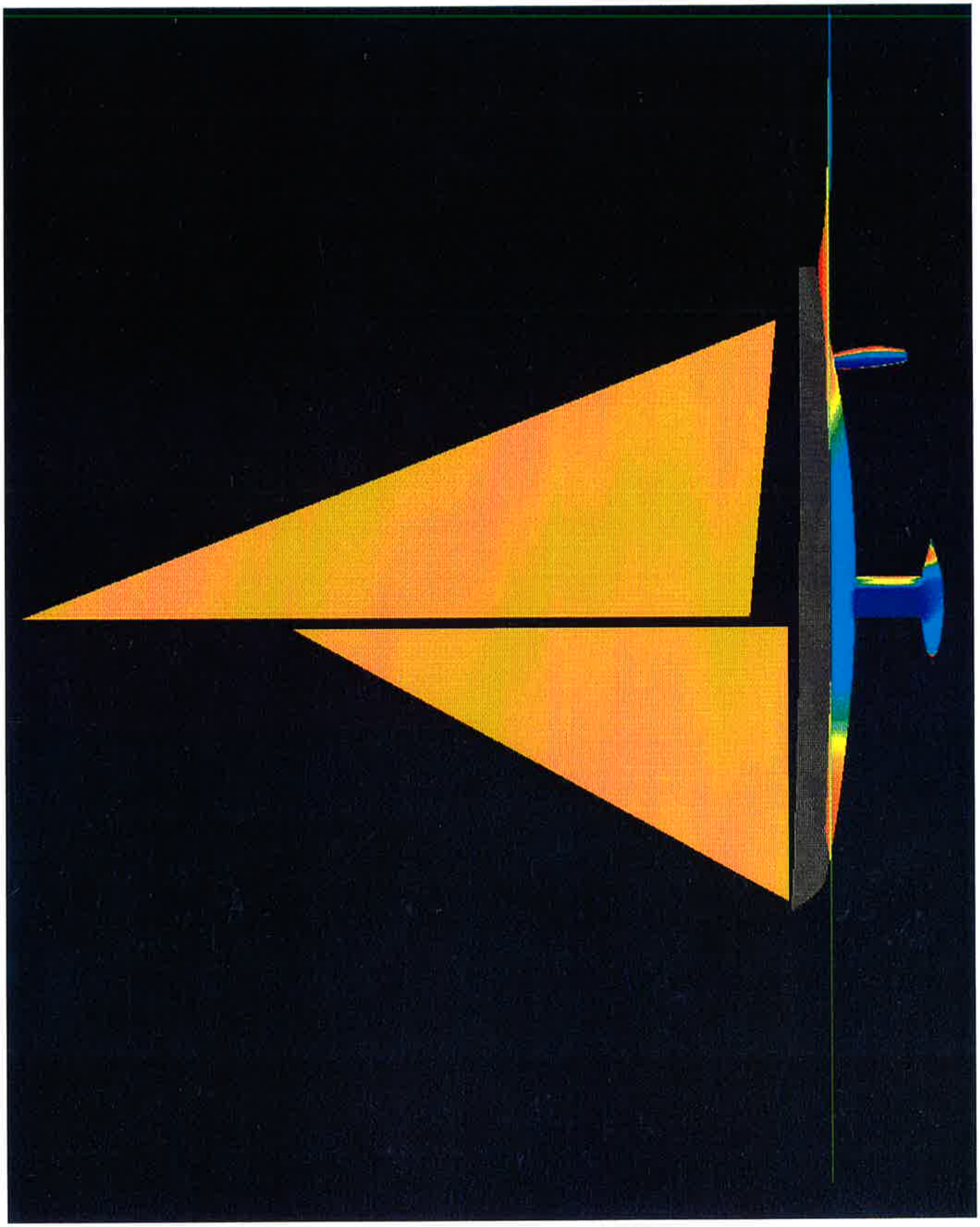
Solution of the Navier-Stokes Equations with Full Nonlinear Boundary Conditions for the Free Surface

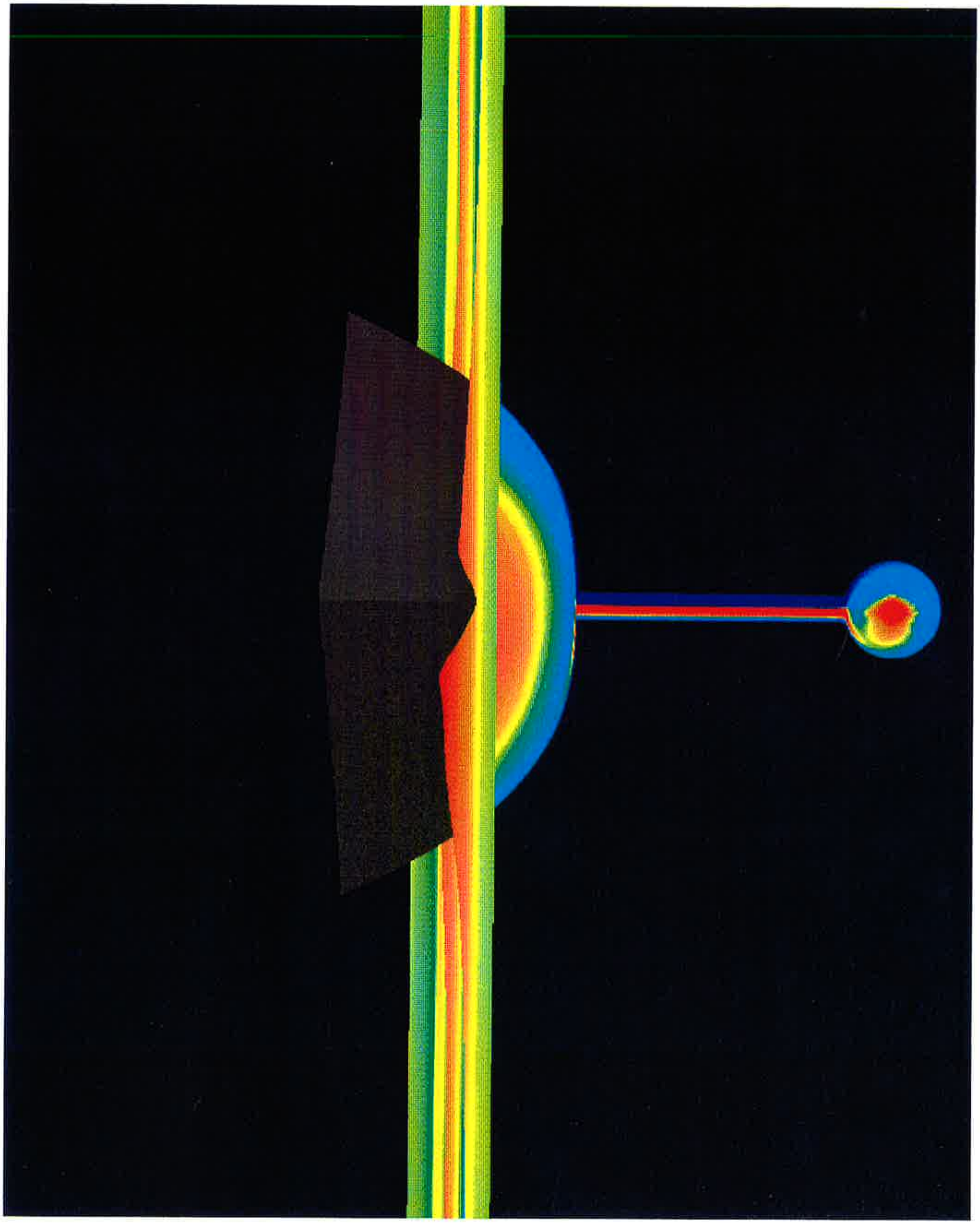
America's Cup Yacht
2.75 Million Mesh Points

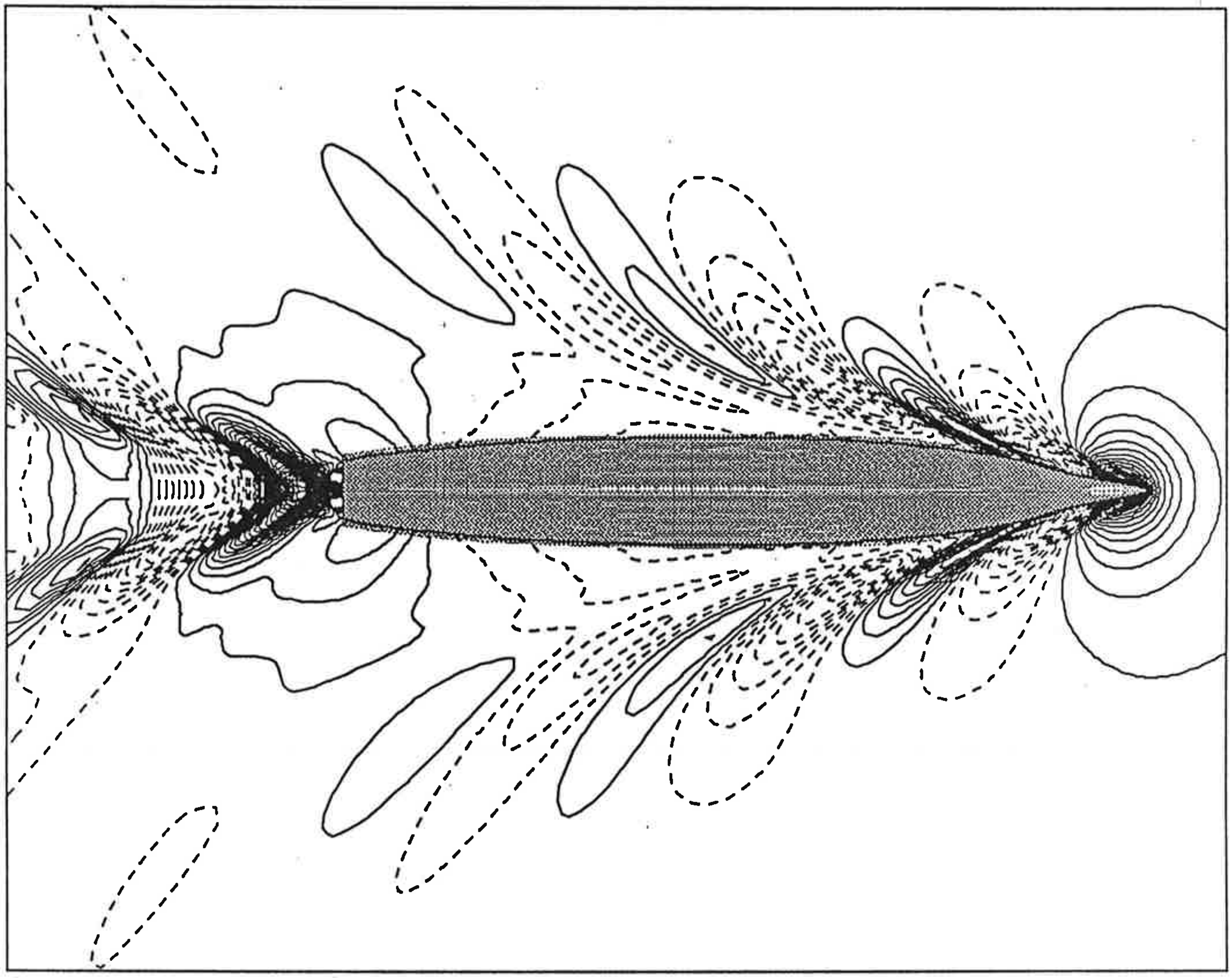
Reynolds Number = 2 Million

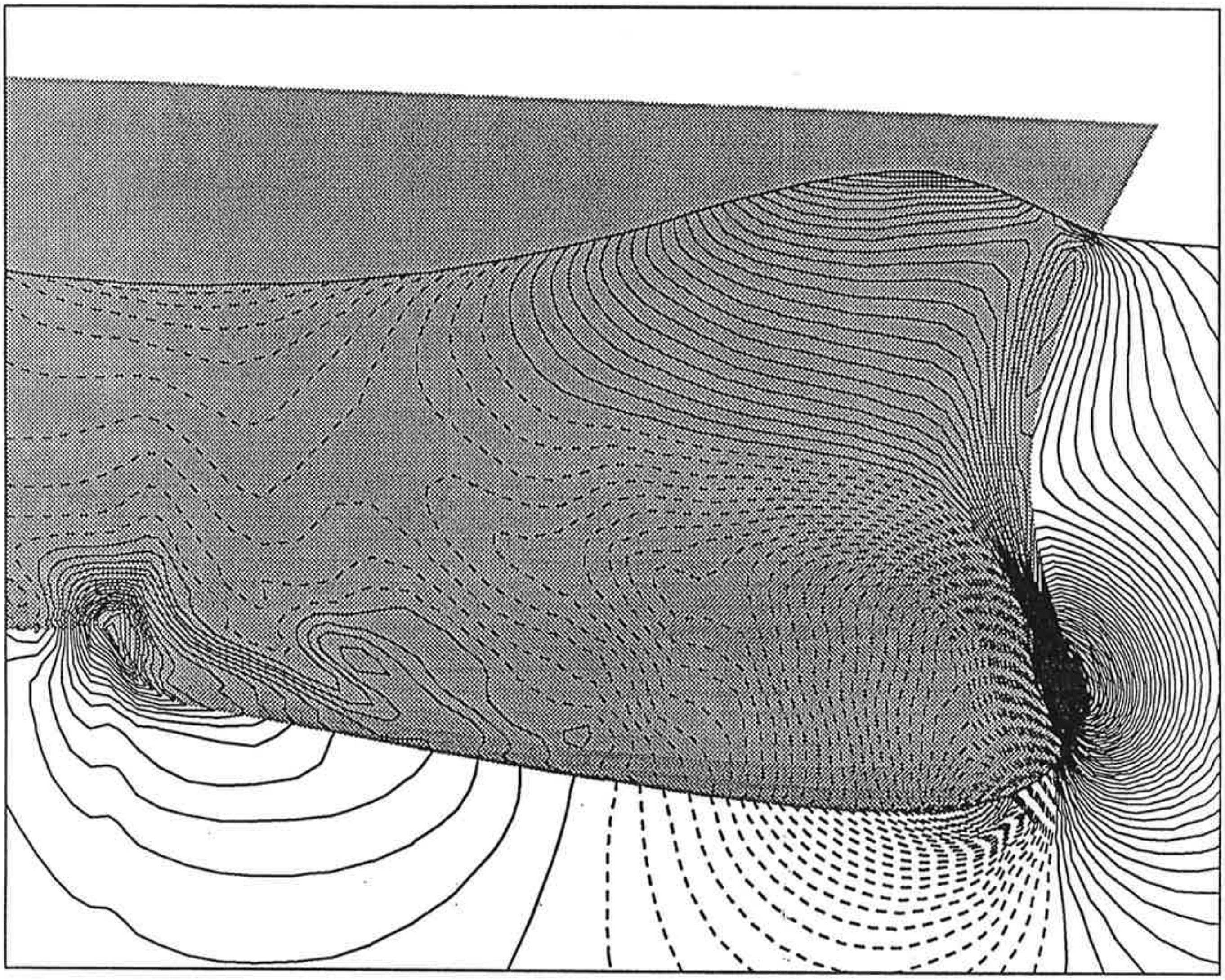
Froude Number = 0.32(9 knots)

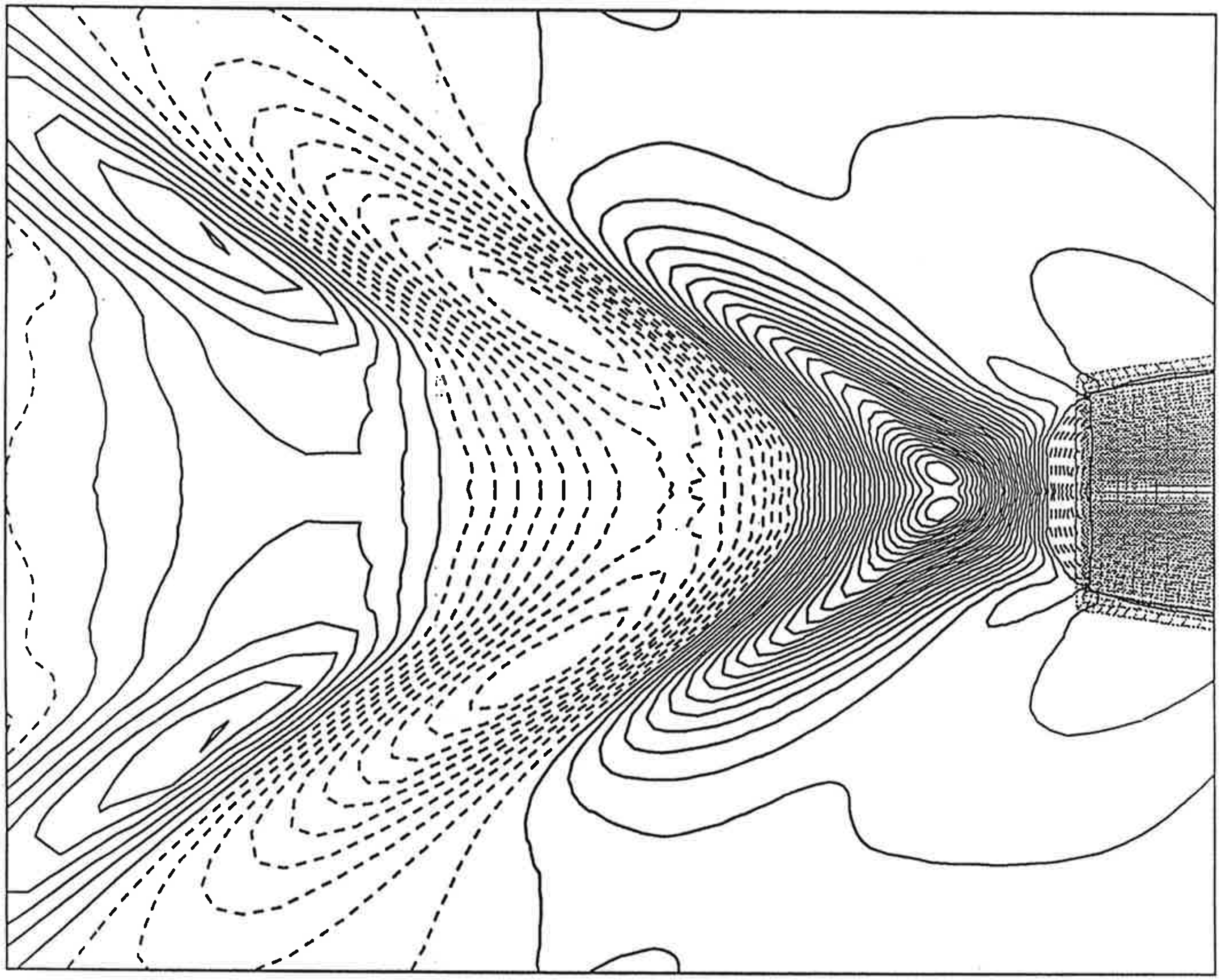
Angle of Attack = 5 degrees











KEY ISSUES

- *Accuracy - High order schemes*
- *Treatment of discontinuities and free surfaces - positivity*
- *Computational efficiency - Multigrid, Implicit schemes*
- *Problems with multiple scales - Stiff equations, boundary layers, non-computable scales*
- *Resolution of viscous effects - separation off smooth surfaces, turbulence, sub-grid modelling*
- *Validation - Interaction with experiments*

ADVANCED CFD PAYOFFS

- **Faster Design Process**
  - Lower Development Cost
- **Improved Design Optimization**
  - Aerodynamic
  - Multi-Disciplinary
- **Better Understanding of Flow Phenomena**
  - Insight for Better Design

- ***Major Targets***
  - High Lift
  - Propulsion
  - Flow with Moving Boundaries

The Future of Fluid Mechanics in Aircraft Design

Part II

Re-engineering Engineering

Antony Jameson
McDonnell Professor of Aerospace Engineering
Princeton University
assisted by
Juan J. Alonso
Luigi Martinelli
James Reuther

Princeton
(609) 258-5138
(609) 258-6123 FAX

West Coast
(415) 854-1443
(415) 854-7292

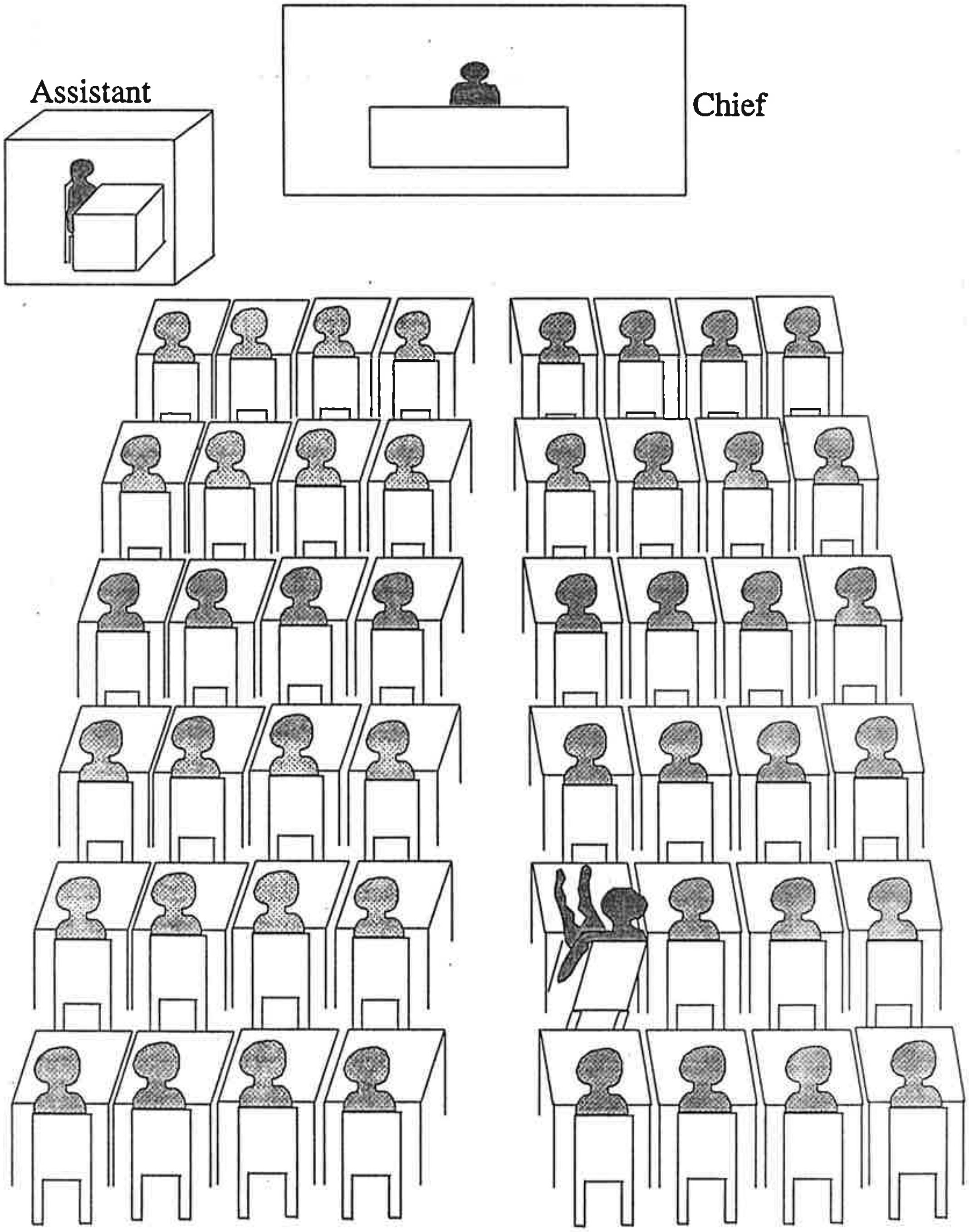
THE OPPORTUNITY

GOOD SCIENCE AND ENGINEERING

- *Good science and engineering requires both:*
  - *Technical mastery of the details ("God is in the details" - Mies van der Rohe)*
  - *A clear vision of the big picture*

As a specialist it is very easy to become immersed in the technical details and lose the big picture

Traditional Engineering Offices
Grumman Aerodynamics Section in 1968



THE NEW SITUATION

- *MODERN WORKSTATIONS such as the SGI Indigo 2 with R8000 processor and the IBM RS6000/590 offer performance near a Cray YMP for $50,000*
- *These can be DISTRIBUTED and LINKED both to each other and to a powerful CENTRAL SERVER. Small groups of engineers now have the power to accomplish tasks that previoulsy required large teams.*

COMPUTING RESOURCES
MAE DEPARTMENT -PRINCETON UNIVERSITY

Period	*Machine*	*Speed(mflops)*	*Memory(mbytes)*
1980-85	*IBM 4341*	*.15*	*2*
1985	*Convex C1*	*3 (x20)*	*32 (x16)*
1988	*Convex C2*	*15 (x100)*	*256 (x128)*
1995	*IBM SP2*	*1500 (x10000)*	*6000 (x3000)*

Avarage speed improvement:	*x20 in 5 years*
	x1.8 in 1 year

COMPUTATIONAL GEOMETRY

- *Computational geometry is an essential tool in modern engineering design*
- *Fundamental advances in COMPUTATIONAL GEOMETRY provide the MATHEMATICAL FOUNDATIONS underlying CAD systems*
- *Many of these developments took place in an industrial context including*
  - *deCasteljou algortihm - Citroen*
  - *Bezier curves -Renault*
  - *Nonuniform Rational B-Splines (NURBS) -Boeing*

BOTTLENECK IN CURRENT USE OF CFD FOR DESIGN

- *Current CAD systems do not produce geometric definitions with the precision required for CFD.*
  - *In the 777 project, Boeing had to translate CATIA files into the AGPS (Automatic Grid and Panelling System) files for their CFD software. This delayed both the response of aerodynamics to changes introduced by other disciplines, and the response of the other disciplines to aerodynamic modifications.*

EARLY IMPACT ON THE DESIGN

- *The effective exploitation of computational methods requires their use at the stages of **conceptual** and **preliminary design**, before the design is **frozen**.*
- *Because of lengthy **turnaround** and **cost**, current computational methods are often only brought into play at a **late stage** of detailed design. This limits their use to a verification tool.*

IMPORTANCE OF EARLY USE OF COMPUTATIONAL ANALYSIS IN THE DESIGN PROCESS

- *Early use of computational methods in the design process allows the exploitation of their power to vary the geometric shape and find the optimal solution over a range of design alternatives.*

TECHNICAL OBJECTIVE

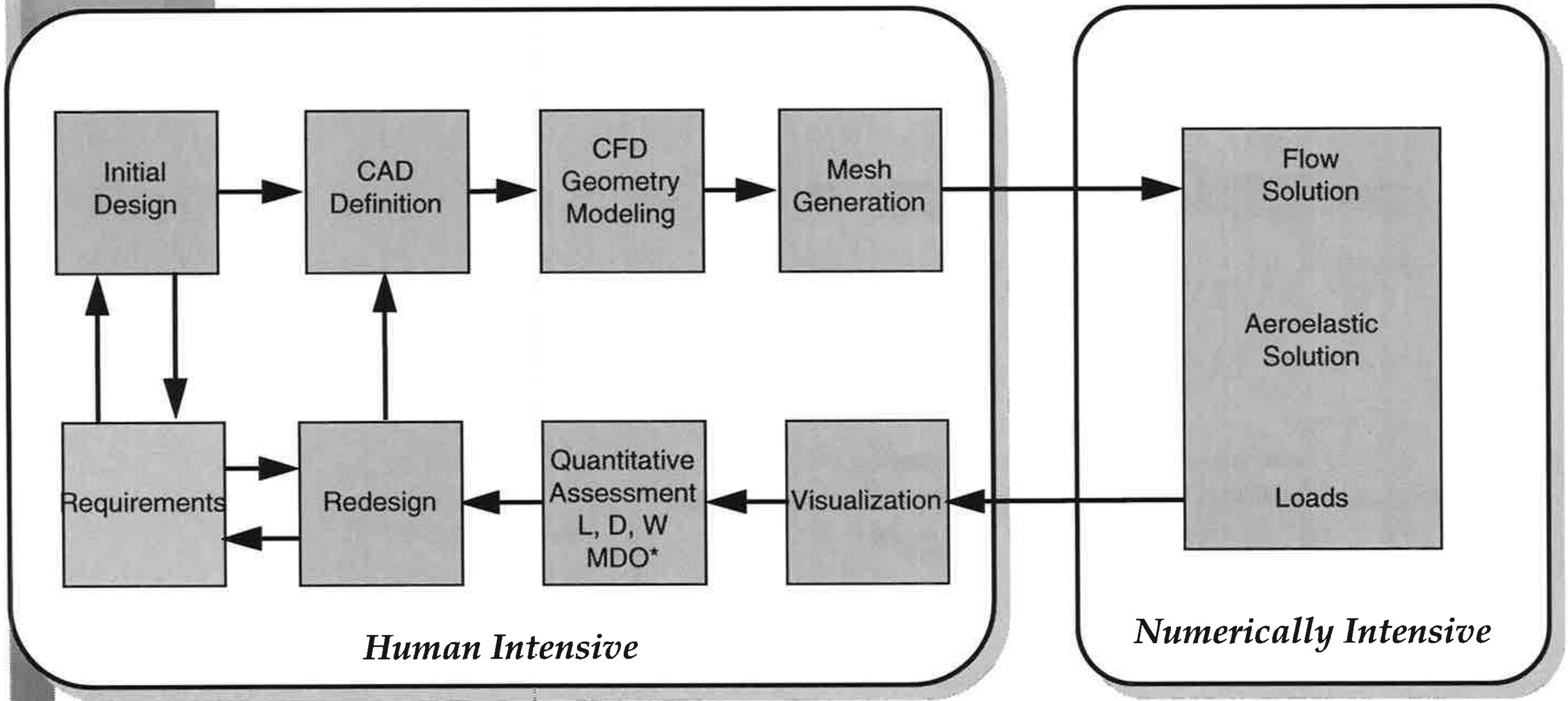
The objective is to develop an advanced computational environment for aerodynamic design to provide fast, cost-effective, computational analysis and optimization capabilities at an early stage in the design cycle. The principal requirements are as follows:

- *Analysis turn-around of half an hour for a full aircraft configuration*
- *Geometry manipulation via a CAD system with access to a central database*
- *Automated optimization of the design*
- *Multi-disciplinary analysis*

NUMERICAL WIND TUNNEL

- *The goal of CFD is captured in the idea of a* ***Numerical Wind Tunnel***
- *To be properly effective numerical solution methods must be integrated with a central database and a geometry management system*

NUMERICAL WIND TUNNEL CONCEPT



Initial Design

CAD Definition

CFD Geometry Modeling

Mesh Generation

Requirements

Redesign

Quantitative Assessment L, D, W MDO*

Visualization

Human Intensive

Flow Solution

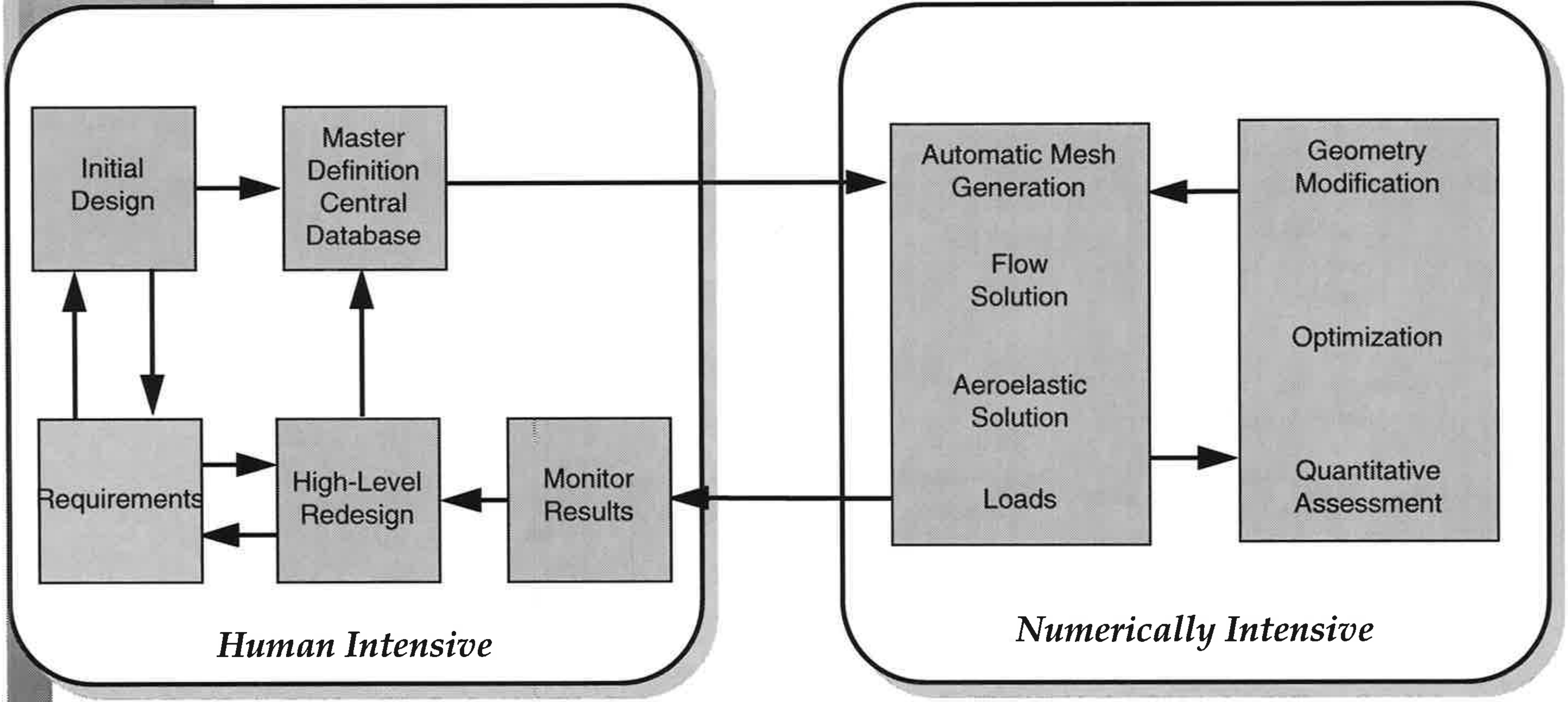
Aeroelastic Solution

Loads

Numerically Intensive

MDO: Multi-Disciplinary Optimization

NUMERICAL WIND TUNNEL WITH INTEGRATED DESIGN ENVIRONMENT


Initial Design

Master Definition Central Database

Requirements

High-Level Redesign

Monitor Results

Human Intensive

Automatic Mesh Generation

Flow Solution

Aeroelastic Solution

Loads

Geometry Modification

Optimization

Quantitative Assessment

Numerically Intensive

OPPORTUNITIES FOR BETTER DESIGN

- *Design improvements can be realized via optimization and control theory leading to automatic design of some components*
- *Disciplines can be united through a shared database allowing concurrent engineering and rational trade-offs*

LEVELS OF CFD CAPABILITY FOR DESIGN

- *Capability to predict the flow past an airplane in different flow regimes*
    - *Takeoff*
    - *Cruise (transonic)*
    - *Flutter*
    - *Present turnaround: weeks*
- *Interactive design calculations to allow immediate improvement*
- *Automatic design optimization*

MULTI-DISCIPLINARY OPTIMIZATION (MDO)

- *Ideally the designer needs effective multi-disciplinary optimization (MDO) methods to make the best trade-offs between aerodynamics, structural, and other requirements while meeting constraints such as take-off and landing field length*
- *If the disciplines are represented by* ***over-simplified models*** *of insufficient accuracy the* ***results*** *of* ***MDO*** *can be very* ***misleading****. The* ***quality*** *of the* ***result*** *is no better than the* ***quality*** *of the* ***least accurate model***

AUTOMATIC SHAPE DESIGN VIA CONTROL THEORY

- *Apply the theory of* **control** *of* **partial differential equations** *(of the flow) by* **boundary control** *(the shape)*
- *Find the* **Frechet derivative** *(infinite dimensional gradient) of the drag (or other performance measure) with respect to the shape by solving and* **adjoint** *equation in addition to the* **flow** *equation*
- *Modify the shape in the sense defined by the smoothed gradient*
- *Repeat the iterations until the performance approaches an optimum value*

Aerodynamic Shape Optimization of Wing and Wing-Body Configurations Using Control Theory

J. Reuther
RIACS/NASA Ames
A. Jameson
Princeton University

AIAA Paper 95-0123

January 1995

Design Using Control Theory

Let I be the **cost** (or **objective**) function

$$I = I(w, \mathcal{F})$$

where

$$\begin{aligned} w &= \text{flowfield variables} \\ \mathcal{F} &= \text{grid variables} \end{aligned}$$

The **first variation** of the cost function is

$$\delta I = \frac{\partial I}{\partial w}^T \delta w + \frac{\partial I}{\partial \mathcal{F}}^T \delta \mathcal{F}$$

The **flowfield equation** and its **first variation** are

$$R(w, \mathcal{F}) = 0$$

$$\delta R = 0 = \left[\frac{\partial R}{\partial w}\right] \delta w + \left[\frac{\partial R}{\partial \mathcal{F}}\right] \delta \mathcal{F}$$

Introducing a **Lagrange Multiplier**, ψ, and using the **flowfield equation** as a **constraint**

$$\begin{aligned}
\delta I &= \frac{\partial I}{\partial w}^T \delta w + \frac{\partial I}{\partial \mathcal{F}}^T \delta \mathcal{F} - \psi^T \left\{ \left[\frac{\partial R}{\partial w}\right] \delta w + \left[\frac{\partial R}{\partial \mathcal{F}}\right] \delta \mathcal{F} \right\} \\
&= \left\{ \frac{\partial I}{\partial w}^T - \psi^T \left[\frac{\partial R}{\partial w}\right] \right\} \delta w + \left\{ \frac{\partial I}{\partial \mathcal{F}}^T - \psi^T \left[\frac{\partial R}{\partial \mathcal{F}}\right] \right\} \delta \mathcal{F}
\end{aligned}$$

By choosing ψ such that it satisfies the **adjoint equation**

$$\left[\frac{\partial R}{\partial w}\right]^T \psi = \frac{\partial I}{\partial w},$$

we have

$$\delta I = \left\{ \frac{\partial I}{\partial \mathcal{F}}^T - \psi^T \left[\frac{\partial R}{\partial \mathcal{F}}\right] \right\} \delta \mathcal{F}$$

This reduces the **gradient** calculation for an arbitrarily large number of design variables to

One Flow Solution

\+ **One Adjoint Solution**

Application to the 3D Euler Equations

Define the **Euler equations** as

$$\frac{\partial w}{\partial t}+\frac{\partial f_i}{\partial x_i}=0$$

where

$$w=\begin{Bmatrix}\rho\\ \rho u_1\\ \rho u_2\\ \rho u_3\\ \rho E\end{Bmatrix}\quad f_i=\begin{Bmatrix}\rho u_i\\ \rho u_i u_1+p\delta_{i1}\\ \rho u_i u_2+p\delta_{i2}\\ \rho u_i u_3+p\delta_{i3}\\ \rho u_i H\end{Bmatrix}.$$

Making a transformation to **general coordinates**, they become

$$\frac{\partial W}{\partial t}+\frac{\partial F_i}{\partial \xi_i}=0\qquad W=J\begin{Bmatrix}\rho\\ \rho u_1\\ \rho u_2\\ \rho u_3\\ \rho E\end{Bmatrix}\quad F_i=J\begin{Bmatrix}\rho U_i\\ \rho U_i u_1+p\frac{\partial \xi_i}{\partial x_1}\\ \rho U_i u_2+p\frac{\partial \xi_i}{\partial x_2}\\ \rho U_i u_3+p\frac{\partial \xi_i}{\partial x_3}\\ \rho U_i H\end{Bmatrix}.$$

The **cost function** for the **inverse problem** can be defined on the wing

$$I = \frac{1}{2} \iint_{B_W} (p - p_d)^2 \, d\xi_1 d\xi_3,$$

Taking the **first variation** of the **cost function**

$$\delta I = \iint_{B_W} (p - p_d)\, \delta p \;\; d\xi_1 d\xi_3.$$

Taking the **first variation** of the **governing equations**

$$\frac{\partial}{\partial \xi_i} (\delta F_i) = 0,$$

where

$$\delta F_i = \left[\frac{\partial f_j}{\partial w}\right] J \frac{\partial \xi_i}{\partial x_j} \delta w + \delta \left(J \frac{\partial \xi_i}{\partial x_j} \right) f_j.$$

Set

$$C_i = \left[\frac{\partial f_j}{\partial w}\right] J \frac{\partial \xi_i}{\partial x_j} \qquad Q_i = \delta \left(J \frac{\partial \xi_i}{\partial x_j} \right) f_j$$

Multiplying by a **Lagrange Multiplier** ψ and integrating by parts gives

$$\int_D \frac{\partial \psi^T}{\partial \xi_i} C_i \delta w \, d\xi_i + \int_D \frac{\partial \psi^T}{\partial \xi_i} Q_i \, d\xi_i + \int_B \left(\bar{n}_i \psi^T \delta F_i \right) d\xi_j = 0$$

On the boundary

$$\delta F_2 = J \left\{ \begin{array}{c} 0 \\ \frac{\partial \xi_2}{\partial x_1} \delta p \\ \frac{\partial \xi_2}{\partial x_2} \delta p \\ \frac{\partial \xi_2}{\partial x_3} \delta p \\ 0 \end{array} \right\} + p \left\{ \begin{array}{c} 0 \\ \delta \left(J \frac{\partial \xi_2}{\partial x_1} \right) \\ \delta \left(J \frac{\partial \xi_2}{\partial x_2} \right) \\ \delta \left(J \frac{\partial \xi_2}{\partial x_3} \right) \\ 0 \end{array} \right\} \quad \text{on} \;\; B_W$$

Choose ψ to satisfy the **adjoint equation**

$$\frac{\partial \psi}{\partial t} - C_i^T \frac{\partial \psi}{\partial \xi_i} = 0 \quad \text{in } D,$$

with the **boundary condition**

$$J \left(\psi_2 \frac{\partial \xi_2}{\partial x_1} + \psi_3 \frac{\partial \xi_2}{\partial x_2} + \psi_4 \frac{\partial \xi_2}{\partial x_3} \right) = (p - p_d) \quad \text{on } B_W.$$

The cost function thus becomes

$$\delta I = - \int_D \frac{\partial \psi^T}{\partial \xi_i} \delta \left(J \frac{\partial \xi_i}{\partial x_j} \right) f_j d\xi_k$$
$$- \iint_{B_W} \left\{ \psi_2 \delta \left(J \frac{\partial \xi_2}{\partial x_1} \right) + \psi_3 \delta \left(J \frac{\partial \xi_2}{\partial x_2} \right) + \psi_4 \delta \left(J \frac{\partial \xi_2}{\partial x_3} \right) \right\} p \, d\xi_1 d\xi_3$$

J WING 5585 DESIGN

Cl 0.550 Mach 0.850

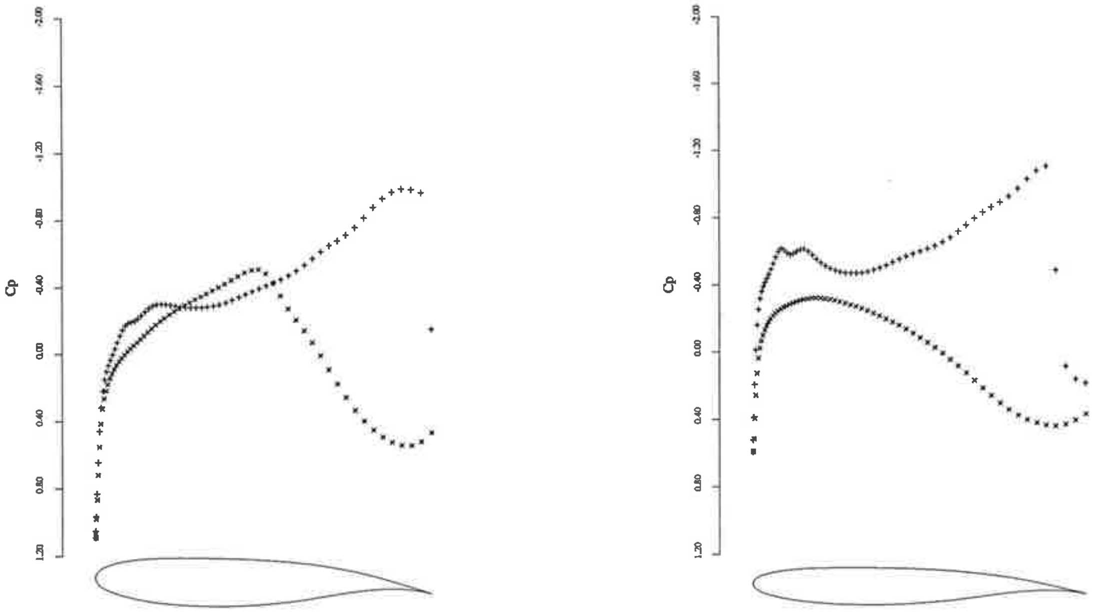
10 Cycles

Initial Cd	*0.0236*
Final Cd	*0.0119*

192 x 32 x 48 = 294,912 Grid Cells
33 x 128 = 4224 Design Variables

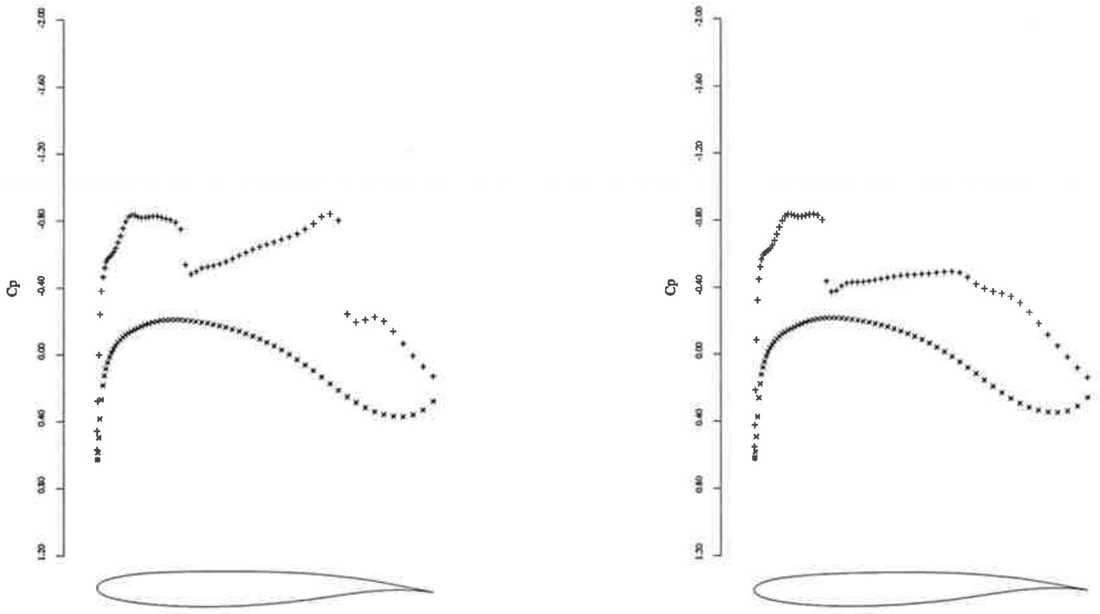
Computational Cost

IBM 530 Workstation	*15.0 hours*
IBM 590 Workstation	*2.5 hours*
Convex C220 (1 CPU)	*7.5 Hours*



9a: span station $z = 0.00$

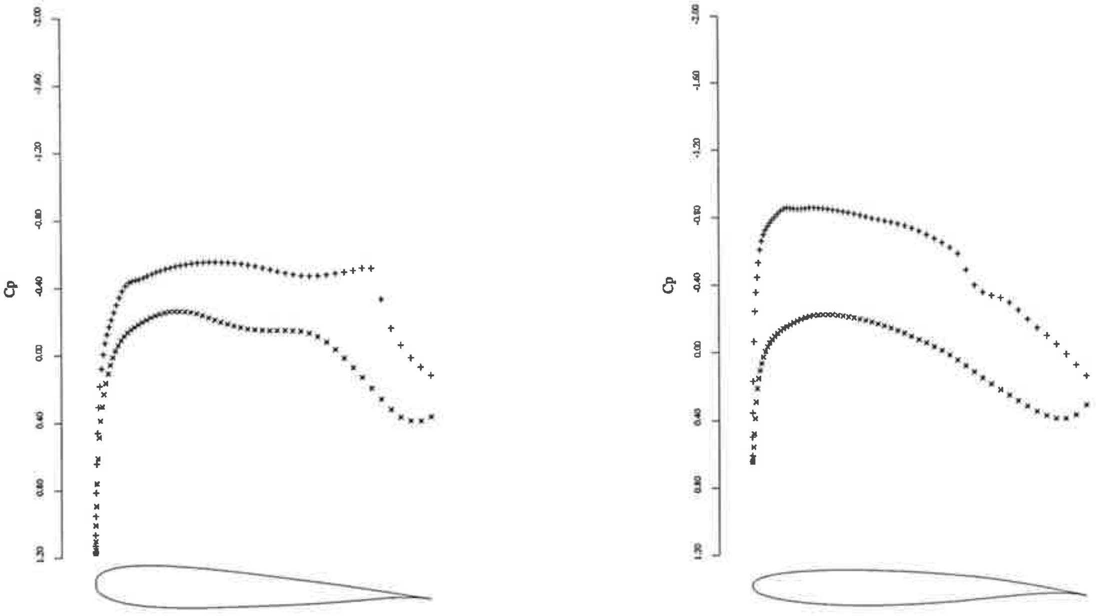
9b: span station $z = 0.312$



9c: span station $z = 0.625$

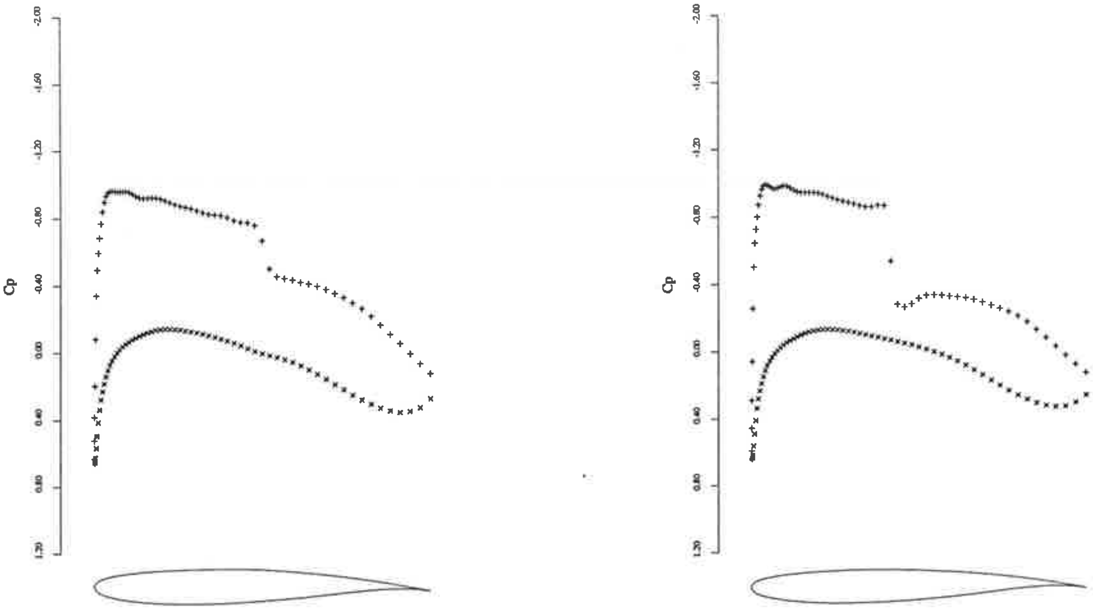
9d: span station $z = 0.937$

Figure 9: FLO67 check on initial wing.
$M = 0.85$, $C_L = 0.5506$, $C_D = 0.0236$, $\alpha = -1.260°$.



10a: span station $z = 0.00$

10b: span station $z = 0.312$



10c: span station $z = 0.625$

10d: span station $z = 0.937$

Figure 10: FLO67 check on redesigned wing.
$M = 0.85$, $C_L = 0.5500$, $C_D = 0.0119$, $\alpha = 0.210°$.

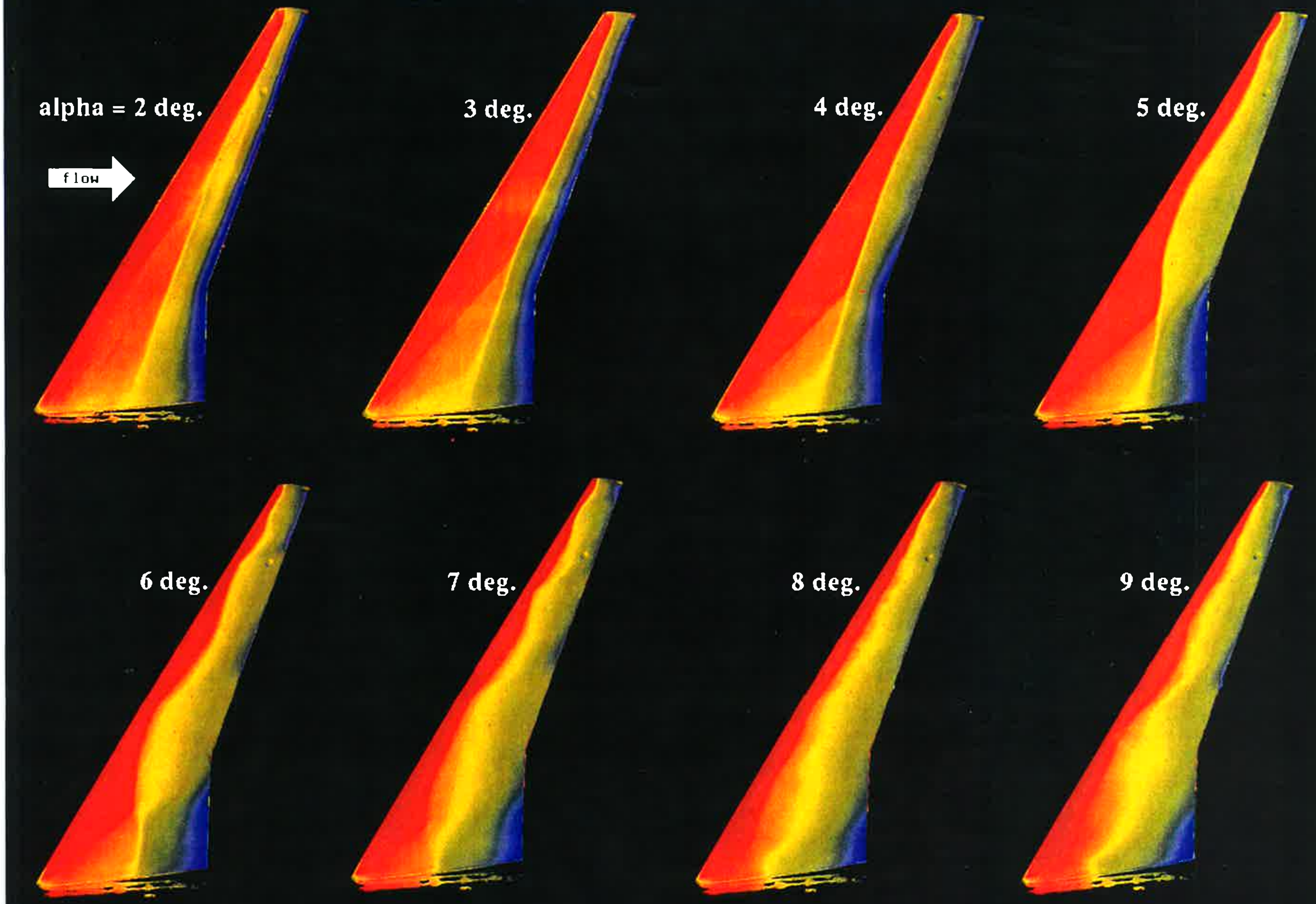
DRAG BREAKDOWN

For a long range transport aircraft:

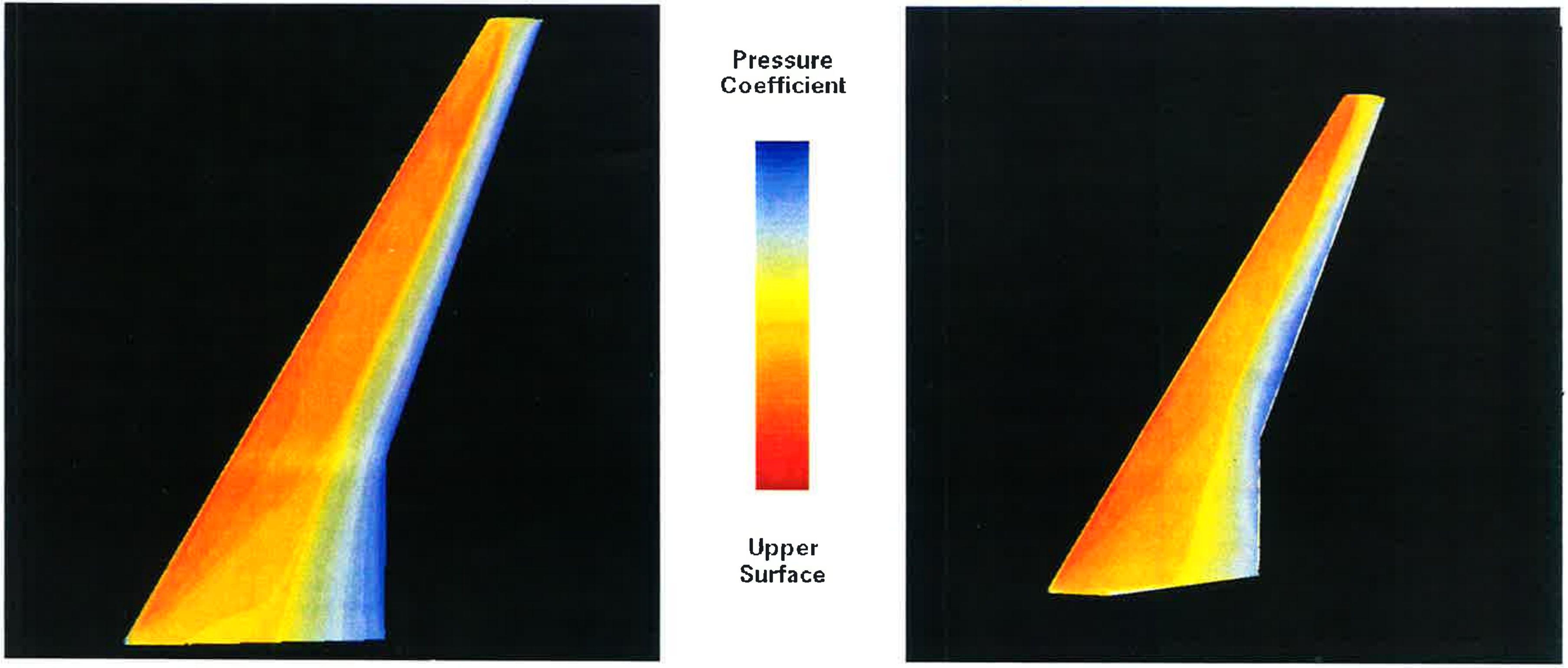
Wing Cd	Vortex	0.0109
	Shock wave	0.0010
	Friction	0.0045
Fuselage		0.0050
Tail		0.0020
Nacelles		0.0015
Excresences		0.0010
Total Cd		0.0259
Cl		0.5500
L/D		21.2

Pressure Maps

Upper Surface, M = 0.81, Alpha Sweep



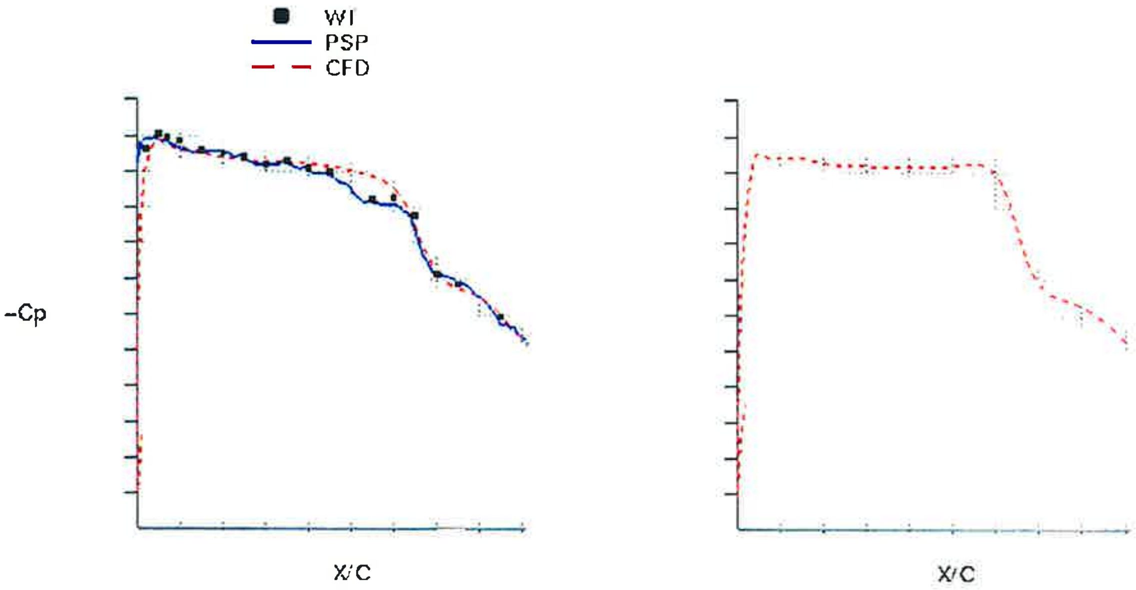
NASA Ames Research Center CompareCP 1.1 – IotVEWT – WT/PSP/CFD Pressure Coefficient Comparison Wed Oct 13 11:38:03 PDT 1993



CFD PSP

Test Conditions

	WT	CFD
Mach	0.810	0.810
Alpha	3.00	3.00
Re/ft	6.04E6	7.41E6
Test	195111	
Config	000001	
Run/Seq	0034/10	
Date	10/13/93	
Time	11:15	



FACTORS WHICH MAKE RE-ENGINEERING OF THE DESIGN PROCESS POSSIBLE AND NECESSARY

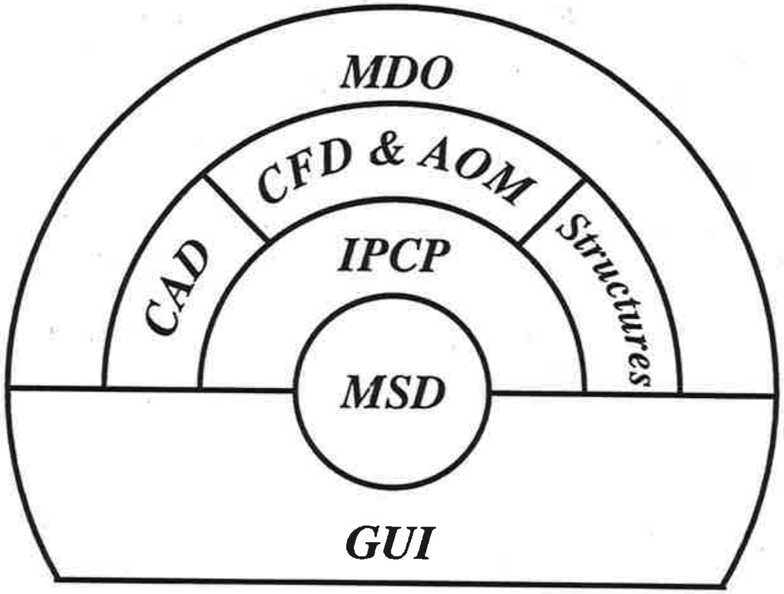
- *Advances in CAD*
- *Advances in numerical and mathematical solution methods*
- *Increased computing power and networking*
- *Shared database*
- *Numerically controlled machine tools and computer control of manufacturing*
- *Fast prototyping*

- *Computational engineering is emerging as the new controlling discipline across a variety of industries:*
  - *Aerospace*
  - *Automotive*
  - *Shipbuilding*

RE-ENGINEERING ENGINEERING

- The engineering process needs to be radically reformulated to take full advantage of advances in:
  - Distributed high performance computing power and techniques
  - Information technology
  - Smart manufacturing
- Equipped with workstations of Cray YMP power a group of 3 or 4 engineers can carry out design analyses that previously might have required a team of 50.
- We can now coordinate the disciplines through a shared database
- Automatic optimization techniques and fast prototyping can drastically accelerate the design cycle

MULTI-DISCIPLINARY AERODYNAMIC DESIGN ENVIRONMENT



AOM	Aerodynamic Optimization Module
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
GUI	Graphic User Interface
IPCP	Inter-Process Communication Protocol
MDO	Multi-Disciplinary Optimization
MSD	Master Surface Definition

RE-ENGINEERING ENGINEERING

- Companies which re-engineer the engineering process for integrated multidisciplinary design will gain a decisive market advantage
- Companies which fail to recognize the new situation may be at a fatal disadvantage
- Universities which fail to respond to these fundamental changes taking place in the engineering process will lose their prominence.

COMPUTATIONAL GEOMETRY

- *Computational geometry is an essential tool in modern engineering design*
- *Fundamental advances in COMPUTATIONAL GEOMETRY provide the MATHEMATICAL FOUNDATIONS underlying CAD systems*
- *Many of these developments took place in an industrial context including*
    - *deCasteljou algortihm - Citroen*
    - *Bezier curves -Renault*
    - *Nonuniform Rational B-Splines (NURBS) -Boeing*

BOTTLENECK IN CURRENT USE OF CFD FOR DESIGN

- *Current CAD systems do not produce geometric definitions with the precision required for CFD.*
  - *In the 777 project, Boeing had to translate CATIA files into the AGPS (Automatic Grid and Panelling System) files for their CFD software. This delayed both the response of aerodynamics to changes introduced by other disciplines, and the response of the other disciplines to aerodynamic modifications.*

EARLY IMPACT ON THE DESIGN

- *The effective exploitation of computational methods requires their use at the stages of* ***conceptual*** *and* ***preliminary design****, before the design is* ***frozen****.*
- *Because of lengthy* ***turnaround*** *and* ***cost****, current computational methods are often only brought into play at a* ***late stage*** *of detailed design. This limits their use to a verification tool.*

IMPORTANCE OF EARLY USE OF COMPUTATIONAL ANALYSIS IN THE DESIGN PROCESS

- *Early use of computational methods in the design process allows the exploitation of their power to vary the geometric shape and find the optimal solution over a range of design alternatives.*