Introduction to Fluid Mechanics

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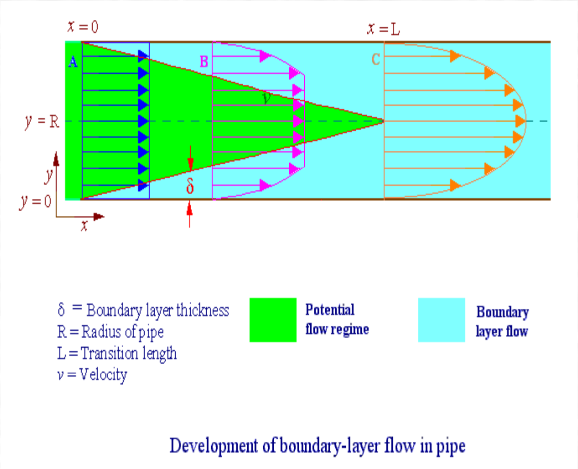
8/29/2008

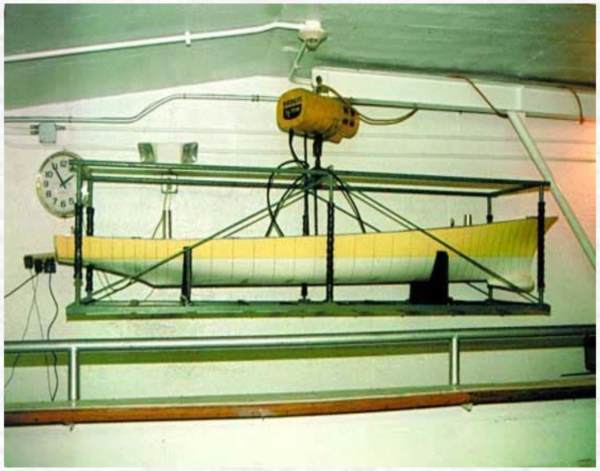
AFD



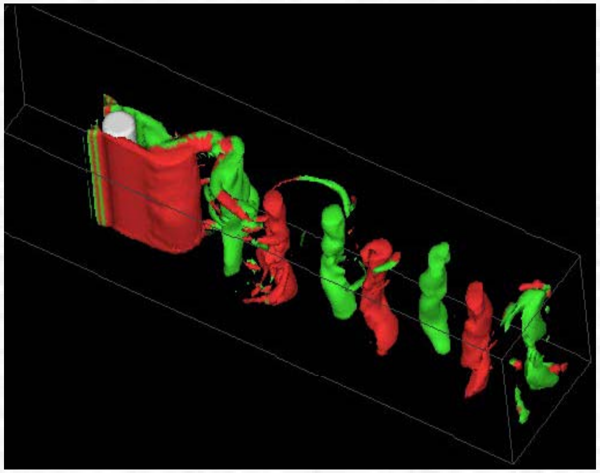
$$\nabla \bullet \mathbf{U} = 0$$

$$\frac{D\mathbf{U}}{Dt} = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2\mathbf{U} + \nabla \bullet \overline{u_i u_j}$$

EFD



CFD

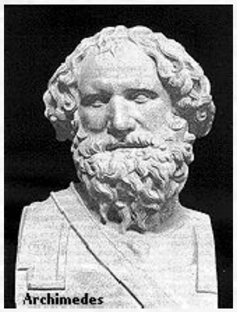


Fluid Mechanics

- Fluids essential to life
  - Human body 65% water
  - Earth's surface is 2/3 water
  - Atmosphere extends 17km above the earth's surface
- History shaped by fluid mechanics
  - Geomorphology
  - Human migration and civilization
  - Modern scientific and mathematical theories and methods
  - Warfare
- Affects every part of our lives

History

Faces of Fluid Mechanics

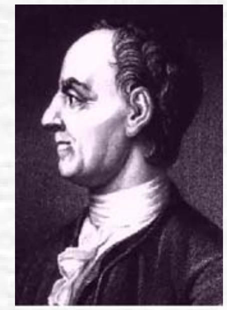


Archimedes
(C. 287-212 BC)

Newton
(1642-1727)

Leibniz
(1646-1716)

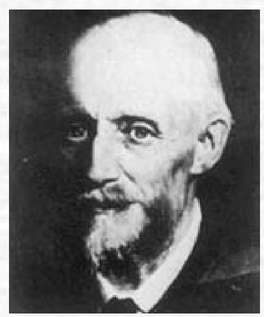
Bernoulli
(1667-1748)



Euler
(1707-1783)

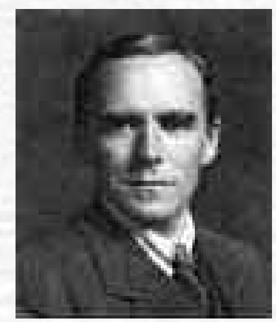
Navier
(1785-1836)

Stokes
(1819-1903)



Reynolds
(1842-1912)

Prandtl
(1875-1953)



Taylor
(1886-1975)

Significance

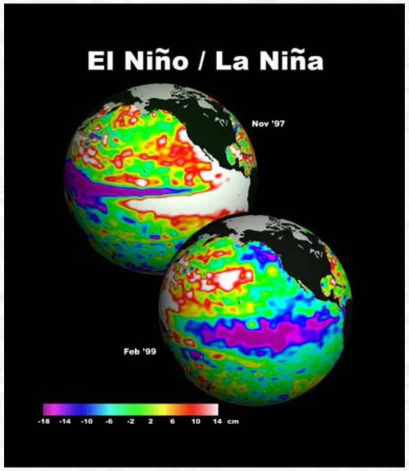
- Fluids omnipresent
  - Weather & climate
  - Vehicles: automobiles, trains, ships, and planes, etc.
  - Environment
  - Physiology and medicine
  - Sports & recreation
  - Many other examples!

Weather & Climate

Tornadoes

Thunderstorm

Global Climate



Hurricanes

Vehicles

Aircraft

Surface ships

High-speed rail

Submarines

Environment

Air pollution

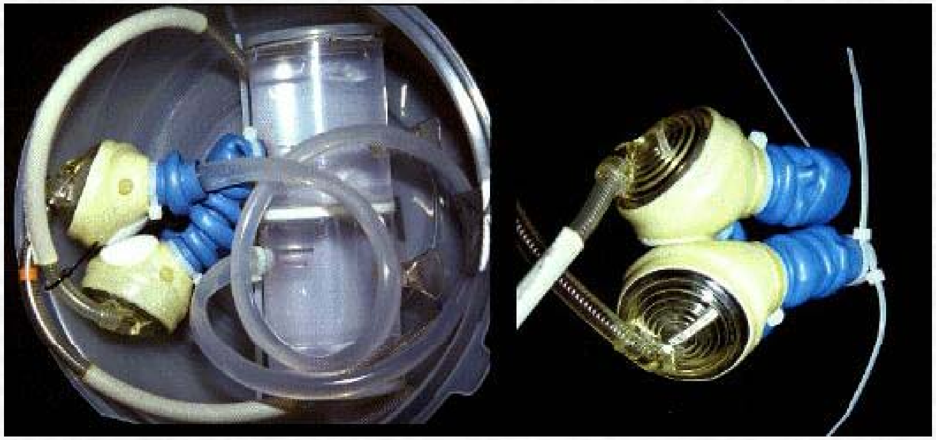
River hydraulics

Physiology and Medicine

Blood pump

Ventricular assist device

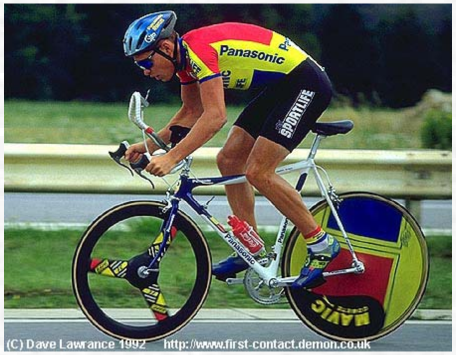
A BVS blood pump



Sports & Recreation

Water sports

Cycling

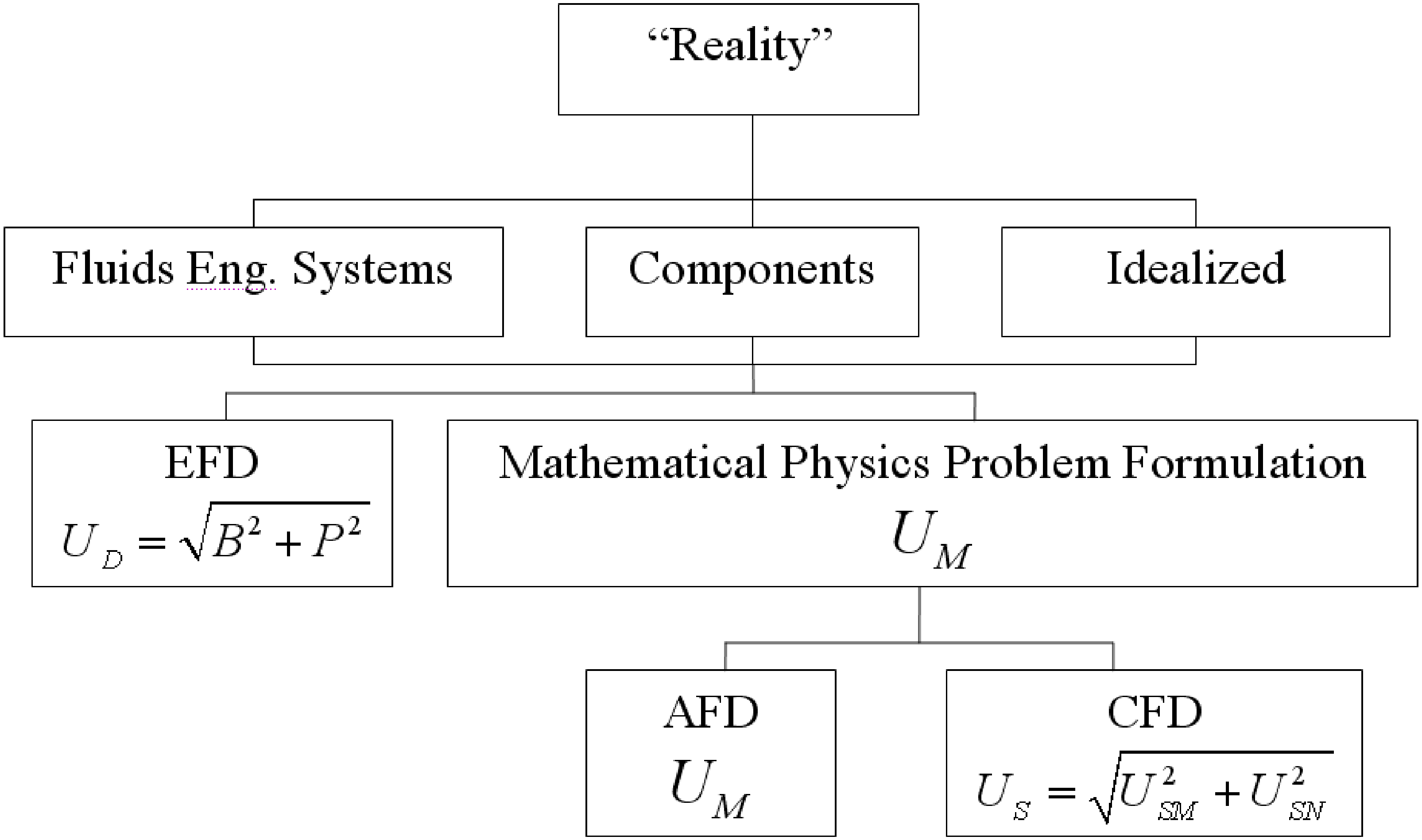


Offshore racing

Auto racing

Surfing

Fluids Engineering



Analytical Fluid Dynamics

- The theory of mathematical physics problem formulation
- Control volume & differential analysis
- Exact solutions only exist for simple geometry and conditions
- Approximate solutions for practical applications
  - Linear
  - Empirical relations using EFD data

Analytical Fluid Dynamics

- Lecture Part of Fluid Class
  - Definition and fluids properties
  - Fluid statics
  - Fluids in motion
  - Continuity, momentum, and energy principles
  - Dimensional analysis and similitude
  - Surface resistance
  - Flow in conduits
  - Drag and lift

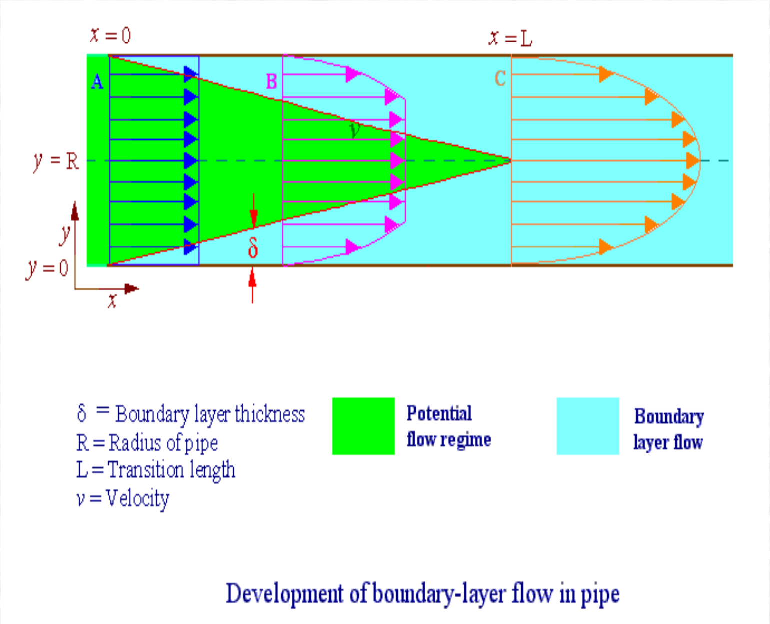
Analytical Fluid Dynamics

- Example: laminar pipe flow

Assumptions: Fully developed, Low $\mathrm{Re} = \frac{\rho U D}{\mu} < 2000$

Approach: Simplify momentum equation, integrate, apply boundary conditions to determine integration constants and use energy equation to calculate head loss

Schematic



Development of boundary-layer flow in pipe

$$\frac{Du}{Dt}^{\,0} = -\frac{\partial p}{\partial x} + \mu\left[\frac{\partial^2 u}{\partial x^2}^{\,0} + \frac{\partial^2 u}{\partial y^2}\right] + g_x^{\,0}$$

Exact solution :

$$u(r) = \frac{1}{4\mu}\left(-\frac{\partial p}{\partial x}\right)(R^2 - r^2)$$

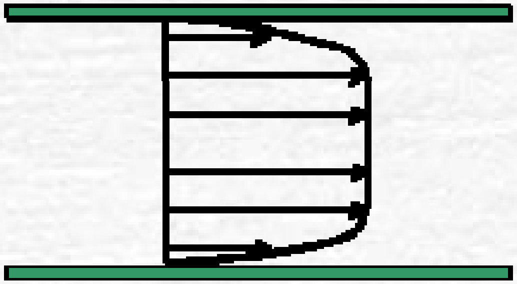
Friction factor: $$f = \frac{8\tau_w}{\rho \bar{V}^2} = \frac{8\mu \left.\frac{du}{dy}\right|_w}{\rho \bar{V}^2} = \frac{64}{\mathrm{Re}}$$

Head loss: $$\frac{p_1}{\gamma} + z_1 = \frac{p_2}{\gamma} + z_2 + h_f \qquad h_f = f\frac{L}{D}\frac{V^2}{2g} = \frac{32\mu L V}{\gamma D^2}$$

Analytical Fluid Dynamics

- Example: turbulent flow in smooth pipe($\mathrm{Re} > 3000$)

Three layer concept (using dimensional analysis)



$$u^+ = u/u^* \qquad y^+ = yu^*/\nu \qquad u^* = \sqrt{\tau_w/\rho}$$

1. Laminar sub-layer (viscous shear dominates)

$$u^+ = y^+ \qquad 0 < y^+ < 5$$

2. Overlap layer (viscous and turbulent shear important)

$$u^+ = \frac{1}{\kappa}\ln y^+ + B \qquad 20 < y^+ < 10^5 \qquad (\kappa=0.41,\ B=5.5)$$

3. Outer layer (turbulent shear dominates) $\frac{U-u}{u^*} = f\left(1 - \frac{r}{r_0}\right) \quad y^+ > 10^5$

Assume log-law is valid across entire pipe: $\frac{u(r)}{u^*} = \frac{1}{\kappa}\ln\frac{(r_0 - r)u^*}{\nu} + B$

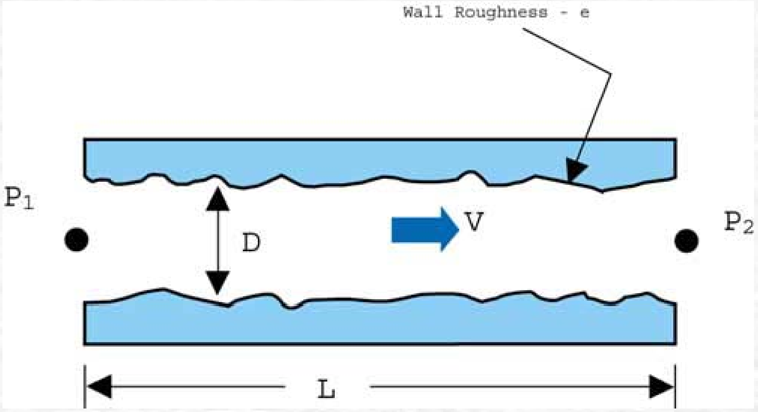
Integration for average velocity and using EFD data to adjust constants:

$$\frac{1}{\sqrt{f}} = 2\log\left(\mathrm{Re}\, f^{1/2}\right) - .8$$

Analytical Fluid Dynamics

- Example: turbulent flow in rough pipe

Both laminar sublayer and overlap layer are affected by roughness



Inner layer: $u^+ = u^+\left(y/k\right)$

Outer layer: unaffected

Overlap layer: $u^+ = \frac{1}{\kappa}\ln\frac{y}{k} + constant$

Three regimes of flow depending on k^+

1. $K^+<5$, hydraulically smooth (no effect of roughness)
2. $5 < K^+ < 70$, transitional roughness (Re dependent)
3. $K^+ > 70$, fully rough (independent Re)

For 3, using EFD data to adjust constants:

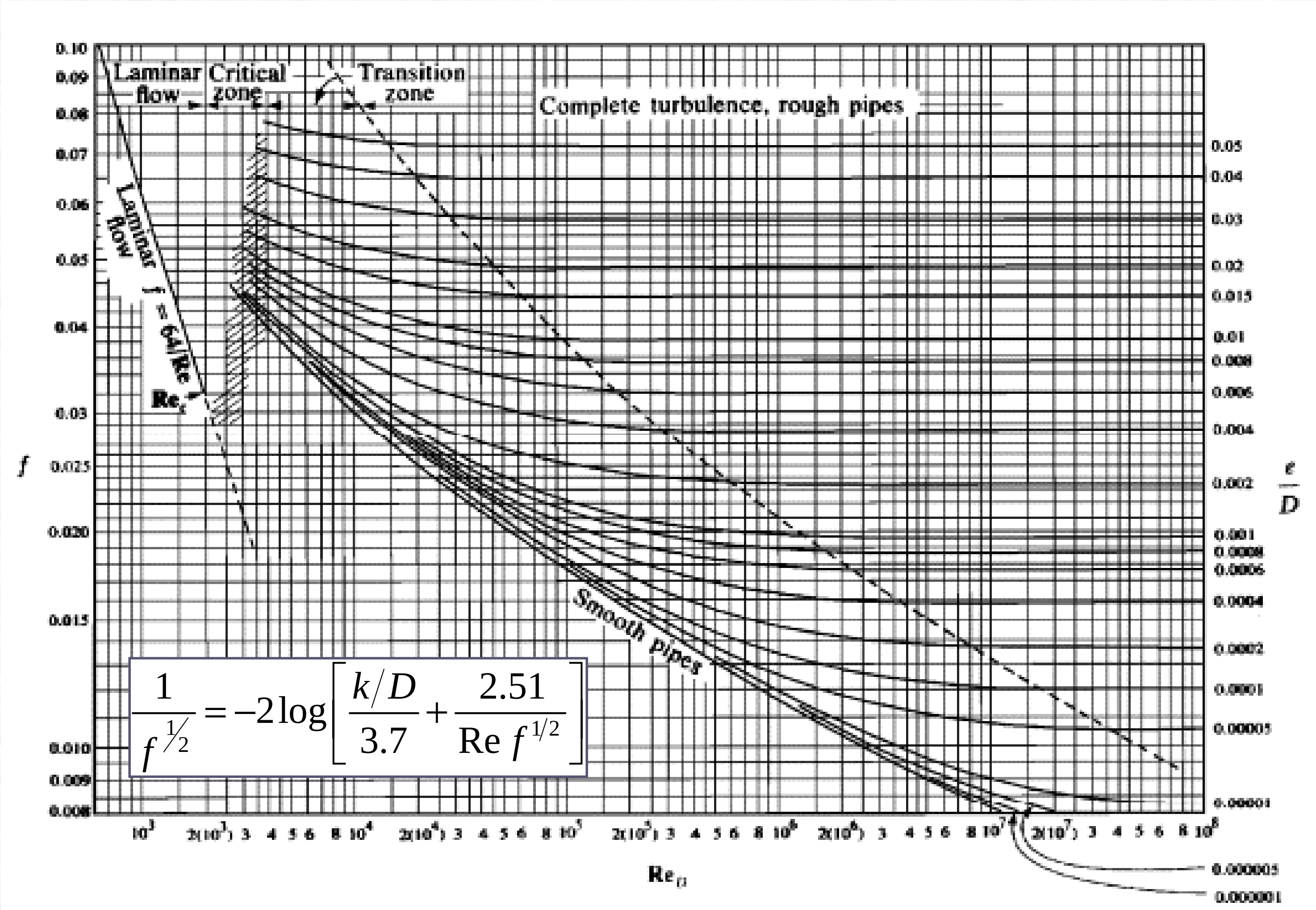
$$u^+ = \frac{1}{\kappa}\ln\frac{y}{k} + 8.5 \neq f\left(\text{Re}\right)$$

Friction factor: $\frac{1}{\sqrt{f}} = -2\log\frac{k/D}{3.7}$

Analytical Fluid Dynamics

- Example: Moody diagram for turbulent pipe flow

Composite Log-Law for smooth and rough pipes is given by the Moody diagram:



$$\frac{1}{f^{1/2}} = -2\log\left[\frac{k/D}{3.7} + \frac{2.51}{\mathrm{Re}\, f^{1/2}}\right]$$

Experimental Fluid Dynamics (EFD)

Definition:

Use of experimental methodology and procedures for solving fluids engineering systems, including full and model scales, large and table top facilities, measurement systems (instrumentation, data acquisition and data reduction), uncertainty analysis, and dimensional analysis and similarity.

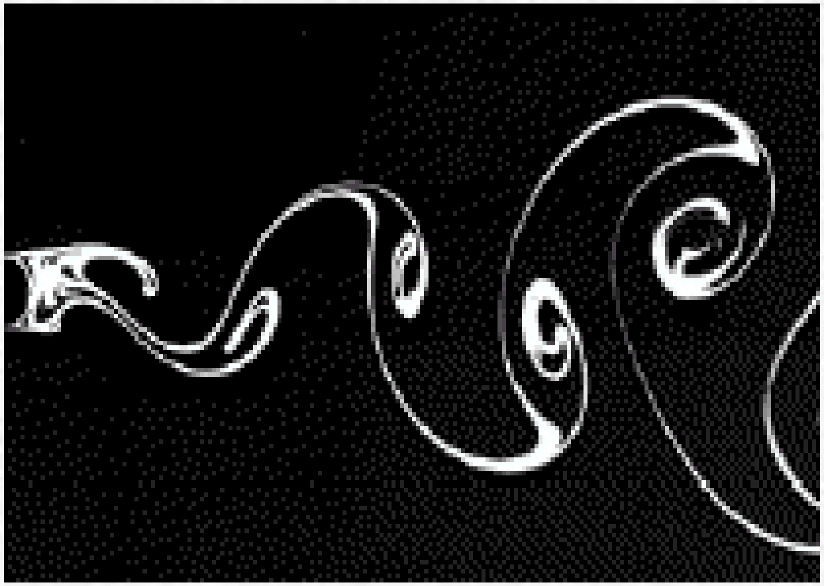
EFD philosophy:

- Decisions on conducting experiments are governed by the ability of the expected test outcome, to achieve the test objectives within allowable uncertainties.
- Integration of UA into all test phases should be a key part of entire experimental program
  - test design
  - determination of error sources
  - estimation of uncertainty
  - documentation of the results

Purpose

- Science & Technology: understand and investigate a phenomenon/process, substantiate and validate a theory (hypothesis)
- Research & Development: document a process/system, provide benchmark data (standard procedures, validations), calibrate instruments, equipment, and facilities
- Industry: design optimization and analysis, provide data for direct use, product liability, and acceptance
- Teaching: instruction/demonstration

Applications of EFD



Application in science & technology

Picture of Karman vortex shedding

Application in research & development

Tropic Wind Tunnel has the ability to create temperatures ranging from 0 to 165 degrees Fahrenheit and simulate rain

Applications of EFD (cont'd)

Example of industrial application

NASA's cryogenic wind tunnel simulates flight conditions for scale models--a critical tool in designing airplanes.

Application in teaching

Fluid dynamics laboratory

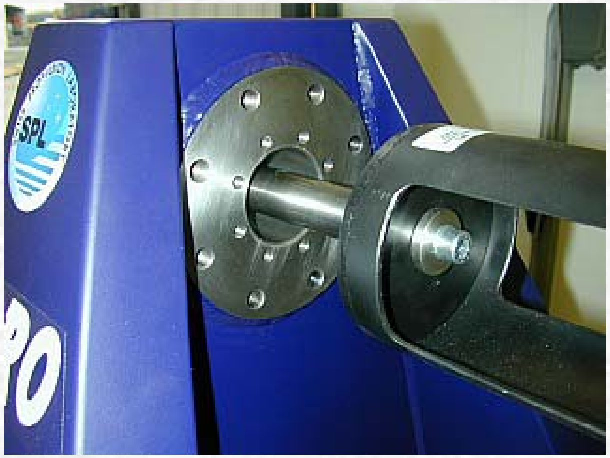
Full and model scale

- Scales: model, and full-scale
- Selection of the model scale: governed by dimensional analysis and similarity

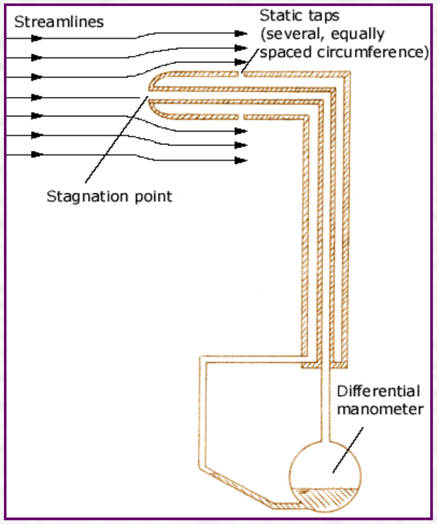
Measurement systems

- Instrumentation
  - Load cell to measure forces and moments
  - Pressure transducers
  - Pitot tubes
  - Hotwire anemometry
  - PIV, LDV
- Data acquisition
  - Serial port devices
  - Desktop PC's
  - Plug-in data acquisition boards
  - Data Acquisition software - Labview
- Data analysis and data reduction
  - Data reduction equations
  - Spectral analysis

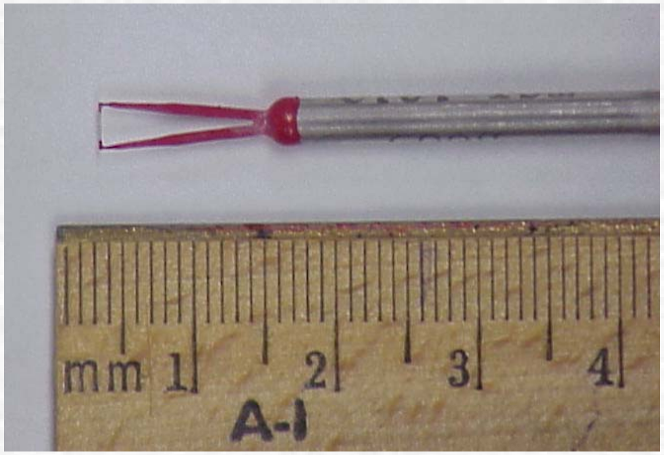
Instrumentation



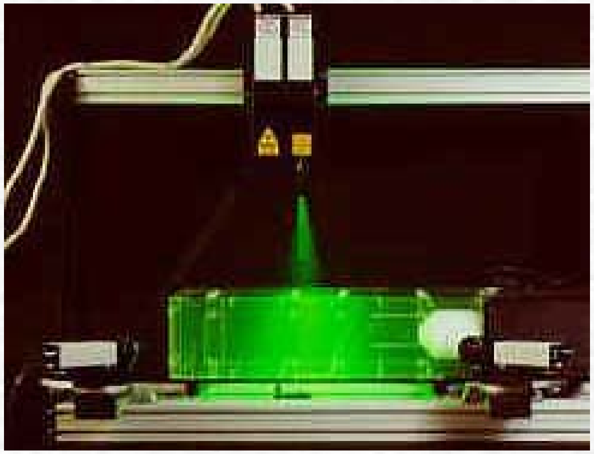
Load cell



Pitot tube



Hotwire

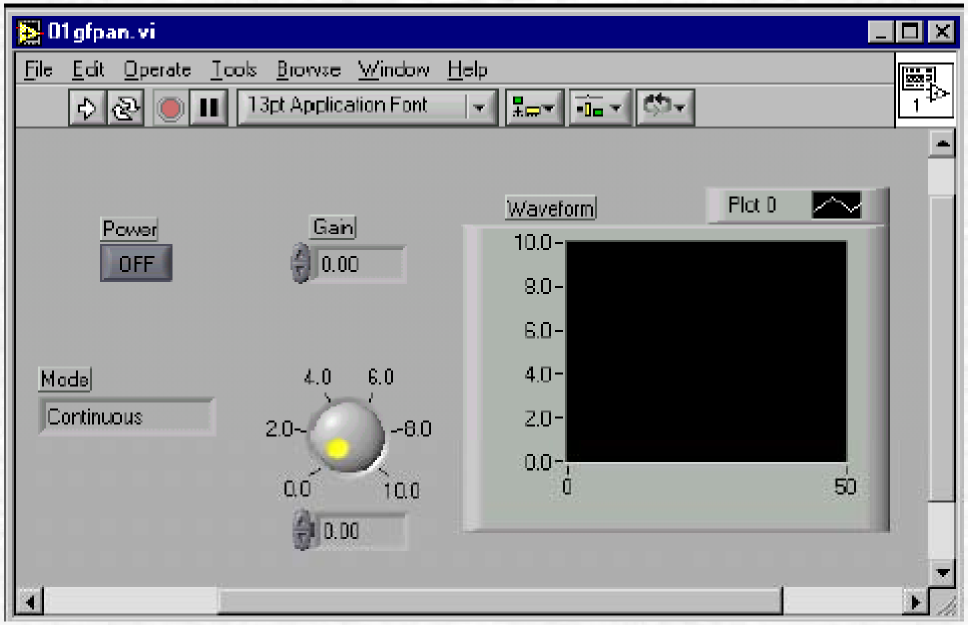


3D - PIV

Data acquisition system

Hardware

Software - Labview



Data reduction methods

- Data reduction equations
- Spectral analysis

$$\rho_w = F(T_w)$$

$$\rho_a = F(T_a)$$

$$Q = F(\Delta z_{DM})$$

$$f = F(\rho_w, \rho_a, z_{SM}, Q) = \frac{g\pi^2 D^5}{8LQ^2} \cdot \frac{\rho_w}{\rho_a}(z_{SM_i} - z_{SM_j})$$

$$u(r) = \left[\frac{2 \cdot g\rho_w}{\rho_a} \cdot \left[z_{SM\,Stag}(r) - z_{SM\,Stat}\right]\right]$$

Example of data reduction equations

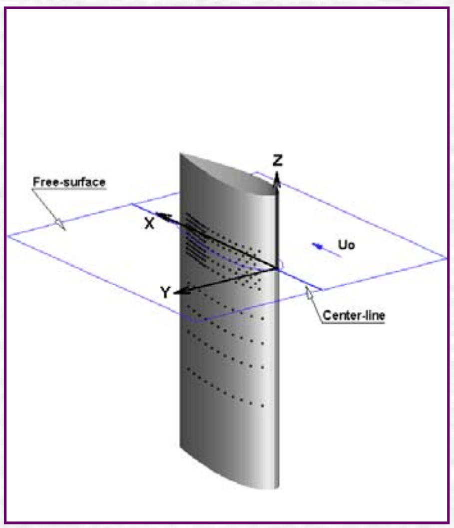
Spectral analysis

Aim: To analyze the natural unsteadiness of the separated flow, around a surface piercing strut, using FFT.

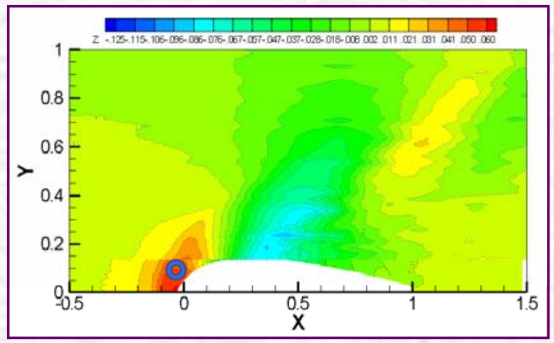
FFT: ***Converts a function from amplitude as function of time to amplitude as function of frequency***

$$x(t) = a_0 + \sum_{k=1}^{\infty}\left(a_k \cos\left(2\pi k f_0 t\right) + b_k \sin\left(2\pi k f_0 t\right)\right)$$

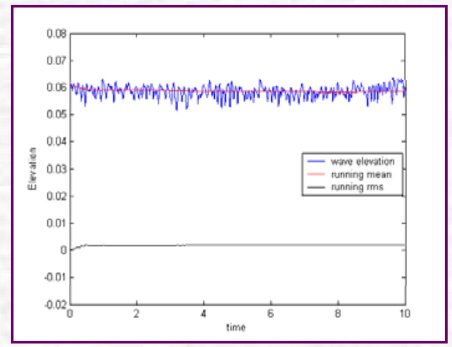
Fast Fourier Transform



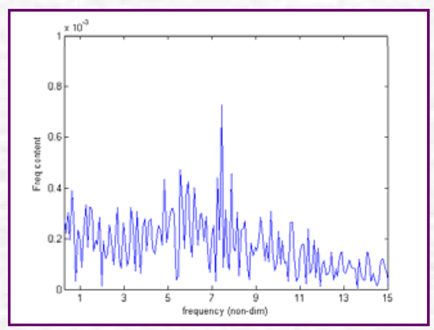
Surface piercing strut



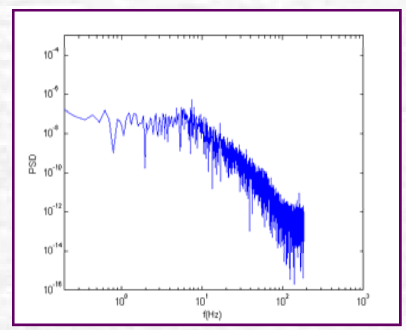
Free-surface wave elevation contours



Time history of wave elevation



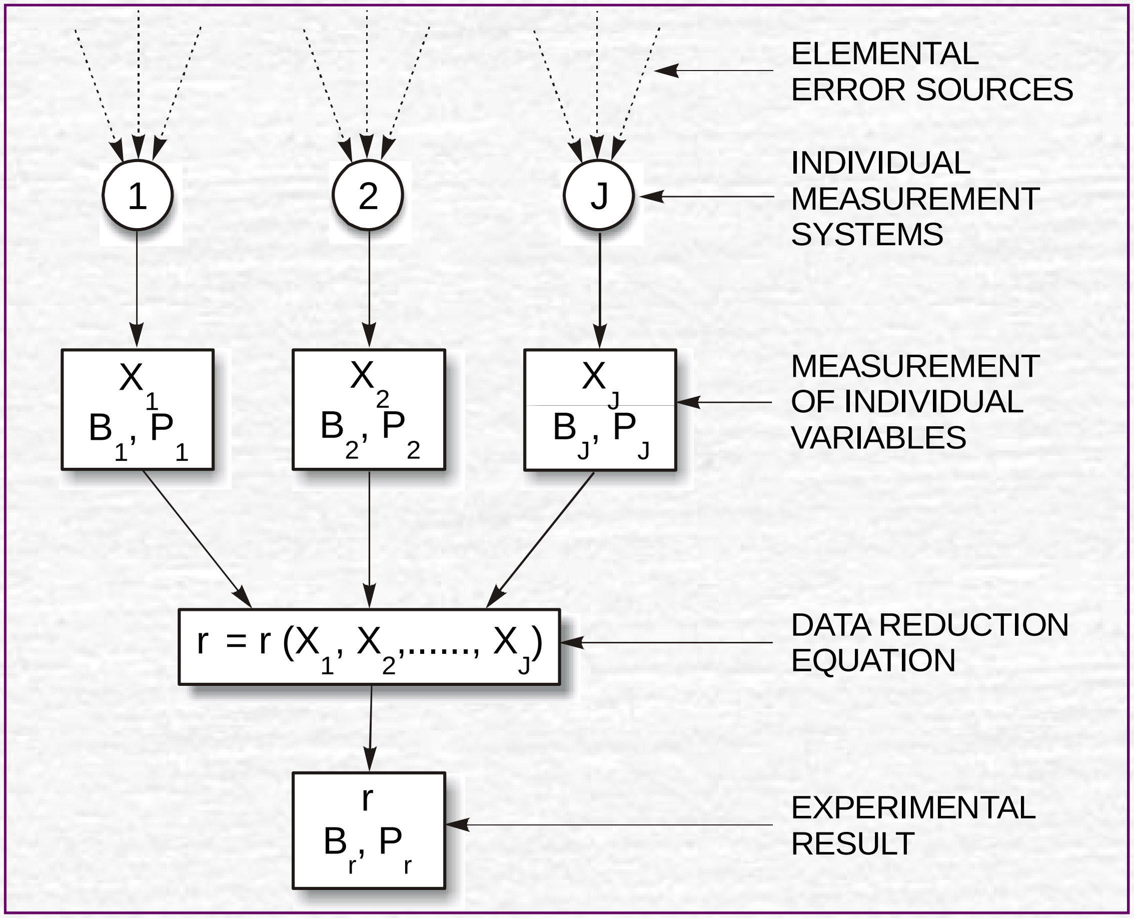
FFT of wave elevation



Power spectral density of wave elevation

Uncertainty analysis

Rigorous methodology for uncertainty assessment using statistical and engineering concepts



Dimensional analysis

- **Definition :** Dimensional analysis is a process of formulating fluid mechanics problems in in terms of non-dimensional variables and parameters.
- **Why is it used :**
  - Reduction in variables (If F(A1, A2, … , An) = 0, then f(Π1, Π2, … Πr < n) = 0, where, F = functional form, Ai = dimensional variables, Πj = non-dimensional parameters, m = number of important dimensions, n = number of dimensional variables, r = n – m). Thereby the number of experiments required to determine f vs. F is reduced.
  - Helps in understanding physics
  - Useful in data analysis and modeling
  - Enables scaling of different physical dimensions and fluid properties

Example

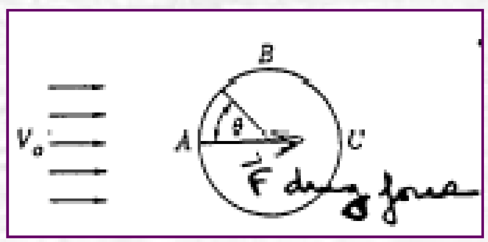
Drag = f(V, L, r, m, c, t, e, T, etc.)

From dimensional analysis,

$$C_D = \frac{\text{Drag}}{\frac{1}{2}\rho V^2 A} = f\left(\text{Re}, \text{Ar}, \frac{t}{L}, \frac{\varepsilon}{L}, \text{T, etc.}\right)$$

(Ar: c/L; $\frac{1}{2}\rho V^2 A$: scale factor)

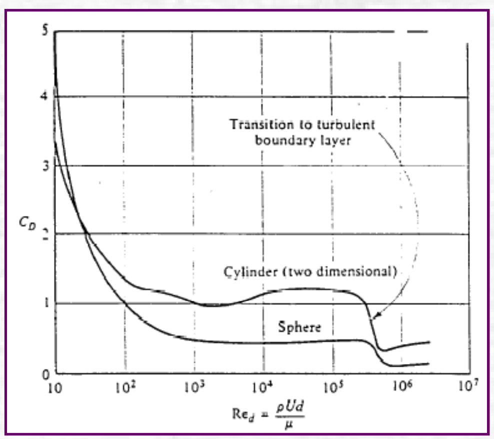
Vortex shedding behind cylinder



Examples of dimensionless quantities : Reynolds number, Froude Number, Strouhal number, Euler number, etc.

Similarity and model testing

- **<u>Definition</u> : Flow conditions for a model test are completely similar if all relevant dimensionless parameters have the same corresponding values for model and prototype.**
  - **Πi model = Πi prototype i = 1**
  - **Enables extrapolation from model to full scale**
  - **However, complete similarity usually not possible. Therefore, often it is necessary to use Re, or Fr, or Ma scaling, i.e., select most important Π and accommodate others as best possible.**
- **<u>Types of similarity</u>:**
  - **Geometric Similarity : all body dimensions in all three coordinates have the same linear-scale ratios.**
  - **Kinematic Similarity : homologous (same relative position) particles lie at homologous points at homologous times.**
  - **Dynamic Similarity : in addition to the requirements for kinematic similarity the model and prototype forces must be in a constant ratio.**



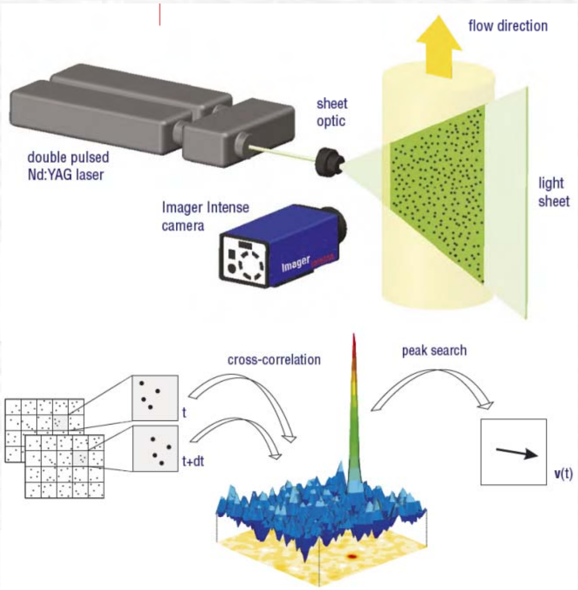
Cylinder length effect ($10^4 < Re < 10^5$)

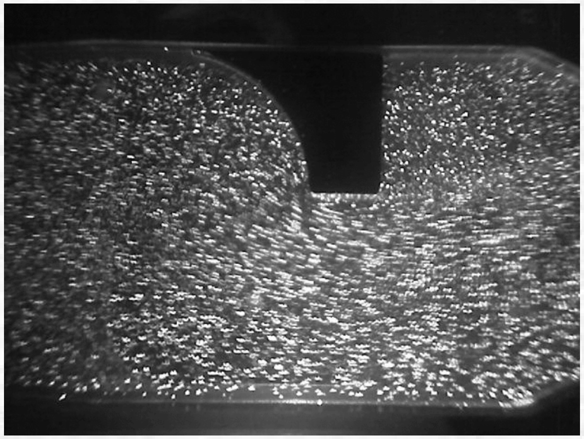
L/d	C_D
∞	1.20
40	0.98
20	0.91
10	0.82
5	0.74
3	0.72
2	0.68
1	0.64

Particle Image Velocimetry (PIV)

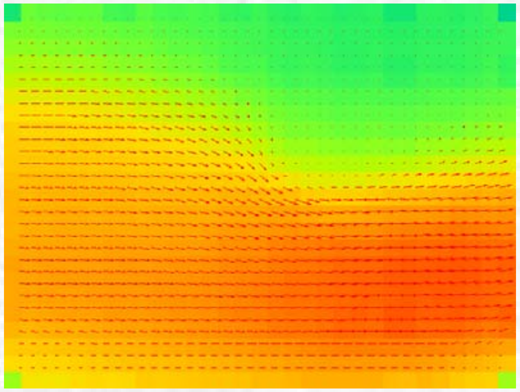
• **Definition :** PIV measures whole velocity fields by taking two images shortly after each other and calculating the distance individual particles travelled within this time. From the known time difference and the measured displacement the velocity is calculated.

- **Seeding:** The flow medium must be seeded with particles.
- **Double Pulsed Laser:** Two laser pulses illuminate these particles with short time difference.
- **Light Sheet Optics:** Laser light is formed into a thin light plane guided into the flow medium.
- **CCD Camera:** A fast frame-transfer CCD captures two frames exposed by laser pulses.
- **Timing Controller:** Highly accurate electronics control the laser and camera(s).
- **Software:** Particle image capture, evaluation and display.





PIV image pair

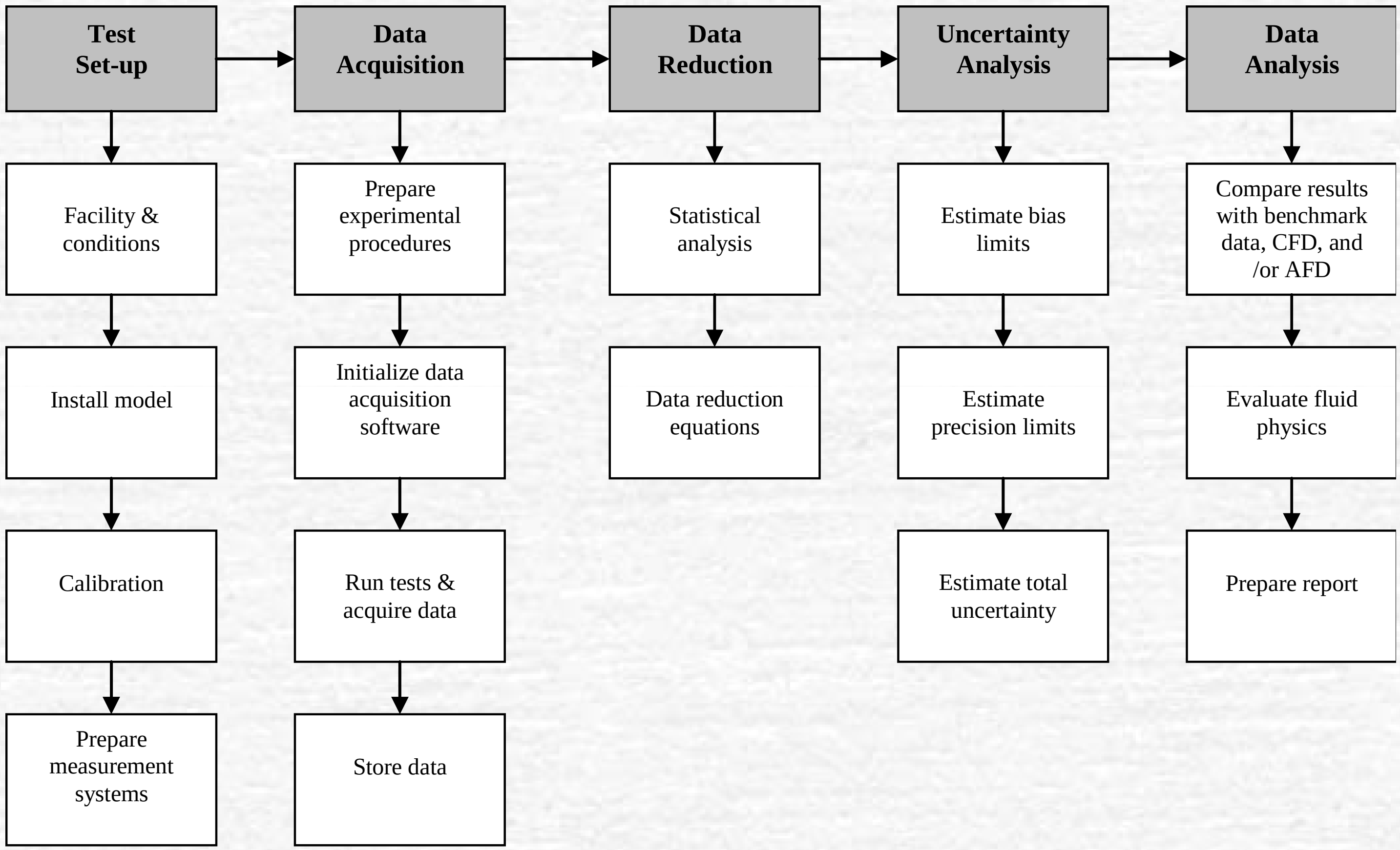


Cross-correlated vector field

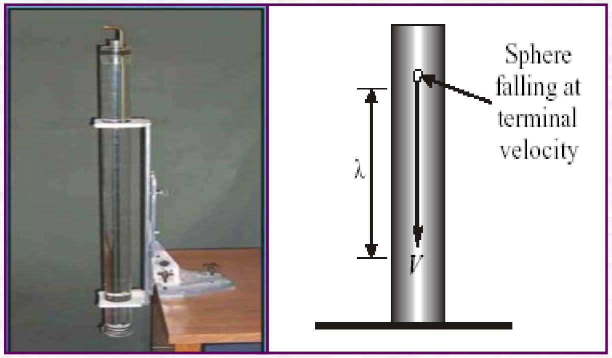
Links: Video clip
PMM-PIV

EFD process

- "EFD process" is the steps to set up an experiment and take data

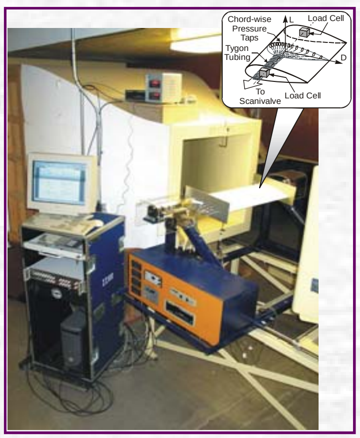


EFD – “hands on” experience

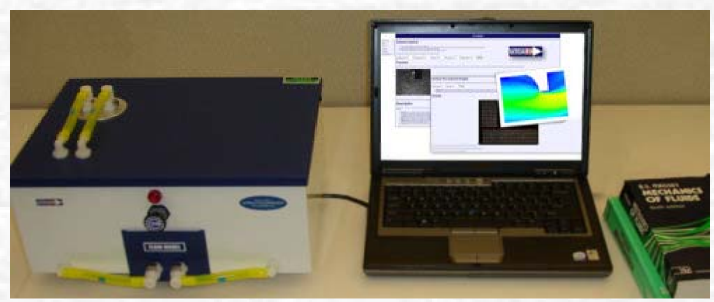


Lab1: Measurement of density and kinematic viscosity of a fluid and visualization of flow around a cylinder.

Lab2: Measurement of flow rate, friction factor and velocity profiles in smooth and rough pipes, and measurement of flow rate through a nozzle using PIV technique.



Lab3: Measurement of surface pressure distribution, lift and drag coefficient for an airfoil, and measurement of flow velocity field around an airfoil using PIV technique.



Lab 1, 2, 3: PIV based flow measurement and visualization

Computational Fluid Dynamics

- CFD is use of computational methods for solving fluid engineering systems, including modeling (mathematical & Physics) and numerical methods (solvers, finite differences, and grid generations, etc.).
- Rapid growth in CFD technology since advent of computer

ENIAC 1, 1946

IBM WorkStation

Purpose

- The objective of CFD is to model the continuous fluids with Partial Differential Equations (PDEs) and discretize PDEs into an algebra problem, solve it, validate it and achieve simulation based design instead of "build & test"

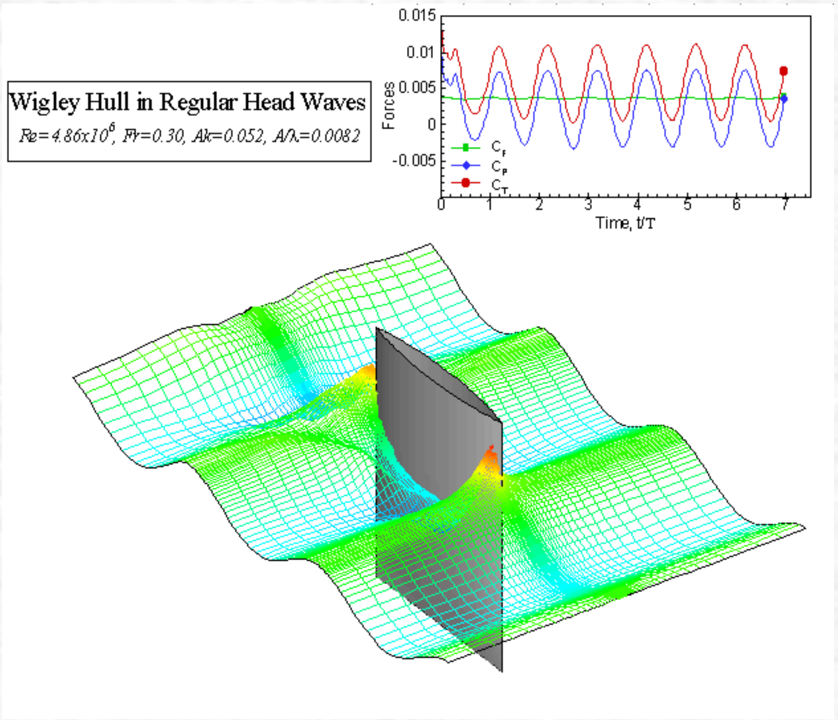
- Simulation of physical fluid phenomena that are difficult to be measured by experiments: scale simulations (full-scale ships, airplanes), hazards (explosions,radiations,pollution), physics (weather prediction, planetary boundary layer, stellar evolution).

Modeling

- Mathematical physics problem formulation of fluid engineering system
- Governing equations: Navier-Stokes equations (momentum), continuity equation, pressure Poisson equation, energy equation, ideal gas law, combustions (chemical reaction equation), multi-phase flows(e.g. Rayleigh equation), and turbulent models (RANS, LES, DES).
- Coordinates: Cartesian, cylindrical and spherical coordinates result in different form of governing equations
- Initial conditions(initial guess of the solution) and Boundary Conditions (no-slip wall, free-surface, zero-gradient, symmetry, velocity/pressure inlet/outlet)
- Flow conditions: Geometry approximation, domain, Reynolds Number, and Mach Number, etc.

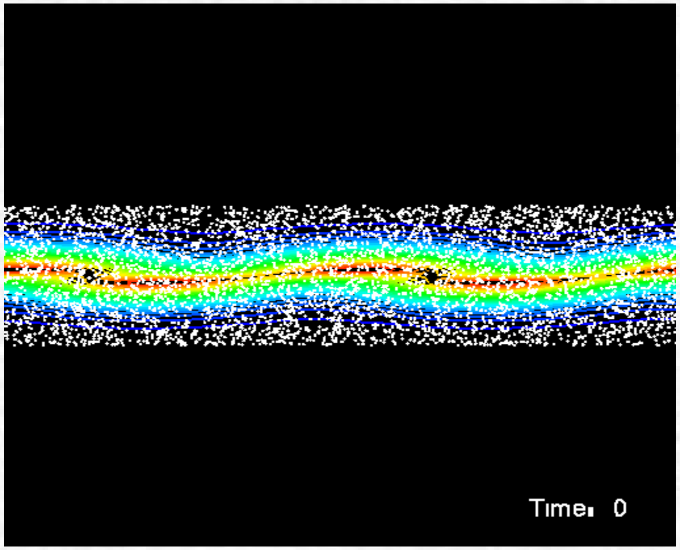
Modeling (examples)

Free surface animation for ship in regular waves

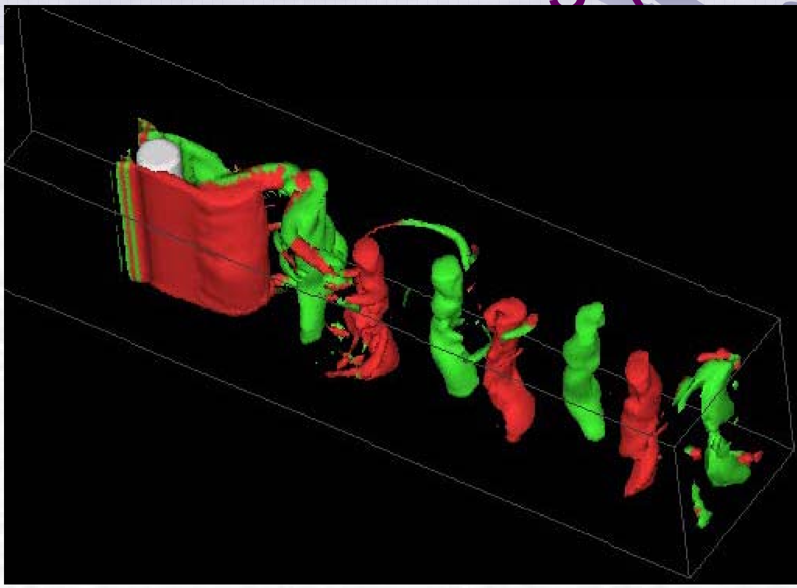


Developing flame surface (Bell et al., 2001)

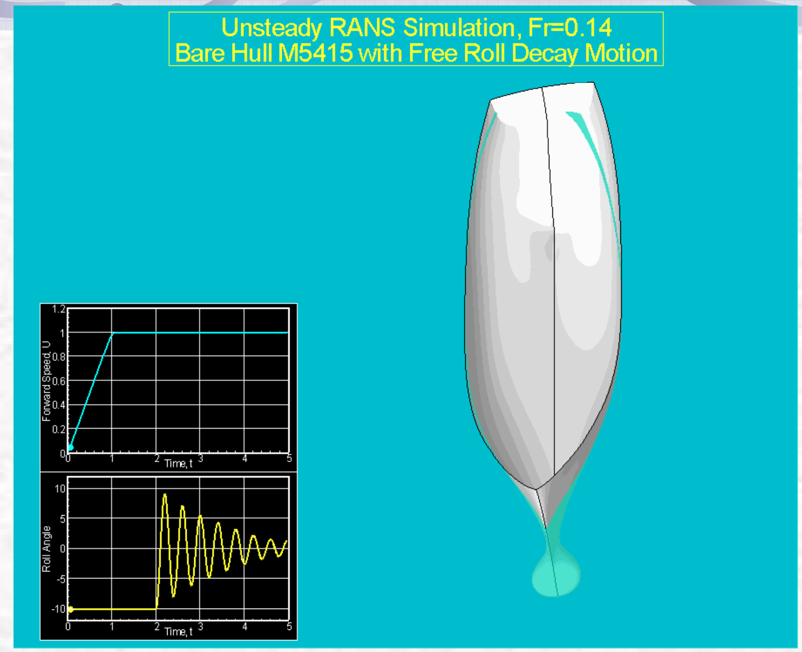
Evolution of a 2D mixing layer laden with particles of Stokes Number 0.3 with respect to the vortex time scale (C.Narayanan)

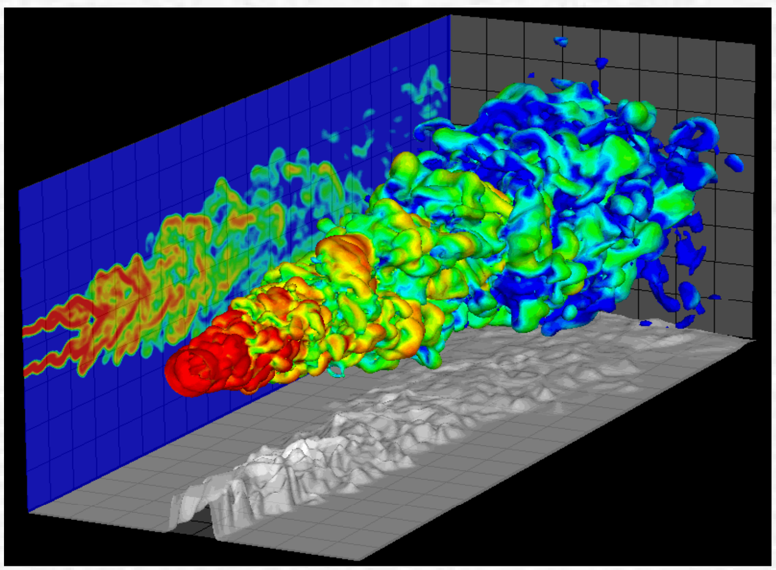


Modeling (examples, cont'd)

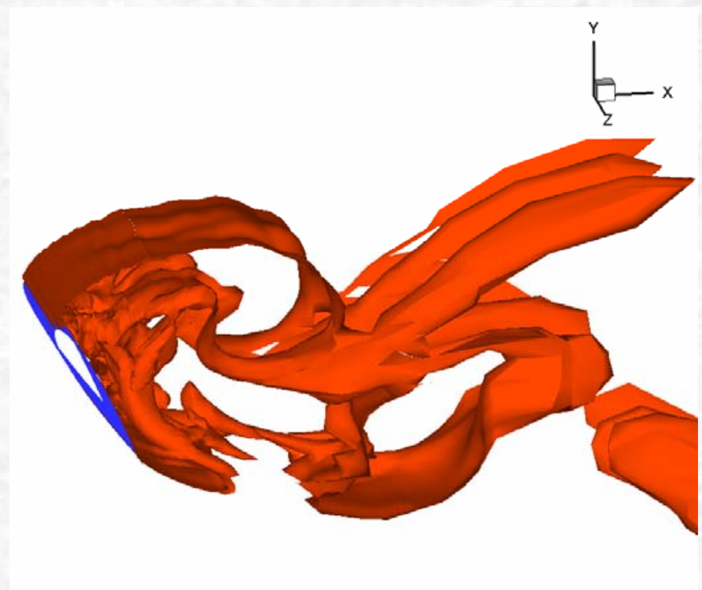


3D vortex shedding behind a circular cylinder (Re=100,**DNS**,J.Dijkstra)





LES of a turbulent jet. Back wall shows a slice of the dissipation rate and the bottom wall shows a carpet plot of the mixture fraction in a slice through the jet centerline, Re=21,000 (D. Glaze).



DES, $Re=10^5$, Iso-surface of Q criterion (0.4) for turbulent flow around NACA12 with angle of attack 60 degrees

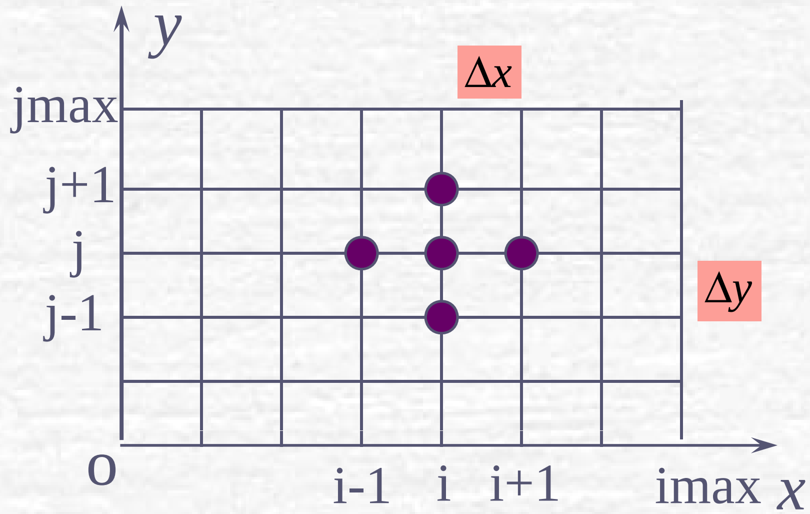
Numerical methods

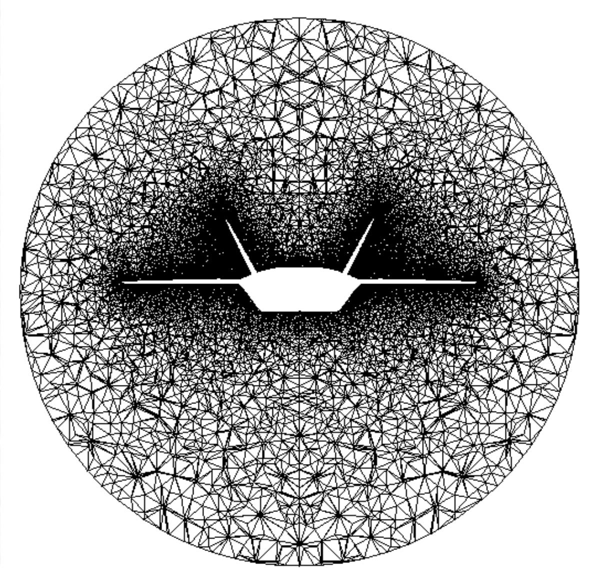
- **Finite difference methods**: using numerical scheme to approximate the exact derivatives in the PDEs

$$\frac{\partial^2 P}{\partial x^2} = \frac{P_{i+1} - 2P_i + P_{i-1}}{\Delta x^2}$$

$$\frac{\partial^2 P}{\partial y^2} = \frac{P_{j+1} - 2P_j + P_{j-1}}{\Delta y^2}$$

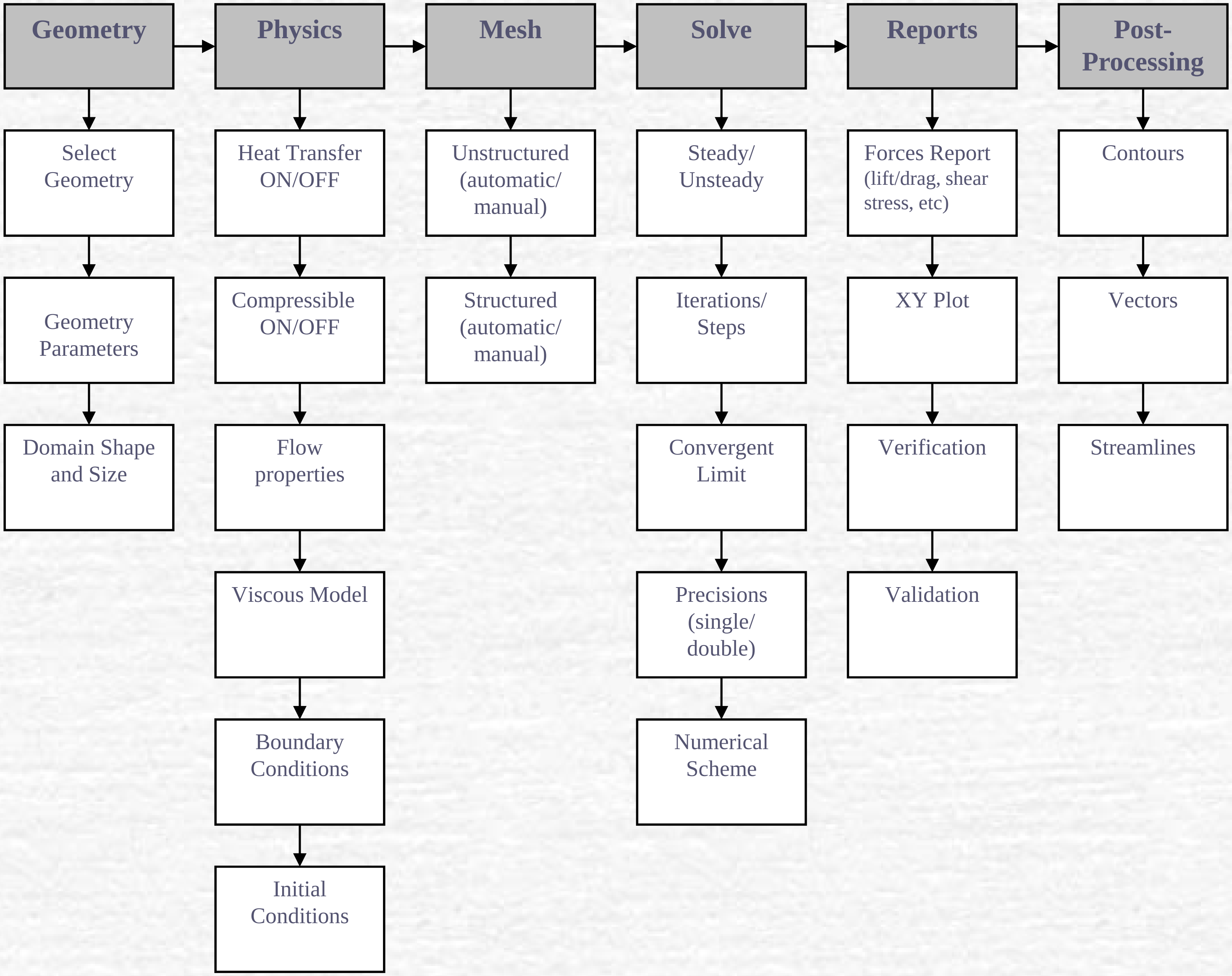
- **Finite volume methods**
- **Grid generation:** conformal mapping, algebraic methods and differential equation methods
- **Grid types**: structured, unstructured
- **Solvers**: direct methods (Cramer's rule, Gauss elimination, LU decomposition) and iterative methods (Jacobi, Gauss-Seidel, SOR)





Slice of 3D mesh of a fighter aircraft

CFD process


Geometry
Physics
Mesh
Solve
Reports
Post-Processing
Select Geometry
Geometry Parameters
Domain Shape and Size
Heat Transfer ON/OFF
Compressible ON/OFF
Flow properties
Viscous Model
Boundary Conditions
Initial Conditions
Unstructured (automatic/ manual)
Structured (automatic/ manual)
Steady/ Unsteady
Iterations/ Steps
Convergent Limit
Precisions (single/ double)
Numerical Scheme
Forces Report (lift/drag, shear stress, etc)
XY Plot
Verification
Validation
Contours
Vectors
Streamlines

Commercial software

- ## CFD software

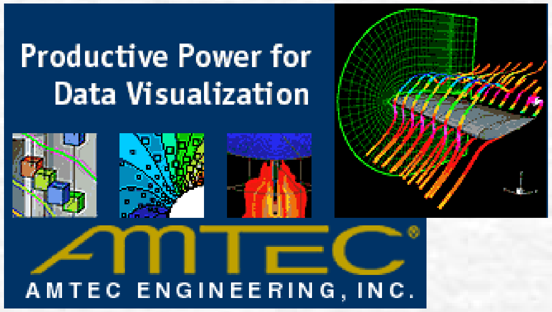
  1. FLUENT: http://www.fluent.com
  2. FLOWLAB: http://www.flowlab.fluent.com
  3. CFDRC: http://www.cfdrc.com
  4. STAR-CD: http://www.cd-adapco.com
  5. CFX/AEA: http://www.software.aeat.com/cfx

- ## Grid Generation software

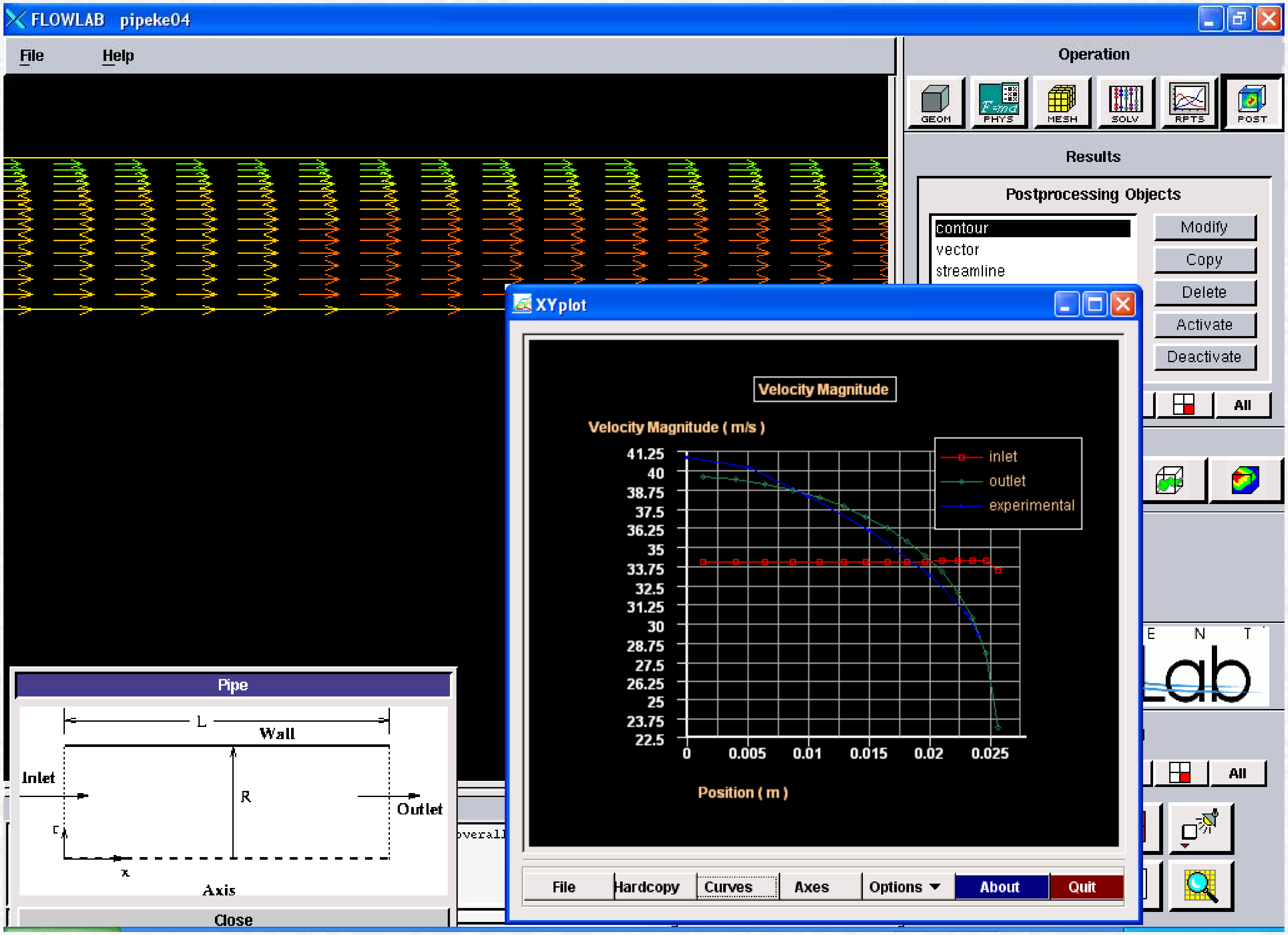
  1. Gridgen: http://www.pointwise.com
  2. GridPro: http://www.gridpro.com

- ## Visualization software

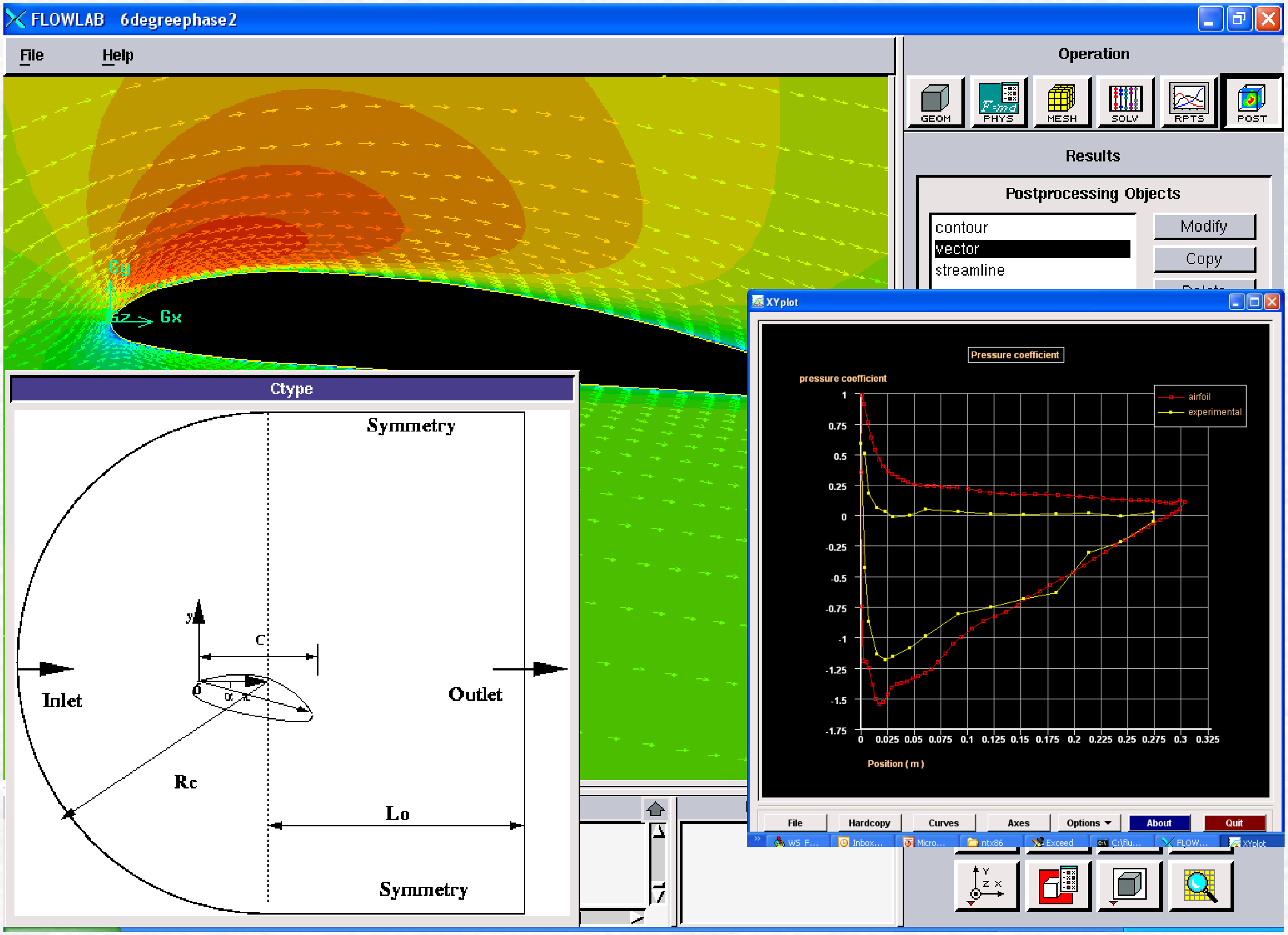
  1. Tecplot: http://www.amtec.com
  2. Fieldview: http://www.ilight.com



"Hands-on" experience using CFD Educational Interface (pipe template)



"Hands-on" experience using CFD Educational Interface (airfoil template)



57:020 Fluid Mechanics

- Lectures cover basic concepts in fluid statics, kinematics, and dynamics, control-volume, and differential-equation analysis methods. Homework assignments, tests, and complementary EFD/CFD labs
- This class provides an introduction to all three tools: AFD through lecture and CFD and EFD through labs
- ISTUE Teaching Modules (http://www.iihr.uiowa.edu/~istue) (next two slides)

TM Descriptions

Table 1: ISTUE Teaching Modules for Introductory Level Fluid Mechanics at Iowa

Teaching Modules	TM for Fluid Property	TM for Pipe Flow	TM for Airfoil Flow
Overall Purpose	*Hands-on* student experience with table-top facility and simple MS for fluid property measurement, including comparison manufacturer values and rigorous implementation standard EFD UA	*Hands-on* student experience with complementary EFD, CFD, and UA for Introductory Pipe Flow, including friction factor and mean velocity measurements and comparisons benchmark data, laminar and turbulent flow CFD simulations, modeling and verification studies, and validation using AFD and EFD.	*Hands-on* student experience with complementary EFD, CFD, and UA for Introductory Airfoil Flow, including lift and drag, surface pressure, and mean and turbulent wake velocity profile measurements and comparisons benchmark data, inviscid and turbulent flow simulations, modeling and verification studies, and validation using AFD and EFD.
Educational Materials	FM and EFD lecture; lab report instructions; pre lab questions, and EFD exercise notes.	FM, EFD and CFD lectures; lab report instructions; pre lab questions, and EFD and CFD exercise notes.	FM, EFD and CFD lectures; lab report instructions; pre lab questions, and EFD and CFD exercise notes.
ISTUE ASEE papers	Paper 1 Paper2 Paper 3		
FM Lecture	Introduction to Fluid Mechanics		
Lab Report Instructions	EFD lab report Instructions CFD lab report Instructions		

Continued in next slide…

http://css.engineering.uiowa.edu/~fluids

TM Descriptions, cont'd

Teaching Modules		TM for Fluid Property	TM for Pipe Flow	TM for Airfoil Flow
CFD	CFD Lecture	Introduction to CFD		
	Exercise Notes	None	CFD Prelab1 PreLab1 Questions CFD Lab 1 Lab1 Concepts CFDLab1-template.doc EFD Data	CFD Prelab2 PreLab 2 Questions CFD Lab2 Lab2 Concepts CFDLab2-template.doc EFD Data
EFD	EFD Lecture	EFD and UA		
	Exercise Notes	PreLab1 Questions Lab1 Lecture Lab 1 exercise notes Lab 1 data reduction sheet Lab1 concepts	PreLab2 Questions Lab2 Lecture Lab 2 exercise notes Lab2 data reduction sheet (smooth & rough) EFDlab2-template.doc Lab2 concepts	PreLab3 Questions Lab3 Lecture Lab 3 exercise notes Lab 3 data reduction sheet Lab3 concepts
UA(EFD)	References: EFD UA Report; EFD UA Summary; EFD UA Example			
UA(CFD)				