**Lecture 1**

GENERAL INTRODUCTION: HISTORICAL BACKGROUND AND SPECTRUM OF APPLICATIONS

1.1 INTRODUCTION

Analysis of physical problems in any area of engineering and science involves a multi-pronged approach:

- Idealized physical model: experiments on scale models of the problem
- Mathematical model: Theoretical analysis (analytical solution) / approximate numerical solution.
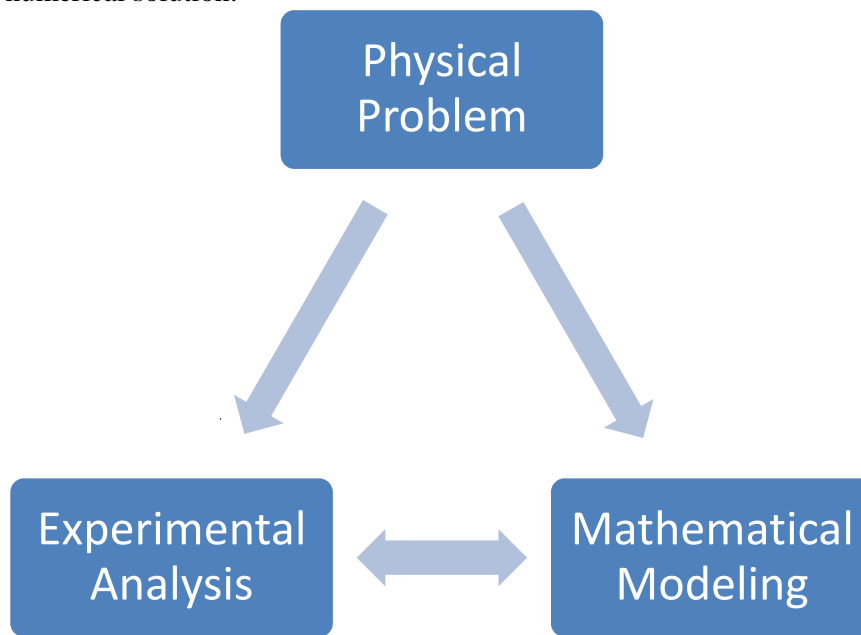
Both physical experiments and analytical/numerical simulations complement each other. Both the approaches have their own limitations, advantages and disadvantages:

- **Physical experiments**
  - o These are usually very time consuming and expensive to set up
  - o There are limitations on extrapolation of the results obtained on scaled model of a problem to the actual prototype.
  - o **BUT** the experimentally observed data provides the **closest possible approximation** of the physical reality within the limits of experimental errors.
- **Numerical Simulation**
  - o Mathematical modelling is based on a set of assumptions with regard to the variation of the problem variables, constitutive relations and material properties.
  - o Numerical simulation process introduces **additional approximation errors** in the solution. Hence, results of any analytical or numerical study must be

carefully validated against physical experiments to establish their practical usefulness.
  o However, once validated, a numerical simulation can be easily performed on the **full scale prototype**, and thereby eliminate the need of extrapolation.

1.2 WHAT IS CFD?

Mathematical modelling of a continuum problem leads to a set of differential, integral or integro-differential equations. Exact analytical solution of such equations is limited to problems in simple geometries. Hence, for most of the problems of practical interest, an approximate numerical solution is sought. In the context of mechanics, *the science and practice of obtaining approximate numerical solution using digital computers* is termed **Computational Mechanics**. For thermo-fluid problems, this approach is popularly known as **Computational Fluid Dynamics (CFD)**. Thus,

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CFD is essentially a branch of continuum mechanics which deals with numerical simulation of fluid flow and heat transfer problems.

Note that although word *heat transfer* is missing from *CFD*, it is an intrinsic part of this discipline.

CFD deals with **approximate numerical** solution of governing equations based on the fundamental conservation laws of physics, namely mass, momentum and energy conservation. The CFD solution involves

- Conversion of the governing equations for a continuum medium into a set of discrete algebraic equations using a process called discretization.
- Solution of the discrete equations can using a high speed digital computer to obtain the numerical solution to desired level of accuracy.

1.3 HISTORICAL PERSPECTIVE

Although development of some of the techniques used in CFD dates back to pre-digital era, history of CFD is intrinsically linked to the advent of the digital computers in late 1950s. It is highly debatable as to who did the first CFD simulation of a flow problem. Hence, instead of looking at chronology of the history of CFD, we focus on the evolution of CFD for motivational and application perspective.

Early Applications
- The early beginning of the CFD can be traced to numerical simulations for aerospace applications at Douglas, Boeing, NASA, and Lockheed in 1960s based on panel methods.
  o The codes based on panel methods still play an important role in the computer aided design of modern day aircraft.
- Meteorologists were the next early users of CFD for weather forecasting applications. Large eddy simulation models for atmospheric turbulent flows appeared in early 1970s.

Algorithmic Front
- 1960s: Development of Particle-In-Cell (PIC), Marker-and-Cell (MAC) and Vorticity-Stream function methods at NASA.

- 1970s: Development of parabolic flow codes (GENMIX), Vorticity-Stream function based codes, and the SIMPLE algorithm by the research group of Professor D. Brian Spalding, at Imperial College, London.
- 1980 onwards vigorous research activity in various parts of the globe addressing different aspects of CFD: new discretization methods, turbulence modelling, numerical algorithms, grid generation methods, post-processing and visualization, parallel implementation etc.

Impact of Developments in CAD on Industrial Applications of CFD
- Industrial applications of CFD boosted by the availability of commercial CFD codes in 1980s.
- Developments in CAD and FEA have inspired development of commercial CFD codes with user-friendly graphical user interface, in-built geometry and solid modelling, and visual post-processing capabilities.
- Availability of commercial and open-source GUI based codes which offer CAD inter-operability has led to the integration of CFD analysis in the design cycle.

1.4 APPLICATIONS OF CFD

CFD is being used for fundamental research as well as industrial R&D. CFD analysis forms an integral part of design cycle in most of the industries: from aerospace, chemical and transportation to bio-medical engineering. The length scales range from planetary boundary layers to micro-channels in electronic equipments. Following is a short-list of some of more prominent applications of CFD:
- Meteorology: weather forecasting
- Aerospace: design of wings to complete aircraft aerodynamic design
- Turbomachines: design of hydraulic, steam, gas, and wind turbines; design of pumps, compressors, blower, fans, diffusers, nozzles.
- Engines: combustion modelling in internal combustion engines
- Electronics: cooling of micro-circuits
- Chemical process engineering
- Energy systems: analysis of thermal and nuclear power plants, modelling of accident situations for nuclear reactors.
- Hydraulics and hydrology: flow in rivers, channels, ground aquifers, sediment transport.
- HVAC: Design of ducts, placement of heating/cooling ducts for optimum comfort in a building
- Surface transport: aerodynamic design of vehicles
- Marine: hydrodynamic design of ships, loads on off-shore structures
- Biomedical: simulation of blood flow through arteries and veins, fluid flow in renal and ocular systems.
- Fundamental flow physics: dynamics of laminar, transitional and turbulent flows.
- ………

The complete list of CFD applications is rather long, and continues to grow each day. Figures on following pages provide graphical illustrations of some applications.

SUGGESTED TEXT-BOOKS / RESOURCES

Anderson, J. D., Jr. (1995). *Computational Fluid Dynamics: The Basics with Applications*. McGraw Hill, New York.

Chung, T. J. (2010). *Computational Fluid Dynamics*. 2nd Ed., Cambridge University Press, Cambridge, UK.

Date, A. W. (2005). *Introduction to Computational Fluid Dynamics.* Cambridge University Press, Cambridge.

Ferziger, J. H. and Peric, M. (2003). *Computational Methods for Fluid Dynamics*. Springer-Verlag, Berlin.

Fletcher, C. A. J. (1988). *Computational Techniques for Fluid Dynamics*. Vol. 1 and 2. Springer-Verlag, Berlin.

Versteeg, H. K. and Malalasekera, W. M. G. (2007). *Introduction to Computational Fluid Dynamics: The Finite Volume Method.* Second Edition (Indian Reprint) Pearson Education

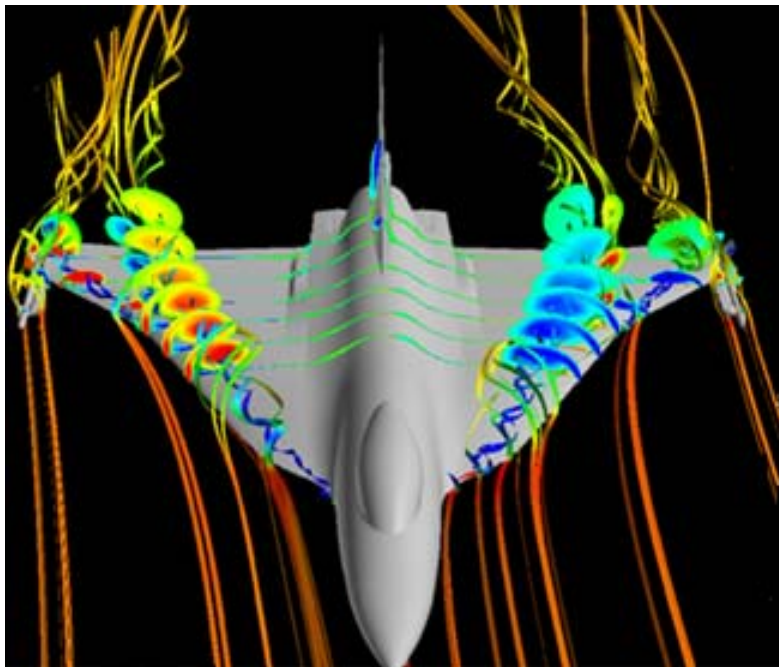## WEB RESOURCES

http://www.cfd-online.com/

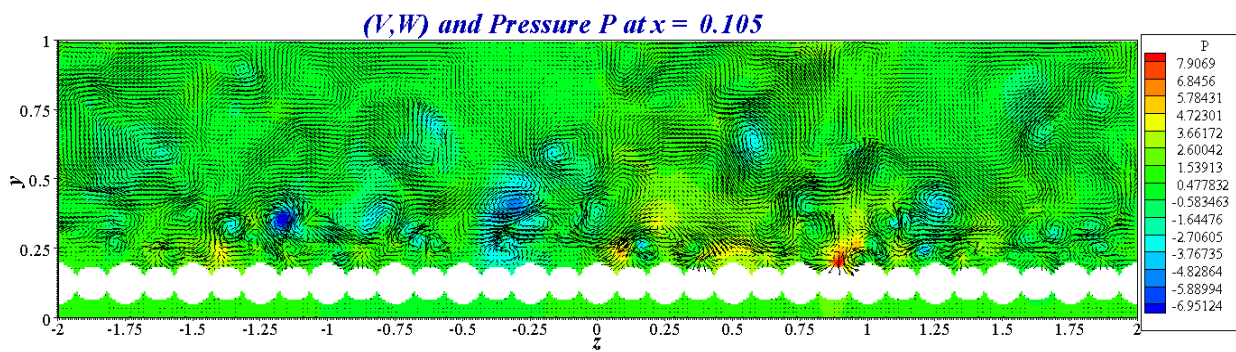Figure 1.1 CFD Simulation of complete fighter aircraft

Figure 1.2 Direct numerical simulation of flow over a rough-bed channel

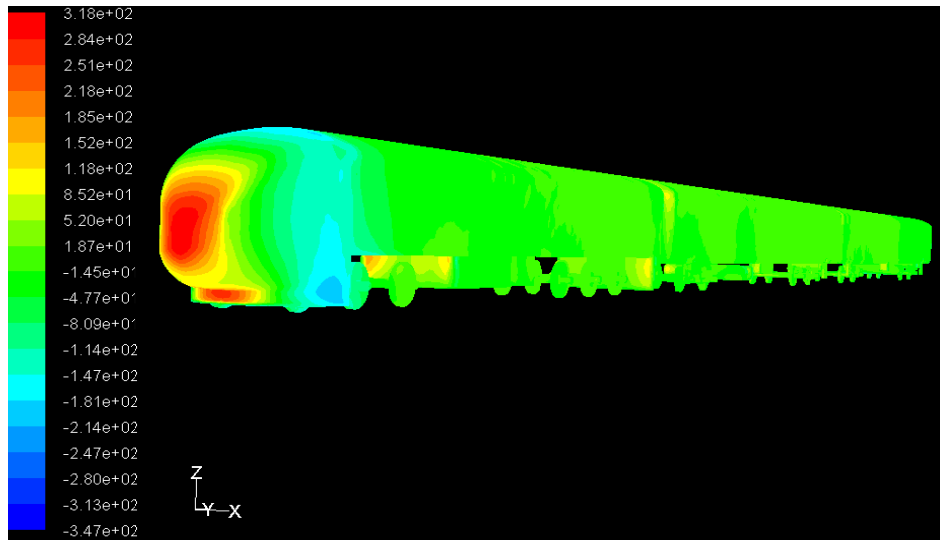Figure 1.3 Pressure distribution around a high-speed train obtained from RANS simulation

(a) CAD model of geometry   (b) Structured Grid used in CFD analysis

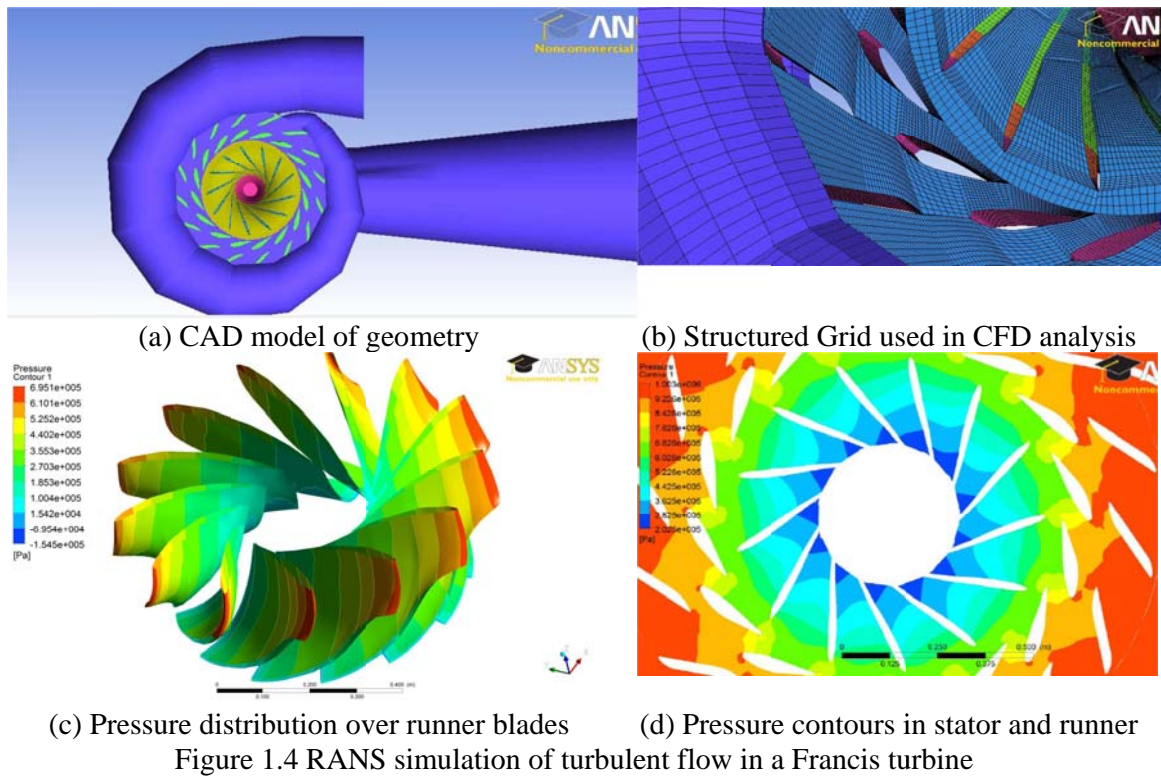(c) Pressure distribution over runner blades   (d) Pressure contours in stator and runner
Figure 1.4 RANS simulation of turbulent flow in a Francis turbine