APPENDIX I: CORE COURSES

CORE COURSE 1: FLUID DYNAMICS 1

COURSE AIM AND OVERALL DESCRIPTION

The aim of this module (and its companion module, Fluid Dynamics – Part 2) is to give students a broad and solid foundation on which to build the ability to understand and appreciate a variety of problems across the fluid dynamics discipline. This module will introduce students to a wide range of important fluid dynamics mechanisms and forces.

LEARNING OUTCOMES

- To demonstrate mastery of the fundamentals of fluid mechanics
- To describe the different flows past a circular cylinder and derive mathematical models in the case of low Reynolds number flows
- To understand the relation between incompressible and irrotational flow past a circular cylinder and the Kutta-Joukowski lift theorem
- To gain familiarity of phenomenology and main parameters of unsteady forcing on aerodynamic surfaces
- To develop an ability to write simplified models based on vortex dynamics
- To gain familiarity with linearized and non-linear methods of aero-elasticity
- To demonstrate understanding and mastery of techniques that can be used to gain insight into the physics and mechanisms underlying behaviour of physical fluid systems
- To understand the basic ideas underlying the classical boundary layer theory and to be able use them to derive the classical boundary-layer equations, and understand the mathematical nature of these equations
- To be able to deduce and derive similarity solutions to boundary-layer equations, gain familiarity with numerical marching methods for solving the boundary-layer equations, and gain a preliminary understanding of interactive boundary-layer (triple-deck) theory

SYLLABUS

Fundamentals

- Scalars, vectors, tensors, and summation notation
- Reference frames, coordinate systems
- Kinematics and dynamics, rate of strain, vorticity
- Irrotational and solenoidal flows, the streamfunction
- Stress: surface and body forces, Cauchy's fundamental theorem of stress
- Conservation equations: mass, linear momentum, angular momentum, and energy – this is the general, full set of equations for a non-isothermal, compressible fluid
- Transport of scalars: heat and mass transfer
- Constitutive equations: stress; Newtonian and non-Newtonian fluids
- The Navier-Stokes equations

D'Alembert's paradox

- Incompressible and irrotational flow past a cylinder and illustration of the paradox

Vorticity, what causes it and the resolution of d'Alembert's paradox

- Cauchy-Lagrange, Stokes, Kelvin and Kelvin minimum energy theorems
- No-slip boundary condition and viscosity
- Pressure (form) and friction (skin) drag forces

Flows past a fixed circular cylinder

- Different Reynolds number regimes
- Stokes paradox and Oseen's equations
- Physical mechanism of flow separation
- Strouhal number and drag coefficient and their dependencies on Reynolds number

Lift

- Viscosity and the Kutta-Joukowski hypothesis/model
- Deflection of airstream and momentum balance (explanation of lift)
- Kutta-Joukowski lift theorem, lift on a rotating body

Turbulence

- Introduction to turbulence properties
- Reynolds decomposition and the log law of the wall in channels and pipes and comparison with Poiseuille flows
- Scale decompositions of the fluctuating velocity field and the Kolmogorov equilibrium cascade theory
- Self-preserving profiles for boundary-free turbulent shear flows

Fluid-structure interactions

- Galloping
- Added mass
- Vortex induced vibration and lock-in
- Buffeting

Boundary layers

- Basic ideas underlying the boundary layer theory, derivation of classical boundary-layer equations
- Mathematical nature of the boundary-layer equations, displacement effects
- Similarity solutions: flows past a flat plate and wedge
- Marching methods
- Goldstein singularity, and elementary interactive boundary-layer (triple-deck) theory

Topics

- Collapsible tubes and waves in flexible tubes as further examples of fluid-structure interactions
- Flow in a porous medium as another example of slow flow
- Stirring and mixing of scalar quantities: how molecular diffusivity interacts with advection

RECOMMENDED TEXT BOOKS

Fundamentals:

- Elementary Fluid Dynamics, D. J. Acheson, Clarendon Press, Oxford, 1990.
- Laminar Flow and Convective Transport Processes, L. G. Leal, Butterworth-Heinemann, 1992.
- Incompressible Flow, R. L. Panton, Wiley, 2005.
- Fluid Mechanics, S. M. Richardson, Hemisphere, 1989.
- Physical Fluid Dynamics, D. J. Tritton, Clarendon Press, Oxford, 1988.
- An Album of Fluid Motion, M. van Dyke, Parabolic Press, 1982.

Lift:

- Elementary Fluid Dynamics, D.J. Acheson, Oxford University Press.
- Aerodynamics, L. J. Clancy, Prentice Hall.

Turbulence:

- Turbulent Flows, S Pope, Cambridge University Press.

Fluid structure interactions:

- Principles of Aeroelasticity, Bisplinghoff, R.L. and Ashley, H., John Wiley and Sons, 1962.

Boundary layers

- Boundary layer theory, H. Schlichting, Springer, 1979; New edition: H. Schlichting and K. Gersten
- Laminar boundary layers, ed. L. Rosenhead, Oxford, 1963. Also Dover, 1988.

Topics:

- Mathematical Models in the Applied Sciences. A. C. Fowler, Cambridge University Press.

ASSESSMENT

Oral examination

CORE COURSE 2: FLUID DYNAMICS 2

COURSE AIM AND OVERALL DESCRIPTION

This course forms the second part of the Fluid Dynamics core course sequence. Building on the concepts learned in Fluid Dynamics 1, this course will delve deeper into several areas that cover fluid dynamics phenomena across scales. The course will be based on four related modules: (i) linear and nonlinear waves in fluids (including propagation of sound waves); (ii) elements of gas dynamics and compressible flows; (iii) hydrodynamic stability theory; (iv) an introduction to multiphase flows. The majority of the phenomena described in this part are fundamental to a wide variety of applications across the scales.

LEARNING OUTCOMES

- Working with water waves (linear and nonlinear theories); fundamental aspects of interfacial wave phenomena in viscous flows; knowledge on the origin and propagation of sound waves in fluids.
- Working with the compressible Euler equations including shock waves; technical knowledge of shock formation and propagation in one-dimensional gasdynamics; steady two-dimensional flows with shocks past blunt bodies.
- Extended knowledge of hydrodynamic stability theory including shear flow, thermal and centrifugal instabilities. Knowledge of theoretical as well as computational aspects of such problems.
- Fundamental knowledge of multiphase flows including solid particles, bubbles and droplets.

SYLLABUS

Waves in Fluids

Water waves

- Derivation of the linear water waves equations
- Gravity and gravity-capillary waves
- Internal waves
- Waves on sloping beaches

(Sample enhanced/independent coursework: Nonlinear water waves, shallow water wave theory, derivation of the Kortweg de-Vries equation, solitary waves; Nonlinear long-wave models in viscous multi-fluid flows, Marangoni effects.)

Sound propagation

- Sound waves in fluids
- Derivation of the wave equation for sound propagation in fluids
- Plane waves
- Acoustic energy
- Acoustic waveguides
- Acoustic sources

Compressible flows

- Elements of gas dynamics and equations of motion
- Theory of characteristics
- Shock waves, Rankine-Hugoniot conditions
- Supersonic flows past wedges and cones

Hydrodynamic stability theory

- Fundamental concepts, Kelvin-Helmholtz, Rayleigh-Taylor, capillary instability; comparisons with experiments.
- Thermal instability, Boussinesq equations, exchange of stabilities, Benard cells.
- Centrifugal instability, Couette flow, Taylor vortices.
- Stability of parallel shear flows, inviscid theory and the Rayleigh equation, viscous theory, Orr-Sommerfeld equation, Squire's theorem, stability of boundary layers – Tollmien-Schlichting waves.

Introduction to multiphase flows

- Single particle motion (flows around a sphere, unsteady effects, particle equation of motion).
- Bubble and droplet translation.
- Multiphase flow patterns (flow regime maps, disperse mixtures, instabilities).

RECOMMENDED TEXT BOOKS

- Waves in Fluids, J. Lighthill, Cambridge University Press, 1978.
- Wave Motion, J. Billingham and A.C. King, Cambridge University Press, 2001.
- Linear and Nonlinear Waves, G.B. Whitham, Wiley, 1976.
- Compressible-fluid dynamics, P.A. Thompson, McGraw-Hill, New York, 1972.
- Hydrodynamic Stability, P.G. Drazin and W.H. Reid, Cambridge University Press, 2004 (2nd edition).
- Stability and Transition in Shear Flows, P.J. Schmid and D.S. Henningson, Springer, 2001.
- Fundamentals of Multiphase Flow, Christopher E. Brennen (CUP, 2009).

ASSESSMENT

Written examination

CORE COURSE 3: COMPUTATIONAL FLUID DYNAMICS

COURSE AIM AND OVERALL DESCRIPTION

The CFD course aims to convey the major elements that contribute to construction and use of computational procedures for calculating general fluid flows by way of solving the differential transport equations that govern the spatial distribution and temporal variation of momentum, energy, mass and scalar species – the flow properties of interest in fluid dynamics applications. These elements include, inter alia: basic techniques for discretising the transport equations, the examination of the properties of alternative technique that characterise their numerical properties, the formulation of computational algorithms for obtaining numerical solutions for incompressible as well as compressible flows, and the description of methods that characterise turbulence and its effects in the context of numerical solutions.

LEARNING OUTCOMES

- Understanding the process of transferring differential transport equations to algebraic equivalents that can be solved on a computer, and an appreciation of numerical properties and relative advantages/disadvantages of alternative numerical approximation techniques.
- Ability to formulate basic numerical solution schemes for incompressible and compressible flows and apply them to simple generic flow problems.
- Appreciation of relationship between the numerical process and particular physical characteristics of the conservation laws for different types of flow.
- Understanding of the process by which numerical solutions can be obtained for flows bounded within geometrically complex domains covered by non-regular grids
- Insight into the role and numerical formulation of boundary conditions at different types of computational boundaries.
- Insight into alternative approaches and theories to representing turbulence and its effects in the context of Reynolds-averaged Navier-Stokes solutions, direct numerical simulation and large eddy simulation

SYLLABUS

Fundamentals

- Conservation laws in fluid mechanics; classification of partial differential equations
- Spatial discretisation; finite differences, finite volumes, and finite elements (overview): finite difference methods: method of undetermined coefficients, order of accuracy, convergence; linear vs nonlinear problems
- Implementation of boundary conditions
- Temporal discretisation; explicit/implicit schemes, stability, boundedness
- Numerical solution of advection-diffusion equations; aliasing; numerical parameters: Pe, CFL and Diff criteria

Incompressible Flow

- The finite volume method and its application to the Navier-Stokes equations.
- The pressure-Poisson equation as representative of mass-conservation principle.
- Structured finite-volume framework and finite-volume equations.
- Velocity, scalars and pressure storage: staggered vs. collocated storage.
- Pressure-velocity coupling: pressure-correction strategy, staggered vs. non-staggered storage; pressure-correction algorithm and Rhie & Chow momentum interpolation for collocated storage.
- Basic aspects of unstructured finite-volume framework for complex geometries.
- Numerical implementation of boundary conditions.
- Best practice guidelines, efficiency, accuracy and confidence.

Compressible Flow

- Review of non-linear conservation laws: Systems of conservation laws, Jacobian matrices, linearized equations, conservative and characteristic variables; discontinuities and Rankine-Hugoniot jump conditions, weak solutions and entropy condition, boundary conditions.
- Numerical representation of discontinuities: shock fitting/capturing; conservative discretisation for shock-capturing: Lax-Wendroff theorem, first-order versus second-order schemes, centred and upwind schemes, monotone schemes and Godunov theorem, TVD property, construction of TVD schemes using limiters.

Turbulence

- Overview of alternative theoretical frameworks and methods for the description of turbulence effects in the context of numerical approximation techniques.
- Reynolds-averaged Navier-Stokes models: different model categories; formulation of eddy-viscosity models using one and two transport equations for scalar turbulence properties; principles of second-moment closure and non-linear eddy-viscosity models.; pro's and con's of different categories.
- Simulation of turbulent flows: direct and large eddy simulation; filtering; LES equations; alternative subgrid-scale models; near-wall treatments; boundary conditions; guidelines on do's and don'ts.

Exercises and Tutorials

- For fundamentals: Numerical solution of dispersion equation using FDM.
- For compressible flow: Numerical solution of 1D Euler equations.
- For incompressible flow: Computational modelling of channel flow.

RECOMMENDED TEXT BOOKS

Numerical methods:

- J. Ferziger & M. Peric, Computational Methods for Fluid Mechanics.
- Ch. Hirsch, Numerical Computation of internal and external flows.
- C.B. Laney, Computational Gas Dynamics.

Turbulence:

- M. Leschziner, Statistical turbulence modelling for fluid dynamics – demystified.
- S. Pope, Turbulence (general background reading).

ASSESSMENT

- Examination: 3 hours, 4 mandatory questions, closed book, contribution 60% to the total course mark
- Coursework: 2 individual reports (typically 4-5 pages) on two computational exercises (incompressible and compressible flows), contributing 40% to total course mark.

CORE COURSE 4: EXPERIMENTAL METHODS IN FLUID MECHANICS

COURSE AIMS

The overall aim of the course is to introduce measurement needs in fluid mechanics and the corresponding data processing and measurement techniques for monitoring and control of engineering processes.

LEARNING OUTCOMES

- Describe applications of — and methods for — data acquisition of signals from instruments and sensors and processing of the recorded data, with special reference to Fluid Mechanics applications.
- Devise an appropriate and effective strategy for measuring and processing data;
- Select an appropriate data acquisition device for instrumenting industrial processes;
- Appraise the data yielded by such a strategy.
- Acquire and process data from laboratory experiments using LabVIEW® software

SYLLABUS

Experimental methods and measurements for Fluid Mechanics applications

- introduction to measurement needs in Fluid Mechanics
- measured quantities and physical meaning for turbulent flows.

Data processing

- data sampling of random variables
- probability density function—definition and examples (e.g. Gaussian PDF)
- mean and standard deviation and estimates of statistical uncertainties
- higher moments for the probability density function
- measurement of auto- and covariance
- autocorrelation and cross-correlation functions
- power spectrum
- measurement of power spectrum
- folding and aliasing
- frequency resolution and leakage

Introduction to Experimental methods for Fluid Mechanics

This part of the course will be delivered through the following four laboratory experiments lasting 4 hours each. The first 2 hours of each laboratory will be focused on the associated experimental techniques.

1. **Flow in Wave Tanks (Civil Eng.)**

Related techniques: Laser Doppler Anemometry and probe for wave propagation measurements

The first experiment of the series will consider the propagation of surface gravity waves. This session will be divided into three parts, incorporating:

i. A demonstration of surface wave effects.
ii. Hands-on experience of collecting and analysing surface wave data.
iii. Calculations appropriate to the real-time control of a wave maker.

The initial demonstration (i) will seek to build upon the earlier lectures on waves, highlighting the role of nonlinearity, unsteadiness and directional spreading; allowing the students to see fundamental properties such as group velocity, wave modulation, and the onset of wave breaking. Part (ii) will involve the design and conduct of an experiment appropriate to the analysis of surface wave properties. This will serve as an introduction to design spectra, crest height and wave height distributions, and the concept of a deterministic 'designer' wave. Finally, part (iii) will involve the analysis of generated wave data, allowing the students to explore the linear control of a wave maker, the occurrence of evanescent wave modes and the difficulties presented by freely propagating spurious wave components, including their relation to the nonlinear free surface boundary conditions. This latter part introduces theoretical aspects appropriate to the design of wave energy convertors. The experiment will be undertaken in the Hydrodynamics Laboratory within the Department of Civil Engineering and will involve the use of several wave facilities including our three-dimensional wave basin.

2. **Flow in the wake of a cylinder (Mech. Eng.)**

Related techniques: Hot Wire Anemometry and Pitot probe

The purpose of the experiment is to quantify the influence of the presence of a cylinder placed normal to the incoming air flow in a wind tunnel and assess the flow characteristics and the frequency of vortex shedding in its wake. The main objectives are as follows:

obtain velocity measurements with a hot-wire anemometer using the developed software based on LABVIEW;

quantify the flow characteristics by appropriately processing the velocity samples using the developed data processing software based on LABVIEW;

demonstrate the physical understanding that can be obtained by the measured flow parameters.

The experiment will be performed in the wind tunnel of the Thermofluids Teaching Laboratory in Mechanical Engineering Dept.

3. **Flow in Compliant Vessels (Bioeng.)**

Related techniques: Particle Image Velocimetry

Focus will be on the design of an appropriate experiment for a chosen physiologic application. Students will decide on a vessel in the body they wish to explore, investigate a particular disease state and how fluid mechanics might play a role in its formation, progression, or treatment. Possible vessels to study include blood vessels, airways, lymphatic vessels, and cerebro-spinal fluid passageways. They will then decide which parameters to include in their model (geometry, unsteadiness, wall viscoelastic properties, non-Newtonian fluid behaviour, upstream/downstream boundary conditions, etc., based on their expected importance in answering the core physiological/medical question. Then, to the degree feasible, they will construct a realistic transparent model of their chosen vessel and perform DPIV to visualise, measure, and estimate relevant flow patterns. The experiment will be hosted in the Bioengineering Dept.

4. **Compressible Flows (Aero)**

Related techniques: Schlieren and pressure transducers

The experiment consists of simultaneous flow visualisation and point pressure measurements in an unsteady shock wave – boundary layer interaction flow in a Mach 2, blow-down configuration supersonic wind tunnel. The technique of Schlieren photography will be implemented, which is sensitive to density gradients within a flow, in order to visualise the large-scale fluctuation of a lambda-shock pattern induced by a compression ramp in a Mach 2 flow. Images will be acquired at frequencies (2 kHz) that are sufficiently high to track the low frequency dynamics of the shock motion but not capture the small-scale, high frequency jitter of the shock pattern. Thus a linear array of high frequency response, wall mounted pressure transducers will be deployed concurrently to the Schlieren imagery in order to capture the high frequency dynamics of the interaction. The assessed coursework will thus seek to use the information from both the Schlieren imagery and wall pressure signals to characterise the spectral content of this complex interaction. The final assessed experiment of the course is hosted in the Department of Aeronautics.

ASSESSMENT

Final exam: Open Book Examination – 2 hours

Coursework: Submission of project reports for each of the four laboratory experiments, which will contribute each 15% of the final mark.

Final Mark: 40% Exam + 60% coursework

The coursework will be based on Laboratory experiments. Two training courses are required and will be provided during the first week of the course, as follows:

- Introduction to LabVIEW® graphical programming: Introduction to LabVIEW® programming. Delivered by National Instruments at the first week of the course over 4 hours.
- Introduction to laboratory and laser safety: These will be delivered at the first week of the course. Tests at the end of the safety course have to be successful.

Coursework reports: Each laboratory experiment will involve using and developing computer programs, based on LabVIEW® software, to acquire data and subsequently process them as required for each experiment. A report together with the program will be submitted for each laboratory.

RECOMMENDED TEXT BOOKS

- J. K. Eaton and L. Eaton, LabTutor — A friendly guide to computer interfacing and LabVIEW® programming.
  (This book will be bought by the CDT and given to students. The students will return it at the end of the course.)
- P. Bradshaw, An introduction to Turbulence and its measurement, Pergamon Press.
- H. Tennekes and J. L. Lumley, A first course in turbulence, MIT Press.

CORE COURSE 5: APPLICATION ACROSS THEMES

COURSE AIM AND OVERALL DESCRIPTION

The aim of this project-based *integrating* module is to strengthen problem solving and mathematical modelling skills. Projects will build on techniques taught in the other four core modules and will expose students to fields they are not acquainted with. The course has a strong focus on problem-based learning and makes use of peer-assessment. The course aims to prepare students for real-world applications, which often require a combination of theoretical underpinnings and/or more than one practical approach.

LEARNING OUTCOMES

- An understanding of how to apply generic problem solving skills to widely different problems
- An understanding on how to use mathematical modelling to strip problems to their essentials
- A broad appreciation of applications of fluid mechanics across the disciplines
- Enhanced team-working, report-writing and presentation skills

SYLLABUS

Introduction

1. *The power of back-of-the-envelope calculations*. Dimensional analysis; Buckingham Π-theorem; dealing with multiple time/length-scales; dimensionless quantities in governing equations
2. *Deconstructing complex problems*. Using dimensional arguments to retain only the essentials of a problem; conceptual models
3. *The big picture: choosing your approach*. How do you choose between theoretical vs numerical vs experimental approaches depending on the research question? How do you select the best aspect of a problem to focus on? Trade-offs between methods.

Small-group projects

Teams of 2-3 students will work under the supervision of a mentor who, through regular meetings, will guide their thinking and practical work, making sure that they do not stray too far from workable solutions. Teams will work on two projects and will have two hours of contact time per week with their supervisor.

ASSESSMENT

The teams will write two project reports (2x35% of mark). Each project is concluded by a 20 minute presentation followed by a 10 minute discussion (2x10% of mark). Peer-assessment will be used: each team reads and assesses the other project reports. The quality of the assessment (fairness, constructive, effort) counts as 2x5% of the mark. The peer-assessed marks will be combined with the supervisor’s marks to establish a final score.

RECOMMENDED TEXT BOOKS

- Mathematical Models in the Applied Sciences. A. C. Fowler, Cambridge University Press.