

# Imperial College London

## Department of Aeronautics

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## Undergraduate Syllabuses\_2005-06

This publication refers to the session 2005-06. The information given, including that relating to the availability of courses, is that current at the time of going to press, October 2005, and is subject to alteration.

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# Aeronautics

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Courses of study in aeronautics lead to the four-year undergraduate degrees of MEng, MEng with a Year in Europe and MEng with a Year in North America and the postgraduate degrees of MSc (one year full-time or two years part-time), MPhil and PhD.

Full details of the normal requirements for admission are given in the *Undergraduate Prospectus* online at [www.imperial.ac.uk/P2729.htm#4](http://www.imperial.ac.uk/P2729.htm#4). Students who have successfully completed appropriate parts of equivalent degree courses elsewhere may be considered for direct entry to the second year of one of the undergraduate courses. Imperial College also welcomes exchange students from other European countries, under the Socrates-ERASMUS scheme, who wish to take the third year of the standard Aeronautics MEng degree course or the fourth year of the Year in Europe course.

The laboratories offer extensive facilities both for teaching and research, including a large number of wind tunnels and a range of structural test equipment. Computing facilities, available to both undergraduate and postgraduate students, include an extensive network of Silicon Graphics workstations and numerous PCs.

A library housing a wide selection of works on aeronautical and related subjects, including reports and periodicals issued by the major aeronautical research laboratories and agencies worldwide is also available to aeronautics students.

Details of postgraduate opportunities can be found in the *Postgraduate Prospectus* online at [www.imperial.ac.uk/pgprospectus](http://www.imperial.ac.uk/pgprospectus)

## Undergraduate courses

Initially all undergraduate students follow either the standard MEng course or the Year in Europe course. Transfer to the Year in North America course could be possible for only one or two students from either of these courses at the end of the second year, subject to availability of places. The syllabuses for the first two years of the undergraduate courses are identical except that for the students taking the Year in Europe course a satisfactory standard in the appropriate language must be achieved, so language studies will usually be compulsory. In the third year those following the standard MEng course will continue studying at Imperial College. For the students taking the Year in Europe or Year in North America course the third year will consist of an agreed programme of study at an approved university in their chosen country. Exchange agreements have been reached with RWTH, Aachen, Ecole Centrale de Lyon, ENSICA and ENSAE, Toulouse, and Massachusetts Institute of Technology (MIT), Boston. All students then return to Imperial for the fourth year of the course. The students on the standard MEng course attend for the first part of this year and then embark on a project for the remaining four months in an industrial organisation or research institution either in the UK (which may include Imperial College) or abroad. For the students returning to Imperial from their year in Europe or North America the final year consists of lectures, coursework and an individual project which is undertaken at Imperial.

In support of formal lectures, an extensive system of subject tutorials and laboratory work is provided in all four years. Engineering applications and design are strong features of the degree courses. In the third year students on the standard MEng course take part in large group design projects, typically the preliminary design of a future aircraft. In the second year all students undertake a design, make and test exercise in groups, which involves a manufacturing phase, during which experience in the use of modern machine tools is gained. A more modest exercise is carried out in-house in the first year.

**FIRST YEAR****MEng and MEng with a Year in Europe**

|   |   | <b>Hours</b> |
|---|---|--------------|
| A.101                                     | Introduction to aerodynamics                | 20           |
| A.102                                     | Aircraft performance                        | 10           |
| A.103                                     | Computing                                   | 20           |
| A.104                                     | Engineering design                          | 20           |
| A.105                                     | Introduction to management* or<br>Languages | 20<br>75     |
| A.106                                     | Properties of materials                     | 25           |
| A.107                                     | Mathematics                                 | 50           |
| A.108                                     | Foundation mechanics                        | 10           |
| A.109                                     | Mechanics                                   | 20           |
| A.110                                     | Introduction to structural analysis         | 20           |
| A.111                                     | Thermodynamics                              | 25           |
| Unexamined: Aeronautical general lectures |   | 11           |

The lectures are supported by personal and subject tutorials. Subject tutorials are generally held in groups of 12 students, at the rate of one tutorial for every four lectures. Coursework consists of laboratory work in aerodynamics, structures and materials; a design, make and test exercise in structures; and a computing applications exercise.

**SECOND YEAR****MEng and MEng with a Year in Europe**

|       |                                      | <b>Hours</b>  |
|-------|--------------------------------------|---------------|
| A.201 | Aerodynamics                         | 30            |
| A.202 | Computing and numerical analysis     | 13            |
| A.203 | Manufacturing processes              | 15            |
| A.204 | Managerial economics or<br>Languages | 22<br>63/75** |
| A.205 | Signals and systems                  | 30            |
| A.208 | Materials                            | 25            |
| A.209 | Mathematics and statistics           | 45            |
| A.211 | Mechanics of flight                  | 20            |
| A.212 | Propulsion and turbomachinery        | 20            |
| A.213 | Structural mechanics and dynamics    | 30            |

The lectures are again supported by subject tutorials held at the rate of one tutorial for every four lectures. Coursework consists of laboratory work in aerodynamics, electrical engineering, materials and structures; further computing exercises; and an extensive design, make and test exercise, involving the use of machine tools, carried out during the autumn and spring terms.

In the second year, students may attend a short flight testing course held at the Cranfield Institute of Technology.

\* All students are required to take at least one management subject during their degree course. Compulsory for students following the standard MEng course.

\*\* Higher figure applies to the Year in Europe course.

**THIRD YEAR****MEng**

| <b>Compulsory subjects</b>                    |                                | <b>Hours</b> |
|---|--------------------------------|--------------|
| A.301   | Aircraft aerodynamics          | 30           |
| A.302   | Control systems                | 20           |
| A.304   | Aircraft structures            | 30           |
| A.3/403                                       | Aerospace vehicle design       | 20           |
| A.3/406                                       | Airframe design                | 15           |
| A.303   | Finite elements                | 20           |
| <b>Optional subjects (three to be chosen)</b> |                                |              |
| A.3/401                                       | Advanced mechanics of flight   | 20           |
| A.3/402                                       | Advanced turbomachinery        | 20           |
| A.3/405                                       | Aircraft systems engineering   | 20           |
| A.3/408                                       | Materials in action            | 20           |
| A.3/409                                       | Materials modelling            | 20           |
| A.3/410                                       | Mathematics                    | 20           |
| A.3/413                                       | Helicopter dynamics            | 20           |
| A.3/414                                       | Computational fluid dynamics   | 20           |
| A.3/4xx                                       | Project management or          | 22           |
|   | Languages or                   | 63           |
|   | Non-language Humanities course | 22           |

The lectures are normally supported by subject tutorial or example classes at the rate of one for every four lectures. The major element of the coursework taken in the third year is a large group design project. Other coursework includes laboratory work related to the lecture courses taken; an applications exercise in composite materials; and assessment exercises for the lecture courses in aerospace vehicle design and airframe design.

**MEng with a Year in Europe/North America**

The third year will be spent at an approved university in the chosen country. The syllabus followed in this year will be broadly similar to that of the standard MEng course listed above.

**FOURTH YEAR****MEng**

| <b>Compulsory subjects</b>                   |                                | <b>Hours</b> |
|--|--------------------------------|--------------|
| A.403  | Structural dynamics            | 20           |
| A.404  | Wing design                    | 20           |
| <b>Optional subjects (four to be chosen)</b> |                                |              |
| A.401  | Applications of fluid dynamics | 20           |
| A.3/401                                      | Advanced mechanics of flight   | 20           |
| A.3/408                                      | Materials in action            | 20           |
| A.3/409                                      | Materials modelling            | 20           |
| A.3/413                                      | Helicopter dynamics            | 20           |
| A.3/414                                      | Computational fluid dynamics   | 20           |
|  | Languages                      | 30           |

All lecture courses are supported by tutorials or example classes and are completed during the autumn term. The examinations are held at the start of the spring term. A four-month project is then undertaken in industry or a research institute, either in the UK or abroad. Students may also remain at Imperial College for their final project.

## FOURTH YEAR

### MEng with a Year in Europe/North America

| <b>Compulsory subjects</b> |                          | <b>Hours</b> |
|----------------------------|--------------------------|--------------|
| A.403                      | Structural dynamics      | 20           |
| A.404                      | Wing design              | 20           |
| A.3/403                    | Aerospace vehicle design | 20           |
| A.3/406                    | Airframe design          | 15           |

#### **Optional subjects (six to be chosen)**

|         |                                |    |
|---------|--------------------------------|----|
| A.302   | Control systems                | 20 |
| A.401   | Applications of fluid dynamics | 20 |
| A.3/401 | Advanced mechanics of flight   |    |
| A.3/402 | Advanced turbomachinery        | 20 |
| A.3/405 | Aircraft systems engineering   | 20 |
| A.3/408 | Materials in action            | 20 |
| A.3/409 | Materials modelling            | 20 |
| A.3/410 | Mathematics                    | 20 |
| A.3/413 | Helicopter dynamics            | 20 |
| A.3/414 | Computational fluid dynamics   | 20 |
| A.4xx   | Introduction to management or  | 20 |
| A.3/4xx | Project management or          | 22 |
|         | Languages or                   | 63 |
|         | Non-language Humanities course | 22 |

In general the lecture courses are supported by tutorial or example classes at the rate of one for every four lectures. The major element of the coursework taken this year is the individual project which is undertaken at Imperial College. Other coursework includes laboratory work related to the lecture courses taken; an applications exercise in composite materials; and assessment exercises for the lecture courses in aerospace vehicle design and airframe design.

## Syllabuses

### FIRST YEAR

#### **A.101 Introduction to aerodynamics**

DR S.J. SHERWIN

*Principles of fluid flow:* stress, rate of strain, viscosity, normal and shear stress.

*Flow over an aerofoil:* lift, boundary layer stall.

*The atmosphere:* properties of the atmosphere.

*Measurement techniques:* measurement of static and total pressure.

*Dimensional analysis:* dimensionless coefficients, similarity parameters, Buckingham's rule, Mach number and Reynolds number.

*Conservation of mass:* control volume analysis, conservation of mass in a compressible flow, incompressible flow, streamlines and stream function.

*Rotation of a fluid element:* vorticity, irrotational flow and Laplace's equation.

*Potential flow:* singularities and simple shapes, source and sink, uniform flow past a source, Rankine oval, uniform flow past a doublet, ideal flow around a circular cylinder, the ideal vortex.

*Conservation of momentum:* Newton's second law, Euler equations, Bernoulli's equation, force on a nozzle.

*Viscous stresses:* skin friction, two-dimensional laminar boundary layer, boundary layer development, flat plate boundary layer, effect of pressure gradient, separation.

*Internal flow:* laminar flow in a two-dimensional duct, laminar flow in a circular cross-section pipe.

*Turbulent flow:* transition, turbulence, turbulent pipe flow.

*Wings:* brief introduction to flow around wings, trailing vortices.

### **A.102 Aircraft performance**

DR R.E. BROWN

The standard atmosphere; true and equivalent airspeed; engine performance as affected by altitude; profile and induced drag; the parabolic drag polar; dimensionless presentation; equations of motion in a vertical plane; steady and quasi-steady flight in a vertical plane; maximum speed and the effect of altitude; the ceiling; aircraft range in level and quasi-level flight and the effect of altitude; design factors affecting optimisation; climbing flight, optimisation and energy considerations; turning flight in a horizontal plane.

### **A.103 Computing**

DR L.D.C. FOULKES

*Introduction to the Linux and Windows operating systems.* Files and directories. The Linux shell. Linux basic commands, utilities, editors and web browsers.

*Introduction to programming and Fortran.* Programming style and techniques. Basic elements of a program. Syntax and keywords. Data types. Assignment statements. Intrinsic functions.

*Flow control.* If structures. CASE statements. Program flow optimisation. Loops and nested loops, EXIT statement. While constructs.

*Introduction to subprograms.* Subroutines and functions. Formal, dummy and local variables. Modules as an aid to program design.

*Formatted input and output.* Formatted and unformatted records. Using external files.

One-dimensional arrays. Dimensioning one-dimensional arrays. Arrays in subroutines and functions.

Implied DO loops. Array access; argument and parameter passing. Input and output of one-dimensional arrays.

*Introduction to two-dimensional arrays.* Manipulation of arrays. Dynamic array allocation. Intrinsic functions for arrays. Sub-arrays using Fortran constructs. Input and output of two-dimensional arrays.

*Review of matrices.* Matrices and index notation. Two-dimensional arrays and matrices. Applications.

*Introduction to MATLAB.* MATLAB windows. Online help. Commands and basic functions. Variables and the workspace. Working with files and directories.

*MATLAB fundamentals.* Introduction to MATLAB matrices and vectors. Operators and statements. Output. Loops and decisions. Elementary maths functions. Plotting simple graphs.

*Programming in MATLAB.* Matrices and matrix operations. M-files: script and function files. Executing a function. Interactive input. Multidimensional matrices. More graphical output. Saving and printing graphs.

*Applications in MATLAB.* Numerical methods using MATLAB. Solving roots of equations.

*Introduction to Numerical Methods using FORTRAN.* Ordinary differential equations. Numerical integration. Solving a linear system of equations: iterative and direct methods.

### **A.104 Engineering design**

DR L. IANNUCCI

*Drawing:* axonometric, isometric and oblique views; first and third angle orthographic projection including true length, true shape, sectioning, development and elementary lofting; standard international symbols, abbreviations, limits, fits and dimensioning.

*Design:* an awareness of basic design of basic aircraft parts and simple sub-assemblies; beams, columns, ties and shafts: bearings, couplings seals: hinges, joints, keys, splines and valves; simple mechanical/hydraulic/electric linear and rotary drives and actuators.

*CAD:* general overview of concepts in computer-aided design systems, initial knowledge and skills for operation of commercial CAD systems. Practical sessions designed to provide sufficient background for students to be able to implement the concepts in the drawing and design sections of the course.

### **A.105 Introduction to management**

DR J. SHELDRAKE

*Introduction to the course:* aims, objectives and learning outcomes of the course. Introduction to course themes. Origins and development of modern management.

*Managerial control:* ways in which management seek to maintain control over organisations and the individuals within them. Influence of scientific management. Technology and control.

*Organisational structures and design:* significance of structure. Bureaucracy and its impact. Current trends—the flexible firm; McDonaldisation.

*Job design:* how should work be allocated? Current issues in the management and organisation of work. Groups and teams.

*Motivation:* Management and motivation. How can managers motivate their workers? An introduction to motivation theory. The implications for organisational effectiveness.

*Strategy and marketing:* how should management identify strategy options? How do organisations respond to changing circumstances? How do organisations market products?

*Leadership and decision-making:* are effective leaders born or created? How are the necessary skills to lead and manage workers obtained?

*Organisational culture and its impacts:* the influence of national culture. What is meant by organisational culture? Can we identify different patterns of organisational culture? Does culture make a difference to organisational performance?

*Managers and values:* health and safety, business ethics and social responsibility. What are the key responsibilities of management in these areas?

*Organisational change and development:* how can managers influence change in organisations? Contemporary ideas and trends. Revision and course review.

### **A.106 Properties of materials**

DR J. MINAY

*Bonding and atomic arrangement:* different types of bonding in materials, effect of type of bonding on material properties and atomic arrangements. Crystal structures in metals, ceramics and polymers. Crystal defects and mechanisms of crystal deformation.

*Mechanical properties:* commonly measured and quoted properties including stiffness, strength, ductility, hardness, toughness, impact strength, fracture, fatigue and creep. Methods of controlling and changing these properties.

*Microstructure:* different microstructural features and their effects on mechanical properties. Phase diagrams and TTT curves are used to describe transformations occurring in the microstructure. Annealing phenomena.

Materials discussed in greater detail include, carbon steel, Al-Cu alloys, fibre-polymer composites and engineering ceramics.

### **A.107 Mathematics**

DR S. LUZZATTO, PROFESSOR A. SKOROBOGATOV

*Analysis:* functions of one variable—odd, even, inverse functions. Limits—continuous and discontinuous functions. Differentiation—continuity and differentiability; implicit and logarithmic differentiation; Leibniz's formula; stationary points and points of inflection; curve sketching; polar coordinates. Mean value theorem; Taylor's and Maclaurin's series; l'Hôpital's rule. Convergence of power series; ratio test; radius of convergence.

*Complex numbers:* the complex plane; polar representation; de Moivre's theorem;  $\ln z$  and  $\exp(z)$ . Hyperbolic functions: inverse functions; series expansions; relations between hyperbolic and trigonometric functions.

*Integration:* definite and indefinite integrals; the fundamental theorem; improper integrals; integration by substitution and by parts; partial fractions; applications.

*Functions of more than one variable:* partial differentiation; total differentials; change of variable; Taylor's theorem for a function of two variables; stationary points; contours

*Linear algebra*: vector algebra—basic rules; Cartesian coordinates; scalar and vector products; applications to geometry; equations of lines and planes; triple products; linear dependence. Matrix algebra—double suffix notation; basic rules; transpose, symmetric, diagonal, unit, triangular, inverse and orthogonal matrices. Determinants—basic properties; Cramer's rule. Linear algebraic equations: consistency; linear dependence; Gauss-Jordan method; Gaussian elimination; LU factorisation. *Ordinary differential equations*: first order equations: separable, homogeneous, exact, linear. Second order linear equations with constant coefficients. Laplace transforms: definition and basic properties. Application to solving ordinary differential equations.

### **A.108 Foundation mechanics**

DR U. GALVANETTO, DR P. ROBINSON, DR I.C. MATTHEWS

*Newtonian mechanics*: historical perspective.

*Idealisations*: rigid body, particle, deformable body, fluid, point force.

*SI units*: basic dimensions: mass, length, time, dimensional standards, symbols.

*Scalars and vectors*: law of vector addition, identify scalar and vector quantities in mechanics.

*Resolution of forces*: parallelogram and triangle laws, force resultant.

*Fundamental laws*: Newton's three laws, law of gravitation.

*Equilibrium of a particle in two dimensions and three dimensions*: free body diagram.

*Equilibrium of a rigid body in two dimensions*: moment of a force, free body diagram, translation of a force.

*Distributed forces in two dimensions*: centre of gravity of a two-dimensional body, centre of area.

*Moments of inertia*: parallel axes and orthogonal axes theorems, second moment of area.

### **A.109 Mechanics**

DR B. FALZON, DR E.S. GREENHALGH

*Review of vectors*: unit vectors, position, displacement, velocity, acceleration vectors.

*Vector products*: scalar and vector products in mechanics: force component, work done, moment of a force, velocity due to angular rotation.

*Statics*: equivalent force systems, translation of a force, the wrench, three-dimensional statics.

*Friction*: Coulomb friction, laws, applications examples, e.g. belt friction.

*Variational mechanics*: definition of a conservative force, work done and potential energy. Equilibrium and stability of equilibrium.

*Kinematics*: motion in a straight line, graphical integration of acceleration/time record. Cylindrical polar coordinates. Coriolis acceleration.

*Particle dynamics*: integration of Newton's equation for rectilinear motion where the force is a constant, a function of velocity or a function of position.

*Mechanical vibrations of single degree of freedom systems*: free, damped and forced vibration.

*Energy methods*: conservation of energy, kinetic energy of a rigid body.

*Momentum methods*: conservation of momentum, impact, angular momentum.

*Orbital mechanics*: central force motion, areal velocity, trajectory equation, circular, elliptic and escape trajectories, eccentricity from launch conditions, conservation of energy.

### **A.110 Introduction to structural analysis**

DR U. GALVANETTO, DR P. ROBINSON

*Introduction*: structural analysis as part of the design process.

*Stress/strain*: definition and convention for all stress components in three dimensions. Definition of strain, thermal strain. Stress/strain law, Young's modulus, shear modulus, bulk modulus, Poisson's ratio.

*Pin-jointed frameworks*: statically determinate: forces and displacements. The unit load method.

*Redundant framework*: solution in terms of joint displacements.

*Engineers theory of beams*: assumptions, strain/curvature and stress/moment relationships.

*Shear force and bending moment diagrams*.

*Direct solution of deflections from curvature*.

*Displacement by unit load method*.

*Statically indeterminate beams*.

*Torsion of circular section beams*.

### A.111 Thermodynamics

DR D. DOORLY

*Introduction and basic definitions:* continuum state, pure substance, special case of a perfect gas, system, control volume, properties, state of a system, cycle, units and dimensions.

*First law of thermodynamics:* heat, work, energy and specific heats, continuity or mass conservation, first law: system and control volume formulations.

*Reversibility—the second law of thermodynamics and entropy:* cyclic heat power plants, reversible processes, second law of thermodynamics, the Clausius inequality and entropy, principle of increase of entropy, reversible heat engines.

*Compressible flow (gas dynamics):* adiabatic, isentropic definitions, speed of sound, Mach number, steady, inviscid flow of a perfect gas, steady one-dimensional nozzle flow, the normal shock wave, further non-isentropic flows.

*Adiabatic processes:* isentropic efficiency: isentropic efficiencies of turbine, propelling nozzle, compressor and diffuser. Adiabatic motion along a streamtube.

*Air standard power producing cycles:* steady flow, the ideal Joule-Brayton cycle, performance of reversible Joule-Brayton cycle, Joule-Brayton cycle with irreversibilities, use of heat exchangers to improve efficiency, aircraft propulsion, open cycle turbo jet, open cycles for reciprocating IC engines, basic environmental considerations for gas turbine and IC engines used for propulsion and power generation.

*Heat transfer:* conduction: introduction, applications and basic numerical solution methods. Radiation, convection, combined modes of heat transfer.

## SECOND YEAR

### A.201 Aerodynamics

PROFESSOR R. HILLIER

*Fundamentals:* basic definitions; dimensionless parameters; Buckingham's theorem; inviscid/viscous/compressible definitions; steady/unsteady flow; partial derivatives and total derivatives; Cartesian and polar axis systems; vorticity and circulation; concept of rate of strain; angular velocity and vorticity, rotational and irrotational motion, creation of vorticity, circulation, free and forced vortex, Rankine vortex; equations of motion for inviscid compressible/incompressible flow; equations of motion for steady streamline motion; Bernoulli equation; normal pressure gradient; relation between vorticity and gradient of total pressure.

*Stream function and velocity potential:* stream function; solution to continuity equation; relation to velocity components in Cartesian and polar coordinates; Laplace equation for irrotational motion; velocity potential; Laplace equation; intermediate summary; what equations are there and when can they be used? some solutions for irrotational flow; stream function and velocity potential for uniform stream at incidence, source/sink, free vortex; superposition of solutions and the linear Laplace equation; generation of closed bodies by source/sink combinations; vortex in free stream; control volume analysis for vortex held in a stream and Joukowski lift theorem; symmetrical inviscid flow past a circular cylinder; the nature of real viscous flows past bluff bodies; the theoretical value of the basic potential solution; circulation and the flow past a cylinder with lift.

*The complex potential:* complex potential; complex coordinates and complex velocity; basic solutions using complex potential; uniform stream, source/sink, vortex, circular cylinder with circulation and incidence; conformal transformation; circle to ellipse and flat plate; relation between values in circle plane and transformed plane; flow past ellipse at zero incidence; flow past ellipse at incidence; control of circulation/lift by specifying rear stagnation point; the Kutta condition; physical explanation; the relevance to aerofoils; lift of a flat plate; lift on a real flat plate and the need for finite leading edge radius; pressure distribution on the flat plate; the explanation for zero drag in two-dimensional inviscid flow; other useful solutions; Camber, thickness and the Joukowski aerofoil; Blasius force theorem; image reflection at walls.

*Lifting wings:* two-dimensional aerofoils; typical pressure distributions, the effect of boundary layers, pressure and skin friction drag; stalling and stall classification, thin aerofoil, leading edge and trailing edge; reference to texts on aerofoil sections and data; three-dimensional wings; aspect ratio;

bound and trailing vortices; lift induced drag and induced downwash; velocity induced by a vortex filament; Biot Savart law; finite length straight vortex filament; high aspect ratio wings; lifting line theory; elliptic lift distribution for minimum induced drag; horseshoe vortex theory; problems where it is of value: formation flight, downwash on tail surface, wind tunnel interference.

*Introduction to compressible flow:* speed of sound, Mach number, subsonic and supersonic flow; propagation of weak waves; Mach waves and Mach cones; basic physical differences between two-dimensional subsonic and supersonic aerofoils; one-dimensional flow, nozzle flow; reminder of Aero 1; continuity, momentum and energy equations; convergent-divergent nozzles, choking; the appearance of shock waves; normal shock waves; control volume formulation; specialisation to ideal gases; the entropy condition and the jump conditions; stationary and moving shock waves; supersonic wind tunnel; diffusers, the need for a second throat, the critical starting condition.

*Two-dimensional compressible flow:* the oblique shock wave; flows with oblique shock waves; sharp wedge, attached and detached shock waves; reflection at a wall, regular and Mach reflection; very weak shock waves; Ackeret theory; lift and drag according to two-dimensional supersonic linear theory; effects of incidence, thickness and camber; wave drag; wave interactions using linear theory; finite strength isentropic waves; the Prandtl-Meyer function; isentropic turning; supersonic aerofoils. Shock expansion theory; aerofoils in subsonic flow; flow fields typical of subcritical and supercritical flow; statement of the Prandtl-Glauert results.

*Viscous flows and boundary layers:* introduction; no slip condition; rates of strain and viscous stresses; the boundary layer concept; comment on difference between laminar and turbulent flow; comment on transition and simple criteria; diffusion of vorticity; statement of the Blasius result for zpg laminar boundary layer; the Navier Stokes equations for two-dimensional laminar motion; the laminar boundary layer equations; relative order of magnitude of terms in NS equations; boundary layer profiles for zpg, adverse pg and favourable pg; constancy of static pressure through the boundary layer; solutions of the laminar boundary layer equations; polynomial representation; example of bl on verge of separation; momentum integral equation; definition of displacement and momentum thicknesses; the momentum integral equation.

### **A.202 Computing and numerical analysis**

DR J. PEIRO

*Brief introduction:* convergence, stability, accuracy. Computer arithmetic—how numbers are manipulated and stored in a computer, exponent and mantissa, etc.

*Root finding of non-linear equations:* bisection method, Newton-Raphson method in one dimension, secant method in one dimension and Newton's method in multidimensions.

*Numerical solution of ordinary differential equations (ODEs):* classification—initial-value problems (IVP) and boundary value problems (BVP). Numerical solution of IVP—Taylor series and Runge-Kutta methods, accuracy, convergence and stability analysis. Numerical solution of BVP—shooting method and approximation by finite differences (FD). Application of the method of FD to linear and non-linear BVP.

*Introduction to finite differences for partial differential equations (PDEs):* types of equations, upwinding for hyperbolic equations.

*Interpolation:* Lagrangian polynomials, Runge phenomenon. Spline interpolation.

*Integration:* introduction to general methods of numerical integration (Gauss method). Numerical integration of functions with singularities.

### **A.203 Manufacturing processes**

DR J. HODGKINSON

*Fabrication processes:* sheet metals: bending, pressing, drawing, spinning, stretch-forming, etc., material limitations and tolerances; super-plastic forming and diffusion bonding; chemical etching; extrusions; forging and casting methods; integral machining; numerical control of machining, riveting, etc.

*Joining methods:* welding, tungsten, inert gas, electron beam, laser; adhesive bonding surface pre-treatment, autoclave techniques, adhesive behaviour; relative cost of various processes and dependence on component size.

Non-destructive testing, monitoring, inspection and repair methods for metals and composites in service. Extensive use will be made of films to illustrate the above.

*Fibre composites*: typical properties; hand lay-up and automated techniques for flat and cylindrical components; laser and water-jet cutting; moulding techniques (open and closed mould); specific methods used by British Aerospace, Rolls Royce and Westland. Applications; reasons for selecting composites.

### **A.204 Managerial economics**

DR T. VALLETTI

The basics of supply and demand. Consumer choice. Market demand and elasticity. Production relationships and cost analysis. Profit maximisation. Perfect competition and social welfare. Monopoly. Price discrimination. Oligopoly and game theory. Investments and the net present value.

### **A.205 Signals and systems**

DR K.G. WOODGATE

*Fundamentals of steady state circuit theory*: potential difference, voltage, current and resistance: Ohm's law. Ideal circuit components: voltage and current sources. Equivalent circuits: theorems of Thevenin and Norton. Network analysis: Kirchoff's laws, mesh and nodal analysis.

*Amplifier circuits*: ideal operational amplifiers: basic feedback configuration. Non-inverting, summing and difference amplifiers. Real amplifiers: input/output impedance, parasitics, effect of feedback. Basic transistor amplifiers: common collector, common emitter and differential pair. Transistor switches.

*Analogue computing*: Op. Amp. Integrators, block diagrams, dynamical system simulation. Diode rectification and basic switching circuit: realisation of piecewise linear systems.

*Time domain analysis of circuit transient response*: response of resistor-inductor-capacitor (RLC) circuits to switched inputs. Transient response to switched inputs via solution of ODEs.

*Laplace transforms and transfer functions*: use of Laplace transform to solve circuit ODEs. Concept of transfer function: free and forced response of RLC circuits.

*Introduction to feedback control*: use of feedback to stabilise a simple system, stability, system response, steady state response.

*Frequency domain analysis*: response to sinusoidal inputs and phasor representation of sinusoids. Bode diagrams and the link with transfer functions and control systems.

*Electrical power*: basic electromagnetic field theory. Transformers, DC motors, induction, single-phase and multi-phase AC motors.

*Digital circuits I—combinational or memoryless logic circuits*: the two-state (binary) system, logic functions and truth tables. Fundamentals of Boolean algebra: De Morgan's laws, Karnaugh maps. Analysis and synthesis of simple logic functions.

*Digital computing I—arithmetic*: non-decimal (binary) number systems. Half-adder circuit, concept of carry digit and full-adder. Subtraction.

*Digital circuits II—sequential or dynamic logic circuits*: bistables and master-slave flip flops.

*Digital computing II—counting and timing*: shift registers, synchronous and asynchronous counters, timing circuits.

### **A.208 Materials**

DR J. MINAY, DR M. JACKSON

*Materials properties and selection for aircraft structures*: survey of available materials and properties, availability, fabricability. Basic mechanical requirements and materials selection. Materials selection maps.

*High strength steels*: steels for shafts, gears and undercarriages. Types, heat treatment and properties.

*Aluminium alloys*: wrought aluminium alloys. 2xxx and 7xxx series and Li containing alloys, heat treatment and properties.

*Titanium alloys*: types, properties and applications.

*Emergent materials*: metal matrix composites and hybrid laminates, types, properties and applications.

*Yield criteria and stress-strain behaviour*: yield criteria, work hardening, necking and superplasticity; effects of temperature and strain rate. Reversed plasticity, shakedown and low cycle fatigue.

*Fatigue*: mechanism of fatigue failure, crack initiation and growth. S-N curves, effect of mean stress, stress concentration, stress rate, cumulative damage.

*Fracture*: introduction to linear elastic fracture mechanics, application to Paris law of fatigue crack growth rate, fracture toughness in plain strain and plain stress.

*Creep*: nature of creep deformation and fracture, relation between stress, creep rate and temperature, correlation of creep data by Larson-Miller parameter.

*Oxidation and corrosion*: electrochemical principles of oxidation and corrosion, anode and cathode reactions. Corrosion in metals and alloys, localised corrosion, stress corrosion and hydrogen embrittlement.

### **A.209 Mathematics and statistics**

PROFESSOR J.D. GIBBON, DR R. JACOBS, DR N. ADAMS

*Vector calculus*: double integrals; inversion of order of integration; mappings, Jacobian; change of variable. Line integrals in plane and Green's theorem. Vector operators; grad, div and curl. Existence of a potential function. Surface and volume integrals; Gauss and Stoke's theorems.

*Linear algebra*: eigenvalues and eigenvectors; linear independence of eigenvectors; diagonalisation; powers of a matrix; Cayley-Hamilton theorem for distinct eigenvalues case; power method. Iterative methods for solving  $Ax = b$ ; Gauss Seidel method; brief discussion of modern iterative methods; proof of spectral radius criterion.

*Ordinary differential equations (ODEs)*: system of ODEs with constant coefficients; matrix from leading to eigenvalue problem.

*Fourier series*: periodic functions; standard formulae; half-range sine and cosine series; complex exponential form.

*Partial differential equations (PDEs)*: first order PDEs: linear and quasi-linear; characteristics. Second order PDEs: classification and reduction to canonical form; nature of boundary conditions for elliptic, parabolic and hyperbolic equations; d'Alembert's solution and separation of variables for the one-dimensional wave equation; separation of variables of two-dimensional Laplace equation in Cartesian and polar coordinates with applications to steady state temperature distributions and velocity potential. Separation of variables and similarity solutions for the diffusion equation with application to heat conduction.

*Complex variables*: differentiability; holomorphic functions Cauchy-Riemann equations; application to potential problems and simple fluid flows; conformal mapping; outline of applications to fluid flow with simple example of Joukowski transformation.

*Probability and statistics*: laws of probability; combining probabilities; conditional probabilities and independence; reliability networks. Random variables: discrete and continuous; probability density functions; cumulative distribution functions; binomial and Poisson random variables; uniform, exponential, normal random variables; normal approximations to the binomial and Poisson random variables.

### **A.211 Mechanics of flight**

DR R.E. BROWN

Performance and handling qualities. Airworthiness requirements. Non-linear dynamics and linearisation. Bifurcations and critical points. Newton and Euler equations for rigid bodies. Equations of motion in inertial and accelerated frames of reference. Earth-fixed coordinate systems. Reduction by linearisation and symmetry. Stability derivatives and their aerodynamic origin. Lateral and longitudinal equations of motion. The characteristic equation. Eigenvalues and eigenvectors and the classical aircraft modes. Numerical solution techniques. Classical concepts of static stability. Stability margin, manoeuvre margin, stick force per 'g'.

### **A.212 Propulsion and turbomachinery**

DR D.J. DOORLY

*Introduction to aircraft propulsion.*

*Gas turbine cycle*: review of the Brayton cycle. Effects of component losses: compressor and turbine losses, combustion chamber losses, mechanical losses. Cycle calculation: design point calculation. Combustion: air-fuel ratio and heat output, combustion efficiency.

*Aircraft engines*: jet propulsion; propulsion efficiency, overall efficiency. Intakes: subsonic and supersonic intakes, intake efficiency. Tailpipes and nozzles: efficiencies, tailpipe nozzle choking condition. Method for presenting the performance of engines. Twin spool and fan engines: mechanical layout, definition of bypass ratio, combination of the bypass and core engine components, fan performance, overall performance. Reheat: description of components, analysis of effect on engine performance.

*Compressors*: introduction: types of machines, stators and rotors, description of mechanical arrangements. Aerodynamics of axial flow machines: cascade theory, notation, flow through cascade, lift and drag, efficiency, aerodynamic performance of blade sections. Pitch line design of a compressor stage: assumptions, repeating stages, reaction, flow angles in fixed and moving frames of reference. *Performance of compressor stage*: stage loading and flow coefficients, their relationship to flow angles, influence of value of the design point reaction on loading/flow coefficients. Performance of a real stage: losses and efficiency, operating characteristics, surge limit and maximum efficiency, complete compressor characteristic. Sample calculation.

### **A.213 Structural mechanics and dynamics**

DR B. FALZON, PROFESSOR M.H. ALIABADI

*Stress and strain at a point*: principal stresses and strains, maximum shearing stress.

*Principle of virtual forces*: application to statically determinate and statically indeterminate pin-jointed frames, beams and rigid jointed frames.

*Stress analysis and deflections of asymmetric-section beams*: principal axes, neutral axis.

*Shear flow and shear centre in open section thin-walled beams*.

*Flexural buckling of struts*: with various boundary conditions, discontinuities, supports, imperfections.

*Elastoplastic behaviour and failure*.

*Review of single-degree-of-freedom systems*: mass, stiffness, damping, equations of motion, resonance. Forced response, convolution integral.

*Vibrations of beams*: differential equation of motion, boundary conditions, resonant frequencies, mode shapes.

*Discrete dynamic models*: spring mass, multi-degree-of-freedom systems, equations of motion in stiffness and flexibility form.

*Eigenvalues and eigenvectors for multi-degree-of-freedom systems*. Orthogonality properties of the vectors. Stiffness matrix and flexibility matrix. Formation of the stiffness matrix by unit displacement. Formation of the flexibility matrix by unit load. A computing exercise is given whereby an existing package is used to modify a framework and assess the effects on stresses and deformations.

## **THIRD AND FOURTH YEARS**

### **Course codes**

A.3\*\* courses taken in third year only

A.3/4\*\* courses available in both third and fourth years

A.4\*\* courses taken in fourth year only

### **A.301 Aircraft aerodynamics**

DR J. PEIRO, DR J.F. MORRISON

*Introduction*: the need for numerical methods. Equations of motion: derivation of three dimensions, incompressible, Navier Stokes equations. Reynold's stresses. Review of small perturbation theory: hierarchy of small disturbances. Numerical solution of incompressible, potential flow. Effects of thickness and camber.

*Surface singularity methods*: surface source method (AMO Smith).

*Introduction to boundary layers*: the thin-shear-layer approximation. Laminar: Thwaites' approximate method. Turbulent boundary layers, Reynold's stresses, the concept of eddy-viscosity, the law of the wall.

*Lifting line theory*: wings of large aspect ratio: basis of theory for wings of finite span. Downwash and induced drag. Prandtl's theory. Use of lifting line theory: solution method. Elliptic loading. Solutions for general planforms—collocation and iteration methods.

*Swept wings in incompressible flow*: introduction Kuchemann's index method: modifications to lifting-line theory to account for the effects of sweep. Comparison with/without sweep: the use of taper. Separated flow and stall.

*Slender wing theory*: wings of small aspect ratio. Definition of a slender wing or body. Classical attached flow theory. Separated flow on slender wings.

*Compressible flow*: governing equations. Waves and speed of sound. Validity of the incompressible assumption. Normal and oblique shock waves. Prandtl-Meyer expansion waves. Shock expansion theory.

Method of characteristics. Introduction: one-dimensional unsteady inviscid flow. Unsteady jump conditions. Unsteady motion in a constant area duct. Characteristic equations and compatibility conditions. Examples: simple and non-simple regions. Shock tube problem. Steady two-dimensional irrotational isentropic flow. Governing equations. Characteristic lines. Compatibility conditions. Example: nozzle design. Aerodynamic analysis methods for compressible flow. Introduction: Characteristics of flight at different regimes. Small perturbation analysis for isentropic irrotational flows. Governing equations. Boundary conditions. Linearised pressure coefficient. Similarity rules for two-dimensional aerofoils (infinite wing). Prandtl-Glauert rule. Critical Mach number. Other similarity relations: Karman-Tsien, Laitonde. Aerofoils in supersonic flow: Ackeret's rule. Spreiter's rule for transonic flow. Similarity rules for three-dimensional wings (finite wing). Gothert's rule (subsonic/supersonic). Critical Mach number for swept back wings. Transonic wings (geometry only). Area rule for wing/body combinations. Numerical solution of the TSP equation. Review of approximation by finite differences. Numerical solution of the Laplace and wave equation. The method of Murman and Cole for the TSP equation.

### **A.302 Control systems**

DR K.G. WOODGATE

*Motivation for automatic feedback control in the aerospace world.*

*Review of Laplace transform methods.*

*Concepts and methods:* Stability of feedback systems (Routh and root/eigenvalue stability criteria), tracking of feedback systems/steady state error (system class, integral action, error constants, final value theorem), transient response of feedback systems (second order step response model).

*Design:* feedback design using dominant pole placement by root locus and the final value theorem.

Proportional, integral and derivative feedback and phase lead and lag compensators.

*Multivariable system:* state-space realisations, state feedback design, controllability, observability and observer design.

*Applications:* flight control systems (conventional fixed-wing lateral and longitudinal control), stability augmentation, auto-pilots, inertial

### **A.303 Finite elements**

DR B. FALZON, DR I.C. MATTHEWS

*Introduction to Matrix Formulation:* Shape, functions and interpolation. Displacement method, element stiffness formulation. Assembly of global stiffness matrix and boundary conditions. Methods of solution. Finite element approximation. Conditions for convergence. Isoparametric formulation. Kinematically equivalent loads.

*Results interpretation:* Nodal stress, Gauss point stress, stress jumps, stress averaging.

*Typical results in case studies:* Idealisation, mesh generation, mesh density, stress concentrations, pilot studies.

*Typical FE system:* Elements and choice of element.

*Application to other field problems:* Potential problem, heat conduction, potential flow. Summary of other field problems solved by finite elements.

### **A.304 Aircraft structures**

DR U. GALVANETTO, DR P. ROBINSON, DR A.R. OLSSON

*Structural airworthiness:* introduction to JAR, BCAR, DEFSTAN 970 and the philosophy of proof and ultimate factors. Design load cases. Fatigue damage tolerance.

*Open thin-walled tube:* under torsion: stiffness, strains and the membrane analogy.

*Single cell tube:* stress distribution and twist when loaded by shear forces. Shear centre.

*Boom/shear panel idealisations.*

*Frame in fuselage:* stress distribution in frame and fuselage under a concentrated load.

*Multi-cell tube:* stress distribution and twist due to transverse shear forces.

*Deflection of a thin-walled tube:* due to bending shear and torsion. Warping of the cross section and axial constraint stresses. Neuber tubes.

*Plate bending:* small deflection of thin plates. Moment/curvature relationship, stress distribution, principal moments.

*Plate buckling:* due to compressive or shear stresses. Postbuckling behaviour.

*Stiffened panels:* overall and local buckling modes. Use of data sheets. The optimum panel.

*Fuselage buckling:* between frames due to bending moments, Brazier effect.

*Introduction to aeroelasticity:* introduction to aeroelastic phenomena and their causes, a review of mathematical methods for flutter modelling.

*Static aeroelasticity:* divergence: uniform section wing. PVD for tapered wing, effect of sweep. Control reversal.

*Dynamic aeroelasticity:* classical flexure-torsion flutter: simple two and three degrees-of-freedom systems.

Supersonic panel flutter. Other forms of flutter: stall flutter, bluff body flutter due to vortex shedding.

*Numerical methods for real aircraft.*

### **A.3/401 Advanced Mechanics of Flight**

DR K.G. WOODGATE

*Introduction:* Recap on Newtonian dynamics: laws, concepts of inertial and non-inertial frames, energy & angular momentum. Velocity and acceleration equations, Coriolis and centripetal accelerations. Co-ordinate systems, rotation matrices and matrix form of equations. Ramifications for spinning spacecraft environments and Earth-local spacecraft flight.

*Mathematics:* Recap on vector and matrix algebra, algebra of rotation matrices, state-space models, linearization of non-linear dynamics, non-linear stability analysis via linearization.

*Orbital mechanics:* The two-body problem, Kepler's 3rd law, stability analysis of the restricted three-body problem.

*Earth-satellite operations:* Impulsive orbit transfers: Hohmann and out-of-plane change manoeuvres.

*Rigid body dynamics:* Derivation of rigid body equations in vector and matrix form with respect to an arbitrary co-ordinate system, alternative representations of rotations by Euler angles and Hamilton's quaternions, significance of body-fixed axis systems.

*Fixed-wing flight dynamics:* Modern, systems- & control-theoretic perspective on traditional flight mechanics. Transformation between axis systems, linearization of equations at an arbitrary equilibrium, the equilibrium of co-ordinated turn.

*Satellite attitude dynamics:* torque-free rotational motion of rigid bodies, stability analysis, torque-free axisymmetric rotational motion, precessional motion (of satellites), attitude control of spinning and non-spinning spacecraft, Yo-Yo spin mechanism, gravity-gradient stabilization.

*Interplanetary trajectories:* Spheres of activity, launch windows and mission duration, arrival & departure, fly-by, optimal planetary capture. Lunar travel.

### **A.3/402 Advanced turbomachinery**

PROFESSOR M.A. LESCHZINER

*Introduction:* operational principles, facts and figures, engine type, engine-station designation, efficiencies, thermodynamic relations.

*Global thermodynamic analysis of gas-turbine cycles – a revision:* intake and exhaust nozzles, simple generic cycles for turbojet and turbofan engines.

*Engine components:* operational aspects of fan, axial core-compressor, radial compressor and turbine, mean-line analysis of blading, combustor characteristics and design.

*Three-dimensional aspects:* origin and nature of three-dimensional features in blade passages, radial equilibrium analysis and application to radial flow-angle distribution in compressor and turbine geometries.

*Non-dimensional engine-variable groups and related component matching:* definition of groups and their meaning, use in matching the operation of components.

*Heat transfer:* relevance to cooling, the energy equation, conduction, convection, global heat-transfer correlations.

### **A.3/403 Aerospace vehicle design**

DR V.C. SERGHIDES

*Design process and tools:* description of all the aircraft project development phases, with particular emphasis on the design process and tools.

*Aerospace vehicle types and roles:* standard classifications of aerospace vehicle types and role definitions.

*Design criteria and constraints:* role-specific aircraft properties and practical constraints.

*Airworthiness requirements and standards:* an overview of existing civil airworthiness requirements and military standards, highlighting items which could influence the initial design and operations safety of a new aircraft.

*Design target specification:* essential contents.

*Baseline configuration development:* design advantages and disadvantages of the possible arrangement and relative location of major aircraft assemblies for both conventional and unconventional configurations, with emphasis on operational effectiveness and safety.

*Initial sizing process:* flight profile-based estimation of weight target values for maximum take-off, empty aircraft, fuel and payload.

*Powerplant selection:* engine types, selection criteria, design point-based sizing and selection.

*Powerplant-airframe integration:* intake and nozzle design, installed performance estimation.

*Systems packaging:* aircraft systems operating and installation requirements, including redundancy design, reliability targets and assessment methodologies.

*Fuselage design:* design procedure and criteria, external shape optimisation, cabin, cockpit and cargo hold layouts, including design provisions for emergency evacuation.

*Flying surface design:* aerofoil selection, design point sizing, geometric definition.

*High-lift device selection and design:* types, applicability, design characteristics, selection criteria and sizing.

*Flight control surface design:* direct and mixed modes, control surface geometry, sizing, deflections, adverse effects, reversal and oscillations.

*Undercarriage layout and design:* optimum layout, ground stability, single-wheel and bogie arrangement, loads, tire characteristics and selection, LCN and wheel spacing calculations, strut and absorber sizing, brakes, steering and retraction.

*Aerodynamic analysis:* estimation of the overall aircraft aerodynamic lift and drag characteristics, including high-lift and aerodynamic centre changes.

*Structural layout, loads and aeroelastics:* major structural component layout, optimum load paths, materials and aeroelastic criteria, fail-safe design and safety factors.

*Weight and balance estimations:* aircraft weight breakdown prediction, CG and CG shift.

*Stability and control, handling qualities:* neutral point and static margin calculations, trim analysis, lateral stability requirements and aircraft handling quality assessment.

*Performance estimation:* field, mission and point performance estimation.

*Cost:* cost drivers and cost reduction techniques.

*Optimisation process:* purpose and overview of available methods.

### **A.3/405 Aircraft systems engineering**

DR R.E. BROWN

*Systems and system properties:* definition of a system. Complexity vs. coupling. Reductionism vs. emergence. Perrow's normal accident theory vs. Sagan's high reliability theory.

*Safety and reliability:* engineering risk and risk analysis techniques. Safe life vs. fail-safe philosophy. Design for redundancy. Advantages and disadvantages of redundant design. Design implementation and verification.

*Human factors:* the 'glass cockpit'. Human-machine interfaces and ergonomics. Modelling human behaviour.

*The aircraft system in context:* environmental issues. Air traffic control. Command and control structures, political and ethical issues.

*Systems implementation in aircraft:* propulsion, fuel, navigation, communication, control systems, their layout and operation. Flaws and pitfalls. Design for reliability.

*Future trends:* current and future topics in aircraft systems engineering.

### **A.3/406 Airframe design**

DR L. IANNUCCI

Design to civil and military airworthiness requirements. Use of flight envelope to demonstrate interaction between design, aerodynamics and stress. Conceptual design of major structural assemblies. Synthesis

of two-dimensional and three-dimensional mechanisms: flaps, undercarriages, aileron, swing wing, etc. Detail design of fatigue-prone components such as root fittings, spar boom splices, windows, etc. Production assembly and maintenance considerations discussed where relevant. Practical fail-safe and safe life design. Survey of data sources: AGARD material properties, ESDU data sheets relating to structural strength, stability and fatigue. Several lectures will be devoted to structural design aspects of the group design project. Occasional lectures may be given by visitors from industry.

### **A.3/408 Materials in action**

DR E.S. GREENHALGH

Review of mechanical, physical and other properties of the various material classes: metals, polymers, ceramics, composites and sandwich. Review of processing and the link with properties and cost. Matching the component to the process. Materials and mechanics. Prediction and measurement of characteristics. Oxidation and corrosion, stress corrosion and life prediction. Criteria for selection of materials. Property charts. Derivation of merit indices. Presentation of a range of case studies over different material types and industrial sectors.

### **A.3/409 Materials Modelling**

DR A.R. OLSSON, PROFESSOR M.H. ALIABADI

*Basic Fracture Mechanics:* The stress intensity factor and energy release rate fracture criteria.

*Linear Elastic Fracture Mechanics:* 2-D and 3-D components. Westergaard equations, relationships with fracture criteria.

*Geometrical Effects on Stress Intensity Factors:* Examples of 2-D and 3-D geometries, mixed-mode fracture, finite element methods for calculating fracture criteria.

*Fatigue Crack Growth:* Paris law, finite element use.

*Post-Yield Fracture Mechanics:* Plasticity fundamentals, the plastic zone size around crack tips, crack opening displacement, thickness effects, HRR fields, fracture criteria, finite element use.

*Creep:* Basics.

*Visco-Elastic Models:* Springs and dashpots, simple models, Laplace transforms for more complicated models.

*The Phenomenon of Creep:* Types of creep curves, constitutive laws, hardening effects, creep rupture, multi-axial stress states, statement of the general boundary value problem for creep, finite element solution procedures, example.

*Introduction to Fibre Composites:* Classification and definition of composites. Basic composite mechanics, elastic properties and laminate plate theory. Interlaminar stresses and free edge effects. Hygrothermal stresses in laminates. Fracture processes and failure criteria. Finite elements applied to composites. Manufacturing processes, testing composites for mechanical properties. Short fibre composites, notch sensitivity in tension and compression and fracture energy, fatigue. Case studies.

### **A.3/410 Mathematics**

DR A. WALTON

*Calculus of variations:* Euler-Lagrange equation; problems with constraints.

*Revision of complex numbers:* triangle inequality; polar coordinate representation; curves in the complex plane. Continuity and differentiability of complex functions; analyticity; the Cauchy-Riemann equations.

Definitions of elementary complex functions. Branches and branch points. Complex line integrals:

definition and properties. Cauchy's integral theorem and its consequences. Cauchy's integral formula.

*Complex power series:* Taylor series; Laurent series. Classification of singularities in the complex plane: essential singularities, poles and residues. The residue theorem; contour integration; evaluation of real integrals; summation of infinite series.

*Laplace transforms:* revision of basic properties; derivation of complex inversion formula; use of contour integration; application to PDEs.

*Conformal mapping:* application to Laplace's equation; the Joukowski transformation.

### A.3/413 Helicopter dynamics

MR. J.E. PERRY, DR R.E. BROWN

*Fundamental principles of the helicopter:* advancing and retreating blade effects in forward flight; problems with the early autogyro rotor, leading to the introduction of hinges; development of the autogyro, leading to the helicopter; methods of rotor control, tilting head, collective and cyclic pitch, the swashplate system.

*Rotorcraft and rotor hub configurations:* single main and tail rotor; tandem and side-by-side; coaxial and intermeshing main rotors; lift and thrust compounding; tip drive and tilt rotor; requirements for rotor hinges; effective hinges in semi-rigid rotors; rotor kinematic coupling—pitch-flap and pitch-lag.

*Aerodynamics of the rotor in axial flight:* momentum theory; figure of merit for hover; vortex ring, turbulent wake, and windmill brake states in descent; vertical descent in autorotation; blade element theory; effect of twist; tip loss; thrust, torque and power estimation.

*Aerodynamics of the rotor in forward flight:* basic considerations; effect of flapping; equivalence of flapping and feathering; momentum theory; Glauert's formula for induced velocity; blade element theory; H-force; thrust, torque and power estimation.

*Some features of aerodynamic design:* aerofoil section design;  $\alpha$ -M diagrams; lift and pitching moment characteristics; dynamic effects during stall; tip shape design; parasite drag.

*Some aspects of performance:* power required to hover in and out of ground effect; power required to climb vertically; power required in forward level flight; power required to climb in forward flight; estimation of maximum speed in level flight; envelope of rotor aerodynamic limits.

*Modern rotor and wake analysis methods:* use of vortex wake models in hover and forward flight; use of free wake analysis and advanced computationally based wake models; integration of detailed aerodynamic models with the rotor and aircraft calculation.

*Fundamental mode flap-wise and lag-wise motion of rotor blades:* natural frequency of rotor blade fundamental flap-wise motion; natural frequency of rotor blade fundamental lag-wise motion.

*The semi-rigid rotor:* range of values of effective flapping hinge offset; control power in pitch and roll compared to the articulated rotor; sub-critical and super-critical lag plane systems; comparison of blade displacement relative to the feathering hinge axis of semi-rigid and articulated systems—parasitic cyclic pitch.

*Vibration:* origin of the vibratory loads; transformation of loads from rotating to fixed axis systems; design of rotor systems to minimise amplification of the basic vibratory loads—Campbell or Spoke diagram; higher harmonic control of rotor blade pitch; effect of the number of blades on the vibratory loading—filtering action of the rotor system; airframe response to the vibratory loads—structural manipulation; design of rotor/gearbox mounting systems to reduce the transmission of vibratory loads to the airframe; rotor system mounted vibration absorbers; airframe mounted vibration absorbers; active reduction of airframe vibration using airframe mounted hydraulic actuators; vortex excited airframe vibration.

*Ground resonance:* description of the basic phenomenon; transformation of oscillatory lag motion frequency from a rotating to a fixed axis system for articulated and semi-rigid rotor systems; basic mechanism of ground resonance; blade and airframe damping requirements to suppress ground resonance; results of the ground resonance analysis of a typical helicopter; Coleman mode frequencies and degrees of stability/instability; effect of head mass on Coleman mode instabilities; effect of fuselage and blade damping on Coleman mode stability/instability; effect of blade lag frequency on blade and fuselage damping requirements; types of blade lag damper; results of ground resonance incidents.

*Future trends in technology and configuration:* evolution of the rotor system to eliminate all hinges; advanced flight control systems—active control technology; advanced vibration reduction systems; health and usage monitoring systems; advanced methods of torque balance and yaw control; the lift and/or thrust compounded helicopter; the advancing blade rotor concept; the reverse flow region circulation control rotor; electric transmission systems; tilt-rotor and tilt-wing aircraft.

### A.3/414 Computational fluid dynamics

DR S.J. SHERWIN, DR J. PEIRO

*Introduction:* governing equations: conservative/integral form. Reduced models and range of applicability and limitations.

*Classification of model equations:* (elliptic, parabolic and hyperbolic) and their relation to fluid problems. Construction of model one-dimensional problems (linear advection-diffusion equations).

*Construction of basic numerical schemes:* finite differences (FD), finite volume (FV) and finite elements (FE).

*Analysis and solution of finite difference schemes:* order, truncation error and consistency of a scheme using Taylor expansions. Solution of algebraic systems (direct and basic iterative methods). Explicit and implicit time integration. Courant-Friedrichs-Lewy condition and diffusive time step restrictions. Lax theorem: consistency, stability and convergence. Von Neumann linear analysis for stability and dispersion/diffusion properties.

*Non-linear conservation laws:* one-dimensional theory. Examples of (one-dimensional) hyperbolic conservation laws. Characteristics. Discontinuities and jump conditions. Weak solutions and entropy condition. Linear versus non-linear advection.

*Systems of conservation laws:* Jacobian matrices, linearized equations, conservative and characteristic variables. Rankine-Hugoniot jump conditions. Entropy condition for systems (Lax). Boundary conditions.

*Numerical representation of discontinuities:* requirements on numerical schemes. Conservative discretisation: Lax-Wendroff theorem. First versus second order schemes. Representation of discontinuities: physical aspects, shock fitting/capturing.

*Numerical schemes for non-linear conservation laws:* centred schemes: one-step and two-step Lax-Wendroff, MacCormack predictor-corrector. Artificial dissipation. Upwind schemes: flux vector and flux difference splitting. Monotone schemes: Godunov and Harten theorems. Exact and approximate Riemann solvers. High-order upwind schemes: the TVD property. The construction of TVD schemes using slope and flux limiters.

*Numerical schemes for multidimensional problems:* finite differences and finite volume. Computational domain and boundary conditions. Discretisation of viscous terms.

*Numerical schemes for incompressible flow:* governing equations, the role of the pressure. Numerical difficulties: locking, spurious pressure modes. Artificial compressibility. Fractional step.

*CFD code validation and assessment:* a practical guide.

### **A.3/4XX Project management**

DR E. HADJICONSTANTINOU

An overview of the scope and meaning of project management; examining its key principles and techniques from a theoretical and a practitioner's viewpoint.

*Project management in context.* Introduction, meaning and scope of projects; project types; project life cycle; project characteristics.

*Key roles and responsibilities.* Project environment. The roles of the project manager, the client and the user. Identification and management of stakeholders.

*Project contract strategy and financial framework.* Forms of contracts; project structure; criteria for project success and failure. The private finance initiative (PFI)/public private partnership (PPP); associated principal risks.

*Project organisation – case study.* Alternative project organisations, delegation of authority, communications requirements. Case study discussion: lessons to be learned.

*Project definition and introduction to project planning.* early project definition: writing a sponsor's requirements definition (SRD) and a project requirements definition (PRD). Developing work breakdown structures (WBS).

*Project networks.* Activity identification; bar charts. Network logic diagrams. Construction of project networks.

*Time-scale planning.* The critical path method; computation of floats. Multiple dependency networks. Time-cost trade-offs.

*Planning under uncertainty.* Resource allocation and scheduling. Time analysis using PERT. Resource allocation procedures; time- and resource-loaded schedules.

*Project Control.* Cost estimation; cost and schedule risk analysis; earned value analysis.

*Computer-based project management systems.* Overview of project management systems and software demonstration. Revision.

### **A.401 Applications of fluid dynamics**

PROFESSOR J.M.R. GRAHAM

*Separated flow:* separation from sharp edges and continuous surfaces. Shear layer instability. Bluff body wakes and vortex sheets.

*Flow-induced vibrations:* fluid inertia and fluid damping. Vortex shedding from two-dimensional bluff bodies, flow around a circular cylinder. Causes of flow-induced vibrations. Vortex shedding response, influence of body motion, vortex lock-in, spanwise correlation. Galloping of structures. Quasi-steady theory. *Building aerodynamics:* introduction to random signals, amplitude characteristics, spectra, correlations and Fourier transforms. Turbulence spectra and scale. The structure of strong winds. Effect of free stream turbulence on the flow around bluff bodies. Loading due to wind shear and turbulence, aerodynamic admittance. Influence of atmospheric turbulence intensity and scale.

*Road vehicle aerodynamics:* testing techniques. Aerodynamics requirements: generation of lift and drag, ground effects. Effects of wheels, underbody. Side winds and stability.

*Wave forces on structures:* linear wave theory, wave breaking, Keulegan-Carpenter number,  $\beta$ -parameter, Morison's equation, forces on cylinders.

*Introduction to wind turbine aerodynamics:* actuator disc theory, Betz limit for power coefficient, types of turbine.

### **A.403 Structural dynamics**

DR U. GALVANETTO, DR I.C. MATTHEWS

Dynamic discretisation. Hamilton's principle. Lagrange's equations. Element and global mass matrix, exact and lumped. The stiffness method in dynamics. Undamped free vibrations. Undamped forced, and damped free oscillations. Orthogonality and structure of damped eigenvectors. General solution for damped forced vibrations. Viscous, hysteretic, and proportional damping. Model solutions in the time and frequency domains. Dynamic condensation and substructuring. Numerical integration of equations of motion, implicit and explicit methods, conditional and unconditional stability.

### **A.404 Wing design**

DR J. PEIRO, PROFESSOR J. FULKER

*Introduction:* an overall view of the design methodology and current techniques.

*Basic design:* hierarchy of equations (from Navier Stokes to linearised potential). Concept of viscous/inviscid matching. Classical hierarchical approach to matching. Optimisation. Review of some design examples.

*Numerical solution techniques for aircraft/wing design:* demonstration of the form of the equations and the specification of appropriate surface and inflow/outflow boundary conditions for standard flow solvers. The lectures demonstrate via two-dimensional examples, the numerical solution of the potential and inviscid Euler equations. Matrix vector form of the compressible Navier Stokes equations. Review of eigenvalues (characteristics) and eigenvectors for two-dimensional isentropic flow and for the three-dimensional Euler equations, and the use of Riemann Invariants in boundary condition specification. Example of applications of mesh generation and flow solution for two-dimensional aerofoils.

*Relation between inviscid linearised compressible and incompressible flow:* similarity rules and their applications. Prandtl-Glauert two-dimensional critical mach numbers, Karman Tsien. Extensions to three-dimensional. Application to CFD (potential methods) and experimental studies. Validity and examples.

*Wind tunnel testing:* Wind tunnel types and their operation (transient/continuous flow, boundary layer bleed and other design requirements.) Instrumentation and measurement techniques. Wind tunnel corrections. Relation of wind tunnel and CFD studies.

*Section and planform design:* supercritical aerofoil sections. Flow-field around aerofoil in transonic regime. Drag rise Mach number, buffet. Typical pressure distributions (conventional/supercritical). Benefits in design. Planform. Sweep. Vortex lift and delta wings. Pohlhausen and compressible extensions. Vortex breakdown, roll instability of delta wings, angle of attack limitations. Vortex flaps. Tangential leading edge blowing, strakes.

*Viscous effects:* boundary conditions for solution of thin shear layer equations. Separation point, breakdown of hierarchical approach. Viscous/inviscid matching for weak separation. Inverse and semi-

inverse methods.

*Transition:* nature of transition (for low turbulence), Orr Sommerfeld, bypass transition, effects of roughness,  $Tu$ , shocks etc. Cross-flow and attachment line contamination. Prediction methods ( $e^9$ , correlation based on  $\theta$ ,  $Tu$ ,  $\lambda$ ). Incorporation of turbulence models in boundary layer solution technique via eddy-viscosity.

*Design exercise:* students apply the package XFOIL (one class session, one session by themselves) to aerofoil design.

*Review of application of techniques:* optimal design: introduction, pitfalls of  $C_p$  specification shape parameter and choice of target function. Correction for viscous effects. Streamline curvature approach. Novel design methods (genetic algorithms), multidisciplinary design.

#### A.4XX Introduction to management

Same as A.105, see page 12.

### Examinations

|                                     | Degree exam for<br>which recognised | Date                         |
|-------------------------------------|-------------------------------------|------------------------------|
| <b>FIRST YEAR</b>                   |                                     |                              |
| Mathematics                         | Final, Part 1                       | June                         |
| Mechanics                           | " "                                 | "                            |
| Introduction to aerodynamics        | " "                                 | "                            |
| Aircraft performance                | " "                                 | "                            |
| Properties of materials             | " "                                 | "                            |
| Introduction to structural analysis | " "                                 | "                            |
| Thermodynamics                      | " "                                 | "                            |
| Introduction to management          | " "                                 | January                      |
| <b>SECOND YEAR</b>                  |                                     |                              |
| Aerodynamics                        | Final, Part II                      | June                         |
| Mechanics of flight                 | " "                                 | "                            |
| Structural mechanics and dynamics   | " "                                 | "                            |
| Propulsion and turbomachinery       | " "                                 | "                            |
| Materials                           | " "                                 | "                            |
| Signals and systems                 | " "                                 | "                            |
| Mathematics                         | " "                                 | "                            |
| Managerial economics                | " "                                 | May                          |
| <b>THIRD YEAR</b>                   |                                     |                              |
| MEng: all subjects                  | Final, Part III                     | January or April**           |
| MEng: Year in Europe/North America  | " "                                 | Set by receiving institution |
| <b>FOURTH YEAR</b>                  |                                     |                              |
| MEng: all subjects                  | Final, Part IV                      | January**                    |
| MEng: Year in Europe/North America  | " "                                 | January or April**           |

\*\*Except languages and management studies.