

Contents

Preface	v
1 INTRODUCTION	1
Preamble	1
1.1 Units and dimensions	1
1.1.1 The fundamental dimensions and units	2
1.1.2 Fractions and multiples	3
1.1.3 The units of other physical quantities	3
1.1.4 Imperial units	4
1.1.5 Dimensional analysis	5
1.2 The relevant properties of a fluid	7
1.2.1 The forms of matter	7
1.2.2 Fluids	8
1.2.3 Pressure	8
1.2.4 Temperature	8
1.2.5 Density	9
1.2.6 Viscosity	9
1.2.7 Bulk elasticity	11
1.2.8 Thermodynamic properties	11
1.3 Hydrostatics and aerostatics, the atmosphere	16
1.3.1 Pressure in fluid at rest	16
1.3.2 The buoyancy equation	18
1.3.3 The atmosphere	20
1.3.4 The aircraft altimeter	30
1.4 Aeronautical definitions	30
1.4.1 Wing geometry	30
1.4.2 Aerofoil geometry	33
1.4.3 Aerodynamic force	35
1.4.4 Dimensional theory	36
1.4.5 Force and moment coefficients	42
1.4.6 Pressure distribution on an aerofoil	43
1.4.7 Relation between the pitching moments at various points along the chord	45
1.4.8 Types of drag	49
1.4.9 Estimation of the lift, drag and pitching moment coefficients from the pressure distribution	53
1.4.10 Trailing vortex drag	58

viii Contents

1.4.11	Lift dependent drag	60
1.4.12	Aerofoil characteristics and lift coefficient versus incidence	61
Exercises		66
2 BASIC FLUID MECHANICS I		70
Preamble		70
2.1	Airflow	70
2.1.1	A comparison of steady and unsteady flow	71
2.2	One-dimensional flow: the basic equations	73
2.2.1	The conservation of mass	73
2.2.2	The conservation of momentum	74
2.2.3	The conservation of energy	76
2.2.4	The equation of state	77
2.2.5	The momentum equation for an incompressible fluid	78
2.3	The measurement of air speed	79
2.3.1	The incompressibility assumption	79
2.3.2	The pressure coefficient	81
2.3.3	The air-speed indicator: indicated and equivalent air speeds	82
2.3.4	The incompressibility assumption	83
2.4	Compressible one-dimensional flow	86
2.4.1	Pressure, density and temperature ratios along a streamline in isentropic flow	89
2.4.2	The ratio of areas at different sections of the stream tube in isentropic flow	92
2.4.3	Velocity along an isentropic stream tube	94
2.4.4	Variation of mass flow with pressure	95
2.5	One-dimensional flow: weak waves	104
2.5.1	The speed of sound (acoustic speed)	105
2.6	One-dimensional flow: plane normal shock waves	106
2.6.1	One-dimensional properties of normal shock waves	107
2.6.2	Pressure-density relations across the shock	108
2.6.3	Static pressure jump across a normal shock	109
2.6.4	Density jump across the normal shock	109
2.6.5	Temperature rise across the normal shock	110
2.6.6	Entropy change across the normal shock	110
2.6.7	Mach number change across the normal shock	111
2.6.8	Velocity change across the normal shock	111
2.6.9	Total pressure change across the normal shock	112
2.6.10	Pitôt tube equation	115
2.7	Mach waves and shock waves in two-dimensional flow	116
2.8	Mach waves	117
2.8.1	Mach wave reflection	125
2.8.2	Mach wave interference	127
2.9	Shock waves	127
2.9.1	Plane oblique shock relations	128

2.9.2	The shock polar	133
2.9.3	Two-dimensional supersonic flow past a wedge	139
Exercises		141
3	BASIC FLUID MECHANICS II	143
	Preamble	143
3.1	The basic equations	144
3.1.1	Component velocities	144
3.1.2	Continuity, the conservation of mass	145
3.1.3	The equation of continuity in Cartesian co-ordinates	145
3.1.4	The equation of continuity in polar co-ordinates	147
3.1.5	The equations of motion	148
3.1.6	Fluid acceleration	148
3.1.7	Euler's equation of motion	149
3.1.8	Vorticity, rotational and irrotational flow	151
3.1.9	The equation for vorticity in rectangular co-ordinates	152
3.1.10	The equation for vorticity in polar co-ordinates	153
3.1.11	Continuous irrotational flow	153
3.2	The stream function and the velocity potential	153
3.2.1	The stream function ψ and the velocity potential ϕ	153
3.2.2	The streamline	157
3.2.3	The equipotential	158
3.2.4	Velocity components in terms of ψ	159
3.2.5	Velocity components in terms of ϕ	161
3.3	Laplace's equation	162
3.4	Standard flows in terms of ψ and ϕ	163
3.4.1	Two dimensional flow from a source (or towards a sink)	164
3.4.2	Line (point) vortex	166
3.4.3	Constant velocity flow	168
3.4.4	Solid boundary substitution and image systems	171
3.4.5	A source in a uniform horizontal stream	173
3.4.6	Source-sink pair	176
3.4.7	A source set upstream of an equal sink in a uniform stream	179
3.4.8	Doublet	181
3.4.9	Flow around a circular cylinder given by a doublet in a uniform horizontal stream	184
3.4.10	A spinning cylinder in a uniform stream	186
3.4.11	Bernoulli's equation for rotational flow	190
3.5	Axisymmetric flows (inviscid and incompressible flows)	192
3.5.1	Axisymmetric flow from a point source (or towards a point sink)	194
3.5.2	Point source and sink in a uniform axisymmetric flow	195
3.5.3	The point doublet and the potential flow around a sphere	196
3.5.4	Flow around slender bodies	199
3.6	Computational (panel) methods	203
Exercises		211

x Contents

4 THE ELEMENTS OF TWO-DIMENSIONAL WING THEORY	215
Preamble	215
4.1 Introduction	215
4.1.1 The Kutta condition	216
4.1.2 Circulation and vorticity	218
4.1.3 Circulation and lift (Kutta–Zhukovsky theorem)	224
4.2 The development of aerofoil theory	226
4.3 The general thin aerofoil theory	228
4.4 The solution of the general equation	233
4.4.1 The thin symmetrical flat plate aerofoil	233
4.4.2 The general thin aerofoil section	235
4.5 The flapped aerofoil	239
4.6 The jet flap	242
4.7 The normal force and pitching moment derivatives due to pitching	243
4.8 Particular camber lines	247
4.8.1 Cubic camber lines	247
4.8.2 The NACA four-digit wing sections	251
4.9 Thickness problem for thin aerofoil theory	253
4.9.1 The thickness problem for thin aerofoils	254
4.10 Computational (panel) methods for two-dimensional lifting flows	257
5 FINITE WING THEORY	266
Preamble	266
5.1 The vortex system	267
5.1.1 The starting vortex	267
5.1.2 The trailing vortex system	268
5.1.3 The bound vortex system	269
5.1.4 The horseshoe vortex	270
5.2 Laws of vortex motion	270
5.2.1 Helmholtz’s theorems	271
5.2.2 The Biot–Savart law	272
5.2.3 Variation of velocity in vortex flow	277
5.3 The simplified horseshoe vortex	279
5.3.1 Formation flying effects	280
5.3.2 Influence of the downwash on the tailplane	281
5.3.3 Ground effects	282
5.4 Vortex sheets	284
5.4.1 The use of vortex sheets to model the lifting effects of a wing	285
5.5 Relationship between spanwise loading and trailing vorticity	291
5.5.1 Induced velocity (downwash)	292
5.5.2 The consequences of downwash—trailing vortex drag	294
5.5.3 The characteristics of a simple symmetric loading—elliptic distribution	298
5.5.4 The general (series) distribution of lift	300
5.5.5 Aerodynamic characteristics for symmetrical general loading	303

5.6	Determination of the load distribution on a given wing	307
5.6.1	The general theory for wings of high aspect ratio	307
5.6.2	General solution of Prandtl's integral equation	309
5.6.3	Load distribution for minimum drag	313
5.7	Swept and delta wings	315
5.7.1	Yawed wings of infinite span	315
5.7.2	Swept wings of finite span	317
5.7.3	Wings of small aspect ratio	319
5.8	Computational (panel) methods for wings	324
6 VISCOUS FLOW AND BOUNDARY LAYERS		326
Preamble		326
6.1	Introduction	326
6.2	The development of the boundary layer	328
6.2.1	Velocity profile	328
6.2.2	Boundary layer thickness	330
6.2.3	Non-dimensional profile	330
6.2.4	Types of boundary layer	330
6.2.5	Growth along a flat surface	332
6.2.6	Effects of an external pressure gradient	333
6.3	Laminar-turbulent transition	334
6.4	Boundary layer separation	340
6.4.1	Separation bubbles	342
6.5	Flow past cylinders and spheres	343
6.5.1	Turbulence spheres	348
6.5.2	Golf balls	349
6.5.3	Cricket balls	350
6.6	Some general definitions relating to, and properties of, boundary layers	351
6.6.1	Displacement thickness (δ^*)	351
6.6.2	Momentum thickness (θ)	353
6.6.3	Kinetic energy thickness (δ^{**})	354
6.6.4	Surface friction drag	354
6.6.5	The momentum integral equation	356
6.6.6	An approximate velocity profile for the laminar boundary layer	360
6.7	Approximate methods for a boundary layer on a flat plate with zero pressure gradient	364
6.7.1	Simplified form of the momentum integral equation	364
6.7.2	Rate of growth of a laminar boundary layer on a flat plate	364
6.7.3	Drag coefficient for a flat plate of streamwise length L with wholly laminar boundary layer	365
6.7.4	Turbulent velocity profile	366
6.7.5	Rate of growth of a turbulent boundary layer on a flat plate	368
6.7.6	Drag coefficient for a flat plate with wholly turbulent boundary layer	371

xii Contents

6.7.7	Conditions at transition	371
6.7.8	Mixed boundary layer flow on a flat plate with zero pressure gradient	373
6.8	Additional examples of the application of the momentum integral equation	377
6.9	Estimation of profile drag force from velocity profile in body wake	380
6.9.1	The momentum integral expression for the drag of a two-dimensional body	381
6.9.2	B. M. Jones' wake traverse method for determining profile drag	382
6.9.3	Growth rate of a two-dimensional wake, using the general momentum integral equation	384
6.10	Computational methods	386
6.11	Some boundary layer effects in supersonic flow	390
6.11.1	Near-normal shock interaction with laminar boundary layer	391
6.11.2	Near-normal shock interaction with turbulent boundary layer	392
6.11.3	Shock wave-boundary layer interaction in supersonic flow	393
7	WINGS IN COMPRESSIBLE FLOW	395
	Preamble	399
7.1	Transonic flow, the critical Mach number	399
7.2	Subcritical flow, small perturbation theory	403
7.2.1	The equations of motion of a compressible fluid	404
7.2.2	Small disturbances	405
7.2.3	Prandtl-Glauert rule, the application of linearized theories of subsonic flow	407
7.2.4	Application to swept wings	413
7.3	Supersonic linearized theory (Ackeret's rule)	415
7.3.1	Symmetrical double wedge aerofoil in supersonic flow	419
7.3.2	Symmetrical biconvex circular arc aerofoil in supersonic flow	423
7.3.3	General aerofoil section	426
7.3.4	Aerofoil section made up of unequal circular arcs	429
7.3.5	Double wedge aerofoil section	431
7.4	Other aspects of supersonic wings	433
7.4.1	The shock-expansion approximation	433
7.4.2	Wings of finite span	436
7.4.3	Computational methods	437
8	ASPECTS OF WING DESIGN AND FLOW CONTROL	438
	Preamble	438
8.1	Introduction	438
8.2	Maximizing lift for single-element aerofoils	439
8.3	Multi-element aerofoils	444
8.3.1	The slat effect	447

8.3.2	The vane effect	447
8.3.3	Off-the-surface recovery	448
8.3.4	Fresh boundary layer effect	450
8.4	Boundary layer control for the prevention of separation	451
8.4.1	Boundary layer suction	451
8.4.2	Control by blowing	452
8.4.3	Passive vortex generating devices	453
8.5	Drag reduction	454
8.5.1	Reduction of skin-friction drag	455
8.5.2	Reduction of form drag	457
8.5.3	Reduction of induced drag	458
8.5.4	Reduction of wave drag	459
9	PROPELLERS AND PROPULSION	460
	Preamble	460
9.1	Froude's momentum theory of propulsion	460
9.2	Airscrew coefficients	466
9.2.1	Thrust coefficient	466
9.2.2	Torque coefficient	467
9.2.3	Efficiency	467
9.2.4	Power coefficient	468
9.2.5	Activity factor	468
9.3	Airscrew pitch	471
9.3.1	Geometric pitch	471
9.3.2	Experimental mean pitch	472
9.3.3	Effect of geometric pitch on airscrew performance	472
9.4	Blade element theory	474
9.4.1	The vortex system of an airscrew	474
9.4.2	The performance of a blade element	475
9.5	The momentum theory applied to the helicopter rotor	482
9.5.1	The actuator disc in hovering flight	482
9.5.2	Vertical climbing flight	483
9.5.3	Slow, powered, descending flight	483
9.5.4	Translational helicopter flight	483
9.6	The rocket motor	485
9.6.1	The free motion of a rocket missile	487
9.7	The hovercraft	490
	Exercises	494
	Bibliography	496
Appendix 1	Symbols and notation	498
Appendix 2	The International Standard Atmosphere	502
Appendix 3	A solution of integrals of the type of Glauert's Integral	504
Appendix 4	Conversion of Imperial units to Système International (SI) units	507
	Index	508