

Contents

Preface	xv
CHAPTER 1 Basic Concepts and Definitions	1
1.1 Introduction	1
1.1.1 Basic Concepts	2
1.1.2 Measures of Dynamical Properties	4
1.2 Units and Dimensions	5
1.2.1 Fundamental Dimensions and Units	6
1.2.2 Fractions and Multiples	7
1.2.3 Units of Other Physical Quantities	7
1.2.4 Imperial Units	9
1.3 Relevant Properties	12
1.3.1 Forms of Matter	12
1.3.2 Fluids	13
1.3.3 Pressure	14
1.3.4 Temperature	16
1.3.5 Density	16
1.3.6 Viscosity	17
1.3.7 Speed of Sound and Bulk Elasticity	19
1.3.8 Thermodynamic Properties	20
1.4 Aeronautical Definitions	25
1.4.1 Airfoil Geometry	25
1.4.2 Wing Geometry	27
1.5 Dimensional Analysis	29
1.5.1 Fundamental Principles	29
1.5.2 Dimensional Analysis Applied to Aerodynamic Force ..	32
1.6 Basic Aerodynamics	38
1.6.1 Aerodynamic Force and Moment	38
1.6.2 Force and Moment Coefficients	40
1.6.3 Pressure Distribution on an Airfoil	41
1.6.4 Pitching Moment	43
1.6.5 Types of Drag	47
1.6.6 Estimation of Lift, Drag, and Pitching Moment Coefficients from the Pressure Distribution	51
1.6.7 Induced Drag	55

1.6.8 Lift-Dependent Drag	58
1.6.9 Airfoil Characteristics	58
1.7 Exercises	65
 CHAPTER 2 Fundamental Equations of Fluid Mechanics	 69
2.1 Introduction	69
2.1.1 Selection of Coordinates	70
2.1.2 A Comparison of Steady and Unsteady Flow	71
2.2 One-Dimensional Flow: The Basic Equations	73
2.2.1 One-Dimensional Flow: The Basic Equations of Conservation	73
2.2.2 Comments on the Momentum and Energy Equations	80
2.3 Measurement of Air Speed	81
2.3.1 Pitôt-Static Tube	81
2.3.2 Pressure Coefficient	82
2.3.3 Air-Speed Indicator: Indicated and Equivalent Air Speeds	83
2.3.4 Incompressibility Assumption	84
2.4 Two-Dimensional Flow	87
2.4.1 Component Velocities	88
2.4.2 Equation of Continuity or Conservation of Mass	91
2.4.3 Equation of Continuity in Polar Coordinates	93
2.5 Stream Function and Streamline	94
2.5.1 Stream Function ψ	94
2.5.2 Streamline	96
2.5.3 Velocity Components in Terms of ψ	97
2.6 Momentum Equation	100
2.6.1 Euler Equations	105
2.7 Rates of Strain, Rotational Flow, and Vorticity	105
2.7.1 Distortion of Fluid Element in Flow Field	106
2.7.2 Rate of Shear Strain	107
2.7.3 Rate of Direct Strain	108
2.7.4 Vorticity	109
2.7.5 Vorticity in Polar Coordinates	109
2.7.6 Rotational and Irrotational Flow	110
2.7.7 Circulation	110
2.8 Navier-Stokes Equations	113
2.8.1 Relationship between Rates of Strain and Viscous Stresses	113
2.8.2 Derivation of the Navier-Stokes Equations	115

2.9	Properties of the Navier-Stokes Equations	117
2.10	Exact Solutions of the Navier-Stokes Equations	121
2.10.1	Couette Flow: Simple Shear Flow	122
2.10.2	Plane Poiseuille Flow: Pressure-Driven Channel Flow	122
2.10.3	Hiemenz Flow: Two-Dimensional Stagnation-Point Flow	124
2.11	Prandtl's Boundary-Layer Equations	128
2.11.1	Development of the Boundary Layer	130
2.11.2	Boundary-Layer Thickness	132
2.11.3	Nondimensional Profile	132
2.11.4	Laminar and Turbulent Flows	133
2.11.5	Growth along a Flat Surface	134
2.11.6	Effects of an External Pressure Gradient	136
2.12	Boundary-Layer Equations	137
2.12.1	Derivation of the Laminar Boundary-Layer Equations	138
2.12.2	Boundary-Layer Thickness for Laminar and Turbulent Flows	143
2.12.3	Boundary-Layer/Potential-Flow Model of Airfoils and Wings	144
2.13	Exercises	144
CHAPTER 3	Potential Flow	149
3.1	Two-Dimensional Flows	149
3.1.1	The Velocity Potential	153
3.1.2	The Equipotential	155
3.1.3	Velocity Components in Terms of ϕ	156
3.2	Standard Flows in Terms of ψ and ϕ	157
3.2.1	Uniform Flow	158
3.2.2	Two-Dimensional Flow from a Source (or towards a Sink)	160
3.2.3	Doublet Located at $(x, y) = (0, 0)$	162
3.2.4	Line (Point) Vortex	163
3.2.5	Solid Boundaries and Image Systems	165
3.2.6	Rankine Leading Edge	168
3.2.7	Rankine Oval	171
3.2.8	Circular Cylinder with Circulation in a Cross Flow	175
3.2.9	Joukowski Airfoil and the Circular Cylinder	182
3.3	Axisymmetric Flows (Inviscid and Incompressible Flows)	183
3.3.1	Cylindrical Coordinate System	184
3.3.2	Spherical Coordinates	185

3.3.3	Axisymmetric Flow from a Point Source (or towards a Point Sink)	186
3.3.4	Point Source and Sink in a Uniform Axisymmetric Flow	187
3.3.5	The Point Doublet and the Potential Flow around a Sphere	189
3.3.6	Flow around Slender Bodies	192
3.4	Computational (Panel) Methods	195
3.5	Exercises	203
CHAPTER 4	Two-Dimensional Wing Theory	209
4.1	Introduction	209
4.1.1	The Kutta Condition	211
4.1.2	Circulation and Vorticity.....	213
4.1.3	Circulation and Lift (The Kutta–Joukowski Theorem).....	218
4.2	The Development of Airfoil Theory	220
4.3	General Thin-Airfoil Theory	223
4.4	Solution to the General Equation	228
4.4.1	Thin Symmetrical Flat-Plate Airfoil	229
4.4.2	General Thin-Airfoil Section	231
4.5	The Flapped Airfoil.....	235
4.5.1	Hinge Moment Coefficient	237
4.6	The Jet Flap	240
4.7	Normal Force and Pitching Moment Derivatives Due to Pitching	240
4.7.1	$(Z_q)(M_q)$ Wing Contributions	241
4.8	Particular Camber Lines	245
4.8.1	Cubic Camber Lines	245
4.8.2	NACA Four-Digit Wing Sections	249
4.9	The Thickness Problem for Thin-Airfoil Theory	251
4.9.1	Thickness Problem for Thin Airfoils.....	252
4.10	Computational (Panel) Methods for Two-Dimensional Lifting Flows	256
4.11	Exercises	265
CHAPTER 5	Wing Theory.....	269
5.1	The Vortex System	270
5.1.1	Starting Vortex	270
5.1.2	Trailing Vortex System	271

5.1.3	Bound Vortex System	272
5.1.4	Horseshoe Vortex	273
5.2	Laws of Vortex Motion	273
5.2.1	Helmholtz's Theorems	275
5.2.2	The Biot-Savart Law	276
5.2.3	Variation of Velocity in Vortex Flow	279
5.3	The Wing as a Simplified Horseshoe Vortex	281
5.3.1	Influence of Downwash on the Tailplane	285
5.3.2	Ground Effects	286
5.4	Vortex Sheets	289
5.4.1	Use of Vortex Sheets to Model the Lifting Effects of a Wing	290
5.5	Relationship between Spanwise Loading and Trailing Vorticity	294
5.5.1	Induced Velocity (Downwash)	296
5.5.2	The Consequences of Downwash—Trailing Vortex Drag	299
5.5.3	Characteristics of Simple Symmetric Loading—Elliptic Distribution	302
5.5.4	General (Series) Distribution of Lift	306
5.5.5	Aerodynamic Characteristics for Symmetrical General Loading	309
5.6	Determination of Load Distribution on a Given Wing	315
5.6.1	General Theory for Wings of High Aspect Ratio	316
5.6.2	General Solution to Prandtl's Integral Equation	318
5.6.3	Load Distribution for Minimum Drag	323
5.7	Swept and Delta Wings	325
5.7.1	Yawed Wings of Infinite Span	326
5.7.2	Swept Wings of Finite Span	327
5.7.3	Wings of Small Aspect Ratio	330
5.8	Computational (Panel) Methods for Wings	337
5.9	Exercises	342

CHAPTER 6 Compressible Flow **349**

6.1	Introduction	350
6.2	Isentropic One-Dimensional Flow	352
6.2.1	Pressure, Density, and Temperature Ratios along a Streamline in Isentropic Flow	355
6.2.2	Ratio of Areas at Different Sections of the Stream Tube in Isentropic Flow	359

6.2.3	Velocity along an Isentropic Stream Tube	361
6.2.4	Variation of Mass Flow with Pressure	363
6.3	One-Dimensional Flow: Weak Waves	375
6.3.1	Speed of Sound (Acoustic Speed).....	376
6.4	One-Dimensional Flow: Plane Normal Shock Waves	380
6.4.1	One-Dimensional Properties of Normal Shock Waves...	381
6.4.2	Pressure-Density Relations across the Shock.....	381
6.4.3	Static Pressure Jump across a Normal Shock.....	383
6.4.4	Density Jump across the Normal Shock	384
6.4.5	Temperature Rise across the Normal Shock	385
6.4.6	Entropy Change across the Normal Shock	385
6.4.7	Mach Number Change across the Normal Shock	386
6.4.8	Velocity Change across the Normal Shock	386
6.4.9	Total Pressure Change across the Normal Shock	388
6.4.10	Pitôt Tube Equation	389
6.4.11	Converging-Diverging Nozzle Operations.....	391
6.5	Mach Waves and Shock Waves in Two-Dimensional Flow	395
6.6	Mach Waves	396
6.6.1	Mach Wave Reflection	404
6.6.2	Mach Wave Interference.....	407
6.7	Shock Waves	407
6.7.1	Plane Oblique Shock Relations	407
6.7.2	Shock Polar.....	412
6.7.3	Two-Dimensional Supersonic Flow Past a Wedge	419
6.8	Exercises	422
CHAPTER 7	Airfoils and Wings in Compressible Flow	427
7.1	Wings in Compressible Flow.....	427
7.1.1	Transonic Flow: The Critical Mach Number	427
7.1.2	Subcritical Flow: The Small-Perturbation Theory (Prandtl-Glauert Rule).....	431
7.1.3	Supersonic Linearized Theory (Ackeret's Rule)	446
7.1.4	Other Aspects of Supersonic Wings	470
7.2	Exercises	476
CHAPTER 8	Viscous Flow and Boundary Layers.....	479
8.1	Introduction	479
8.2	Boundary-Layer Theory	484
8.2.1	Blasius's Solution	485
8.2.2	Definitions of Boundary-Layer Thickness	487

8.2.3	Skin-Friction Drag	491
8.2.4	Laminar Boundary-Layer Thickness along a Flat Plate	495
8.2.5	Solving the General Case	496
8.3	Boundary-Layer Separation	498
8.3.1	Separation Bubbles	500
8.4	Flow Past Cylinders and Spheres	501
8.4.1	Turbulence on Spheres	507
8.4.2	Golf Balls	509
8.4.3	Cricket Balls	509
8.5	The Momentum-Integral Equation	511
8.5.1	An Approximate Velocity Profile for the Laminar Boundary Layer	515
8.6	Approximate Methods for a Boundary Layer on a Flat Plate with Zero Pressure Gradient	519
8.6.1	Simplified Form of the Momentum-Integral Equation	519
8.6.2	Rate of Growth of a Laminar Boundary Layer on a Flat Plate	520
8.6.3	Drag Coefficient for a Flat Plate of Streamwise Length L with a Wholly Laminar Boundary Layer	520
8.6.4	Turbulent Velocity Profile	521
8.6.5	Rate of Growth of a Turbulent Boundary Layer on a Flat Plate	523
8.6.6	Drag Coefficient for a Flat Plate with a Wholly Turbulent Boundary Layer	527
8.6.7	Conditions at Transition	528
8.6.8	Mixed Boundary-Layer Flow on a Flat Plate with Zero Pressure Gradient	529
8.7	Additional Examples of the Momentum-Integral Equation	534
8.8	Laminar-Turbulent Transition	538
8.9	The Physics of Turbulent Boundary Layers	545
8.9.1	Reynolds Averaging and Turbulent Stress	545
8.9.2	Boundary-Layer Equations for Turbulent Flows	548
8.9.3	Eddy Viscosity	549
8.9.4	Prandtl's Mixing-Length Theory of Turbulence	553
8.9.5	Regimes of Turbulent Wall Flow	554
8.9.6	Formulae for Local Skin-Friction Coefficient and Drag	556

8.9.7	Distribution of Reynolds Stresses and Turbulent Kinetic Energy across the Boundary Layer	558
8.9.8	Turbulence Structures in the Near-Wall Region	558
8.10	Computational Methods	565
8.10.1	Methods Based on the Momentum-Integral Equation ..	565
8.10.2	Transition Prediction	569
8.10.3	Computational Solution for the Laminar Boundary-Layer Equations	570
8.10.4	Computational Solution for Turbulent Boundary Layers	575
8.10.5	Zero-Equation Methods	576
8.10.6	$k - \varepsilon$: A Typical Two-Equation Method	577
8.10.7	Large-Eddy Simulation	579
8.11	Estimation of Profile Drag from the Velocity Profile in a Wake	581
8.11.1	Momentum-Integral Expression for the Drag of a Two-Dimensional Body	581
8.11.2	Jones's Wake Traverse Method for Determining Profile Drag	582
8.11.3	Growth Rate of a Two-Dimensional Wake Using the General Momentum-Integral Equation	584
8.12	Some Boundary-Layer Effects in Supersonic Flow	587
8.12.1	Near-Normal Shock Interaction with the Laminar Boundary Layer	588
8.12.2	Near-Normal Shock Interaction with the Turbulent Boundary Layer	589
8.12.3	Shock-Wave/Boundary-Layer Interaction in Supersonic Flow	590
8.13	Exercises	598
CHAPTER 9	Flow Control and Wing Design	601
9.1	Introduction	601
9.2	Maximizing Lift for Single-Element Airfoils	602
9.3	Multi-Element Airfoils	608
9.3.1	The Slat Effect	611
9.3.2	The Flap Effect	612
9.3.3	Off-the-Surface Recovery	612
9.3.4	Fresh Boundary-Layer Effect	614
9.3.5	The Gurney Flap	615
9.3.6	Movable Flaps: Artificial Bird Feathers	619

9.4	Boundary Layer Control Prevention to Separation	621
9.4.1	Boundary-Layer Suction.....	622
9.4.2	Control by Tangential Blowing.....	623
9.4.3	Other Methods of Separation Control.....	630
9.5	Reduction of Skin-Friction Drag	631
9.5.1	Laminar Flow Control by Boundary-Layer Suction	631
9.5.2	Compliant Walls: Artificial Dolphin Skins	633
9.5.3	Riblets	636
9.6	Reduction of Form Drag	638
9.7	Reduction of Induced Drag.....	639
9.8	Reduction of Wave Drag	642
CHAPTER 10	Propulsion Devices	645
10.1	Froude's Momentum Theory of Propulsion	645
10.2	Airscrew Coefficients.....	652
10.2.1	Thrust Coefficient	652
10.2.2	Torque Coefficient.....	654
10.2.3	Efficiency	654
10.2.4	Power Coefficient	654
10.2.5	Activity Factor.....	655
10.3	Airscrew Pitch	659
10.3.1	Geometric Pitch	659
10.3.2	Effect of Geometric Pitch on Airscrew Performance ...	660
10.3.3	Experimental Mean Pitch	662
10.4	Blade-Element Theory	662
10.4.1	Vortex System of an Airscrew	662
10.4.2	Performance of a Blade Element	664
10.5	The Momentum Theory Applied to the Helicopter Rotor	671
10.5.1	Actuator Disc in Hovering Flight.....	671
10.5.2	Vertical Climbing Flight	672
10.5.3	Slow, Powered Descending Flight	673
10.5.4	Translational Helicopter Flight	673
10.6	The Rocket Motor	675
10.6.1	Free Motion of a Rocket-Propelled Body	677
10.7	The Hovercraft	682
10.8	Exercises	685
	Appendix A: Symbols and Notation.....	689
	Appendix B	695

Appendix C: A Solution of Integrals of the Type of Glauret's Integral.....	701
Appendix D: Conversion of Imperial Units to Système	
International (SI) Units	705
Bibliography	707
Index	715