Contents

About the Author xv

Preface xvii

1 Basics 1
- 1.1 Introduction 1
- 1.2 Lift and Drag 1
- 1.3 Monoplane Aircraft 4
  - *1.3.1 Types of Monoplane* 5
- 1.4 Biplane 5
  - *1.4.1 Advantages and Disadvantages* 6
- 1.5 Triplane 6
  - *1.5.1 Chord of a Profile* 7
  - *1.5.2 Chord of an Aerofoil* 8
- 1.6 Aspect Ratio 9
- 1.7 Camber 10
- 1.8 Incidence 11
- 1.9 Aerodynamic Force 12
- 1.10 Scale Effect 15
- 1.11 Force and Moment Coefficients 17
- 1.12 The Boundary Layer 18
- 1.13 Summary 20

Exercise Problems 21

Reference 22

2 Essence of Fluid Mechanics 23
- 2.1 Introduction 23
- 2.2 Properties of Fluids 23
  - *2.2.1 Pressure* 23
  - *2.2.2 Temperature* 24
  - *2.2.3 Density* 24
  - *2.2.4 Viscosity* 25
  - *2.2.5 Absolute Coefficient of Viscosity* 25
  - *2.2.6 Kinematic Viscosity Coefficient* 27
  - *2.2.7 Thermal Conductivity of Air* 27
  - *2.2.8 Compressibility* 28
- 2.3 Thermodynamic Properties 28
  - *2.3.1 Specific Heat* 28
  - *2.3.2 The Ratio of Specific Heats* 29

2.4 Surface Tension 30
2.5 Analysis of Fluid Flow 31
2.5.1 Local and Material Rates of Change 32
2.5.2 Graphical Description of Fluid Motion 33
2.6 Basic and Subsidiary Laws 34
2.6.1 System and Control Volume 34
2.6.2 Integral and Differential Analysis 35
2.6.3 State Equation 35
2.7 Kinematics of Fluid Flow 35
2.7.1 Boundary Layer Thickness 37
2.7.2 Displacement Thickness 38
2.7.3 Transition Point 39
2.7.4 Separation Point 39
2.7.5 Rotational and Irrotational Motion 40
2.8 Streamlines 41
2.8.1 Relationship between Stream Function and Velocity Potential 41
2.9 Potential Flow 42
2.9.1 Two-dimensional Source and Sink 43
2.9.2 Simple Vortex 45
2.9.3 Source-Sink Pair 46
2.9.4 Doublet 46
2.10 Combination of Simple Flows 49
2.10.1 Flow Past a Half-Body 49
2.11 Flow Past a Circular Cylinder without Circulation 57
2.11.1 Flow Past a Circular Cylinder with Circulation 59
2.12 Viscous Flows 63
2.12.1 Drag of Bodies 65
2.12.2 Turbulence 70
2.12.3 Flow through Pipes 75
2.13 Compressible Flows 78
2.13.1 Perfect Gas 79
2.13.2 Velocity of Sound 80
2.13.3 Mach Number 80
2.13.4 Flow with Area Change 80
2.13.5 Normal Shock Relations 82
2.13.6 Oblique Shock Relations 83
2.13.7 Flow with Friction 84
2.13.8 Flow with Simple T_0-Change 86
2.14 Summary 87
Exercise Problems 97
References 102

3 Conformal Transformation **103**
3.1 Introduction 103
3.2 Basic Principles 103
3.2.1 Length Ratios between the Corresponding Elements in the Physical and Transformed Planes 106
3.2.2 Velocity Ratios between the Corresponding Elements in the Physical and Transformed Planes 106
3.2.3 Singularities 107

3.3 Complex Numbers 107
3.3.1 Differentiation of a Complex Function 110
3.4 Summary 112
Exercise Problems 113

4 Transformation of Flow Pattern 115
4.1 Introduction 115
4.2 Methods for Performing Transformation 115
4.2.1 By Analytical Means 116
4.3 Examples of Simple Transformation 119
4.4 Kutta–Joukowski Transformation 122
4.5 Transformation of Circle to Straight Line 123
4.6 Transformation of Circle to Ellipse 124
4.7 Transformation of Circle to Symmetrical Aerofoil 125
4.7.1 Thickness to Chord Ratio of Symmetrical Aerofoil 127
4.7.2 Shape of the Trailing Edge 129
4.8 Transformation of a Circle to a Cambered Aerofoil 129
4.8.1 Thickness-to-Chord Ratio of the Cambered Aerofoil 132
4.8.2 Camber 134
4.9 Transformation of Circle to Circular Arc 134
4.9.1 Camber of Circular Arc 137
4.10 Joukowski Hypothesis 137
4.10.1 The Kutta Condition Applied to Aerofoils 139
4.10.2 The Kutta Condition in Aerodynamics 140
4.11 Lift of Joukowski Aerofoil Section 141
4.12 The Velocity and Pressure Distributions on the Joukowski Aerofoil 144
4.13 The Exact Joukowski Transformation Process and Its Numerical Solution 146
4.14 The Velocity and Pressure Distribution 147
4.15 Aerofoil Characteristics 155
4.15.1 Parameters Governing the Aerodynamic Forces 157
4.16 Aerofoil Geometry 157
4.16.1 Aerofoil Nomenclature 157
4.16.2 NASA Aerofoils 161
4.16.3 Leading-Edge Radius and Chord Line 161
4.16.4 Mean Camber Line 161
4.16.5 Thickness Distribution 162
4.16.6 Trailing-Edge Angle 162
4.17 Wing Geometrical Parameters 162
4.18 Aerodynamic Force and Moment Coefficients 166
4.18.1 Moment Coefficient 169
4.19 Summary 171
Exercise Problems 180
Reference 181

5 Vortex Theory 183
5.1 Introduction 183
5.2 Vorticity Equation in Rectangular Coordinates 184
5.2.1 Vorticity Equation in Polar Coordinates 186

5.3 Circulation 188
5.4 Line (point) Vortex 192
5.5 Laws of Vortex Motion 194
5.6 Helmholtz's Theorems 195
5.7 Vortex Theorems 196
5.7.1 Stoke's Theorem 200
5.8 Calculation of u_R, the Velocity due to Rotational Flow 204
5.9 Biot-Savart Law 207
5.9.1 A Linear Vortex of Finite Length 210
5.9.2 Semi-Infinite Vortex 211
5.9.3 Infinite Vortex 211
5.9.4 Helmholtz's Second Vortex Theorem 216
5.9.5 Helmholtz's Third Vortex Theorem 220
5.9.6 Helmholtz's Fourth Vortex Theorem 220
5.10 Vortex Motion 220
5.11 Forced Vortex 223
5.12 Free Vortex 224
5.12.1 Free Spiral Vortex 226
5.13 Compound Vortex 229
5.14 Physical Meaning of Circulation 230
5.15 Rectilinear Vortices 235
5.15.1 Circular Vortex 236
5.16 Velocity Distribution 237
5.17 Size of a Circular Vortex 239
5.18 Point Rectilinear Vortex 239
5.19 Vortex Pair 240
5.20 Image of a Vortex in a Plane 241
5.21 Vortex between Parallel Plates 242
5.22 Force on a Vortex 244
5.23 Mutual action of Two Vortices 244
5.24 Energy due to a Pair of Vortices 244
5.25 Line Vortex 247
5.26 Summary 248
Exercise Problems 254
References 256

6 Thin Aerofoil Theory **257**
6.1 Introduction 257
6.2 General Thin Aerofoil Theory 258
6.3 Solution of the General Equation 261
6.3.1 Thin Symmetrical Flat Plate Aerofoil 262
6.3.2 The Aerodynamic Coefficients for a Flat Plate 265
6.4 The Circular Arc Aerofoil 269
6.4.1 Lift, Pitching Moment, and the Center of Pressure Location for Circular Arc Aerofoil 271
6.5 The General Thin Aerofoil Section 275
6.6 Lift, Pitching Moment and Center of Pressure Coefficients for a Thin Aerofoil 278
6.7 Flapped Aerofoil 283
6.7.1 Hinge Moment Coefficient 286

6.7.2 *Jet Flap* 288
6.7.3 *Effect of Operating a Flap* 288
6.8 Summary 289
Exercise Problems 294
References 295

7 Panel Method **297**
7.1 Introduction 297
7.2 Source Panel Method 297
7.2.1 *Coefficient of Pressure* 300
7.3 The Vortex Panel Method 302
7.3.1 *Application of Vortex Panel Method* 302
7.4 Pressure Distribution around a Circular Cylinder by Source Panel Method 305
7.5 Using Panel Methods 309
7.5.1 *Limitations of Panel Method* 309
7.5.2 *Advanced Panel Methods* 309
7.6 Summary 329
Exercise Problems 330
Reference 330

8 Finite Aerofoil Theory **331**
8.1 Introduction 331
8.2 Relationship between Spanwise Loading and Trailing Vorticity 331
8.3 Downwash 332
8.4 Characteristics of a Simple Symmetrical Loading – Elliptic Distribution 335
8.4.1 *Lift for an Elliptic Distribution* 336
8.4.2 *Downwash for an Elliptic Distribution* 336
8.4.3 *Drag D_v due to Downwash for Elliptical Distribution* 338
8.5 Aerofoil Characteristic with a More General Distribution 339
8.5.1 *The Downwash for Modified Elliptic Loading* 341
8.6 The Vortex Drag for Modified Loading 343
8.6.1 *Condition for Vortex Drag Minimum* 345
8.7 Lancaster – Prandtl Lifting Line Theory 347
8.7.1 *The Lift* 349
8.7.2 *Induced Drag* 350
8.8 Effect of Downwash on Incidence 353
8.9 The Integral Equation for the Circulation 355
8.10 Elliptic Loading 356
8.10.1 *Lift and Drag for Elliptical Loading* 357
8.10.2 *Lift Curve Slope for Elliptical Loading* 359
8.10.3 *Change of Aspect Ratio with Incidence* 359
8.10.4 *Problem II* 360
8.10.5 *The Lift for Elliptic Loading* 363
8.10.6 *The Downwash Velocity for Elliptic Loading* 366
8.10.7 *The Induced Drag for Elliptic Loading* 366
8.10.8 *Induced Drag Minimum* 369
8.10.9 *Lift and Drag Calculation by Impulse Method* 370

8.10.10 The Rectangular Aerofoil 371
8.10.11 Cylindrical Rectangular Aerofoil 372
8.11 Aerodynamic Characteristics of Asymmetric Loading 372
8.11.1 Lift on the Aerofoil 372
8.11.2 Downwash 372
8.11.3 Vortex Drag 373
8.11.4 Rolling Moment 374
8.11.5 Yawing Moment 376
8.12 Lifting Surface Theory 378
8.12.1 Velocity Induced by a Lifting Line Element 378
8.12.2 Munk's Theorem of Stagger 381
8.12.3 The Induced Lift 382
8.12.4 Blenk's Method 383
8.12.5 Rectangular Aerofoil 384
8.12.6 Calculation of the Downwash Velocity 385
8.13 Aerofoils of Small Aspect Ratio 387
8.13.1 The Integral Equation 388
8.13.2 Zero Aspect Ratio 390
8.13.3 The Acceleration Potential 390
8.14 Lifting Surface 391
8.15 Summary 394
Exercise Problems 401

9 Compressible Flows **405**
9.1 Introduction 405
9.2 Thermodynamics of Compressible Flows 405
9.3 Isentropic Flow 409
9.4 Discharge from a Reservoir 411
9.5 Compressible Flow Equations 413
9.6 Crocco's Theorem 414
9.6.1 Basic Solutions of Laplace's Equation 418
9.7 The General Potential Equation for Three-Dimensional Flow 418
9.8 Linearization of the Potential Equation 420
9.8.1 Small Perturbation Theory 420
9.9 Potential Equation for Bodies of Revolution 423
9.9.1 Solution of Nonlinear Potential Equation 425
9.10 Boundary Conditions 425
9.10.1 Bodies of Revolution 427
9.11 Pressure Coefficient 428
9.11.1 Bodies of Revolution 429
9.12 Similarity Rule 429
9.13 Two-Dimensional Flow: Prandtl-Glauert Rule for Subsonic Flow 429
9.13.1 The Prandtl-Glauert Transformations 429
9.13.2 The Direct Problem-Version I 431
9.13.3 The Indirect Problem (Case of Equal Potentials): P-G Transformation – Version II 434
9.13.4 The Streamline Analogy (Version III): Gothert's Rule 435
9.14 Prandtl-Glauert Rule for Supersonic Flow: Versions I and II 436
9.14.1 Subsonic Flow 436
9.14.2 Supersonic Flow 436

9.15 The von Karman Rule for Transonic Flow 439
9.15.1 Use of Karman Rule 440
9.16 Hypersonic Similarity 442
9.17 Three-Dimensional Flow: The Gothert Rule 444
9.17.1 The General Similarity Rule 444
9.17.2 Gothert Rule 446
9.17.3 Application to Wings of Finite Span 447
9.17.4 Application to Bodies of Revolution and Fuselage 448
9.17.5 The Prandtl-Glauert Rule 450
9.17.6 The von Karman Rule for Transonic Flow 454
9.18 Moving Disturbance 455
9.18.1 Small Disturbance 456
9.18.2 Finite Disturbance 457
9.19 Normal Shock Waves 457
9.19.1 Equations of Motion for a Normal Shock Wave 457
9.19.2 The Normal Shock Relations for a Perfect Gas 458
9.20 Change of Total Pressure across a Shock 462
9.21 Oblique Shock and Expansion Waves 463
9.21.1 Oblique Shock Relations 464
9.21.2 Relation between β and θ 466
9.21.3 Supersonic Flow over a Wedge 469
9.21.4 Weak Oblique Shocks 471
9.21.5 Supersonic Compression 473
9.21.6 Supersonic Expansion by Turning 475
9.21.7 The Prandtl-Meyer Function 477
9.21.8 Shock-Expansion Theory 477
9.22 Thin Aerofoil Theory 479
9.22.1 Application of Thin Aerofoil Theory 480
9.23 Two-Dimensional Compressible Flows 485
9.24 General Linear Solution for Supersonic Flow 486
9.24.1 Existence of Characteristics in a Physical Problem 488
9.24.2 Equation for the Streamlines from Kinematic Flow Condition 489
9.25 Flow over a Wave-Shaped Wall 491
9.25.1 Incompressible Flow 491
9.25.2 Compressible Subsonic Flow 492
9.25.3 Supersonic Flow 493
9.25.4 Pressure Coefficient 494
9.26 Summary 495
Exercise Problems 509
References 512

10 Simple Flights **513**
10.1 Introduction 513
10.2 Linear Flight 513
10.3 Stalling 514
10.4 Gliding 516
10.5 Straight Horizontal Flight 518
10.6 Sudden Increase of Incidence 520
10.7 Straight Side-Slip 521

10.8 Banked Turn 522
10.9 Phugoid Motion 523
10.10 The Phugoid Oscillation 525
10.11 Summary 529
Exercise Problems 531

Further Readings **533**

Index **535**