

Preface xix

PART 1 **Fundamental Principles 1**

Chapter 1

Aerodynamics: Some Introductory Thoughts 3

- 1.1** Importance of Aerodynamics: Historical Examples 5
- 1.2** Aerodynamics: Classification and Practical Objectives 11
- 1.3** Road Map for This Chapter 14
- 1.4** Some Fundamental Aerodynamic Variables 15
 - 1.4.1 Units 18*
- 1.5** Aerodynamic Forces and Moments 19
- 1.6** Center of Pressure 32
- 1.7** Dimensional Analysis: The Buckingham Pi Theorem 34
- 1.8** Flow Similarity 40
- 1.9** Fluid Statics: Buoyancy Force 51
- 1.10** Types of Flow 57
 - 1.10.1 Continuum Versus Free Molecule Flow 58*
 - 1.10.2 Inviscid Versus Viscous Flow 58*
 - 1.10.3 Incompressible Versus Compressible Flows 60*
 - 1.10.4 Mach Number Regimes 60*
- 1.11** Viscous Flow: Introduction to Boundary Layers 64

- 1.12** Applied Aerodynamics: The Aerodynamic Coefficients—Their Magnitudes and Variations 71
- 1.13** Historical Note: The Illusive Center of Pressure 83
- 1.14** Historical Note: Aerodynamic Coefficients 87
- 1.15** Summary 91
- 1.16** Problems 92

Chapter 2

Aerodynamics: Some Fundamental Principles and Equations 95

- 2.1** Introduction and Road Map 96
- 2.2** Review of Vector Relations 97
 - 2.2.1 Some Vector Algebra 98*
 - 2.2.2 Typical Orthogonal Coordinate Systems 99*
 - 2.2.3 Scalar and Vector Fields 102*
 - 2.2.4 Scalar and Vector Products 102*
 - 2.2.5 Gradient of a Scalar Field 103*
 - 2.2.6 Divergence of a Vector Field 105*
 - 2.2.7 Curl of a Vector Field 106*
 - 2.2.8 Line Integrals 106*
 - 2.2.9 Surface Integrals 107*
 - 2.2.10 Volume Integrals 108*
 - 2.2.11 Relations Between Line, Surface, and Volume Integrals 109*
 - 2.2.12 Summary 109*
- 2.3** Models of the Fluid: Control Volumes and Fluid Elements 109
 - 2.3.1 Finite Control Volume Approach 110*
 - 2.3.2 Infinitesimal Fluid Element Approach 111*
 - 2.3.3 Molecular Approach 111*

- 2.3.4 *Physical Meaning of the Divergence of Velocity* 112
- 2.3.5 *Specification of the Flow Field* 113
- 2.4** Continuity Equation 117
- 2.5** Momentum Equation 122
- 2.6** An Application of the Momentum Equation: Drag of a Two-Dimensional Body 127
- 2.6.1 *Comment* 136
- 2.7** Energy Equation 136
- 2.8** Interim Summary 141
- 2.9** Substantial Derivative 142
- 2.10** Fundamental Equations in Terms of the Substantial Derivative 145
- 2.11** Pathlines, Streamlines, and Streaklines of a Flow 147
- 2.12** Angular Velocity, Vorticity, and Strain 152
- 2.13** Circulation 162
- 2.14** Stream Function 165
- 2.15** Velocity Potential 169
- 2.16** Relationship Between the Stream Function and Velocity Potential 171
- 2.17** How Do We Solve the Equations? 172
- 2.17.1 *Theoretical (Analytical) Solutions* 172
- 2.17.2 *Numerical Solutions—Computational Fluid Dynamics (CFD)* 174
- 2.17.3 *The Bigger Picture* 181
- 2.18** Summary 181
- 2.19** Problems 185
- PART 2**
Inviscid, Incompressible Flow 187
- Chapter 3**
Fundamentals of Inviscid, Incompressible Flow 189
- 3.1** Introduction and Road Map 190
- 3.2** Bernoulli's Equation 193
- 3.3** Incompressible Flow in a Duct: The Venturi and Low-Speed Wind Tunnel 197
- 3.4** Pitot Tube: Measurement of Airspeed 210
- 3.5** Pressure Coefficient 219
- 3.6** Condition on Velocity for Incompressible Flow 221
- 3.7** Governing Equation for Irrotational, Incompressible Flow: Laplace's Equation 222
- 3.7.1 *Infinity Boundary Conditions* 225
- 3.7.2 *Wall Boundary Conditions* 225
- 3.8** Interim Summary 226
- 3.9** Uniform Flow: Our First Elementary Flow 227
- 3.10** Source Flow: Our Second Elementary Flow 229
- 3.11** Combination of a Uniform Flow with a Source and Sink 233
- 3.12** Doublet Flow: Our Third Elementary Flow 237
- 3.13** Nonlifting Flow over a Circular Cylinder 239
- 3.14** Vortex Flow: Our Fourth Elementary Flow 245
- 3.15** Lifting Flow over a Cylinder 249
- 3.16** The Kutta-Joukowski Theorem and the Generation of Lift 262
- 3.17** Nonlifting Flows over Arbitrary Bodies: The Numerical Source Panel Method 264
- 3.18** Applied Aerodynamics: The Flow over a Circular Cylinder—The Real Case 274
- 3.19** Historical Note: Bernoulli and Euler—The Origins of Theoretical Fluid Dynamics 282
- 3.20** Historical Note: d'Alembert and His Paradox 287
- 3.21** Summary 288
- 3.22** Problems 291

Chapter 4**Incompressible Flow over Airfoils 295**

- 4.1 Introduction 297
- 4.2 Airfoil Nomenclature 300
- 4.3 Airfoil Characteristics 302
- 4.4 Philosophy of Theoretical Solutions for Low-Speed Flow over Airfoils: The Vortex Sheet 307
- 4.5 The Kutta Condition 312
 - 4.5.1 *Without Friction Could We Have Lift?* 316
- 4.6 Kelvin's Circulation Theorem and the Starting Vortex 316
- 4.7 Classical Thin Airfoil Theory: The Symmetric Airfoil 319
- 4.8 The Cambered Airfoil 329
- 4.9 The Aerodynamic Center: Additional Considerations 338
- 4.10 Lifting Flows over Arbitrary Bodies: The Vortex Panel Numerical Method 342
- 4.11 Modern Low-Speed Airfoils 348
- 4.12 Viscous Flow: Airfoil Drag 352
 - 4.12.1 *Estimating Skin-Friction Drag: Laminar Flow* 353
 - 4.12.2 *Estimating Skin-Friction Drag: Turbulent Flow* 355
 - 4.12.3 *Transition* 357
 - 4.12.4 *Flow Separation* 362
 - 4.12.5 *Comment* 367
- 4.13 Applied Aerodynamics: The Flow over an Airfoil—The Real Case 368
- 4.14 Historical Note: Early Airplane Design and the Role of Airfoil Thickness 379
- 4.15 Historical Note: Kutta, Joukowski, and the Circulation Theory of Lift 384
- 4.16 Summary 386
- 4.17 Problems 388

Chapter 5**Incompressible Flow over Finite Wings 391**

- 5.1 Introduction: Downwash and Induced Drag 395
- 5.2 The Vortex Filament, the Biot-Savart Law, and Helmholtz's Theorems 400
- 5.3 Prandtl's Classical Lifting-Line Theory 404
 - 5.3.1 *Elliptical Lift Distribution* 410
 - 5.3.2 *General Lift Distribution* 415
 - 5.3.3 *Effect of Aspect Ratio* 418
 - 5.3.4 *Physical Significance* 424
- 5.4 A Numerical Nonlinear Lifting-Line Method 433
- 5.5 The Lifting-Surface Theory and the Vortex Lattice Numerical Method 437
- 5.6 Applied Aerodynamics: The Delta Wing 444
- 5.7 Historical Note: Lanchester and Prandtl—The Early Development of Finite-Wing Theory 456
- 5.8 Historical Note: Prandtl—The Man 460
- 5.9 Summary 463
- 5.10 Problems 464

Chapter 6**Three-Dimensional Incompressible Flow 467**

- 6.1 Introduction 467
- 6.2 Three-Dimensional Source 468
- 6.3 Three-Dimensional Doublet 470
- 6.4 Flow over a Sphere 472
 - 6.4.1 *Comment on the Three-Dimensional Relieving Effect* 474
- 6.5 General Three-Dimensional Flows: Panel Techniques 475
- 6.6 Applied Aerodynamics: The Flow over a Sphere—The Real Case 477
- 6.7 Summary 480
- 6.8 Problems 481

PART 3 **Inviscid, Compressible Flow 483**

Chapter 7

Compressible Flow: Some Preliminary Aspects 485

- 7.1** Introduction 486
- 7.2** A Brief Review of Thermodynamics 488
 - 7.2.1 *Perfect Gas* 488
 - 7.2.2 *Internal Energy and Enthalpy* 488
 - 7.2.3 *First Law of Thermodynamics* 492
 - 7.2.4 *Entropy and the Second Law of Thermodynamics* 493
 - 7.2.5 *Isentropic Relations* 495
- 7.3** Definition of Compressibility 497
- 7.4** Governing Equations for Inviscid, Compressible Flow 499
- 7.5** Definition of Total (Stagnation) Conditions 501
- 7.6** Some Aspects of Supersonic Flow: Shock Waves 507
- 7.7** Summary 510
- 7.8** Problems 513

Chapter 8

Normal Shock Waves and Related Topics 515

- 8.1** Introduction 516
- 8.2** The Basic Normal Shock Equations 517
- 8.3** Speed of Sound 521
- 8.4** Special Forms of the Energy Equation 527
- 8.5** When Is a Flow Compressible? 534
- 8.6** Calculation of Normal Shock-Wave Properties 537
- 8.7** Measurement of Velocity in a Compressible Flow 548
 - 8.7.1 *Subsonic Compressible Flow* 548
 - 8.7.2 *Supersonic Flow* 549

- 8.8** Summary 553

- 8.9** Problems 556

Chapter 9

Oblique Shock and Expansion Waves 559

- 9.1** Introduction 560
- 9.2** Oblique Shock Relations 566
- 9.3** Supersonic Flow over Wedges and Cones 580
- 9.4** Shock Interactions and Reflections 583
- 9.5** Detached Shock Wave in Front of a Blunt Body 589
- 9.6** Prandtl-Meyer Expansion Waves 591
- 9.7** Shock-Expansion Theory: Applications to Supersonic Airfoils 602
- 9.8** A Comment on Lift and Drag Coefficients 606
- 9.9** Viscous Flow: Shock-Wave/Boundary-Layer Interaction 606
- 9.10** Historical Note: Ernst Mach—A Biographical Sketch 609
- 9.11** Summary 611
- 9.12** Problems 612

Chapter 10

Compressible Flow Through Nozzles, Diffusers, and Wind Tunnels 617

- 10.1** Introduction 618
- 10.2** Governing Equations for Quasi-One-Dimensional Flow 620
- 10.3** Nozzle Flows 629
 - 10.3.1 *More on Mass Flow* 643
- 10.4** Diffusers 644
- 10.5** Supersonic Wind Tunnels 646
- 10.6** Viscous Flow: Shock-Wave/Boundary-Layer Interaction Inside Nozzles 652
- 10.7** Summary 654
- 10.8** Problems 655

Chapter 11**Subsonic Compressible Flow over Airfoils:
Linear Theory 657**

- 11.1 Introduction 658
- 11.2 The Velocity Potential Equation 660
- 11.3 The Linearized Velocity Potential Equation 663
- 11.4 Prandtl-Glauert Compressibility Correction 668
- 11.5 Improved Compressibility Corrections 673
- 11.6 Critical Mach Number 674
 - 11.6.1 *A Comment on the Location of Minimum Pressure (Maximum Velocity)* 683
- 11.7 Drag-Divergence Mach Number: The Sound Barrier 683
- 11.8 The Area Rule 691
- 11.9 The Supercritical Airfoil 693
- 11.10 CFD Applications: Transonic Airfoils and Wings 695
- 11.11 Historical Note: High-Speed Airfoils—Early Research and Development 700
- 11.12 Historical Note: Richard T. Whitcomb—Architect of the Area Rule and the Supercritical Wing 704
- 11.13 Summary 706
- 11.14 Problems 707

Chapter 12**Linearized Supersonic Flow 709**

- 12.1 Introduction 710
- 12.2 Derivation of the Linearized Supersonic Pressure Coefficient Formula 710
- 12.3 Application to Supersonic Airfoils 714
- 12.4 Viscous Flow: Supersonic Airfoil Drag 720
- 12.5 Summary 723
- 12.6 Problems 724

Chapter 13**Introduction to Numerical Techniques
for Nonlinear Supersonic Flow 725**

- 13.1 Introduction: Philosophy of Computational Fluid Dynamics 726
- 13.2 Elements of the Method of Characteristics 728
 - 13.2.1 *Internal Points* 734
 - 13.2.2 *Wall Points* 735
- 13.3 Supersonic Nozzle Design 736
- 13.4 Elements of Finite-Difference Methods 739
 - 13.4.1 *Predictor Step* 745
 - 13.4.2 *Corrector Step* 745
- 13.5 The Time-Dependent Technique: Application to Supersonic Blunt Bodies 746
 - 13.5.1 *Predictor Step* 750
 - 13.5.2 *Corrector Step* 750
- 13.6 Summary 754
- 13.7 Problem 754

Chapter 14**Elements of Hypersonic Flow 757**

- 14.1 Introduction 758
- 14.2 Qualitative Aspects of Hypersonic Flow 759
- 14.3 Newtonian Theory 763
- 14.4 The Lift and Drag of Wings at Hypersonic Speeds: Newtonian Results for a Flat Plate at Angle of Attack 767
 - 14.4.1 *Accuracy Considerations* 774
- 14.5 Hypersonic Shock-Wave Relations and Another Look at Newtonian Theory 778
- 14.6 Mach Number Independence 782
- 14.7 Hypersonics and Computational Fluid Dynamics 784
- 14.8 Summary 787
- 14.9 Problems 787

PART 4

Viscous Flow 789

Chapter 15

Introduction to the Fundamental Principles and Equations of Viscous Flow 791

- 15.1 Introduction 792
- 15.2 Qualitative Aspects of Viscous Flow 793
- 15.3 Viscosity and Thermal Conduction 801
- 15.4 The Navier-Stokes Equations 806
- 15.5 The Viscous Flow Energy Equation 810
- 15.6 Similarity Parameters 814
- 15.7 Solutions of Viscous Flows: A Preliminary Discussion 818
- 15.8 Summary 821
- 15.9 Problems 823

Chapter 16

Some Special Cases; Couette and Poiseuille Flows 825

- 16.1 Introduction 825
- 16.2 Couette Flow: General Discussion 826
- 16.3 Incompressible (Constant Property) Couette Flow 830
 - 16.3.1 Negligible Viscous Dissipation 836
 - 16.3.2 Equal Wall Temperatures 837
 - 16.3.3 Adiabatic Wall Conditions (Adiabatic Wall Temperature) 839
 - 16.3.4 Recovery Factor 842
 - 16.3.5 Reynolds Analogy 843
 - 16.3.6 Interim Summary 844
- 16.4 Compressible Couette Flow 846
 - 16.4.1 Shooting Method 848
 - 16.4.2 Time-Dependent Finite-Difference Method 850
 - 16.4.3 Results for Compressible Couette Flow 854
 - 16.4.4 Some Analytical Considerations 856

16.5 Two-Dimensional Poiseuille Flow 861

16.6 Summary 865

16.6.1 Couette Flow 865

16.6.2 Poiseuille Flow 865

Chapter 17

Introduction to Boundary Layers 867

- 17.1 Introduction 868
- 17.2 Boundary-Layer Properties 870
- 17.3 The Boundary-Layer Equations 876
- 17.4 How Do We Solve the Boundary-Layer Equations? 879
- 17.5 Summary 881

Chapter 18

Laminar Boundary Layers 883

- 18.1 Introduction 883
- 18.2 Incompressible Flow over a Flat Plate: The Blasius Solution 884
- 18.3 Compressible Flow over a Flat Plate 891
 - 18.3.1 A Comment on Drag Variation with Velocity 902
- 18.4 The Reference Temperature Method 903
 - 18.4.1 Recent Advances: The Meador-Smart Reference Temperature Method 906
- 18.5 Stagnation Point Aerodynamic Heating 907
- 18.6 Boundary Layers over Arbitrary Bodies: Finite-Difference Solution 913
 - 18.6.1 Finite-Difference Method 914
- 18.7 Summary 919
- 18.8 Problems 920

Chapter 19

Turbulent Boundary Layers 921

- 19.1 Introduction 922
- 19.2 Results for Turbulent Boundary Layers on a Flat Plate 922

19.2.1	<i>Reference Temperature Method for Turbulent Flow</i>	924	20.4	The Issue of Accuracy for the Prediction of Skin Friction Drag	942
19.2.2	<i>The Meador-Smart Reference Temperature Method for Turbulent Flow</i>	926	20.5	Summary	947
19.2.3	<i>Prediction of Airfoil Drag</i>	927		Appendix A	
19.3	Turbulence Modeling	927		Aerodynamic Research Activities in India	949
19.3.1	<i>The Baldwin-Lomax Model</i>	928		Appendix B	
19.4	Final Comments	930		Isentropic Flow Properties	975
19.5	Summary	931		Appendix C	
19.6	Problems	932		Normal Shock Properties	981
Chapter 20					
Navier-Stokes Solutions: Some Examples 933					
20.1	Introduction	934		Appendix D	
20.2	The Approach	934		Prandtl-Meyer Function and Mach Angle	985
20.3	Examples of Some Solutions	935		Appendix E	
20.3.1	<i>Flow over a Rearward-Facing Step</i>	935		Standard Atmosphere, SI Units	989
20.3.2	<i>Flow over an Airfoil</i>	935		Appendix F	
20.3.3	<i>Flow over a Complete Airplane</i>	938		Standard Atmosphere, English Engineering Units	999
20.3.4	<i>Shock-Wave/Boundary-Layer Interaction</i>	939		Bibliography	1007
20.3.5	<i>Flow over an Airfoil with a Protuberance</i>	940		Index	1013