

Preface to the Sixth Edition XV

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 15
- 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 41
- 1.9** Fluid Statics: Buoyancy Force 52
- 1.10** Types of Flow 62
 - 1.10.1 Continuum Versus Free Molecule Flow* 62
 - 1.10.2 Inviscid Versus Viscous Flow* 62
 - 1.10.3 Incompressible Versus Compressible Flows* 64
 - 1.10.4 Mach Number Regimes* 64
- 1.11** Viscous Flow: Introduction to Boundary Layers 68
- 1.12** Applied Aerodynamics: The Aerodynamic Coefficients—Their Magnitudes and Variations 75

1.13 Historical Note: The Illusive Center of Pressure 89

1.14 Historical Note: Aerodynamic Coefficients 93

1.15 Summary 97

1.16 Integrated Work Challenge: Forward-Facing Axial Aerodynamic Force on an Airfoil—Can It Happen and, If So, How? 98

1.17 Problems 101

Chapter 2

Aerodynamics: Some Fundamental Principles and Equations 105

- 2.1** Introduction and Road Map 106
- 2.2** Review of Vector Relations 107
 - 2.2.1 Some Vector Algebra* 108
 - 2.2.2 Typical Orthogonal Coordinate Systems* 109
 - 2.2.3 Scalar and Vector Fields* 112
 - 2.2.4 Scalar and Vector Products* 112
 - 2.2.5 Gradient of a Scalar Field* 113
 - 2.2.6 Divergence of a Vector Field* 115
 - 2.2.7 Curl of a Vector Field* 116
 - 2.2.8 Line Integrals* 116
 - 2.2.9 Surface Integrals* 117
 - 2.2.10 Volume Integrals* 118
 - 2.2.11 Relations Between Line, Surface, and Volume Integrals* 119
 - 2.2.12 Summary* 119
- 2.3** Models of the Fluid: Control Volumes and Fluid Elements 119
 - 2.3.1 Finite Control Volume Approach* 120
 - 2.3.2 Infinitesimal Fluid Element Approach* 121
 - 2.3.3 Molecular Approach* 121

2.3.4 *Physical Meaning of the Divergence of Velocity* 122

2.3.5 *Specification of the Flow Field* 123

2.4 Continuity Equation 127

2.5 Momentum Equation 132

2.6 An Application of the Momentum Equation: Drag of a Two-Dimensional Body 137

2.6.1 *Comment* 146

2.7 Energy Equation 146

2.8 Interim Summary 151

2.9 Substantial Derivative 152

2.10 Fundamental Equations in Terms of the Substantial Derivative 158

2.11 Pathlines, Streamlines, and Streaklines of a Flow 160

2.12 Angular Velocity, Vorticity, and Strain 165

2.13 Circulation 176

2.14 Stream Function 179

2.15 Velocity Potential 183

2.16 Relationship Between the Stream Function and Velocity Potential 186

2.17 How Do We Solve the Equations? 187

2.17.1 *Theoretical (Analytical) Solutions* 187

2.17.2 *Numerical Solutions—Computational Fluid Dynamics (CFD)* 189

2.17.3 *The Bigger Picture* 196

2.18 Summary 196

2.19 Problems 200

3.4 Pitot Tube: Measurement of Airspeed 226

3.5 Pressure Coefficient 235

3.6 Condition on Velocity for Incompressible Flow 237

3.7 Governing Equation for Irrotational, Incompressible Flow: Laplace's Equation 238

3.7.1 *Infinity Boundary Conditions* 241

3.7.2 *Wall Boundary Conditions* 241

3.8 Interim Summary 242

3.9 Uniform Flow: Our First Elementary Flow 243

3.10 Source Flow: Our Second Elementary Flow 245

3.11 Combination of a Uniform Flow with a Source and Sink 249

3.12 Doublet Flow: Our Third Elementary Flow 253

3.13 Nonlifting Flow over a Circular Cylinder 255

3.14 Vortex Flow: Our Fourth Elementary Flow 264

3.15 Lifting Flow over a Cylinder 268

3.16 The Kutta-Joukowski Theorem and the Generation of Lift 282

3.17 Nonlifting Flows over Arbitrary Bodies: The Numerical Source Panel Method 284

3.18 Applied Aerodynamics: The Flow over a Circular Cylinder—The Real Case 294

3.19 Historical Note: Bernoulli and Euler—The Origins of Theoretical Fluid Dynamics 302

3.20 Historical Note: d'Alembert and His Paradox 307

3.21 Summary 308

3.22 Integrated Work Challenge: Relation Between Aerodynamic Drag and the Loss of Total Pressure in the Flow Field 311

3.23 Integrated Work Challenge: Conceptual Design of a Subsonic Wind Tunnel 314

3.24 Problems 318

PART 2

Inviscid, Incompressible Flow 203

Chapter 3

Fundamentals of Inviscid, Incompressible Flow 205

3.1 Introduction and Road Map 206

3.2 Bernoulli's Equation 209

3.3 Incompressible Flow in a Duct: The Venturi and Low-Speed Wind Tunnel 213

Chapter 4**Incompressible Flow over Airfoils 321**

- 4.1** Introduction 323
- 4.2** Airfoil Nomenclature 326
- 4.3** Airfoil Characteristics 328
- 4.4** Philosophy of Theoretical Solutions for Low-Speed Flow over Airfoils: The Vortex Sheet 333
- 4.5** The Kutta Condition 338
 - 4.5.1 Without Friction Could We Have Lift? 342*
- 4.6** Kelvin's Circulation Theorem and the Starting Vortex 342
- 4.7** Classical Thin Airfoil Theory: The Symmetric Airfoil 346
- 4.8** The Cambered Airfoil 356
- 4.9** The Aerodynamic Center: Additional Considerations 365
- 4.10** Lifting Flows over Arbitrary Bodies: The Vortex Panel Numerical Method 369
- 4.11** Modern Low-Speed Airfoils 375
- 4.12** Viscous Flow: Airfoil Drag 379
 - 4.12.1 Estimating Skin-Friction Drag: Laminar Flow 380*
 - 4.12.2 Estimating Skin-Friction Drag: Turbulent Flow 382*
 - 4.12.3 Transition 384*
 - 4.12.4 Flow Separation 389*
 - 4.12.5 Comment 394*
- 4.13** Applied Aerodynamics: The Flow over an Airfoil—The Real Case 395
- 4.14** Historical Note: Early Airplane Design and the Role of Airfoil Thickness 406
- 4.15** Historical Note: Kutta, Joukowski, and the Circulation Theory of Lift 411
- 4.16** Summary 413
- 4.17** Integrated Work Challenge: Wall Effects on Measurements Made in Subsonic Wind Tunnels 415
- 4.18** Problems 419

Chapter 5**Incompressible Flow over Finite Wings 423**

- 5.1** Introduction: Downwash and Induced Drag 427
- 5.2** The Vortex Filament, the Biot-Savart Law, and Helmholtz's Theorems 432
- 5.3** Prandtl's Classical Lifting-Line Theory 436
 - 5.3.1 Elliptical Lift Distribution 442*
 - 5.3.2 General Lift Distribution 447*
 - 5.3.3 Effect of Aspect Ratio 450*
 - 5.3.4 Physical Significance 456*
- 5.4** A Numerical Nonlinear Lifting-Line Method 465
- 5.5** The Lifting-Surface Theory and the Vortex Lattice Numerical Method 469
- 5.6** Applied Aerodynamics: The Delta Wing 476
- 5.7** Historical Note: Lanchester and Prandtl—The Early Development of Finite-Wing Theory 488
- 5.8** Historical Note: Prandtl—The Man 492
- 5.9** Summary 495
- 5.10** Problems 496

Chapter 6**Three-Dimensional Incompressible Flow 499**

- 6.1** Introduction 499
- 6.2** Three-Dimensional Source 500
- 6.3** Three-Dimensional Doublet 502
- 6.4** Flow over a Sphere 504
 - 6.4.1 Comment on the Three-Dimensional Relieving Effect 506*
- 6.5** General Three-Dimensional Flows: Panel Techniques 507
- 6.6** Applied Aerodynamics: The Flow over a Sphere—The Real Case 509

6.7	Applied Aerodynamics: Airplane Lift and Drag	512
6.7.1	Airplane Lift	512
6.7.2	Airplane Drag	514
6.7.3	<i>Application of Computational Fluid Dynamics for the Calculation of Lift and Drag</i>	519
6.8	Summary	523
6.9	Problems	524

PART 3
Inviscid, Compressible Flow 525

Chapter 7

Compressible Flow: Some Preliminary Aspects 527

7.1	Introduction	528
7.2	A Brief Review of Thermodynamics	530
7.2.1	<i>Perfect Gas</i>	530
7.2.2	<i>Internal Energy and Enthalpy</i>	530
7.2.3	<i>First Law of Thermodynamics</i>	535
7.2.4	<i>Entropy and the Second Law of Thermodynamics</i>	536
7.2.5	<i>Isentropic Relations</i>	538
7.3	Definition of Compressibility	542
7.4	Governing Equations for Inviscid, Compressible Flow	543
7.5	Definition of Total (Stagnation) Conditions	545
7.6	Some Aspects of Supersonic Flow: Shock Waves	552
7.7	Summary	556
7.8	Problems	558

Chapter 8

8.1	Normal Shock Waves and Related Topics	561
8.2	Introduction	562
8.2	The Basic Normal Shock Equations	563

8.3	Speed of Sound	567
8.3.1	<i>Comments</i>	575
8.4	Special Forms of the Energy Equation	576
8.5	When Is a Flow Compressible?	584
8.6	Calculation of Normal Shock-Wave Properties	587
8.6.1	<i>Comment on the Use of Tables to Solve Compressible Flow Problems</i>	602
8.7	Measurement of Velocity in a Compressible Flow	603
8.7.1	<i>Subsonic Compressible Flow</i>	603
8.7.2	<i>Supersonic Flow</i>	604
8.8	Summary	608
8.9	Problems	611

Chapter 9

Oblique Shock and Expansion Waves 613

9.1	Introduction	614
9.2	Oblique Shock Relations	620
9.3	Supersonic Flow over Wedges and Cones	634
9.3.1	<i>A Comment on Supersonic Lift and Drag Coefficients</i>	637
9.4	Shock Interactions and Reflections	638
9.5	Detached Shock Wave in Front of a Blunt Body	644
9.5.1	<i>Comment on the Flow Field Behind a Curved Shock Wave: Entropy Gradients and Vorticity</i>	648
9.6	Prandtl-Meyer Expansion Waves	648
9.7	Shock-Expansion Theory: Applications to Supersonic Airfoils	660
9.8	A Comment on Lift and Drag Coefficients	664
9.9	The X-15 and Its Wedge Tail	664
9.10	Viscous Flow: Shock-Wave/Boundary-Layer Interaction	669
9.11	Historical Note: Ernst Mach—A Biographical Sketch	671

9.12 Summary 674
9.13 Integrated Work Challenge: Relation Between Supersonic Wave Drag and Entropy Increase—Is There a Relation? 675
9.14 Integrated Work Challenge: The Sonic Boom 678
9.15 Problems 681

Chapter 10

Compressible Flow Through Nozzles, Diffusers, and Wind Tunnels 689

10.1 Introduction 690
10.2 Governing Equations for Quasi-One-Dimensional Flow 692
10.3 Nozzle Flows 701
 10.3.1 *More on Mass Flow* 715
10.4 Diffusers 716
10.5 Supersonic Wind Tunnels 718
10.6 Viscous Flow: Shock-Wave/ Boundary-Layer Interaction Inside Nozzles 724
10.7 Summary 726
10.8 Integrated Work Challenge: Conceptual Design of a Supersonic Wind Tunnel 727
10.9 Problems 736

Chapter 11

Subsonic Compressible Flow over Airfoils: Linear Theory 739

11.1 Introduction 740
11.2 The Velocity Potential Equation 742
11.3 The Linearized Velocity Potential Equation 745
11.4 Prandtl-Glauert Compressibility Correction 750
11.5 Improved Compressibility Corrections 755

11.6 Critical Mach Number 756
 11.6.1 *A Comment on the Location of Minimum Pressure (Maximum Velocity)* 765
11.7 Drag-Divergence Mach Number: The Sound Barrier 765
11.8 The Area Rule 773
11.9 The Supercritical Airfoil 775
11.10 CFD Applications: Transonic Airfoils and Wings 777
11.11 Applied Aerodynamics: The Blended Wing Body 782
11.12 Historical Note: High-Speed Airfoils—Early Research and Development 788
11.13 Historical Note: The Origin of the Swept-Wing Concept 792
11.14 Historical Note: Richard T. Whitcomb—Architect of the Area Rule and the Supercritical Wing 801
11.15 Summary 802
11.16 Integrated Work Challenge: Transonic Testing by the Wing-Flow Method 804
11.17 Problems 808

Chapter 12

Linearized Supersonic Flow 811

12.1 Introduction 812
12.2 Derivation of the Linearized Supersonic Pressure Coefficient Formula 812
12.3 Application to Supersonic Airfoils 816
12.4 Viscous Flow: Supersonic Airfoil Drag 822
12.5 Summary 825
12.6 Problems 826

Chapter 13

Introduction to Numerical Techniques for Nonlinear Supersonic Flow 829

13.1 Introduction: Philosophy of Computational Fluid Dynamics 830

Appendix A	
Isentropic Flow Properties	1079
Appendix B	
Normal Shock Properties	1085
Appendix C	
Prandtl-Meyer Function and Mach	
Angle	1089
Appendix D	
Standard Atmosphere,	
SI Units	1093
Appendix E	
Standard Atmosphere, English Engineering	
Units	1103
References	1111
Index	1117