

Preface to the First Edition xix

Preface to the Fourth Edition xxiii

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

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

Chapter 4	Chapter 5
Incompressible Flow over Airfoils 295	Incompressible Flow over Finite Wings 391
1 Introduction 297	5.1 Introduction: Downwash and Induced Drag 395
2 Airfoil Nomenclature 300	5.2 The Vortex Filament, the Biot-Savart Law, and Helmholtz's Theorems 400
3 Airfoil Characteristics 302	5.3 Prandtl's Classical Lifting-Line Theory 404
4 Philosophy of Theoretical Solutions for Low-Speed Flow over Airfoils: The Vortex Sheet 307	5.3.1 <i>Elliptical Lift Distribution</i> 410
5 The Kutta Condition 312	5.3.2 <i>General Lift Distribution</i> 415
4.5.1 <i>Without Friction Could We Have Lift?</i> 316	5.3.3 <i>Effect of Aspect Ratio</i> 418
6 Kelvin's Circulation Theorem and the Starting Vortex 316	5.3.4 <i>Physical Significance</i> 424
7 Classical Thin Airfoil Theory: The Symmetric Airfoil 319	5.4 A Numerical Nonlinear Lifting-Line Method 433
8 The Cambered Airfoil 329	5.5 The Lifting-Surface Theory and the Vortex Lattice Numerical Method 437
9 The Aerodynamic Center: Additional Considerations 338	5.6 Applied Aerodynamics: The Delta Wing 444
10 Lifting Flows over Arbitrary Bodies: The Vortex Panel Numerical Method 342	5.7 Historical Note: Lanchester and Prandtl—The Early Development of Finite-Wing Theory 456
11 Modern Low-Speed Airfoils 348	5.8 Historical Note: Prandtl—The Man 460
12 Viscous Flow: Airfoil Drag 352	5.9 Summary 463
4.12.1 <i>Estimating Skin-Friction Drag: Laminar Flow</i> 353	5.10 Problems 464
4.12.2 <i>Estimating Skin-Friction Drag: Turbulent Flow</i> 355	
4.12.3 <i>Transition</i> 357	Chapter 6
4.12.4 <i>Flow Separation</i> 362	Three-Dimensional Incompressible Flow 467
4.12.5 <i>Comment</i> 367	6.1 Introduction 467
13 Applied Aerodynamics: The Flow over an Airfoil—The Real Case 368	6.2 Three-Dimensional Source 468
14 Historical Note: Early Airplane Design and the Role of Airfoil Thickness 379	6.3 Three-Dimensional Doublet 470
15 Historical Note: Kutta, Joukowski, and the Circulation Theory of Lift 384	6.4 Flow over a Sphere 472
16 Summary 386	6.4.1 <i>Comment on the Three-Dimensional Relieving Effect</i> 474
17 Problems 388	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

CONTENTS

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 *Iisentropic 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
19.2.2	<i>The Meador-Smart Reference Temperature Method for Turbulent Flow</i>	926
19.2.3	<i>Prediction of Airfoil Drag</i>	927
19.3	Turbulence Modeling	927
19.3.1	<i>The Baldwin-Lomax Model</i>	928
19.4	Final Comments	930
19.5	Summary	931
19.6	Problems	932
Chapter 20		
Navier-Stokes Solutions: Some Examples 933		
20.1	Introduction	934
20.2	The Approach	934
20.3	Examples of Some Solutions	935
20.3.1	<i>Flow over a Rearward-Facing Step</i>	935
20.3.2	<i>Flow over an Airfoil</i>	935
20.3.3	<i>Flow over a Complete Airplane</i>	938
20.3.4	<i>Shock-Wave/Boundary-Layer Interaction</i>	939
20.3.5	<i>Flow over an Airfoil with a Protuberance</i>	940

20.4	The Issue of Accuracy for the Prediction of Skin Friction Drag	942
------	--	-----

20.5	Summary	947
------	---------	-----

Appendix A	Isentropic Flow Properties	949
-------------------	-----------------------------------	------------

Appendix B	Normal Shock Properties	955
-------------------	--------------------------------	------------

Appendix C	Prandtl-Meyer Function and Mach Angle	959
-------------------	--	------------

Appendix D	Standard Atmosphere, SI Units	963
-------------------	--------------------------------------	------------

Appendix E	Standard Atmosphere, English Engineering Units	973
-------------------	---	------------

Bibliography	981
---------------------	------------

Index	987
--------------	------------