

# Contents

Preface .....	xv
<b>CHAPTER 1 Basic Concepts and Definitions .....</b>	<b>1</b>
<b>1.1 Introduction .....</b>	<b>1</b>
1.1.1 Basic Concepts .....	2
1.1.2 Measures of Dynamical Properties .....	4
<b>1.2 Units and Dimensions .....</b>	<b>5</b>
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
<b>1.3 Relevant Properties .....</b>	<b>12</b>
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
<b>1.4 Aeronautical Definitions .....</b>	<b>25</b>
1.4.1 Airfoil Geometry .....	25
1.4.2 Wing Geometry .....	27
<b>1.5 Dimensional Analysis .....</b>	<b>29</b>
1.5.1 Fundamental Principles .....	29
1.5.2 Dimensional Analysis Applied to Aerodynamic Force ..	32
<b>1.6 Basic Aerodynamics .....</b>	<b>38</b>
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	2.9	Properties of the Navier-Stokes Equations .....	117
1.6.9	Airfoil Characteristics .....	58	2.10	Exact Solutions of the Navier-Stokes Equations .....	121
1.7	Exercises .....	65	2.10.1	Couette Flow: Simple Shear Flow .....	122
<b>CHAPTER 2</b>	<b>Fundamental Equations of Fluid Mechanics .....</b>	<b>69</b>	2.10.2	Plane Poiseuille Flow: Pressure-Driven Channel Flow .....	122
2.1	Introduction .....	69	2.10.3	Hiemenz Flow: Two-Dimensional Stagnation-Point Flow .....	124
2.1.1	Selection of Coordinates .....	70	2.11	Prandtl's Boundary-Layer Equations .....	128
2.1.2	A Comparison of Steady and Unsteady Flow .....	71	2.11.1	Development of the Boundary Layer .....	130
2.2	One-Dimensional Flow: The Basic Equations .....	73	2.11.2	Boundary-Layer Thickness .....	132
2.2.1	One-Dimensional Flow: The Basic Equations of Conservation .....	73	2.11.3	Nondimensional Profile .....	132
2.2.2	Comments on the Momentum and Energy Equations .....	80	2.11.4	Laminar and Turbulent Flows .....	133
2.3	Measurement of Air Speed .....	81	2.11.5	Growth along a Flat Surface .....	134
2.3.1	Pitôt-Static Tube .....	81	2.11.6	Effects of an External Pressure Gradient .....	136
2.3.2	Pressure Coefficient .....	82	2.12	Boundary-Layer Equations .....	137
2.3.3	Air-Speed Indicator: Indicated and Equivalent Air Speeds .....	83	2.12.1	Derivation of the Laminar Boundary-Layer Equations .....	138
2.3.4	Incompressibility Assumption .....	84	2.12.2	Boundary-Layer Thickness for Laminar and Turbulent Flows .....	143
2.4	Two-Dimensional Flow .....	87	2.12.3	Boundary-Layer/Potential-Flow Model of Airfoils and Wings .....	144
2.4.1	Component Velocities .....	88	2.13	Exercises .....	144
2.4.2	Equation of Continuity or Conservation of Mass .....	91	<b>CHAPTER 3</b>	<b>Potential Flow .....</b>	<b>149</b>
2.4.3	Equation of Continuity in Polar Coordinates .....	93	3.1	Two-Dimensional Flows .....	149
2.5	Stream Function and Streamline .....	94	3.1.1	The Velocity Potential .....	153
2.5.1	Stream Function $\psi$ .....	94	3.1.2	The Equipotential .....	155
2.5.2	Streamline .....	96	3.1.3	Velocity Components in Terms of $\phi$ .....	156
2.5.3	Velocity Components in Terms of $\psi$ .....	97	3.2	Standard Flows in Terms of $\psi$ and $\phi$ .....	157
2.6	Momentum Equation .....	100	3.2.1	Uniform Flow .....	158
2.6.1	Euler Equations .....	105	3.2.2	Two-Dimensional Flow from a Source (or towards a Sink) .....	160
2.7	Rates of Strain, Rotational Flow, and Vorticity .....	105	3.2.3	Doublet Located at $(x, y) = (0, 0)$ .....	162
2.7.1	Distortion of Fluid Element in Flow Field .....	106	3.2.4	Line (Point) Vortex .....	163
2.7.2	Rate of Shear Strain .....	107	3.2.5	Solid Boundaries and Image Systems .....	165
2.7.3	Rate of Direct Strain .....	108	3.2.6	Rankine Leading Edge .....	168
2.7.4	Vorticity .....	109	3.2.7	Rankine Oval .....	171
2.7.5	Vorticity in Polar Coordinates .....	109	3.2.8	Circular Cylinder with Circulation in a Cross Flow .....	175
2.7.6	Rotational and Irrotational Flow .....	110	3.2.9	Joukowski Airfoil and the Circular Cylinder .....	182
2.7.7	Circulation .....	110	3.3	Axisymmetric Flows (Inviscid and Incompressible Flows) .....	183
2.8	Navier-Stokes Equations .....	113	3.3.1	Cylindrical Coordinate System .....	184
2.8.1	Relationship between Rates of Strain and Viscous Stresses .....	113	3.3.2	Spherical Coordinates .....	185
2.8.2	Derivation of the Navier-Stokes Equations .....	115			

3.3.3 Axisymmetric Flow from a Point Source (or towards a Point Sink) .....	186	5.1.3 Bound Vortex System.....	272
3.3.4 Point Source and Sink in a Uniform Axisymmetric Flow .....	187	5.1.4 Horseshoe Vortex .....	273
3.3.5 The Point Doublet and the Potential Flow around a Sphere .....	189	<b>5.2</b> Laws of Vortex Motion .....	273
3.3.6 Flow around Slender Bodies .....	192	5.2.1 Helmholtz's Theorems.....	275
<b>3.4</b> Computational (Panel) Methods .....	195	5.2.2 The Biot-Savart Law.....	276
<b>3.5</b> Exercises .....	203	5.2.3 Variation of Velocity in Vortex Flow .....	279
 		<b>5.3</b> The Wing as a Simplified Horseshoe Vortex .....	281
<b>CHAPTER 4 Two-Dimensional Wing Theory .....</b>	<b>209</b>	5.3.1 Influence of Downwash on the Tailplane .....	285
<b>4.1</b> Introduction .....	209	5.3.2 Ground Effects .....	286
4.1.1 The Kutta Condition .....	211	<b>5.4</b> Vortex Sheets.....	289
4.1.2 Circulation and Vorticity.....	213	5.4.1 Use of Vortex Sheets to Model the Lifting Effects of a Wing.....	290
4.1.3 Circulation and Lift (The Kutta–Joukowski Theorem) .....	218	<b>5.5</b> Relationship between Spanwise Loading and Trailing Vorticity .....	294
<b>4.2</b> The Development of Airfoil Theory .....	220	5.5.1 Induced Velocity (Downwash) .....	296
<b>4.3</b> General Thin-Airfoil Theory .....	223	5.5.2 The Consequences of Downwash—Trailing Vortex Drag .....	299
<b>4.4</b> Solution to the General Equation .....	228	5.5.3 Characteristics of Simple Symmetric Loading—Elliptic Distribution .....	302
4.4.1 Thin Symmetrical Flat-Plate Airfoil .....	229	5.5.4 General (Series) Distribution of Lift .....	306
4.4.2 General Thin-Airfoil Section .....	231	5.5.5 Aerodynamic Characteristics for Symmetrical General Loading .....	309
<b>4.5</b> The Flapped Airfoil.....	235	<b>5.6</b> Determination of Load Distribution on a Given Wing.....	315
4.5.1 Hinge Moment Coefficient .....	237	5.6.1 General Theory for Wings of High Aspect Ratio.....	316
<b>4.6</b> The Jet Flap .....	240	5.6.2 General Solution to Prandtl's Integral Equation.....	318
<b>4.7</b> Normal Force and Pitching Moment Derivatives Due to Pitching .....	240	5.6.3 Load Distribution for Minimum Drag .....	323
4.7.1 $(Z_q)(M_q)$ Wing Contributions .....	241	<b>5.7</b> Swept and Delta Wings .....	325
<b>4.8</b> Particular Camber Lines.....	245	5.7.1 Yawed Wings of Infinite Span.....	326
4.8.1 Cubic Camber Lines .....	245	5.7.2 Swept Wings of Finite Span .....	327
4.8.2 NACA Four-Digit Wing Sections .....	249	5.7.3 Wings of Small Aspect Ratio.....	330
<b>4.9</b> The Thickness Problem for Thin-Airfoil Theory .....	251	<b>5.8</b> Computational (Panel) Methods for Wings.....	337
4.9.1 Thickness Problem for Thin Airfoils.....	252	<b>5.9</b> Exercises .....	342
<b>4.10</b> Computational (Panel) Methods for Two-Dimensional Lifting Flows .....	256	 	
<b>4.11</b> Exercises .....	265	<b>CHAPTER 6 Compressible Flow.....</b>	<b>349</b>
 		<b>6.1</b> Introduction .....	350
<b>CHAPTER 5 Wing Theory.....</b>	<b>269</b>	<b>6.2</b> Isentropic One-Dimensional Flow .....	352
<b>5.1</b> The Vortex System.....	270	6.2.1 Pressure, Density, and Temperature Ratios along a Streamline in Isentropic Flow .....	355
5.1.1 Starting Vortex .....	270	6.2.2 Ratio of Areas at Different Sections of the Stream Tube in Isentropic Flow .....	359
5.1.2 Trailing Vortex System .....	271		

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
<b>8.10</b>	<b>Computational Methods .....</b>	<b>565</b>
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
<b>8.11</b>	<b>Estimation of Profile Drag from the Velocity Profile in a Wake .....</b>	<b>581</b>
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
<b>8.12</b>	<b>Some Boundary-Layer Effects in Supersonic Flow .....</b>	<b>587</b>
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
<b>8.13</b>	<b>Exercises .....</b>	<b>598</b>
<b>CHAPTER 9</b>	<b>Flow Control and Wing Design .....</b>	<b>601</b>
<b>9.1</b>	<b>Introduction .....</b>	<b>601</b>
<b>9.2</b>	<b>Maximizing Lift for Single-Element Airfoils .....</b>	<b>602</b>
<b>9.3</b>	<b>Multi-Element Airfoils .....</b>	<b>608</b>
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

<b>9.4</b>	<b>Boundary Layer Control Prevention to Separation .....</b>	<b>621</b>
9.4.1	Boundary-Layer Suction.....	622
9.4.2	Control by Tangential Blowing.....	623
9.4.3	Other Methods of Separation Control.....	630
<b>9.5</b>	<b>Reduction of Skin-Friction Drag.....</b>	<b>631</b>
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
<b>9.6</b>	<b>Reduction of Form Drag .....</b>	<b>638</b>
<b>9.7</b>	<b>Reduction of Induced Drag .....</b>	<b>639</b>
<b>9.8</b>	<b>Reduction of Wave Drag .....</b>	<b>642</b>
<b>CHAPTER 10</b>	<b>Propulsion Devices .....</b>	<b>645</b>
<b>10.1</b>	<b>Froude's Momentum Theory of Propulsion .....</b>	<b>645</b>
<b>10.2</b>	<b>Airscrew Coefficients.....</b>	<b>652</b>
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
<b>10.3</b>	<b>Airscrew Pitch .....</b>	<b>659</b>
10.3.1	Geometric Pitch .....	659
10.3.2	Effect of Geometric Pitch on Airscrew Performance ...	660
10.3.3	Experimental Mean Pitch .....	662
<b>10.4</b>	<b>Blade-Element Theory .....</b>	<b>662</b>
10.4.1	Vortex System of an Airscrew .....	662
10.4.2	Performance of a Blade Element .....	664
<b>10.5</b>	<b>The Momentum Theory Applied to the Helicopter Rotor .....</b>	<b>671</b>
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
<b>10.6</b>	<b>The Rocket Motor .....</b>	<b>675</b>
10.6.1	Free Motion of a Rocket-Propelled Body .....	677
<b>10.7</b>	<b>The Hovercraft.....</b>	<b>682</b>
<b>10.8</b>	<b>Exercises .....</b>	<b>685</b>
<b>Appendix A: Symbols and Notation .....</b>	<b>689</b>	
<b>Appendix B .....</b>	<b>695</b>	

<b>Appendix C: A Solution of Integrals of the Type of Glauert's Integral.....</b>	<b>701</b>
<b>Appendix D: Conversion of Imperial Units to Systéme</b>	
<b>International (SI) Units .....</b>	<b>705</b>
<b>Bibliography .....</b>	<b>707</b>
<b>Index .....</b>	<b>715</b>