

Contents

1	Fundamentals of Fluid Dynamics.	1
1.1	Basic Fluid Kinematics	1
1.1.1	Description and Visualization of Fluid Motion	1
1.1.2	Dilatation and Vorticity	7
1.1.3	Velocity Gradient and Its Decompositions	9
1.1.4	Local and Global Material Derivatives.	15
1.2	Dynamic Equations of Fluid Motion	19
1.2.1	Dynamic Equations for General Fluids	19
1.2.2	Constitutive Relations and Thermodynamics.	22
1.2.3	Navier-Stokes Equations and Perfect Gas.	27
1.2.4	Dominant Non-dimensional Parameters	29
1.3	Wall-Bounded Flows.	32
1.3.1	Boundary Conditions.	32
1.3.2	Fluid Reaction to Solid Boundaries.	33
1.4	Problems for Chapter 1	36
2	Fundamental Processes in Fluid Motion.	39
2.1	Preliminary Observations	39
2.2	Intrinsic Decomposition of Fundamental Processes	42
2.2.1	Helmholtz Decomposition	42
2.2.2	Dynamic Equations for Vorticity and Dilatation	44
2.3	Coupling and Splitting of Fundamental Processes	47
2.3.1	Process Nonlinearity and Coupling Inside the Flow.	48
2.3.2	Process Linear Coupling on Boundaries.	50
2.3.3	Linearized Process Splitting in Unbounded Space.	54
2.4	Far-Field Asymptotics in Unbounded Flow	56
2.4.1	Vorticity and Dilatation Far Fields	56
2.4.2	Velocity Far Field.	58
2.4.3	Far-Field Asymptotics for Steady Flow	61

2.5	A Decoupled Model Flow: Inviscid Gas Dynamics	64
2.5.1	Basic Equations	64
2.5.2	Unsteady Potential Flows.	65
2.5.3	Steady Isentropic Flow	66
2.6	Minimally-Coupled Model: Incompressible Flow	67
2.6.1	Momentum Formulation versus Vorticity Formulation	67
2.6.2	Incompressible Potential Flow	70
2.6.3	Accelerated Body Motion and Virtual Mass	73
2.6.4	Force on a Body in Steady Flow	74
2.7	Problems for Chapter 2	75
3	Vorticity Dynamics	77
3.1	Kinematic Properties of Vorticity Field	77
3.1.1	Vorticity Tube and Circulation	77
3.1.2	Geometric Relation of Velocity and Vorticity	80
3.1.3	Two-Dimensional and Axisymmetric Vortical Flows	86
3.1.4	Biot-Savart Formulas.	88
3.2	Vorticity Kinetic Vector and Circulation-Preserving Flow	93
3.2.1	General Evolution Formulas.	93
3.2.2	Local Material Invariants	95
3.2.3	Vorticity-Tube Stretching and Tilting	98
3.2.4	Bernoulli Integrals	100
3.3	Vorticity Integrals and Their Invariance	103
3.3.1	Total Vorticity and Circulation	104
3.3.2	Lamb-Vector Integrals	105
3.3.3	Vortical and Potential Impulses	107
3.3.4	Helicity	113
3.3.5	Total Kinetic Energy	115
3.4	Physical Causes of Vorticity Kinetics	117
3.4.1	Coriolis Force in Rotating Fluid	118
3.4.2	Baroclinicity.	120
3.4.3	Vorticity Diffusion and Enstrophy Dissipation	123
3.4.4	Vorticity Creation at Boundary	125
3.5	Problems for Chapter 3	128
4	Attached and Free Vortex Layers	135
4.1	Parallel Shear Flows on Upper-Half Plane	135
4.1.1	General Solution in Vorticity Formulation	136
4.1.2	Singular BVF: Stokes First Problem (Rayleigh Problem).	138
4.1.3	Oscillatory BVF: Stokes Second Problem	139

4.2	Boundary Layers: Formulation and Physics	141
4.2.1	From d'Alembert's Paradox to Prandtl's Theory	141
4.2.2	From Rayleigh Problem to Boundary Layer Equations	144
4.2.3	Blasius Boundary Layers	147
4.2.4	Further Issues	148
4.2.5	Vorticity Dynamics in Boundary Layer	152
4.3	High-Frequency Oscillatory Boundary Layer	155
4.4	Free Steady Vortex Layers	158
4.4.1	Free Shear Layer	158
4.4.2	Jet	159
4.4.3	Far Wakes	163
4.5	Problems for Chapter 4	165
5	Vortex Sheet Dynamics	167
5.1	Basic Properties of Free Vortex Sheet	167
5.1.1	Strength and Velocity of Free Vortex Sheet	168
5.1.2	Circulation, Lamb Vector, and Bernoulli Equation	169
5.2	Attached Vortex Sheet and Its Separation	171
5.2.1	Attached and Bound Vortex Sheet	171
5.2.2	Kutta Condition and Vortex-Sheet Separation	174
5.3	Motion of Free Vortex Sheet	177
5.3.1	Rolling up and Kaden's Similarity Law	177
5.3.2	Methods of Computing Vortex Sheet Motion	181
5.4	Formation of Wing Vortices	182
5.4.1	Formation of Wingtip Vortices	182
5.4.2	Formation of Leading-Edge Vortex	184
5.5	On the Role of Vortex-Sheet Dynamics	185
5.6	Problems for Chapter 5	188
6	Axisymmetric Columnar Vortices	191
6.1	General Background	192
6.1.1	Governing Equations and Their Simplifications	192
6.1.2	Simplified Axisymmetric Model Equations	194
6.2	Two-Dimensional Stretch-Free Vortices	195
6.2.1	Steady and Inviscid Pure Vortices	195
6.2.2	Unsteady and Viscous Pure Vortices	196
6.3	Radial-Axial Flow Coupling and Stretched Vortices	198
6.3.1	Burgers Vortex	199
6.3.2	Sullivan Vortex	200
6.4	Azimuthal-Axial Flow Coupling and Batchelor Vortex	202
6.4.1	Slender and Light-Loading Approximation	203
6.4.2	Azimuthal-Axial Flow Coupling	204
6.4.3	Batchelor Vortex	205

6.5	Trailing Vortex with Composite Core Structure	207
6.5.1	Composite Core Structure	208
6.5.2	Moore-Saffman Trailing Vortex	209
6.6	Problems for Chapter 6	211
7	Vortex Rings	215
7.1	General Formulation and Properties	215
7.1.1	Governing Equations	215
7.1.2	Integral Invariants	219
7.1.3	Stokes Streamfunction	220
7.2	Inviscid Vortex Rings	222
7.2.1	Thin-Core Vortex Ring	222
7.2.2	Hill's Spherical Vortex	225
7.2.3	Fraenkel-Norbury Vortex Ring Family	228
7.3	Evolution of Viscous Vortex Rings	230
7.3.1	Early Stage at $\nu T/R_0^2 \ll 1$	230
7.3.2	Matured Stage at $\nu T/R_0^2 = O(1)$	232
7.3.3	Late Stage at $\nu T/R_0^2 \gg 1$	233
7.4	Problems for Chapter 7	235
8	Flow Separation and Separated Flows	237
8.1	Orientation	237
8.2	Generic Steady Flow Separation	239
8.2.1	Separation Criteria	239
8.2.2	Dynamic System and Fixed Points	243
8.2.3	Near-Wall Dynamic System for Flow Separation	246
8.3	Steady Boundary-Layer Separation	249
8.3.1	Deck Structure and Scale Analysis	250
8.3.2	Triple-Deck Equations and Self-induced Pressure Gradient	252
8.3.3	Three-Dimensional Triple Deck	254
8.4	Steady Separated Flows	256
8.4.1	Steady Separated Bubble Flow	256
8.4.2	Fixed-Point Index and Topology of Vector Field	259
8.4.3	Topological Diagnosis of Separated Flows	263
8.4.4	Structural Stability	264
8.4.5	Open Separation with Boundary-Layer Breaking Away	267
8.5	Unsteady Separation and Separated Flow	268
8.5.1	A Highlight of Unsteady Separation	269
8.5.2	Formation of Airfoil Circulation in Starting Flow	270
8.5.3	Separated Flow Over Circular Cylinder	274
8.5.4	Falling Disk in Still Water	277
8.6	Problems for Chapter 8	280

9	Vortical Fluid-Dynamic Force and Moment	283
9.1	Origin of Lift	284
9.1.1	Inviscid Circulation Theory and Criticisms	285
9.1.2	Viscous Circulation Theory	289
9.1.3	Further Issues	293
9.2	Classic Steady Vortical Aerodynamics	295
9.2.1	Steady Lift on Airfoil	295
9.2.2	Steady Lifting-Line Theory	299
9.3	Classic Unsteady Vortical Aerodynamics	303
9.3.1	Vortical Impulse Theory	303
9.3.2	Force and Moment on Unsteady Thin Airfoil	305
9.4	A General Formulation of Vortical-Force Theory	312
9.4.1	Pressure Removal	312
9.4.2	Advection Form of Vortical Force	313
9.4.3	Diffusion Form of Vortical Force	317
9.4.4	Boundary Form of Vortical Force	318
9.5	Problems for Chapter 9	320
10	Vortex Instability, Breakdown, and Transition to Turbulence	325
10.1	Basic Concepts of Vortical-Flow Stability	325
10.1.1	Normal-Mode Analysis	326
10.1.2	Nonmodal Analysis and Transient Growth	330
10.1.3	Receptivity	332
10.2	Instability of Axisymmetric Columnar Vortices	332
10.2.1	Stability of Pure Vortices	333
10.2.2	Temporal Instability of Swirling Vortices	334
10.2.3	Absolute and Convective Instability of Swirling Vortices	337
10.2.4	Instability of Trailing Vortex Pair	340
10.3	Vortex Breakdown	344
10.3.1	Breakdown in Terms of Vorticity Dynamics	346
10.3.2	Breakdown in Term of AI/CI	348
10.4	Vortex Ring Instability and Transition	349
10.4.1	Linear Instability: Single Vortex Ring	350
10.4.2	Nonlinear Instability and Transition: Single Vortex Ring	351
10.4.3	Instability and Transition: Multiple Vortex Rings	352
10.5	Problems for Chapter 10	354
11	Vortical Structures in Transitional and Turbulent Shear Flows	361
11.1	Overview and Background	361
11.1.1	What Is Turbulence	361
11.1.2	Mean Turbulent Flow	366
11.1.3	Vorticity Equations and Statistics	370

11.2	Instability and Transition of Free Shear Layer	372
11.2.1	Instability of Free Shear Layer	372
11.2.2	Free and Forced Evolutions of Spanwise Vortices. . . .	374
11.2.3	Secondary Instability and Formation of Streamwise Vortices	379
11.2.4	Vortex Interaction and Small-Scale Transition	380
11.3	Instability and Transition of Wall Shear Layer	382
11.3.1	Instability Waves and Coherent Structures	382
11.3.2	Secondary Instability and Self-sustaining Cycle of Wall Turbulence	385
11.3.3	Transient Growth and Bypass Transition	387
11.3.4	Hairpin Vortices and Hairpin-Vortex Packets	389
11.3.5	Hypersonic Boundary-Layer Instability and Transition	395
11.4	Two Basic Physical Processes in Turbulence	400
Appendix: Fields of Vectors and Tensors		405
References.		431
Index		441

Vortical Flows

Wu, J.-Z.; Ma, H.-Y.; Zhou, M.-D.

2015, XIV, 446 p. 202 illus., Hardcover

ISBN: 978-3-662-47060-2