

Contents

Preface	xi
1 Continuous matter	1
1.1 Molecules	2
1.2 The continuum approximation	6
1.3 Newtonian mechanics	9
1.4 Reference frames	11
1.5 Cartesian coordinate systems	14
1.6 Fields	15
I Fluids at rest	19
2 Pressure	21
2.1 What is pressure?	21
2.2 The pressure field	24
2.3 Hydrostatics	27
2.4 Equation of state	29
2.5 Bulk modulus	33
2.6 Application: Earth's homentropic atmosphere	34
2.7 Application: The Sun's convective envelope	38
3 Buoyancy and stability	41
3.1 Archimedes' principle	41
3.2 The gentle art of ballooning	44
3.3 Stability of floating bodies	46
3.4 Ship stability	48
4 Hydrostatic shapes	57
4.1 Fluid interfaces in hydrostatic equilibrium	57
4.2 The centrifugal force	58
4.3 The figure of Earth	60
4.4 The Earth, the Moon, and the tides	62
4.5 Application: The tides of Io	66
5 Surface tension	69
5.1 Basic physics of surface tension	69
5.2 Soap bubbles	73
5.3 Pressure discontinuity	76
5.4 The Rayleigh–Plateau instability	78
5.5 Contact angle	81

5.6 Meniscus at a flat wall	84
5.7 Meniscus in a cylindrical tube	86
5.8 Application: Sessile drops and captive bubbles	88
5.9 Application: Pendant drops and tethered bubbles	90
II Solids at rest	95
6 Stress	97
6.1 Friction	97
6.2 Stress fields	99
6.3 The nine components of stress	101
6.4 Mechanical equilibrium	104
6.5 Asymmetric stress tensors	106
7 Strain	109
7.1 Displacement	109
7.2 The displacement field	112
7.3 Geometrical meaning of the strain tensor	116
7.4 Work and energy	119
7.5 Large deformations	120
8 Hooke's law	125
8.1 Young's modulus and Poisson's ratio	125
8.2 Hooke's law in isotropic matter	128
8.3 Static uniform deformation	132
8.4 Elastic energy	134
9 Basic elastostatics	139
9.1 Equations of elastostatics	139
9.2 Standing up to gravity	142
9.3 Bending a beam	146
9.4 Twisting a shaft	150
9.5 Application: Radial deformation of a spherical body	153
9.6 Application: Radial deformation of a cylindrical body	156
10 Slender rods	163
10.1 Small deflections without torsion	163
10.2 Buckling instability	166
10.3 Large deflections without torsion	169
10.4 Mixed bending and twisting	171
10.5 Application: The helical spring	173
11 Computational elastostatics	177
11.1 Theory of the numeric method	177
11.2 Discretization of space	180
11.3 Application: Gravitational settling in two dimensions	182
III Fluids in motion	187
12 Continuum dynamics	189
12.1 The velocity field	189
12.2 Incompressible flow	192

12.3 Mass conservation	194
12.4 Equations of continuum dynamics	198
12.5 Application: Big Bang	200
12.6 Application: Newtonian cosmology	201
13 Nearly ideal flow	207
13.1 Euler equation for incompressible ideal flow	207
13.2 Application: Collapse of a spherical cavity	209
13.3 Steady incompressible ideal flow	211
13.4 Vorticity	216
13.5 Circulation	219
13.6 Potential flow	220
13.7 Application: Cylinder in uniform crosswind	222
13.8 Application: Sphere in a uniform stream	225
13.9 d'Alembert's paradox	226
14 Compressible flow	229
14.1 Small-amplitude sound waves	229
14.2 Steady compressible flow	233
14.3 Application: The Laval nozzle	237
15 Viscosity	243
15.1 Shear viscosity	243
15.2 Velocity-driven planar flow	246
15.3 Dynamics of incompressible Newtonian fluids	250
15.4 Classification of flows	253
15.5 Dynamics of compressible Newtonian fluids	255
15.6 Application: Viscous attenuation of sound	257
16 Channels and pipes	261
16.1 Steady, incompressible, viscous flow	261
16.2 Pressure-driven channel flow	262
16.3 Gravity-driven planar flow	265
16.4 Laminar pipe flow	268
16.5 Phenomenology of turbulent pipe flow	274
16.6 Laminar cylindric flow	277
16.7 Secondary flow and Taylor vortices	281
17 Creeping flow	287
17.1 Stokes flow	287
17.2 Creeping flow around a solid ball	289
17.3 Beyond Stokes' law	294
17.4 Lubrication	298
17.5 Application: Loaded journal bearing	304
18 Rotating fluids	309
18.1 Fictitious forces	309
18.2 Steady flow in a rotating system	312
18.3 The Ekman layer	315
18.4 Application: Steady bathtub vortex	318
18.5 Debunking an urban legend	320
19 Computational fluid dynamics	323
19.1 Unsteady, incompressible flow	323

19.2 Temporal discretization	325
19.3 Spatial discretization	326
19.4 Application: Laminar channel entry flow	330
IV Balance and conservation	337
20 Mechanical balances	339
20.1 Quantities and sources	339
20.2 Mass balance	342
20.3 Momentum balance	343
20.4 Angular momentum balance	346
20.5 Kinetic energy balance	348
20.6 Mechanical energy balance	351
21 Action and reaction	355
21.1 Reaction force	355
21.2 Reaction moment	359
21.3 Application: The Francis turbine	366
22 Energy	371
22.1 First Law of Thermodynamics	371
22.2 Incompressible fluid at rest	375
22.3 Incompressible fluid in motion	380
22.4 General homogeneous isotropic fluids	384
23 Entropy	393
23.1 Entropy in classical thermodynamics	393
23.2 Entropy balance	395
23.3 Fluctuations	398
V Selected topics	401
24 Elastic vibrations	403
24.1 Elastodynamics	403
24.2 Harmonic vibrations	406
24.3 Refraction and reflection	409
24.4 Surface waves	414
25 Gravity waves	419
25.1 Basic wave concepts	419
25.2 Harmonic surface waves	422
25.3 Open surface gravity waves	424
25.4 Capillary waves	429
25.5 Internal waves	431
25.6 Global wave properties	434
25.7 Statistics of wind-generated ocean waves	439
26 Jumps and shocks	443
26.1 Hydraulic jumps	443
26.2 Circular jump	448
26.3 Stationary shocks in uniformly moving fluids	450
26.4 Application: Atmospheric blast wave	454

27 Whirls and vortices	461
27.1 Free cylindrical vortices	461
27.2 Basic vortex theory	464
27.3 Line vortices	466
27.4 Advective vortex spin-up	471
27.5 Steady vortex sustained by secondary flow	472
27.6 Application: The bathtub vortex	475
28 Boundary layers	481
28.1 Basic physics of boundary layers	481
28.2 Boundary layer theory	485
28.3 The Blasius layer	487
28.4 Turbulence in the Blasius layer	492
28.5 Planar stagnation flow	496
28.6 Self-similar boundary layers	498
28.7 Laminar boundary layer separation	501
28.8 Wall-anchored model	502
28.9 Wall derivative plus momentum balance	505
28.10 Momentum plus energy balance	506
28.11 Integral approximation to separation	508
29 Subsonic flight	513
29.1 Aircraft controls	513
29.2 Aerodynamic forces and moments	516
29.3 Steady flight	517
29.4 Estimating lift	520
29.5 Estimating drag	527
29.6 Lift, drag, and the trailing wake	532
29.7 Two-dimensional airfoil theory	537
29.8 The distant laminar wake	541
30 Convection	547
30.1 Heat-driven convection	547
30.2 Convective instability	552
30.3 Linear stability analysis of convection	555
30.4 Application: Rayleigh–Bénard convection	557
31 Turbulence	565
31.1 Scaling in fully developed turbulence	565
31.2 Mean flow and fluctuations	571
31.3 Universal inner layer near a smooth wall	574
31.4 The outer layer	579
31.5 Application: Turbulent channel flow	581
31.6 Application: Turbulent pipe flow	582
31.7 Turbulence modeling	584
VI Appendices	587
A Newtonian mechanics	589
A.1 Dynamic equations	589
A.2 Force and momentum	590
A.3 Moment of force and angular momentum	591

A.4 Power and kinetic energy	592
A.5 Internal and external forces	593
A.6 Hierarchies of particle interactions	594
B Cartesian coordinates	595
B.1 Cartesian vectors	595
B.2 Vector algebra	596
B.3 Basis vectors	598
B.4 Index notation	599
B.5 Cartesian coordinate transformations	601
B.6 Scalars, vectors, and tensors	604
C Field calculus	611
C.1 Spatial derivatives	611
C.2 Spatial integrals	613
C.3 Fundamental integral theorems	614
C.4 Proofs of the fundamental integral theorems	615
C.5 Field transformations	616
D Curvilinear coordinates	619
D.1 Cylindrical coordinates	619
D.2 Spherical coordinates	623
E Ideal gases	627
E.1 Internal energy	627
E.2 Entropy	629
Answers to problems	631
References	665
Index	673