

# Contents

Preface	xi
<b>I Introduction</b>	<b>1</b>
<b>1 Continuous matter</b>	<b>3</b>
1.1 Molecules . . . . .	4
1.2 The continuum approximation . . . . .	6
1.3 Newtonian mechanics . . . . .	9
1.4 Continuum physics . . . . .	10
<i>Problems</i> . . . . .	14
<b>2 Space and time</b>	<b>15</b>
2.1 Reference frames . . . . .	16
2.2 Time . . . . .	16
2.3 Space . . . . .	17
2.4 Vector algebra . . . . .	20
2.5 Basis vectors . . . . .	21
2.6 Index notation . . . . .	23
2.7 Cartesian coordinate transformations . . . . .	24
2.8 Scalars, vectors, and tensors . . . . .	27
2.9 Scalar, vector, and tensor fields . . . . .	29
2.10 Pseudo and improper quantities . . . . .	30
<i>Problems</i> . . . . .	33
<b>3 Gravity</b>	<b>37</b>
3.1 Mass density . . . . .	38
3.2 Gravitational acceleration . . . . .	40

3.3	Sources of gravity . . . . .	43
3.4	Gravitational potential . . . . .	46
3.5	Potential energy . . . . .	49
	<i>Problems</i> . . . . .	52
<b>II Hydrostatics</b>		<b>55</b>
<b>4</b>	<b>Fluids at rest</b>	<b>57</b>
4.1	Pressure . . . . .	58
4.2	Formal definition of pressure . . . . .	61
4.3	Hydrostatic equilibrium . . . . .	63
4.4	Equation of state . . . . .	67
4.5	Barotropic fluid states . . . . .	68
4.6	The homentropic atmosphere . . . . .	71
	<i>Problems</i> . . . . .	75
<b>5</b>	<b>Buoyancy</b>	<b>77</b>
5.1	Archimedes' principle . . . . .	78
5.2	The gentle art of ballooning . . . . .	80
5.3	Stability of floating bodies . . . . .	81
5.4	Ship stability . . . . .	84
	<i>Problems</i> . . . . .	90
<b>6</b>	<b>Planets and stars</b>	<b>93</b>
6.1	Gravitational flux . . . . .	94
6.2	Spherical bodies . . . . .	97
6.3	The homentropic star . . . . .	99
6.4	Field energy . . . . .	104
	<i>Problems</i> . . . . .	107
<b>7</b>	<b>Hydrostatic shapes</b>	<b>109</b>
7.1	Fluid interfaces in hydrostatic equilibrium . . . . .	110
7.2	Shape of rotating fluids . . . . .	111
7.3	The Earth, the Moon and the tides . . . . .	113
7.4	Shape of a rotating fluid planet . . . . .	118
	<i>Problems</i> . . . . .	123
<b>8</b>	<b>Surface tension</b>	<b>125</b>
8.1	Definition of surface tension . . . . .	126
8.2	Contact angle . . . . .	129
8.3	Capillary effect at a vertical wall . . . . .	131
8.4	Axially invariant shapes . . . . .	133
	<i>Problems</i> . . . . .	138

<b>III</b>	<b>Deformable solids</b>	<b>139</b>
<b>9</b>	<b>Stress</b>	<b>141</b>
9.1	Friction . . . . .	142
9.2	The concept of stress . . . . .	143
9.3	Nine components of stress . . . . .	145
9.4	Mechanical equilibrium . . . . .	148
9.5	“Proof” of symmetry of the stress tensor . . . . .	150
	<i>Problems</i> . . . . .	152
<b>10</b>	<b>Strain</b>	<b>155</b>
10.1	Displacement . . . . .	156
10.2	Local deformation . . . . .	158
10.3	Geometrical meaning of the strain tensor . . . . .	162
10.4	Work and energy . . . . .	164
10.5	Finite local deformation . . . . .	165
	<i>Problems</i> . . . . .	168
<b>11</b>	<b>Linear elasticity</b>	<b>171</b>
11.1	Hooke’s law . . . . .	172
11.2	Hooke’s law in isotropic materials . . . . .	174
11.3	Static uniform deformation . . . . .	178
11.4	Energy of deformation . . . . .	180
	<i>Problems</i> . . . . .	185
<b>12</b>	<b>Solids at rest</b>	<b>187</b>
12.1	Equations of elastostatics . . . . .	188
12.2	Standing up to gravity . . . . .	190
12.3	Bending a beam . . . . .	193
12.4	Twisting a shaft . . . . .	196
12.5	Tube under pressure . . . . .	198
12.6	Elastic spherical shell . . . . .	204
	<i>Problems</i> . . . . .	208
<b>13</b>	<b>Elastic vibrations</b>	<b>211</b>
13.1	Elastic waves . . . . .	212
13.2	Free elastic waves . . . . .	213
13.3	Rayleigh waves . . . . .	217
13.4	Radial waves . . . . .	219
	<i>Problems</i> . . . . .	221
<b>14</b>	<b>Numeric elastostatics</b>	<b>223</b>
14.1	Relaxing towards equilibrium . . . . .	224
14.2	Discretization of space . . . . .	225
14.3	Gravitational settling in two dimensions . . . . .	228
	<i>Problems</i> . . . . .	233

<b>IV Basic fluid dynamics</b>	<b>235</b>
<b>15 Fluids in motion</b>	<b>237</b>
15.1 The velocity field . . . . .	238
15.2 Visualization of flow patterns . . . . .	242
15.3 Mass conservation . . . . .	244
15.4 Continuum dynamics . . . . .	248
15.5 Little bangs and Big Bang . . . . .	250
15.6 Newtonian cosmology . . . . .	252
<i>Problems</i> . . . . .	257
<b>16 Nearly ideal flow</b>	<b>259</b>
16.1 The Euler equation . . . . .	260
16.2 Small-amplitude sound waves . . . . .	261
16.3 Steady incompressible flow . . . . .	263
16.4 Steady compressible flow . . . . .	269
16.5 Vorticity . . . . .	275
16.6 Steady, incompressible potential flow . . . . .	278
16.7 Circulation . . . . .	284
<i>Problems</i> . . . . .	288
<b>17 Global laws of balance</b>	<b>291</b>
17.1 Connected tubes . . . . .	292
17.2 Overview of the global laws . . . . .	293
17.3 The control volume . . . . .	294
17.4 Mass balance . . . . .	296
17.5 Momentum balance . . . . .	296
17.6 Reaction forces . . . . .	300
17.7 Angular momentum balance . . . . .	306
17.8 Reaction moments . . . . .	309
17.9 Kinetic energy balance . . . . .	316
17.10 Mechanical energy balance . . . . .	320
17.11 Energy balance in an elastic fluid . . . . .	322
<i>Problems</i> . . . . .	325
<b>18 Viscosity</b>	<b>327</b>
18.1 Shear viscosity . . . . .	328
18.2 Velocity-driven planar flow . . . . .	331
18.3 Incompressible Newtonian fluids . . . . .	334
18.4 Classification of flows . . . . .	338
18.5 Compressible Newtonian fluids . . . . .	342
18.6 Viscous attenuation of sound . . . . .	343
<i>Problems</i> . . . . .	347

<b>19 Channels and pipes</b>	<b>349</b>
19.1 Steady, incompressible flow . . . . .	350
19.2 Planar geometry . . . . .	351
19.3 Pressure driven flow between fixed plates . . . . .	352
19.4 Gravity driven flow with an open surface . . . . .	354
19.5 Tubular geometry . . . . .	355
19.6 Laminar pipe flow . . . . .	356
19.7 Phenomenology of turbulent pipe flow . . . . .	361
19.8 Down the drain, again . . . . .	365
19.9 Circulating cylindrical flow . . . . .	367
19.10 Couette flow between rotating cylinders . . . . .	369
19.11 Secondary flow and Taylor vortices . . . . .	373
<i>Problems</i> . . . . .	376
<b>20 Creeping flow</b>	<b>379</b>
20.1 Steady incompressible creeping flow . . . . .	380
20.2 Stokes' solution for a sphere . . . . .	381
20.3 Beyond Stokes' law . . . . .	385
20.4 Beyond spherical shape . . . . .	388
<i>Problems</i> . . . . .	390
<b>21 Computational fluid dynamics</b>	<b>393</b>
21.1 Unsteady, incompressible flow . . . . .	394
21.2 Temporal discretization . . . . .	396
21.3 Spatial discretization . . . . .	397
21.4 Channel entrance flow . . . . .	402
<i>Problems</i> . . . . .	409
<b>V Special topics</b>	<b>411</b>
<b>22 Small-amplitude surface waves</b>	<b>413</b>
22.1 Basic physics of surface waves . . . . .	414
22.2 Small-amplitude gravity waves . . . . .	420
22.3 Wave energy and momentum . . . . .	425
22.4 Capillary surface waves . . . . .	430
22.5 Internal waves . . . . .	433
22.6 Attenuation of small-amplitude waves . . . . .	437
22.7 Statistics of wind-generated ocean waves . . . . .	439
<i>Problems</i> . . . . .	443

<b>23 Whirls and vortices</b>	<b>447</b>
23.1 Basic vortex dynamics . . . . .	448
23.2 Free cylindrical vortices . . . . .	450
23.3 Steady vortex sustained by secondary flow . . . . .	453
23.4 Advective spin-up of a cylindrical vortex . . . . .	456
23.5 Bathtub-like vortices . . . . .	458
<i>Problems</i> . . . . .	464
<b>24 Lubrication</b>	<b>467</b>
24.1 Lift and drag near a boundary . . . . .	468
24.2 Flow in a narrow gap . . . . .	471
24.3 Flat wing . . . . .	474
24.4 Loaded journal bearing . . . . .	477
<i>Problems</i> . . . . .	481
<b>25 Boundary layers</b>	<b>483</b>
25.1 Physics of boundary layers . . . . .	484
25.2 Growth of a boundary layer . . . . .	489
25.3 Boundary layer theory . . . . .	491
25.4 Laminar boundary layer in uniform flow . . . . .	493
25.5 Turbulent boundary layer in uniform flow . . . . .	496
25.6 Boundary layers with varying slip-flow . . . . .	501
25.7 Boundary layer separation . . . . .	504
25.8 Locating the Goldstein singularity . . . . .	506
<i>Problems</i> . . . . .	513
<b>26 Rotating fluids</b>	<b>517</b>
26.1 Fictitious forces . . . . .	518
26.2 Flow in a rotating system . . . . .	521
26.3 Geostrophic flow . . . . .	523
26.4 The Ekman layer . . . . .	526
26.5 Steady vortex in rotating container . . . . .	530
26.6 Debunking an urban legend . . . . .	534
<i>Problems</i> . . . . .	535
<b>27 Subsonic flight</b>	<b>537</b>
27.1 Aircraft controls . . . . .	538
27.2 Aerodynamic forces and moments . . . . .	541
27.3 Steady flight . . . . .	542
27.4 Estimating lift . . . . .	546
27.5 Estimating drag . . . . .	552
27.6 Lift, drag, and the trailing wake . . . . .	557
27.7 Lift in two-dimensional airfoil theory . . . . .	563
27.8 The distant laminar wake . . . . .	568
<i>Problems</i> . . . . .	574

<b>28 Heat</b>	<b>577</b>
28.1 Energy balance . . . . .	578
28.2 Heat equation for isotropic matter at rest . . . . .	581
28.3 Heat equation for fluids in motion . . . . .	586
28.4 Advective cooling or heating . . . . .	589
<i>Problems</i> . . . . .	594
<b>29 Convection</b>	<b>595</b>
29.1 Convection . . . . .	596
29.2 Convective instability . . . . .	602
29.3 Linear stability analysis of convection . . . . .	605
29.4 Rayleigh-Bénard convection . . . . .	608
<i>Problems</i> . . . . .	616
<b>30 Nonlinear waves</b>	<b>619</b>
30.1 Hydraulic jumps . . . . .	620
30.2 Normal shocks in ideal gases . . . . .	627
30.3 Atmospheric blast wave . . . . .	631
30.4 Nonlinear surface waves . . . . .	636
30.5 The shallow-water approximation . . . . .	637
30.6 Nonlinear deep-water gravity waves . . . . .	639
<i>Problems</i> . . . . .	642
<b>31 Turbulence</b>	<b>643</b>
<b>A Units and constants</b>	<b>645</b>
<b>B Newtonian particle mechanics</b>	<b>647</b>
B.1 Dynamic equations . . . . .	648
B.2 Force and momentum . . . . .	648
B.3 Moment of force and angular momentum . . . . .	650
B.4 Power and kinetic energy . . . . .	651
B.5 Internal and external forces . . . . .	652
B.6 Hierarchies of particle interactions . . . . .	653
<i>Problems</i> . . . . .	654
<b>C Curvilinear coordinates</b>	<b>655</b>
C.1 Cylindrical coordinates . . . . .	655
C.2 Spherical coordinates . . . . .	658
<b>D Thermodynamics of ideal gases</b>	<b>661</b>
D.1 Internal energy . . . . .	661
D.2 Heat capacity . . . . .	662
D.3 Entropy . . . . .	663
D.4 Specific quantities . . . . .	666

<i>Problems</i> . . . . .	667
<b>Answers to problems</b>	<b>669</b>
1 Continuous matter . . . . .	669
2 Space and time . . . . .	670
3 Gravity . . . . .	672
4 Fluids at rest . . . . .	675
5 Buoyancy . . . . .	677
6 Planets and stars . . . . .	681
7 Hydrostatic shapes . . . . .	683
8 Surface tension . . . . .	684
9 Stress . . . . .	684
10 Strain . . . . .	686
11 Elasticity . . . . .	688
12 Solids at rest . . . . .	688
13 Vibrations . . . . .	689
14 Numeric elastostatics . . . . .	690
15 Matter in motion . . . . .	690
16 Nearly ideal flow . . . . .	692
17 Laws of balance . . . . .	693
18 Viscosity . . . . .	697
19 Plates and tubes . . . . .	698
20 Creeping flow . . . . .	700
21 Computational fluid dynamics . . . . .	702
22 Surface waves . . . . .	703
23 Whirls and vortices . . . . .	706
24 Lubrication . . . . .	708
25 Boundary layers . . . . .	709
26 Rotating fluids . . . . .	710
27 Aerodynamics . . . . .	711
28 Heat . . . . .	712
29 Convection . . . . .	713
30 Nonlinear waves . . . . .	714
31 Turbulence . . . . .	715
A Units and constants . . . . .	715
B Newtonian particle mechanics . . . . .	715
C Curvilinear coordinates . . . . .	715
D Thermodynamics of ideal gases . . . . .	715
<b>Bibliography</b>	<b>717</b>
<b>Index</b>	<b>723</b>