

Contents

Preface	xi
I Introduction	1
1 Continuous matter	3
1.1 Molecules	3
1.2 The continuum approximation	5
1.3 Newtonian mechanics	8
1.4 Continuum physics	9
<i>Problems</i>	10
2 Space and time	13
2.1 Reference frames	13
2.2 Time	14
2.3 Space	14
2.4 Vector algebra	16
2.5 Basis vectors	18
2.6 Index notation	19
2.7 Cartesian coordinate transformations	20
2.8 Scalars, vectors, and tensors	22
2.9 Scalar, vector, and tensor fields	23
2.10 Pseudo and improper quantities	24
<i>Problems</i>	25
3 Gravity	29
3.1 Mass density	29
3.2 Gravitational acceleration	30
3.3 Sources of gravity	33
3.4 Gravitational potential	35
3.5 Potential energy	38
<i>Problems</i>	39
II Fluids at rest	43
4 Pressure	45
4.1 The concept of pressure	45
4.2 Formal definition of pressure	47

4.3	Hydrostatic equilibrium	49
4.4	Equation of state	52
4.5	Barotropic fluid states	52
4.6	The homentropic atmosphere	54
	<i>Problems</i>	57
5	Buoyancy	59
5.1	Archimedes' principle	59
5.2	The gentle art of ballooning	61
5.3	Stability of floating bodies	62
5.4	Ship stability	64
	<i>Problems</i>	69
6	Planets and stars	71
6.1	Gravitational flux	71
6.2	Spherical bodies	74
6.3	The homentropic star	75
6.4	Gravitational energy	79
	<i>Problems</i>	81
7	Hydrostatic shapes	83
7.1	Fluid interfaces in hydrostatic equilibrium	83
7.2	Shape of rotating fluids	84
7.3	The Earth, the Moon and the tides	85
7.4	Shape of a rotating fluid planet	90
	<i>Problems</i>	93
8	Surface tension	95
8.1	The Young-Laplace law for surface tension	95
8.2	Contact angle	98
8.3	Capillary effect at a vertical wall	99
8.4	Axially invariant surface shapes	101
	<i>Problems</i>	104
III Deformable solids		105
9	Stress	107
9.1	Friction	107
9.2	The concept of stress	108
9.3	Nine components of stress	109
9.4	Mechanical equilibrium	112
9.5	"Proof" of symmetry of the stress tensor	113
	<i>Problems</i>	114
10	Strain	117
10.1	Displacement	117
10.2	Local deformation	119
10.3	Geometrical meaning of the strain tensor	122
10.4	Work and energy	124
10.5	Finite deformations	125
	<i>Problems</i>	128

11 Linear elasticity	131
11.1 Hooke's law	131
11.2 Hooke's law in isotropic materials	133
11.3 Static uniform deformation	136
11.4 Energy of deformation	137
<i>Problems</i>	140
12 Solids at rest	141
12.1 Equations of elastostatics	141
12.2 Standing up to gravity	143
12.3 Bending a beam	145
12.4 Twisting a shaft	149
12.5 Tube under pressure	151
<i>Problems</i>	156
13 Computational elastostatics	159
13.1 Relaxing towards equilibrium	159
13.2 Discretization of space	160
13.3 Gravitational settling in two dimensions	162
<i>Problems</i>	166
14 Elastic vibrations	167
14.1 Elastodynamics	167
14.2 Refraction and reflection	172
14.3 Surface waves	175
<i>Problems</i>	178
IV Basic hydrodynamics	181
15 Fluids in motion	183
15.1 The velocity field	183
15.2 Incompressible flow	186
15.3 Mass conservation	188
15.4 Moving along with the flow	190
15.5 Continuum dynamics	191
15.6 Big Bang	193
15.7 Newtonian cosmology	195
<i>Problems</i>	198
16 Nearly ideal flow	199
16.1 The Euler equation	199
16.2 Small-amplitude sound waves	200
16.3 Steady incompressible flow	202
16.4 Steady compressible flow	208
16.5 Vorticity	212
16.6 Circulation	215
16.7 Potential flow	216
16.8 Potential flow for cylinder in cross-wind	217
16.9 Potential flow around a sphere in a stream	219
16.10 D'Alembert's paradox	220
<i>Problems</i>	221

17 Viscosity	223
17.1 Shear viscosity	223
17.2 Velocity-driven planar flow	225
17.3 Incompressible Newtonian fluids	228
17.4 Classification of flows	231
17.5 Compressible Newtonian fluids	233
17.6 Viscous attenuation of sound	235
<i>Problems</i>	236
18 Plates and pipes	239
18.1 Steady, incompressible, viscous flow	239
18.2 Pressure-driven planar flow	240
18.3 Gravity-driven planar flow	242
18.4 Pipe flow	244
18.5 Phenomenology of turbulent pipe flow	249
18.6 Circulating cylindrical flow	252
18.7 Secondary flow and Taylor vortices	256
<i>Problems</i>	258
19 Creeping flow	261
19.1 Steady incompressible creeping flow	261
19.2 Creeping flow around a solid ball	263
19.3 Beyond Stokes' law	266
19.4 Beyond spherical shape	269
<i>Problems</i>	270
20 Rotating fluids	273
20.1 Fictitious forces	273
20.2 Flow in a rotating system	275
20.3 Geostrophic flow	277
20.4 The Ekman layer	278
20.5 Steady bathtub vortex in rotating container	281
20.6 Debunking an urban legend	283
<i>Problems</i>	284
21 Computational fluid dynamics	285
21.1 Unsteady, incompressible flow	285
21.2 Temporal discretization	287
21.3 Spatial discretization	288
21.4 Channel entrance flow	291
<i>Problems</i>	296
V Special topics	299
22 Global laws of balance	301
22.1 Connected tubes	301
22.2 Overview of the global laws	302
22.3 The control volume	303
22.4 Mass balance	304
22.5 Momentum balance	305
22.6 Angular momentum balance	307
22.7 Kinetic energy balance	309
22.8 Mechanical energy balance	312
22.9 Energy balance in elastic fluids	313
<i>Problems</i>	315

23 Reaction forces	
and moments	317
23.1 Reaction forces	317
23.2 Formal definition of reaction force	320
23.3 Reaction moments	322
<i>Problems</i>	326
24 Small-amplitude	
surface waves	329
24.1 Basic physics of surface waves	329
24.2 Harmonic line waves	332
24.3 Gravity waves	333
24.4 Capillary surface waves	338
24.5 Internal waves	340
24.6 Energy and attenuation	343
24.7 Statistics of wind-generated ocean waves	345
24.8 Global wave properties	348
<i>Problems</i>	349
25 Jumps and shocks	353
25.1 Hydraulic jumps	353
25.2 Shocks in ideal gases	358
25.3 Atmospheric blast wave	362
<i>Problems</i>	366
26 Whirls and vortices	367
26.1 Free cylindrical vortices	367
26.2 Ideal vortex dynamics	370
26.3 Parallel line vortices	371
26.4 Steady vortex sustained by secondary flow	375
26.5 Advective spin-up of a vortex	377
26.6 Bathtub-like vortices	378
<i>Problems</i>	381
27 Lubrication	385
27.1 Physics of lubrication	385
27.2 Creeping flow in a long narrow gap	388
27.3 Flat wing	390
27.4 Loaded journal bearing	392
<i>Problems</i>	394
28 Boundary layers	397
28.1 Physics of boundary layers	397
28.2 The Stokes layer	401
28.3 Boundary layer theory	403
28.4 The Blasius layer	404
28.5 Turbulent boundary layer in uniform flow	407
28.6 Self-similar boundary layers	410
28.7 Exact results for varying slip-flow	413
28.8 Laminar boundary layer separation	415
<i>Problems</i>	421

29 Subsonic flight	425
29.1 Aircraft controls	425
29.2 Aerodynamic forces and moments	427
29.3 Steady flight	428
29.4 Estimating lift	431
29.5 Estimating drag	436
29.6 Lift, drag, and the trailing wake	440
29.7 Two-dimensional airfoil theory	445
29.8 The distant laminar wake	448
<i>Problems</i>	452
30 Heat	455
30.1 Energy balance	455
30.2 Heat equation for isotropic matter at rest	457
30.3 Heat equation for fluids in motion	461
30.4 Advective cooling or heating	464
<i>Problems</i>	466
31 Convection	469
31.1 Convection	469
31.2 Convective instability	474
31.3 Linear stability analysis of convection	476
31.4 Rayleigh-Bénard convection	479
<i>Problems</i>	484
32 Turbulence	485
32.1 Fully developed turbulence	485
32.2 The energy cascade	486
32.3 Mean flow and fluctuations	490
32.4 Turbulence near a smooth solid wall	493
32.5 Inner layer structure	493
32.6 Outer layer structure	498
32.7 Planar turbulent flows	499
32.8 Turbulent pipe flow	503
32.9 Turbulent boundary layer in uniform flow	505
32.10 Turbulence modeling	508
<i>Problems</i>	509
A Newtonian particle mechanics	511
A.1 Dynamic equations	511
A.2 Force and momentum	512
A.3 Moment of force and angular momentum	513
A.4 Power and kinetic energy	514
A.5 Internal and external forces	514
A.6 Hierarchies of particle interactions	515
<i>Problems</i>	515
B Curvilinear coordinates	517
B.1 Cylindrical coordinates	517
B.2 Spherical coordinates	519
C Thermodynamics of ideal gases	521
C.1 Internal energy	521
C.2 Heat capacity	522
C.3 Entropy	522
C.4 Specific quantities	524
<i>Problems</i>	525

Answers to problems	527
1 Continuous matter	527
2 Space and time	528
3 Gravity	529
4 Fluids at rest	532
5 Buoyancy	534
6 Planets and stars	537
7 Hydrostatic shapes	539
8 Surface tension	539
9 Stress	541
10 Strain	542
11 Elasticity	544
12 Solids at rest	545
13 Computational elastostatics	547
14 Vibrations	547
15 Fluids in motion	548
16 Nearly ideal flow	550
17 Viscosity	552
18 Plates and pipes	553
19 Creeping flow	555
20 Rotating fluids	558
21 Computational fluid dynamics	559
22 Global laws of balance	559
23 Reaction forces and moments	562
24 Jumps and shocks	562
25 Surface waves	563
26 Whirls and vortices	565
27 Lubrication	568
28 Boundary layers	569
29 Subsonic flight	570
30 Heat	573
31 Convection	573
32 Turbulence	574
A Newtonian particle mechanics	575
B Curvilinear coordinates	575
C Thermodynamics of ideal gases	575
List of literature	577
Index	581

