
Contents

→ **Matrices, Vectors, and Vector Calculus 1**

- 1.1 Introduction 1
- 1.2 Concept of a Scalar 2
- 1.3 Coordinate Transformations 3
- 1.4 Properties of Rotation Matrices 6
- 1.5 Matrix Operations 9
- 1.6 Further Definitions 12
- 1.7 Geometrical Significance of Transformation Matrices 14
- 1.8 Definitions of a Scalar and a Vector in Terms of Transformation Properties 20
- 1.9 Elementary Scalar and Vector Operations 20
- 1.10 Scalar Product of Two Vectors 21
- 1.11 Unit Vectors 23
- 1.12 Vector Product of Two Vectors 25
- 1.13 Differentiation of a Vector with Respect to a Scalar 29
- 1.14 Examples of Derivatives—Velocity and Acceleration 30
- 1.15 Angular Velocity 34
- 1.16 Gradient Operator 37
- 1.17 Integration of Vectors 40
- Problems 43

→ **Newtonian Mechanics—Single Particle 48**

- 2.1 Introduction 48
- 2.2 Newton's Laws 49
- 2.3 Frames of Reference 53
- 2.4 The Equation of Motion for a Particle 55

- 2.5 Conservation Theorems 76
- 2.6 Energy 82
- 2.7 Limitations of Newtonian Mechanics 88
- Problems 90




3 Oscillations 99

- 3.1 Introduction 99
- 3.2 Simple Harmonic Oscillator 100
- 3.3 Harmonic Oscillations in Two Dimensions 104
- 3.4 Phase Diagrams 106
- 3.5 Damped Oscillations 108
- 3.6 Sinusoidal Driving Forces 117
- 3.7 Physical Systems 123
- 3.8 Principle of Superposition—Fourier Series 126
- 3.9 The Response of Linear Oscillators to Impulsive Forcing Functions (Optional) 129
- Problems 138

4 Nonlinear Oscillations and Chaos 144

- 4.1 Introduction 144
- 4.2 Nonlinear Oscillations 146
- 4.3 Phase Diagrams for Nonlinear Systems 150
- 4.4 Plane Pendulum 155
- 4.5 Jumps, Hysteresis, and Phase Lags 160
- 4.6 Chaos in a Pendulum 163
- 4.7 Mapping 169
- 4.8 Chaos Identification 174
- Problems 178

5 Gravitation 182

-  5.1 Introduction 182
-  5.2 Gravitational Potential 184
-  5.3 Lines of Force and Equipotential Surfaces 194
- 5.4 When Is the Potential Concept Useful? 195
- 5.5 Ocean Tides 198
- Problems 204

6 Some Methods in the Calculus of Variations 207

- 6.1 Introduction 207
- 6.2 Statement of the Problem 207
- 6.3 Euler's Equation 210

- 6.4 The “Second Form” of the Euler Equation 216
- 6.5 Functions with Several Dependent Variables 218
- 6.6 Euler Equations When Auxiliary Conditions Are Imposed 219
- 6.7 The δ Notation 224
- Problems 226

5 **Hamilton’s Principle—Lagrangian and Hamiltonian Dynamics 228**

- 7.1 Introduction 228
- 7.2 Hamilton’s Principle 229
- 7.3 Generalized Coordinates 233
- 7.4 Lagrange’s Equations of Motion in Generalized Coordinates 237
- 7.5 Lagrange’s Equations with Undetermined Multipliers 248
- 7.6 Equivalence of Lagrange’s and Newton’s Equations 254
- 7.7 Essence of Lagrangian Dynamics 257
- 7.8 A Theorem Concerning the Kinetic Energy 258
- 7.9 Conservation Theorems Revisited 260
- 7.10 Canonical Equations of Motion—Hamiltonian Dynamics 265
- ~~7.11 Some Comments Regarding Dynamical Variables and Variational Calculations in Physics 272~~
- ~~7.12 Phase Space and Liouville’s Theorem (Optional) 274~~
- 7.13 Virial Theorem (Optional) 277
- Problems 280

8 **Central-Force Motion 287**

- 8.1 Introduction 287
- 8.2 Reduced Mass 287
- 8.3 Conservation Theorems—First Integrals of the Motion 289
- 8.4 Equations of Motion 291
- 8.5 Orbits in a Central Field 295
- 8.6 Centrifugal Energy and the Effective Potential 296
- 8.7 Planetary Motion—Kepler’s Problem 300
- ~~8.8 Orbital Dynamics 305~~
- ~~8.9 Apical Angles and Precession (Optional) 312~~
- ~~8.10 Stability of Circular Orbits (Optional) 316~~
- Problems 323

9 **Dynamics of a System of Particles 328**

- 9.1 Introduction 328
- 9.2 Center of Mass 329
- 9.3 Linear Momentum of the System 331

- 9.4 Angular Momentum of the System 336
- 9.5 Energy of the System 339
- 9.6 Elastic Collisions of Two Particles 345
- 9.7 Kinematics of Elastic Collisions 352
- 9.8 Inelastic Collisions 358
- ~~9.9 Scattering Cross Sections 363~~
- ~~9.10 Rutherford Scattering Formula 369~~
- 9.11 Rocket Motion 371
 - Problems 378

10 Motion in a Noninertial Reference Frame 387

- 10.1 Introduction 387
- 10.2 Rotating Coordinate Systems 388
- 10.3 Centrifugal and Coriolis Forces 391
- 10.4 Motion Relative to the Earth 395
 - Problems 408

11 Dynamics of Rigid Bodies 411

- 11.1 Introduction 411
- 11.2 Simple Planar Motion 412
- 11.3 Inertia Tensor 415
- 11.4 Angular Momentum 419
- 11.5 Principal Axes of Inertia 424
- 11.6 Moments of Inertia for Different Body Coordinate Systems 428
- 11.7 Further Properties of the Inertia Tensor 433
- 11.8 Eulerian Angles 440
- 11.9 Euler's Equations for a Rigid Body 444
- 11.10 Force-Free Motion of a Symmetric Top 448
- 11.11 Motion of a Symmetric Top with One Point Fixed 454
- 11.12 Stability of Rigid-Body Rotations 460
 - Problems 463

12 Coupled Oscillations 468

- 12.1 Introduction 468
- 12.2 Two Coupled Harmonic Oscillators 469
- 12.3 Weak Coupling 473
- 12.4 General Problem of Coupled Oscillations 475
- 12.5 Orthogonality of the Eigenvectors (Optional) 481
- 12.6 Normal Coordinates 483
- 12.7 Molecular Vibrations 490
- 12.8 Three Linearly Coupled Plane Pendula—an Example of Degeneracy 495

- 12.9 The Loaded String 498
- Problems 507

13 Continuous Systems; Waves 512

- 13.1 Introduction 512
- 13.2 Continuous String as a Limiting Case of the Loaded String 513
- 13.3 Energy of a Vibrating String 516
- 13.4 Wave Equation 520
- 13.5 Forced and Damped Motion 522
- 13.6 General Solutions of the Wave Equation 524
- 13.7 Separation of the Wave Equation 527
- 13.8 Phase Velocity, Dispersion, and Attenuation 533
- 13.9 Group Velocity and Wave Packets 538
- Problems 542

14 Special Theory of Relativity 546

- 14.1 Introduction 546
- 14.2 Galilean Invariance 547
- 14.3 Lorentz Transformation 548
- 14.4 Experimental Verification of the Special Theory 555
- 14.5 Relativistic Doppler Effect 558
- 14.6 Twin Paradox 561
- 14.7 Relativistic Momentum 562
- 14.8 Energy 566
- 14.9 Spacetime and Four-Vectors 569
- 14.10 Lagrangian Function in Special Relativity 578
- 14.11 Relativistic Kinematics 579
- Problems 583

Appendices

A Taylor's Theorem 589

- Problems 593

B Elliptic Integrals 594

- B.1 Elliptic Integrals of the First Kind 594
- B.2 Elliptic Integrals of the Second Kind 595
- B.3 Elliptic Integrals of the Third Kind 595
- Problems 598

C	Ordinary Differential Equations of Second Order	599
	C.1 Linear Homogeneous Equations	599
	C.2 Linear Inhomogeneous Equations	603
	Problems	606
D	Useful Formulas	608
	D.1 Binomial Expansion	608
	D.2 Trigonometric Relations	609
	D.3 Trigonometric Series	610
	D.4 Exponential and Logarithmic Series	610
	D.5 Complex Quantities	611
	D.6 Hyperbolic Functions	611
	Problems	612
E	Useful Integrals	613
	E.1 Algebraic Functions	613
	E.2 Trigonometric Functions	614
	E.3 Gamma Functions	615
F	Differential Relations in Different Coordinate Systems	617
	F.1 Rectangular Coordinates	617
	F.2 Cylindrical Coordinates	617
	F.3 Spherical Coordinates	619
G	A “Proof” of the Relation $\sum_{\mu} x_{\mu}^2 = \sum_{\mu} x'_{\mu}{}^2$	621
H	Numerical Solution for Example 2.7	623
	Selected References	626
	Bibliography	628
	Answers to Even-Numbered Problems	633
	Index	643