## THEORY AND PROBLEMS

OF

## LAGRANGIAN DYNAMICS

with a treatment of

Euler's Equations of Motion, Hamilton's Equations and Hamilton's Principle

BY
DARE A. WELLS, Ph.D.
Professor of Physics
University of Cincinnati


## CONTENTS

Page
Chapter 1 BACKGROUND MATERIAL, I. .....  1
1.1 Regarding background requirements. .....  1
1.2 The basic laws of classical Newtonian dynamics and various ways of express- ing them .....  1
1.3 The choice of formulation. .....  1
1.4 Origin of the basic laws. .....  1
1.5 Regarding the basic quantities and concepts employed .....  2
1.6 Conditions under which Newton's laws are valid. .....  2
1.7 Two general types of dynamical problems .....  5
1.8 General methods of treating dynamical problems .....  5
$1.9 \quad$ A speciflc example illustrating Sections 1.7 and 1.8 .....  6
Chapter 2 BACKGROUND MATERIAL, II. ..... 10
2.1 Introductory remarks. ..... 10
2.2 Coordinate Systems and transformation equations. ..... 10
2.3 Generalized coordinates. Degrees of freedom. ..... 15
2.4 Degrees of constraint, equations of constraint, superfluous coordinates. ..... 18
2.5 Moving constraints. ..... 18
2.6 'Reduced" transformation equations ..... 19
2.7 Velocity expressed in generalized coordinates. ..... 19
2.8 Work and kinetic energy. ..... 22
2.9 Examples illustrating kinetic energy. ..... 24
2.10 "Center of mass" theorem for kinetic energy ..... 26
2.11 A general expression for the kinetic energy of $p$ partides. ..... 26
2.12 Acceleration defined and illustrated. ..... 28
2.13 "Virtual displacements" and "Virtual work" ..... 29
2.14 Examples. ..... 31
Chapter 3 LAGRANGE'S EQUATIONS OF MOTION FOR A SINGLE PARTICLE. ..... 39
3.1 Preliminary considerations. ..... 39
3.2 Derivation of Lagrange's equations for a Single particle. No moving coordinates or moving constraints. ..... 39
3.3 Synopsis of important details regarding Lagrange's equations. ..... 42
3.4 Integrating the differential equations of motion ..... 44
3.5 Illustrative examples. ..... 44
3.6 Lagrange's equations for a Single particle, assuming a moving frame of reference and/or moving constraints. ..... 46
3.7 Regarding kinetic energy, generalized forces and other matters when the frame of reference and/or constraints are moving. ..... 46
3.8 Illustrative examples. ..... 47
3.9 Determination of acceleration by means of Lagrange's equations. ..... 48
3.10 Another look at Lagrange's equations. ..... 50
3.11 Suggested experiments. ..... 50

## CONTENTS

Chapter $\dot{4}$ LAGRANGE'S EQUATIONS OF MOTION FOR A SYSTEM OF PARTICLES. ..... 58
4.1 Introductory remarks. ..... 58
4.2 Derivation of Lagrange's equations for a system of particles. ..... 58
4.3 Expressing $T$ in proper form. ..... 60
4.4 Physical meaning of generalized forces. ..... 60
4.5 Finding expressions for generalized forces. ..... 61
4.6 Examples illustrating the application of Lagrange's equations to Systems involving several particles. ..... 62
4.7 Forces on and motion of charged particles in an electromagnetic field. ..... 68
4.8 Regarding the physical meaning of Lagrange's equations. ..... 69
4.9 Suggested experiment. ..... 71
Chapter 5 CONSERVATIVE SYSTEMS. ..... 81
5.1 Certain basic principles illustrated. ..... 81
5.2 Important definitions. ..... 82
5.3 General expression for $V$ and a test for conservative forces. ..... 82
5.4 Determination of expressions for $V$. ..... 83
5.5 Simple examples. ..... 83
5.6 Generalized forces as derivatives of $V$. ..... 85
5.7 Lagrange's equations for conservative Systems. ..... 85
5.8 Partly conservative and partly non-conservative Systems. ..... 86
5.9 Examples illustrating the application of Lagrange's equations to conservative Systems. ..... 86
5.10 Approximate expression for the potential energy of a system of Springs. ..... 89
5.11 Systems in which potential energy varies with time. Examples. ..... 90
5.12 Vector potential function for a Charge moving in an electromagnetic field ..... 91
5.13 The 'energy integral". ..... 91
5.14 Suggested experiments. ..... 92
Chapter 6 DETERMINATION OF $\boldsymbol{F}_{Q f}$ FOR DISSIPATIVE FORCES. ..... 99
6.1 Definition and classiflcation. ..... 99
6.2 General procedure for determination of $\mathbf{F}$, ..... 99
6.3 Examples: Generalized frictional forces. ..... 100
6.4 Examples: Generalized viscous forces. ..... 102
6.5 Example: Forces proportional to nth power of speed, $\mathbf{n}>1$. ..... 103
6.6 Forces expressed by a power series. ..... 103
6.7 Certain interesting consequences of friction and other forces. ..... 103
6.8 A 'power function", $P$, for the determination of generalized forces. ..... 104
6.9 Special forms for the power function. ..... 105
6.10 Examples illustrating the use of $P$. ..... 106
6.11 Forces which depend on relative velocity ..... 107
6.12 Forces not opposite in direction to the motion. ..... 107
6.13 Suggested experiment. ..... 110

## CONTENTS

Chapter ${ }_{7}^{m}$ GENERAL TREATMENT OF MOMENTS AND PRODUCTS OF INERTIA ..... 117
7.1 General expression for the moment of inertia of a rigid body about any axis. ..... 117
72 The ellipsoid of inertia ..... 118
7.3 Principal moments of inertia. Principal axes and their directions ..... 119
7.4 Given moments and products of inertia relative to any rectangular axes with origin at the center of mass. To find corresponding quantities referred to any parallel system of axes ..... 120
7.5 Given moments and products of inertia relative to any frame. To find corresponding quantities relative to any other parallel frame ..... 121
7.6 To find moments and products of inertia relative to rotated frames ..... 122
7.7 Examples of moments, products and ellipsoids of inertia ..... 124
7.8 "Foci" and "spherical" points of inertia. ..... 129
7.9 Physical significance of products of inertia. ..... 130
7.10 Dynamically equivalent bodies ..... 131
7.11 Experimental determination of moments and products of inertia. ..... 132
7.12 Suggested project on the ellipsoid of inertia ..... 133
7.13 Suggested experiment. ..... 134
Chapter 8 LAGRANGIAN TREATMENT OF RIGID BODY DYNAMICS ..... 139
8.1 Preliminary remarks ..... 139
8.2 Necessary background material. ..... 139
8.3 General expression for the kinetic energy of a free rigid body. ..... 148
8.4 Summary of important considerations regarding $T$. ..... 148
8.5 Setting up equations of motion. ..... 149
8.6 Examples illustrating kinetic energy and equations of motion. ..... 149
8.7 Euler angles deflned. Expressing $a$ and its components in these angles. ..... 156
8.8 Use of Euler angles: Body moving in any manner ..... 157
8.9 Kinetic energy making use of direction-fixed axes. ..... 161
8.10 Motion of a rigid body relative to a translating and rotating frame of reference. ..... 162
8.11 Suggested experiment. ..... 167
Chapter 9 THE EULER METHOD OF RIGID BODY DYNAMICS. ..... 176
9.1 Preliminary remarks ..... 176
9.2 Translational equations of motion of the center of mass. ..... 176
9.3 Various ways of expressing the scalar equations corresponding to $\mathrm{MA}=\mathrm{F}$ ..... 177
9.4 Background material for a determination of Euler's rotational equations. ..... 178
9.5 Euler's three rotational equations bf motion for a rigid body. General form. ..... 181
9.6 Important points regarding Euler's rotational equations. ..... 182
9.7 Vector form of Euler's rotational equations. ..... 183
9.8 Specific examples illustrating the use of the translational equations of motion of the center of mass and Euler's rotational equations. ..... 184
9.9 Examples illustrating component form about any line. ..... 188
9.10 Equations of motion relative to a moving frame of reference. ..... 191
9.11 Finding the motions of a space ship and object inside, each acted upon by known forces. ..... 191
9.12 Non-holonomic constraints. ..... 193
9.13 Euler's rotational equations from the point of view of angular momentum ..... 195
9.14 Comparison of the Euler and Lagrangian treatments. ..... 197

## CONTENTS

Chapter 10 SMALL OSCILLATIONS ABOUT POSITIONS OF EQUILIBRIUM ..... 203
10.1 The type of problem considered. ..... 203
10.2 Restrictions on the general problem. ..... 203
10.3 Additional background material. ..... 206
10.4 The differential equations of motion ..... 209
10.5 Solutions of the equations of motion; conservative forces only. ..... 209
10.6 Summary of important facts regarding oscillatory motion. ..... 211
10.7 Examples ..... 211
10.8 Special cases of the roots of $D$ ..... 215
10.9 Normal coordinates. ..... 217
10.10 Proof of the orthogonality relation ..... 21»
10.11 Important points regarding normal coordinates. ..... 220
10.12 Advantages of normal coordinates. ..... 220
10.13 Finding expressions for normal coordinates. ..... 221
10.14 Amplitude and direction of motion of any one particle when a particular mode of oscillation is excited. ..... 222
10.15 Determination of arbitrary constants with the help of orthogonality conditions ..... 224
10.16 Small oscillations with viscous and conservative forces acting ..... 224
10.17 Regarding stability of motion ..... 226
10.18 Use of normal coordinates when external forces are acting ..... 226
10.19 Use of normal coordinates when viscous and external forces are acting. ..... 227
10.20 Suggested experiments. .....  228
Chapter 11 SMALL OSCILLATIONS ABOUT STEADY MOTION. ..... 234
11.1 Important preliminary considerations. ..... 234
11.2 Eliminating ignorable coordinates from the general equations of motion ..... 236
11.3 Elimination of ignorable coordinates employing the Routhian function ..... 236
11.4 Conditions required for steady motion. ..... 237
11.5 Equations of motion assuming steady motion slightly disturbed ..... 237
11.6 Solving the equations of motion ..... 238
11.7 Ignorable coordinates as functions of time after the disturbance ..... 239
11.8 Examples ..... 239
11.9 Oscillation about steady motion when the system contains moving constraints. ..... 246
11.10 When the system is acted upon by dissipative forces ..... 248
11.11 Stability of steady motion ..... 248
Chapter 12 FORCES OF CONSTRAINT. ..... 256
12.1 Preliminary considerations ..... 256
12.2 General procedure for finding forces of constraint ..... 258
12.3 Illustrative examples. ..... 259
12.4 Forces of constraint using Euler's equations ..... 263
12.5 Forces of constraint and equations of motion when constraints are rough ..... 264
Chapter 13 DRIVING FORCES REQUIRED TO ESTABLISH KNOWNMOTIONS. ..... 268
13.1 Preliminary considerations. ..... 268
13.2 General method ..... 269
13.3 Illustrative examples. ..... 270
13.4 Equilibrium pf a system ..... 272
13.5 Examples illustrating problems in static equilibrium ..... t. ..... 273

## CONTENTS

Chapter ${ }^{\boldsymbol{t}} \dot{4}$ EFFECTS OF EARTH'S FIGURE AND DAILY ROTATION ON DYNAMICAL PROBLEMS.
Page
14.1 Introductory remarks ..... 281
14.2 Regarding the earth's figure. Geocentric and geographic latitude and radius.. ..... 282
14.3 Acceleration of gravity on or near the earth's surface ..... 282
14.4 Computational formulas and certain constants. ..... 283
14.5 Ref erences on the figure of the earth and its gravitational field ..... 285
14.6 Kinetic energy and equations of motion of a particle in various coordinates. Frame of reference attached to earth's surface ..... 286
14.7 $T$ for a particle, frame of reference in motion relative to earth's surface ..... 290
14.8 Motion of a rigid body near the surface of the earth. ..... 290
14.9 Specific illustrative examples ..... 291
Chapter 15 APPLICATION OF LAGRANGE'S EQUATIONS TO ELECTRICAL AND ELECTROMECHANICAL SYSTEMS. ..... 302
15.1 Preliminary remarks. ..... 302
15.2 Expressions for $T, V, P, F_{Q}$ and Lagrange's equations for electrical circuits.. ..... 302
15.3 Illustrative examples. ..... 304
15.4 Electromechanical Systems: The appropriate Lagrangian; determination of generalized forces ..... 306
15.5 Oscillations of electrical and electromechanical Systems ..... 307
15.6 Forces and voltages required to produce given motions and currents in an electromechanical system ..... 308
15.7 Analogous electrical and mechanical Systems ..... 309
15.8 Ref ..... 311
Chapter 16 HAMILTON'S EQUATIONS OF MOTION. ..... 316
16.1 General remarks. ..... 316
16.2 A word about "generalized momentum" ..... 316
16.3 Derivation of Hamilton's equations ..... 316
16.4 Procedure for setting up $H$ and writing Hamiltonian equations ..... 318
16.5 Special cases of $H$. ..... 318
16.6 Important energy and power relations. ..... 318
16.7 Examples. The Hamiltonian and Hamiltonian equations of motion ..... 319
16.8 Examples of $H$ for system in which there are moving coordinates and/or moving constraints. ..... 321
16.9 Fields in which the Hamiltonian method is employed ..... 322
Chapter 17 HAMILTON'S PRINCIPLE. ..... 326
17.1 Preliminary Statement ..... 326
17.2 Introductory problems ..... 326
17.3 Certain techniques in the calculus of variations ..... 327
17.4 Solutions to previously proposed examples. ..... 330
17.5 Hamilton's principle from the calculus of variations ..... 331
17.6 Hamilton's principle from D'Alembert's equation ..... 331
17.7 Lagrange's equations from Hamilton's principle ..... 333
17.8 Examples ..... 334
17.9 Applications of Hamilton's principle ..... 336
Chapter 18 BASIC EQUATIONS OF DYNAMICS IN VECTOR AND TENSOR NOTATION. ..... 339
Appendix RELATIONS BETWEEN DIRECTION COSINES. ..... 343
INDEX. ..... 351

