

## *Contents*

<i>Preface</i>	<i>page</i> xv
<i>Acknowledgments</i>	xvii
<b>Chapter 1 Introduction</b>	<b>1</b>
1.1 Overview	1
1.2 Illustrative Example	1
1.2.1 Attitude and Orbit Control System Hardware	2
1.2.2 Mission Sequence	2
1.3 Outline of the Book	5
1.4 Notation and Abbreviations	7
<i>References</i>	7
 <b>Chapter 2 Orbit Dynamics</b>	 <b>8</b>
2.1 Basic Physical Principles	8
2.1.1 The Laws of Kepler and Newton	8
2.1.2 Work and Energy	9
2.2 The Two-Body Problem	10
2.3 Moment of Momentum	11
2.4 Equation of Motion of a Particle in a Central Force Field	12
2.4.1 General Equation of Motion of a Body in Keplerian Orbit	12
2.4.2 Analysis of Keplerian Orbits	15
2.5 Time and Keplerian Orbits	18
2.5.1 True and Eccentric Anomalies	18
2.5.2 Kepler's Second Law (Law of Areas) and Third Law	19
2.5.3 Kepler's Time Equation	20
2.6 Keplerian Orbits in Space	22
2.6.1 Definition of Parameters	22
2.6.2 Transformation between Cartesian Coordinate Systems	24
2.6.3 Transformation from $\alpha = [a e i \Omega \omega M]^T$ to $[\mathbf{v}, \mathbf{r}]$	26
2.6.4 Transformation from $[\mathbf{v}, \mathbf{r}]$ to $\alpha = [a e i \Omega \omega M]^T$	27
2.7 Perturbed Orbits: Non-Keplerian Orbits	28
2.7.1 Introduction	28
2.7.2 The Perturbed Equation of Motion	29
2.7.3 The Gauss Planetary Equations	30
2.7.4 Lagrange's Planetary Equations	33
2.8 Perturbing Forces and Their Influence on the Orbit	33
2.8.1 Definition of Basic Perturbing Forces	33
2.8.2 The Nonhomogeneity and Oblateness of the Earth	34

viii	<i>Contents</i>
2.8.3 A Third-Body Perturbing Force	39
2.8.4 Solar Radiation and Solar Wind	41
2.9 Perturbed Geostationary Orbits	42
2.9.1 Redefinition of the Orbit Parameters	42
2.9.2 Introduction to Evolution of the Inclination Vector	43
2.9.3 Analytical Computation of Evolution of the Inclination Vector	45
2.9.4 Evolution of the Eccentricity Vector	50
2.9.5 Longitudinal Acceleration Due to Oblateness of the Earth	56
2.10 Euler–Hill Equations	57
2.10.1 Introduction	57
2.10.2 Derivation	58
2.11 Summary	62
<i>References</i>	62
<b>Chapter 3 Orbital Maneuvers</b>	<b>64</b>
3.1 Introduction	64
3.2 Single-Impulse Orbit Adjustment	65
3.2.1 Changing the Altitude of Perigee or Apogee	65
3.2.2 Changing the Semimajor Axis $a_1$ and Eccentricity $e_1$ to $a_2$ and $e_2$	65
3.2.3 Changing the Argument of Perigee	68
3.2.4 Restrictions on Orbit Changes with a Single Impulsive $\Delta V$	69
3.3 Multiple-Impulse Orbit Adjustment	70
3.3.1 Hohmann Transfers	70
3.3.2 Transfer between Two Coplanar and Coaxial Elliptic Orbits	71
3.3.3 Maintaining the Altitude of Low-Orbit Satellites	72
3.4 Geostationary Orbits	73
3.4.1 Introduction	73
3.4.2 GTO-to-GEO Transfers	73
3.4.3 Attitude Errors During GTO-to-GEO Transfers	76
3.4.4 Station Keeping of Geostationary Satellites	78
3.5 Geostationary Orbit Corrections	80
3.5.1 North–South (Inclination) Station Keeping	81
3.5.2 Eccentricity Corrections	84
3.5.3 Fuel Budget for Geostationary Satellites	84
3.6 Summary	86
<i>References</i>	86
<b>Chapter 4 Attitude Dynamics and Kinematics</b>	<b>88</b>
4.1 Introduction	88
4.2 Angular Momentum and the Inertia Matrix	88
4.3 Rotational Kinetic Energy of a Rigid Body	90
4.4 Moment-of-Inertia Matrix in Selected Axis Frames	90
4.4.1 Moment of Inertia about a Selected Axis in the Body Frame	90

<i>Contents</i>	ix
4.4.2 Principal Axes of Inertia	91
4.4.3 Ellipsoid of Inertia and the Rotational State of a Rotating Body	93
4.5 Euler's Moment Equations	95
4.5.1 Solution of the Homogeneous Equation	95
4.5.2 Stability of Rotation for Asymmetric Bodies about Principal Axes	96
4.5.3 Solution of the Homogeneous Equation for Unequal Moments of Inertia	97
4.6 Characteristics of Rotational Motion of a Spinning Body	98
4.6.1 Nutation of a Spinning Body	98
4.6.2 Nutational Destabilization Caused by Energy Dissipation	99
4.7 Attitude Kinematics Equations of Motion for a Nonspinning Spacecraft	100
4.7.1 Introduction	100
4.7.2 Basic Coordinate Systems	101
4.7.3 Angular Velocity Vector of a Rotating Frame	102
4.7.4 Time Derivation of the Direction Cosine Matrix	104
4.7.5 Time Derivation of the Quaternion Vector	104
4.7.6 Derivation of the Velocity Vector $\omega_{RI}$	105
4.8 Attitude Dynamic Equations of Motion for a Nonspinning Satellite	107
4.8.1 Introduction	107
4.8.2 Equations of Motion for Spacecraft Attitude	107
4.8.3 Linearized Attitude Dynamic Equations of Motion	108
4.9 Summary	111
<i>References</i>	111
<b>Chapter 5 Gravity Gradient Stabilization</b>	<b>112</b>
5.1 Introduction	112
5.2 The Basic Attitude Control Equation	113
5.3 Gravity Gradient Attitude Control	114
5.3.1 Purely Passive Control	114
5.3.2 Time-Domain Behavior of a Purely Passive GG-Stabilized Satellite	117
5.3.3 Gravity Gradient Stabilization with Passive Damping	122
5.3.4 Gravity Gradient Stabilization with Active Damping	126
5.3.5 GG-Stabilized Satellite with Three-Axis Magnetic Active Damping	129
5.4 Summary	129
<i>References</i>	130
<b>Chapter 6 Single- and Dual-Spin Stabilization</b>	<b>132</b>
6.1 Introduction	132
6.2 Attitude Spin Stabilization during the $\Delta V$ Stage	132
6.3 Active Nutation Control	135
6.4 Estimation of Fuel Consumed during Active Nutation Control	137

6.5	Despinning and Denutation of a Satellite	139
6.5.1	Despinning	140
6.5.2	Denutation	141
6.6	Single-Spin Stabilization	144
6.6.1	Passive Wheel Nutation Damping	144
6.6.2	Active Wheel Nutation Damping	146
6.7	Dual-Spin Stabilization	148
6.7.1	Passive Damping of a Dual-Spin-Stabilized Satellite	148
6.7.2	Momentum Bias Stabilization	150
6.8	Summary	151
	<i>References</i>	151
<b>Chapter 7 Attitude Maneuvers in Space</b>		<b>152</b>
7.1	Introduction	152
7.2	Equations for Basic Control Laws	152
7.2.1	Control Command Law Using Euler Angle Errors	152
7.2.2	Control Command Law Using the Direction Cosine Error Matrix	153
7.2.3	Control Command Law about the Euler Axis of Rotation	155
7.2.4	Control Command Law Using the Quaternion Error Vector	156
7.2.5	Control Laws Compared	156
7.2.6	Body-Rate Estimation without Rate Sensors	158
7.3	Control with Momentum Exchange Devices	160
7.3.1	Model of the Momentum Exchange Device	161
7.3.2	Basic Control Loop for Linear Attitude Maneuvers	164
7.3.3	Momentum Accumulation and Its Dumping	165
7.3.4	A Complete Reaction Wheel-Based ACS	167
7.3.5	Momentum Management and Minimization of the $ \mathbf{h}_w $ Norm	169
7.3.6	Effect of Noise and Disturbances on ACS Accuracy	172
7.4	Magnetic Attitude Control	185
7.4.1	Basic Magnetic Torque Control Equation	185
7.4.2	Special Features of Magnetic Attitude Control	186
7.4.3	Implementation of Magnetic Attitude Control	188
7.5	Magnetic Unloading of Momentum Exchange Devices	189
7.5.1	Introduction	189
7.5.2	Magnetic Unloading of the Wheels	190
7.5.3	Determination of the Unloading Control Gain $k$	192
7.6	Time-Optimal Attitude Control	195
7.6.1	Introduction	195
7.6.2	Control about a Single Axis	197
7.6.3	Control with Uncertainties	201
7.6.4	Elimination of Chatter and of Time-Delay Effects	201
7.7	Technical Features of the Reaction Wheel	206
7.8	Summary	208
	<i>References</i>	208

<i>Contents</i>	xi
<b>Chapter 8 Momentum-Biased Attitude Stabilization</b>	<b>210</b>
8.1 Introduction	210
8.2 Stabilization without Active Control	210
8.3 Stabilization with Active Control	214
8.3.1 Active Control Using Yaw Measurements	215
8.3.2 Active Control without Yaw Measurements	217
8.4 Roll–Yaw Attitude Control with Magnetic Torques	222
8.5 Active Nutation Damping via Products of Inertia	225
8.6 Roll–Yaw Attitude Control with Solar Torques	229
8.6.1 Dynamic Equations for Solar Panels and Flaps	230
8.6.2 Mechanization of the Control Algorithm	233
8.7 Roll–Yaw Attitude Control with Two Momentum Wheels	237
8.7.1 Introduction	237
8.7.2 Adapting the Equation of Rotational Motion	238
8.7.3 Designing the Control Networks $G_Y(s)$ and $G_Z(s)$	240
8.7.4 Momentum Dumping of the MW with Reaction Thrust Pulses	241
8.8 Reaction Thruster Attitude Control	242
8.8.1 Introduction	242
8.8.2 Control of $\phi$ (Roll) and $\psi$ (Yaw)	244
8.8.3 Immunity to Sensor Noise	246
8.8.4 Determining the Necessary Momentum Bias $h_w$	247
8.8.5 Active Nutation Damping via Products of Inertia	248
8.8.6 Wheel Momentum Dumping and the Complete Attitude Controller	250
8.8.7 Active Nutation Damping without Products of Inertia	251
8.9 Summary	256
<i>References</i>	257
<b>Chapter 9 Reaction Thruster Attitude Control</b>	<b>260</b>
9.1 Introduction	260
9.2 Set-Up of Reaction Thruster Control	260
9.2.1 Calculating the Torque Components of a Single Thruster	261
9.2.2 Transforming Torque Commands into Thruster Activation Time	263
9.3 Reaction Torques and Attitude Control Loops	265
9.3.1 Introduction	265
9.3.2 Control Systems Based on PWPF Modulators	266
9.3.3 Control Loop Incorporating a PWPF Modulator	270
9.4 Reaction Attitude Control via Pulse Width Modulation	273
9.4.1 Introduction	273
9.4.2 Feedback Control Loop of a Pulsed Reaction System	273
9.5 Reaction Control System Using Only Four Thrusters	287
9.6 Reaction Control and Structural Dynamics	289
9.7 Summary	289
<i>References</i>	289

<b>Chapter 10</b>	<b>Structural Dynamics and Liquid Sloshing</b>	<b>291</b>
10.1	Introduction	291
10.2	Modeling Solar Panels	291
10.2.1	Classification of Techniques	291
10.2.2	The Lagrange Equations and One-Mass Modeling	292
10.2.3	The Mass–Spring Concept and Multi-Mass Modeling	296
10.3	Eigenvalues and Eigenvectors	299
10.4	Modeling of Liquid Slosh	301
10.4.1	Introduction	301
10.4.2	Basic Assumptions	301
10.4.3	One–Vibrating Mass Model	302
10.4.4	Multi-Mass Model	308
10.5	Generalized Modeling of Structural and Sloshing Dynamics	309
10.5.1	A System of Solar Panels	309
10.5.2	A System of Fuel Tanks	310
10.5.3	Coupling Coefficients and Matrices	310
10.5.4	Complete Dynamical Modeling of Spacecraft	311
10.5.5	Linearized Equations of Motion	312
10.6	Constraints on the Open-Loop Gain	313
10.6.1	Introduction	313
10.6.2	Limitations on the Crossover Frequency	313
10.7	Summary	316
	<i>References</i>	316
<b>Appendix A</b>	<b>Attitude Transformations in Space</b>	<b>318</b>
A.1	Introduction	318
A.2	Direction Cosine Matrix	318
A.2.1	Definitions	318
A.2.2	Basic Properties	319
A.3	Euler Angle Rotation	320
A.4	The Quaternion Method	322
A.4.1	Definition of Parameters	322
A.4.2	Euler’s Theorem of Rotation and the Direction Cosine Matrix	323
A.4.3	Quaternions and the Direction Cosine Matrix	324
A.4.4	Attitude Transformation in Terms of Quaternions	325
A.5	Summary	326
	<i>References</i>	326
<b>Appendix B</b>	<b>Attitude Determination Hardware</b>	<b>328</b>
B.1	Introduction	328
B.2	Infrared Earth Sensors	329
B.2.1	Spectral Distribution and Oblateness of the Earth	329
B.2.2	Horizon-Crossing Sensors	330
B.2.3	IRHCES Specifications	339
B.2.4	Static Sensors	343

<i>Contents</i>	xiii
<b>B.3 Sun Sensors</b>	<b>345</b>
B.3.1 Introduction	345
B.3.2 Analog Sensors	345
B.3.3 Digital Sensors	351
<b>B.4 Star Sensors</b>	<b>353</b>
B.4.1 Introduction	353
B.4.2 Physical Characteristics of Stars	357
B.4.3 Tracking Principles	366
<b>B.5 Rate and Rate Integrating Sensors</b>	<b>373</b>
B.5.1 Introduction	373
B.5.2 Rate-Sensor Characteristics	375
<i>References</i>	376
 <b>Appendix C Orbit and Attitude Control Hardware</b>	 <b>379</b>
C.1 Introduction	379
C.2 Propulsion Systems	379
C.2.1 Cold Gas Propulsion	381
C.2.2 Chemical Propulsion – Solid	381
C.2.3 Chemical Propulsion – Liquid	382
C.2.4 Electrical Propulsion	385
C.2.5 Thrusters	387
C.3 Solar Pressure Torques	388
C.3.1 Introduction	388
C.3.2 Description	388
C.3.3 Maximization	392
C.4 Momentum Exchange Devices	393
C.4.1 Introduction	393
C.4.2 Simplified Model of a RW Assembly	393
C.4.3 Electronics	396
C.4.4 Specifications	396
C.5 Magnetic Torqrods	397
C.5.1 Introduction	397
C.5.2 Performance Curve	398
C.5.3 Specifications	401
<i>References</i>	401
 <i>Index</i>	 403