

CONTENTS

Preface xiii

Nomenclature xxi

Chapter 1

Introduction and Topical Review 1

- 1.1 Small Perturbation Theory for Nonlinear Systems 1
- 1.2 Coordinate Systems 2
- 1.3 Vectors, Coordinate Transformations, and Direction-Cosine Matrices 4
- 1.4 Vector Differentiation 10
- 1.5 Newton's Second Law 14
- 1.6 Small Perturbation Analysis Revisited 18
- 1.7 Summary 21
- 1.8 Problems 22
- References 24

Chapter 2

Equations of Motion of the Rigid Vehicle 25

- 2.1 Vector Equations of Motion—Flat Earth 25
- 2.2 Scalar Equations of Motion—Flat Earth 33
- 2.3 Reference and Perturbation Equations—Flat Earth 42
- 2.4 Effects of Rotating Masses 48
- 2.5 Effects of Variable Mass 58
- 2.6 Effects of a Spherical, Rotating Earth 65
- 2.7 Point-Mass Performance Equations 76

- 2.8 Summary 80
- 2.9 Problems 81
- References 82

Chapter 3

Structural Vibrations—A “Just-In-Time Tutorial” 83

- 3.1 Lumped-Mass Idealizations and Lagrange's Equation 83
- 3.2 Modal Analysis 86
- 3.3 Orthogonality of the Vibration Modes 89
- 3.4 Rigid-Body Degrees of Freedom 91
- 3.5 Reference Axes and Relative Motion 98
- 3.6 Modal Analysis of the Generalized Eigensolution 102
- 3.7 Multi-Directional Motion 107
- 3.8 Preferred Derivation of Equations of Motion 117
- 3.9 Forced Motion and Virtual Work 119
- 3.10 Forced Motion of the Unrestrained Beam Model 122
- 3.11 Summary 125
- 3.12 Problems 126
- References 127

Chapter 4

Equations of Motion for Elastic Vehicles 128

- 4.1 Lagrange's Equation—Kinetic and Potential Energies 129
- 4.2 The Vehicle-Fixed Frame—The Mean Axes 131
- 4.3 Modal Expansion Using Free-Vibration Modes 134

- 4.4 Selection of the Generalized Coordinates 136
- 4.5 Equations of Motion Governing Rigid-Body Translation 138
- 4.6 Equations of Motion Governing Rigid-Body Rotation 142
- 4.7 Equations of Motion Governing Elastic Deformation 146
- 4.8 Motion of a Particular Point on the Elastic Vehicle 150
- 4.9 Reference and Perturbation Equation Sets for Perturbation Analysis 153
- 4.10 Summary 154
- 4.11 Problems 154
References 155

Chapter 5

Basic Aerodynamics of Lifting Surfaces 156

- 5.1 Subsonic Airfoil Section Characteristics 157
 - 5.1.1 *Section Lift and Drag* 160
 - 5.1.2 *Section Pitching Moment* 161
 - 5.1.3 *Section Data* 163
- 5.2 Effects of Flaps on Subsonic Airfoil Section Characteristics 168
- 5.3 Wing Planform Characteristics 174
 - 5.3.1 *Wing Lift* 177
 - 5.3.2 *Wing Zero-Lift Angle of Attack* 178
 - 5.3.3 *Wing Pitching Moment and Aerodynamic Center* 183
 - 5.3.4 *Wing Rolling Moment* 189
 - 5.3.5 *Wing Drag* 197
- 5.4 Effects of Flaps on Wing Aerodynamic Characteristics 203
 - 5.4.1 *Flaps and Control Surfaces* 203
 - 5.4.2 *Ailerons* 206
- 5.5 Downwash 214
- 5.6 Summary 218
- 5.7 Problems 218
References 218

Chapter 6

Modeling the Forces and Moments on the Vehicle 219

- 6.1 Taylor-Series Expansion of Aerodynamic Forces and Moments 221
- 6.2 Aerodynamic Forces and Moments Acting on the Vehicle 226
 - 6.2.1 *Vehicle Lift* 227
 - 6.2.2 *Vehicle Side Force* 231
 - 6.2.3 *Vehicle Drag* 232
 - 6.2.4 *Vehicle Rolling Moment* 234
 - 6.2.5 *Vehicle Pitching Moment* 237
 - 6.2.6 *Vehicle Yawing Moment* 245
- 6.3 Propulsive Forces and Moments Acting on the Vehicle 249
- 6.4 Fuselage-Reference and Stability Axes 254
- 6.5 Aerodynamic and Propulsive Forces and Moments at the Reference Condition 255
- 6.6 Forces and Moments Due to Translational Velocity Perturbations 258
 - 6.6.1 *Surge-Velocity Perturbation u* 262
 - 6.6.2 *Plunge-Velocity Perturbation w* 272
 - 6.6.3 *Sideslip-Velocity Perturbation v* 279
- 6.7 Forces and Moments Due to Angular-Velocity Perturbations 284
 - 6.7.1 *Pitch-Rate Perturbation q* 285
 - 6.7.2 *Roll-Rate Perturbation p* 292
 - 6.7.3 *Yaw-Rate Perturbation r* 297
 - 6.7.4 *Perturbation in Rate of Change of Angle of Attack $\dot{\alpha}$* 302
- 6.8 Effects of Atmospheric Turbulence on the Forces and Moments 307
- 6.9 Dimensional Versus Nondimensional Derivatives 311
- 6.10 Integration of Forces and Moments into the Equations of Motion 315
 - 6.10.1 *Integration into the Nonlinear Equations of Motion* 315
 - 6.10.2 *Integration into the Linearized Equations of Motion* 316

6.11	Summary	320
6.12	Problems	320
	References	322

Chapter 7

Effects of Elastic Deformation on the Forces and Moments 323

7.1	A Motivational Aeroelastic Example	324
7.2	Elastic Deformation Revisited	328
7.3	Elastic Effects on Lift	330
	7.3.1 <i>Effects of Modal Displacement</i>	332
	7.3.2 <i>Effects of Modal Velocity</i>	336
7.4	Elastic Effects on Side Force	342
	7.4.1 <i>Effects of Modal Displacement</i>	343
	7.4.2 <i>Effects of Modal Velocity</i>	345
7.5	Elastic Effects on Pitching Moment	346
	7.5.1 <i>Effects of Modal Displacement</i>	347
	7.5.2 <i>Effects of Modal Velocity</i>	349
7.6	Elastic Effects on Rolling Moment	351
	7.6.1 <i>Effects of Modal Displacement</i>	353
	7.6.2 <i>Effects of Modal Velocity</i>	355
7.7	Elastic Effects on Yawing Moment	358
	7.7.1 <i>Effects of Modal Displacement</i>	359
	7.7.2 <i>Effects of Modal Velocity</i>	360
7.8	Generalized Forces Acting on the Elastic Degrees of Freedom	361
7.9	Elastic Effects on the Forces and Moments for a Large High-Speed Aircraft—A Case Study	371
7.10	Integrating Elastic Effects into the Equations of Motion	375
	7.10.1 <i>Integrating into the Nonlinear Equations</i>	376
	7.10.2 <i>Integrating into the Linearized Equations</i>	378
7.11	Static-Elastic Effects on a Vehicle's Aerodynamics	384
	7.11.1 <i>Static-Elastic Deformations</i>	384
	7.11.2 <i>Effects on the Aerodynamics</i>	387

7.12	Summary	392
7.13	Problems	393
	References	393

Chapter 8

Math Model Assembly and Flight Simulation 394

8.1	Linear Model Assembly and Simulation	395
	8.1.1 <i>Linear Equations of Motion</i>	395
	8.1.2 <i>Linear Models of the Forces and Moments</i>	400
	8.1.3 <i>Decoupling the Equations of Motion in Level Flight</i>	405
	8.1.4 <i>Decoupled Models in State-Variable Format</i>	407
	8.1.5 <i>Linear Models for Flexible Vehicles</i>	412
	8.1.6 <i>Adding Feedback Control Laws to a Simulation Model</i>	420
	8.1.7 <i>Adding Atmospheric Turbulence to a Simulation Model</i>	425
	8.1.8 <i>Numerical Simulation Methods for Linear Models—A JITT</i>	428
	8.1.9 <i>Linear-Simulation Examples</i>	432
8.2	Nonlinear Model Assembly and Simulation	445
	8.2.1 <i>Nonlinear Equations of Motion</i>	445
	8.2.2 <i>Models for the Aerodynamic and Propulsive Forces and Moments</i>	447
	8.2.3 <i>Assembling the Nonlinear Mathematical Model</i>	449
	8.2.4 <i>Models for Flexible Vehicles</i>	451
	8.2.5 <i>Adding Feedback Control Laws to a Simulation Model</i>	455
	8.2.6 <i>Adding Atmospheric Turbulence to a Simulation Model</i>	456
	8.2.7 <i>Numerical Simulation Techniques—A JITT</i>	456
	8.2.8 <i>Examples of Nonlinear Simulations</i>	465
8.3	Summary	478
8.4	Problems	478
	References	479

Chapter 9**Analysis of Steady and Quasi-Steady Flight** 480

- 9.1** Equilibrium Reference Conditions 481
- 9.2** Concept of Aerodynamic Static Stability—and Criteria 485
 - 9.2.1 *Longitudinal Static Stability* 488
 - 9.2.2 *Lateral-Directional Static Stability* 496
- 9.3** Analysis of Steady Rectilinear Flight 500
 - 9.3.1 *Longitudinal Trim Analysis* 501
 - 9.3.2 *Control Forces* 514
 - 9.3.3 *Engine-Out Effects* 518
- 9.4** Analysis of Steady Turning Flight 524
 - 9.4.1 *Kinematic Analysis of the Turn* 524
 - 9.4.2 *Lateral-Directional Trim Analysis* 527
 - 9.4.3 *Longitudinal Trim Analysis* 528
 - 9.4.4 *Control Forces and Gradients* 532
- 9.5** Analysis of Quasi-Steady Pull-Up Maneuvers 538
 - 9.5.1 *Kinematic Analysis of the Pull-Up Maneuver* 538
 - 9.5.2 *Longitudinal Trim Analysis* 540
 - 9.5.3 *Control Forces and Gradients* 542
- 9.6** Summary 544
- 9.7** Problems 545
 - References 547

Chapter 10**Linear Flight-Dynamics Analysis** 548

- 10.1** Linear Systems Analysis—A JITT 548
 - 10.1.1 *State-Variable Descriptions and Modal Analysis* 549
 - 10.1.2 *Transfer Functions, Bode Plots, and Residues* 553
 - 10.1.3 *Polynomial-Matrix System Descriptions* 557
- 10.2** Linear Flight-Dynamics Perturbation Equations 562
- 10.3** Decoupled Longitudinal and Lateral Directional Linear Models 565

- 10.4** Longitudinal Transfer Functions and Modal Analysis 572
- 10.5** Approximate Models for Aircraft Longitudinal Dynamics 584
 - 10.5.1 *The Short-Period Approximation* 585
 - 10.5.2 *The Phugoid Approximation* 589
- 10.6** Lateral-Directional Transfer Functions and Modal Analysis 597
- 10.7** Approximate Models for Aircraft Lateral-Directional Dynamics 604
 - 10.7.1 *The Roll-Mode Approximation* 604
 - 10.7.2 *The Dutch-Roll Approximation* 605
 - 10.7.3 *The Spiral Approximation* 608
- 10.8** Configuration Design to Achieve Desirable Dynamic Characteristics 611
 - 10.8.1 *Effects of Static Margin and Tail Size on the Longitudinal Eigenvalues* 611
 - 10.8.2 *Improving Spiral and Dutch-Roll Stability* 615
- 10.9** Cross-Axis Coupling 616
- 10.10** On the Flight Dynamics of Flexible Vehicles 621
- 10.11** Summary 627
- 10.12** Problems 628
 - References 629

Chapter 11**Feedback Stability Augmentation** 631

- 11.1** Block Diagrams, Feedback, and Root-Locus Plots—A JITT 632
- 11.2.** On Multi-Input/Multi-Output Systems and Coupling Numerators 639
- 11.3** Augmenting the Longitudinal Dynamics 645
 - 11.3.1 *Increasing Short-Period Damping* 647
 - 11.3.2 *Increasing Short-Period Frequency* 655
 - 11.3.3 *Stabilizing an Unstable Short-Period Mode* 661
 - 11.3.4 *Stabilizing an Unstable Phugoid Mode* 664

- 11.4** Lateral-Directional Stability Augmentation 667
 - 11.4.1 Increasing Dutch-Roll Damping* 669
 - 11.4.2 Reducing Aileron Excitation of the Dutch Roll* 675
 - 11.4.3 Increasing Yaw-Damper Effectiveness* 678
 - 11.4.4 Reducing the Roll-Mode Time Constant* 681
- 11.5** Comments on Elastic Effects 682
- 11.6** Summary 683
- 11.7** Problems 684
References 685

Chapter 12

Automatic Guidance and Control—Autopilots 686

- 12.1** Feedback Control-Law Synthesis Via Loop Shaping—A JITT 687
 - 12.1.1 Bode Plots Revisited* 687
 - 12.1.2 Nyquist Stability Theory* 689
 - 12.1.3 The Loop-Shaping Technique* 696
- 12.2** Inner and Outer Loops, and Frequency Separation 703
- 12.3** The Flight-Dynamics Frequency Spectra 706
- 12.4** Attitude Control 708
 - 12.4.1 Pitch-Attitude Control* 709
 - 12.4.2 Other Pitch-Attitude-Control Approaches* 721
 - 12.4.3 Bank-Angle Control* 724
 - 12.4.4 Turn Coordination and Turn Compensation* 735
- 12.5** Response Holds 737
 - 12.5.1 Speed (Mach) Hold* 737
 - 12.5.2 Altitude Hold* 742

- 12.5.3 Heading Hold* 749
- 12.6** Path Guidance—ILS Couplers and VOR Homing 753
 - 12.6.1 Longitudinal Path Guidance* 754
 - 12.6.2 Lateral-Directional Path Guidance* 765
- 12.7** Elastic Effects and Structural-Mode Control 772
- 12.8** Summary 786
- 12.9** Problems 787
References 787

Chapter 13

Control Characteristics of the Human Pilot 789

- 13.1** Background 789
- 13.2** The Crossover Model 790
- 13.3** Flight-Dynamics Implications of the Human Pilot's Control Characteristics 798
- 13.4** Summary 807
- 13.5** Problems 807
References 808

Appendix A Properties of the Atmosphere 809

Appendix B Data for Several Aircraft 814

Appendix C Models of Atmospheric Turbulence 839

Appendix D Cramer's Rule for Solving Simultaneous Equations 852

Index 853