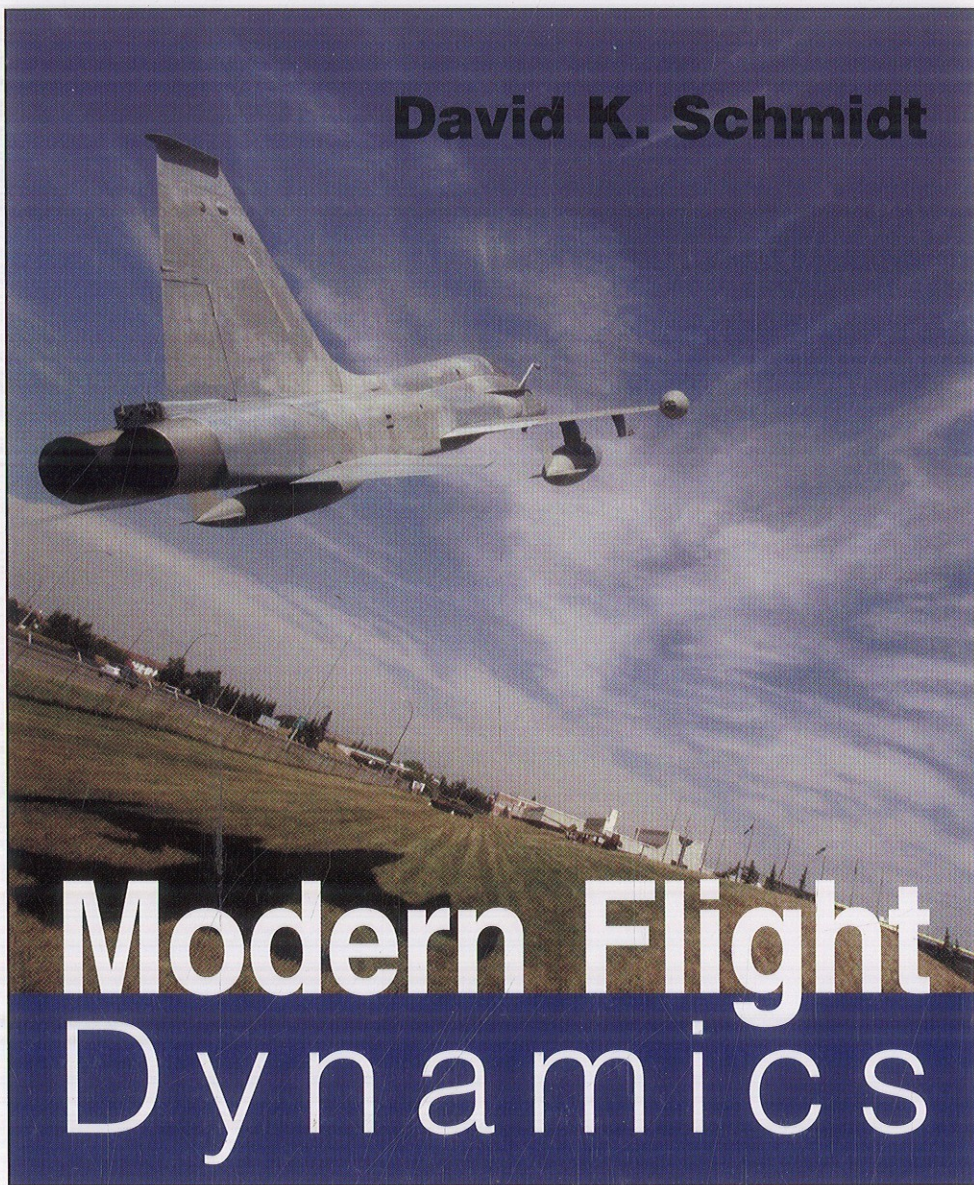


**David K. Schmidt**



# Modern Flight Dynamics

**M c G R A W - H I L L I N T E R N A T I O N A L E D I T I O N**



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 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 *Effects of Modal Displacement* 333
  - 7.3.2 *Effects of Modal Velocity* 337
- 7.4 Elastic Effects on Side Force 342
  - 7.4.1 *Effects of Modal Displacement* 343
  - 7.4.2 *Effects of Modal Velocity* 345
- 7.5 Elastic Effects on Pitching Moment 346
  - 7.5.1 *Effects of Modal Displacement* 347
  - 7.5.2 *Effects of Modal Velocity* 349
- 7.6 Elastic Effects on Rolling Moment 351
  - 7.6.1 *Effects of Modal Displacement* 353
  - 7.6.2 *Effects of Modal Velocity* 355
- 7.7 Elastic Effects on Yawing Moment 358
  - 7.7.1 *Effects of Modal Displacement* 359
  - 7.7.2 *Effects of Modal Velocity* 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 *Integrating into the Nonlinear Equations* 376
  - 7.10.2 *Integrating into the Linearized Equations* 378
- 7.11 Static-Elastic Effects on a Vehicle's Aerodynamics 384
  - 7.11.1 *Static-Elastic Deformations* 384
  - 7.11.2 *Effects on the Aerodynamics* 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 *Linear Equations of Motion* 395
  - 8.1.2 *Linear Models of the Forces and Moments* 400
  - 8.1.3 *Decoupling the Equations of Motion in Level Flight* 405
  - 8.1.4 *Decoupled Models in State-Variable Format* 407
  - 8.1.5 *Linear Models for Flexible Vehicles* 412
  - 8.1.6 *Adding Feedback Control Laws to a Simulation Model* 420
  - 8.1.7 *Adding Atmospheric Turbulence to a Simulation Model* 425
  - 8.1.8 *Numerical Simulation Methods for Linear Models—A JITT* 428
  - 8.1.9 *Linear-Simulation Examples* 432
- 8.2 Nonlinear Model Assembly and Simulation 445
  - 8.2.1 *Nonlinear Equations of Motion* 445
  - 8.2.2 *Models for the Aerodynamic and Propulsive Forces and Moments* 447
  - 8.2.3 *Assembling the Nonlinear Mathematical Model* 449
  - 8.2.4 *Models for Flexible Vehicles* 451
  - 8.2.5 *Adding Feedback Control Laws to a Simulation Model* 455
  - 8.2.6 *Adding Atmospheric Turbulence to a Simulation Model* 456
  - 8.2.7 *Numerical Simulation Techniques—A JITT* 456
  - 8.2.8 *Examples of Nonlinear Simulations* 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 854