

## **Preface**

### **Chapter 1. Introduction to Aeroelasticity**

- 1.1 The Scope of Aeroelasticity 1
  - 1.2 The Terminology in Aeroelastic Analyses 3
  - 1.3 The Role of Aeroelasticity in Aerospace Vehicle Design 6
  - 1.4 Force and Coordinate Systems 8
- 14

### **Chapter 2. A Brief History of Aeroelasticity**

- 2.1 Early Examples of Aeroelastic Phenemena 21
- 2.2 Aeroelasticity in Aeronautics 30
- 2.3 Insights Gained During World War I 32
- 2.4 Developments After World War I 36
- 2.5 Some Accident Statistics 36
- 2.6 Developments Since World War II 45
- 2.7 Aeroelasticity in Stability and Control 46
- 2.8 Development of Unsteady Aerodynamic Theory 47
- 2.9 Early Experimental Techniques 49

### **Chapter 3. Aerodynamics: Steady and Unsteady Theory**

- 3.1 Aerodynamic Characteristics of Airfoils 59
- 3.2 The Unsteady Two-Dimensional Airfoil 60
- 3.3 Estimation of Dynamic Stability Derivatives 66
- 3.4 Unsteady Potential Theory 92
- 3.5 Approximate Analytical Solutions for Wings and Bodies 97
- 3.6 Numerical Solutions for Lifting Surfaces in Steady Flow 112
- 3.7 Numerical Solutions for Lifting Surfaces in 127
- Oscillatory Motion 138
- 3.8 Numerical Solutions for Interfering Lifting Surfaces 153
- and Bodies
- 3.9 Aerodynamic Influence Coefficients 164
- 3.10 Computational Fluid Dynamics 168

### **Chapter 4. Structures: Deflection Theory**

- 4.1 Elementary Bending and Torsion Theory 177
  - 4.2 Energy Theorems 177
  - 4.3 Shear Center and Torsional Stiffness of a Torque Box 181
  - 4.4 Deflections of an Elastic Axis with Variable Stiffness 184
  - 4.5 Interpolation of Flexibility Influence Coefficients 191
- 198

4.6	Thin Plate Theory and Surface Splines	208
4.7	Finite Element Analysis	229
4.8	The Direct Stiffness Method	230
4.9	A Stiffness Matrix from Assumed Deflections	243
4.10	Reciprocity of Flexibility and Stiffness	246
4.11	A Stiffness Matrix from Assumed Stresses	248
<b>Chapter 5. Vibrations: Frequencies and Modes</b>		<b>253</b>
5.1	A Single Degree-of-Freedom System	253
5.2	Structural Damping	260
5.3	A Two Degree-of-Freedom System	264
5.4	The Vibrating String	268
5.5	Torsional Vibrations of a Rod	275
5.6	Bending Vibrations of a Beam	279
5.7	Vibrations of an Elastic Axis	283
5.8	The Coupled Mass Matrix	284
5.9	Matrix Formulation of the Vibration Problem	293
5.10	Orthogonality of Calculated and Measured Vibration Modes	296
5.11	A Method for Deriving Flexibility Matrices from Ground Vibration Tests	301
<b>Chapter 6. Quasistatic Aeroelasticity: Maneuvering Flight</b>		<b>311</b>
6.1	The Two-Dimensional Airfoil	311
6.2	A Rigid Swept Wing on Flexible Supports	319
6.3	The Slender Straight Wing	324
6.4	Influence Coefficient Formulation for General Planforms	331
6.5	Stiffness Matrix Formulation for General Configurations	344
6.6	Divergence of a Restrained Vehicle	349
6.7	Modal Formulation for Static Aeroelasticity	350
6.8	Equations of Motion Including the Effects of the Dynamic Structure	351
6.9	Speed Derivatives and Aeroelastic Effects on Drag	358
6.10	Dihedral Effect of a Flexible Wing	360
6.11	Corrections to Measurements on "Rigid" Wind Tunnel Models	364
<b>Chapter 7. Flutter: The Dynamic Aeroelastic Instability</b>		<b>367</b>
7.1	Quasistatic Flutter Analysis	368
7.2	First Order Unsteady Flutter Analysis	373
7.3	The American or K-Method of Flutter Analysis	378
7.4	The British or PK-Method of Flutter Analysis	394
7.5	The Generalized Aeroelastic Analysis Method (GAAM)	400
7.6	The Similarity Parameters of Flutter	404

7.7	Control Surface Flutter	409
7.8	Panel Flutter	411
7.9	Propeller/Nacelle Whirl Flutter	416
7.10	T-tail Flutter	428

**Chapter 8. Transient Response: Landing and Gust Loads** **437**

8.1	Response to Arbitrary Time-Dependent External Forces	438
8.2	Numerical Methods for Response Calculations	448
8.3	Transient Lift on a Maneuvering Airfoil	458
8.4	Response of a Two-Dimensional Airfoil to a Discrete Gust	461
8.5	Methods for Calculating Transient Stresses	469
8.6	Response of a Flight Vehicle to a Discrete Uniform Atmospheric Gust	472

**Chapter 9. Random Response: Atmospheric Turbulence and Runway Roughness** **477**

9.1	Statistical Description of Random Loading	478
9.2	Random Response in Terms of Covariance Functions	481
9.3	Random Response in Terms of Power Spectra	489
9.4	Frequency of Exceeding a Specified Value	499
9.5	The Harmonic Gust Functions	501
9.6	Examples of Power Spectral Densities	505
9.7	Design Loads for Random Atmospheric Gusts	511
9.8	Examples of Random Gust Response	520

**Chapter 10. Aeroservoelasticity: Control System Interaction** **531**

10.1	Transfer Functions	532
10.2	Equations of Motion in State-Space	536
10.3	Functions for Approximating Generalized Oscillatory Aerodynamic Forces	547
10.4	Presentation of Results of Stability Analyses	550
10.5	Design of Active Controls	552
10.6	Design of a Structural Mode Control System	553
10.7	Design of a Gust Alleviation System	556
10.8	Design of a Flutter Suppression System	559

**Chapter 11. Aerothermoelasticity: High Speed Atmospheric Flight** **563**

11.1	Large Deflections of Heated Structures	563
11.2	Aerodynamic Heating	567
11.3	Example of Aerothermoelastic Flutter	568

<b>Chapter 12. Aeroelastic Design: Optimization</b>	<b>575</b>
by Erwin H. Johnson, Ph. D., and Garret N. Vanderplaats, Ph. D., PE	
12.1 Aeroelastic Optimization	578
12.2 Numerical Optimization Basics	580
12.3 Aeroelastic Responses	586
12.4 Design Sensitivities	587
12.5 Aeroelastic Design Sensitivities	591
12.6 The Optimizer	594
12.7 Example of an Aeroelastic Design	599
<b>Appendix A. Matrix Algebra</b>	<b>607</b>
A.1 Definitions	607
A.2 Addition and Subtraction	608
A.3 Multiplication	608
A.4 Inversion	609
A.5 Differentiation	610
A.6 Integration	611
A.7 Partitioning	611
A.8 Eigenvalues and Eigenvectors	613
<b>Appendix B. Laplace and Fourier Transforms</b>	<b>619</b>
B.1 The Laplace Transform	619
B.2 Some General Properties of the Laplace Transform	620
B.3 Laplace Transforms of Simple Functions	623
B.4 The Solution of a Differential Equation by Means of a Laplace Transform Table	625
B.5 The Inverse Laplace Transform	627
B.6 The Fourier Transform	629
<b>Appendix C. Probability and Its Distributions</b>	<b>637</b>
C.1 Basic Notions	637
C.2 Random Variables and Their Probability Functions	639
C.3 Expectation and Moments	643
C.4 The Gaussian Distribution	645
C.5 The Rayleigh Distribution	648
<b>Appendix D. The Development of the Doublet-Lattice Method</b>	<b>651</b>
1. Introduction	651
2. The Doublet-Lattice Method (DLM)	652
3. Later Developments	654
4. Publicizing the DLM	655

5. Continued Developments	657
6. Recent Developments	658
7. Concluding Remarks	659
<b>Appendix E. Flight Mechanics of a Rigid Vehicle</b>	<b>661</b>
Introduction	661
Symbols	663
Vector Equations of Motion	665
Scalar Equations	667
Concluding Remarks	668
<b>Appendix F. Some Correspondence with the Federal Aviation Administration</b>	<b>671</b>
<b>Appendix G. Galerkin – The Man and the Method</b>	<b>699</b>
The Man	699
The Method	700
<b>Appendix H. Autobiography</b>	<b>747</b>
1. Introduction	748
2. Early Aerospace Employment	748
3. Graduate Study	749
4. Flutter Analysis	749
5. Teaching	750
6. Consulting	750
7. Retirement	753
8. My Favorite Contributions to the Literature	753
9. My Least Favorite Contribution to the Literature	755
<b>References and Abbreviations</b>	<b>757</b>
<b>Index of Authors</b>	<b>795</b>
<b>Index of Subjects</b>	<b>805</b>