Contents

PREFACE ***xvii***

HISTORICAL INTRODUCTION ***1***

1 The Origins of Vibration Theory 1
2 The Early Modern Era 8
3 Modern Times 10
4 Conclusion 12
References and Further Reading 15

1 KINEMATICS OF VIBRATION ***16***

1.1 Periodic Motion 16
1.2 Vector and Complex Number Representation 22
1.3 The Simple Pendulum 25
1.4 Harmonic Analysis 29
1.5 Complex Form of the Fourier Series 33

1.6 Vibration Analysis by Symbolic Processing 37
1.7 Numerical Vibration Analysis by Symbolic Computation 37
Summary of Equations in Chapter 1 40
References and Further Reading 41
Exercises and Problems 41

2 NATURAL VIBRATION ABOUT EQUILIBRIUM 50

2.1 Vibrating Systems 50
2.2 Discrete Elements of Vibrating Systems: Stiffness Elements 53
2.3 Modeling of Vibrating Systems 60
2.4 Newton's Second Law of Motion 62
2.5 Principle of Virtual Work, D'Alembert's Principle 63
2.6 Conservation of Energy 66
2.7 Undamped Vibration 69
2.8 Damping Elements 81
2.9 Damped Natural Vibration 84
2.10 Torsional Vibration 93
2.11 Mass Elements 95
2.12 Damping Due to Dry Friction: Bilinear Systems 98
2.13 Dynamic Response by Symbolic Processing 102
Summary of Equations in Chapter 2 103
References and Further Reading 105
Exercises and Problems 105

3 FORCED HARMONIC VIBRATION 127

3.1 Introduction 127
3.2 Forced Vibration of an Undamped System: Harmonic Excitation 128
3.3 Forced Vibration of a Damped System: Harmonic Excitation 131
3.4 Linearity: Principle of Superposition 138
3.5 Vector Representation 140
3.6 Other Harmonic Excitations 143
Whirling of Rotating Shafts, 144
Base Excitation, 147
Higher Harmonics of Torque on Electric Machines, 151

3.7 Material and Interface Damping 152
3.8 Measuring Instruments in Vibration Analysis 160
3.9 Foundations: Vibration Isolation 165
3.10 Microcomputed-Assisted Vibration Measurements 168
3.11 Dynamic Response of Linear Systems by Symbolic Processors 170
Summary of Equations in Chapter 3 172
References and Further Reading 173
Exercises and Problems 173

4 ENERGY METHODS, STABILITY **186**

4.1 Conservation of Energy 186
4.2 Rayleigh's Method 189
4.3 Lagrange's Equation 191
4.4 Stability 197
4.5 Dynamic Instability: Self-Excited Vibration 199
4.6 Parametrically Excited Vibration 202
4.7 Fluid-Flow-Induced Vibration 206
Galloping of Electric Lines, 206
Von Kármán Vortex Trails, 207
4.8 Friction-Induced Vibration and Stick-Slip 209
4.9 Stability of Mechanical Systems 211
Summary of Equations in Chapter 4 214
References and Further Reading 214
Exercises and Problems 215

5 NONHARMONIC EXCITATION **227**

5.1 Introduction 227
5.2 Periodic Excitation 227
5.3 Nonperiodic Excitation 232
5.4 The Method of Laplace Transform 239
5.5 Direct Numerical Integration 243
5.6 Response Spectra 244
5.7 Earthquake Response 245
5.8 Piecewise Linearization 251
5.9 Response to General Excitation Using Symbolic Computation 255
Summary of Equations in Chapter 5 257

References and Further Reading 258
Exercises and Problems 258

6 COUPLED VIBRATING SYSTEMS **268**

6.1 Introduction 268
6.2 Equations of Motion for Two-Degree-of-Freedom Coupled Systems 272
Application of Newton's Laws of Motion, 272
Use of Lagrange's Equations, 274
6.3 Natural Vibration of Coupled Systems 275
6.4 Harmonic Excitation 280
6.5 Matrix Formulation 284
6.6 Dynamic Vibration Absorbers 286
Undamped Absorber, 268
Damped Absorber, 289
Optimal Design of Dynamic Vibration Absorbers, 291
Torsional Absorber, 292
6.7 Coupled Electromechanical Systems 296
Summary of Equations in Chapter 6 298
References and Further Reading 300
Exercises and Problems 300

7 LUMPED MASS SYSTEMS: NATURAL VIBRATION **314**

7.1 Introduction 314
7.2 Direct Methods of Analysis 315
Equations of Motion, 315
Natural Vibration: Method of the Frequency Determinant, 318
7.3 Influence Coefficients 326
Stiffness Influence Coefficients, 326
Flexibility Influence Coefficients, 326
Potential Energy, 327
Potential Energy in Terms of Influence Coefficients, 330
7.4 Matrix Methods 334
Stiffness Matrix Method, 334
Flexibility Matrix Method, 336
Lagrange's Equations, 337
7.5 Natural Modes of Vibration: The Eigenvalue Problem 339
7.6 Free Vibration: The Initial Value Problem 341
Distinct Eigenvalues, 341
Multiple Eigenvalues, 343
Zero Eigenvalues and Rigid-Body Motion, 344

7.7 Orthogonality of the Natural Modes: Normal Coordinates and Modal Analysis 346
7.8 Damped Natural Vibration 351
7.9 Numerical Methods 354
Undamped Systems, 355
Damped Systems, 357
7.10 Natural Vibration Analysis by Symbolic Computation 359
Summary of Equations in Chapter 7 360
References and Further Reading 362
Exercises and Problems 362

8 LUMPED MASS SYSTEMS: FORCED VIBRATION **372**

8.1 Introduction 372
8.2 Exact Methods 373
8.3 Matrix Formulation: Periodic Excitation 379
8.4 Nonperiodic Excitation: Direct Method 384
8.5 Modal Analysis: Transients 387
8.6 Modal Analysis: Harmonic Excitation 394
8.7 Forced Harmonic Vibration Analysis by Symbolic Computation 396
Summary of Equations in Chapter 8 397
References and Further Reading 398
Exercises and Problems 398

9 CONTINUOUS SYSTEMS **403**

9.1 Introduction 403
9.2 The One-Dimensional Structural Member Wave Equation 405
The Taut String, 406
Longitudinal Vibrations of Rods, 407
Lateral Vibration: The Euler–Bernoulli Beam, 408
Torsional Vibration of Rods, 409
Wave Propagation, 410
9.3 Initial and Boundary Conditions 414
Taut Spring, 415
Longitudinal Vibration of Rods, 415
Torsional Vibration of Rods, 415
Lateral Vibration of Beams, 415
9.4 Modes of Natural Vibration: The Eigenvalue Problem 417
Second-Order Operator L, *419*
Principle of Orthogonality of the Natural Modes, 424
Fourth-Order Operator L, *425*

9.5 Natural Vibration: The Initial Value Problem 431
9.6 Forced Vibration 434
Distributed Harmonic Excitation, 435
Harmonic Motion of the Boundaries, 436
Harmonic Force on the Boundary, 438
General Excitation: Modal Analysis, 439
9.7 Special Topics 441
Effects of the Rotary Inertia and Shear Deformation: the Rayleigh–Timoshenko Beam, 441
The Moving Taut String, 443
Vibration of Pipes at High Flow Velocities, 445
Vibration of Membranes, 446
Beams on Elastic Foundation, 449
Summary of Equations in Chapter 9 451
References and Further Reading 452
Exercises and Problems 452

10 APPROXIMATE AND NUMERICAL METHODS 463

10.1 Introduction 463
10.2 Rayleigh's Method 465
10.3 The Method of Constraints 472
10.4 The Holzer–van den Dungen Method: Transfer Matrices 477
Static Deflection of Beams, 478
Natural Vibration, 481
Forced Harmonic Vibration, 484
10.5 The Finite Elements Method 486
Direct Method, 486
Consistent Mass Method, 487
Vibration of Framed Structures, 492
Node Restraints, 493
10.6 The Rayleigh–Ritz Method 494
10.7 The Galerkin Method 498
10.8 The Stodola Method: Power Iteration 500
Fundamental Natural Frequency, 500
Higher Modes: Matrix Deflation, 503
10.9 Concurrent Computation Methods 505
Jacobi Method of Matrix Rotation, 505
Cholesky Method of Matrix Decomposition, 506
10.10 The Dunkerley Procedure 511
10.11 Vibration of Plates 513
Summary of Equations in Chapter 10 518
References and Further Reading 520
Exercises and Problems 520

11 ROTOR DYNAMICS 533

11.1 Dynamics of a Rotor on a Flexible Shaft 533
The De Laval Rotor, 533
Polar Representation, Whirl, and Precession, 536
Unbalance and Critical Speeds, 53
Damping, 541
Viscous Damping, 541
Hysteretic Damping, 542
Vector Methods, 543
Acceleration Through the Critical Speed, 544
Gyroscopic Effects on the Critical Speeds, 546

11.2 Rotors on Flexible Bearings 553
Bearing Properties, 553
Fluid or Magnetic Forces on the Shaft, 558

11.3 Stability of Rotors 559
Internal Friction, 561
Bearing Instabilities: Orthotropic Bearings, 562
Bearing Instabilities: Rigid Rotor, 562
Bearing Instabilities: Elastic Shaft, 563
Asymmetry of Rotating Parts, 568
Thermal Unbalance: The Newkirk Effect, 572

11.4 The Transfer Matrix Method 572
Natural Vibration: Critical Speeds, 572
Forced Vibration, 576

11.5 The Finite Element Method 577

Summary of Equations in Chapter 11 583

References and Further Reading 586

Problems 587

12 VIBRATION OF NONLINEAR SYSTEMS 597

12.1 Geometric Methods: The Phase Plane 597
Nonlinear Elements, 597
The Phase Plane, 598
The Delta Method, 600
Phase-Plane Transient Solutions, 601
Classification of Nonlinear Systems, 604
Autonomous Systems, 606
Nonautonomous Systems, 607

12.2 Exact Solutions: Period of Vibration of Undamped Systems 609

12.3 Approximate Analytical Methods 610
Duffing Method of Successive Approximations, 610
Linstedt Perturbation Method, 613
The Ritz–Galerkin Method, 614

12.4 Numerical Methods 615
Point Methods, 615

Extrapolation Methods, 617
Integration Eerrors, 618
12.5 Stability 623
The First Method of Liapounov, 625
The Second Method of Liapounov, 629
Liapounov Function for Linear Autonomous Systems, 631
Limit Cycles of Autonomous Systems: Chaotic Vibration, 633
Friction-Induced Vibration: Stick-Slip, 636
Mechanical Systems With Backlash 637
12.6 Dynamic Response of Nonlinear Systems by Symbolic Processing 639
Summary of Equations in Chapter 12 643
References and Further Reading 644
Problems 644

13 VIBRATING SYSTEMS DESIGN 648

13.1 Acceptable Vibration Levels 648
13.2 Effects of Vibration on Machinery Deterioration and Failures 650
13.3 Vibrating Systems Synthesis 655
13.4 The General Design Problem 656
System Properties Dependent on Frequency, 656
Constant System Properties, 658
The Modal Analysis Method, 660
13.5 Masses Needed to Establish Known Motion Balancing 662
One-Plane Balancing, 665
Two-Plane Balancing, 667
13.6 Inverse Vibration Engineering 672
Summary of Equations in Chapter 13 674
References and Further Reading 675
Problems 675

14 ELEMENTS OF VIBRATION SIGNAL PROCESSING AND RANDOM EXCITATION 678

14.1 Introduction 678
14.2 Sampled Time Functions 679
14.3 Random Signals 685
Random Processes, 685
The Normal Distribution, 691
The Rayleigh Distribution, 693
Time-Domain Description, 694
Frequency-Domain Description, 697

14.4 Response of a Single-Degree-of-Freedom System to Random Excitation 700
Response Parameters, 700
Derivative Processes, 703
14.5 Response of a Linear System to Random Excitation 704
Superposition of Stationary Processes, 704
Direct Method, 705
Modal Analysis Method, 706
14.6 Numerical Vibration Analysis By Symbolic Processing 711
Summary of Equations in Chapter 14 713
References and Further Reading 715
Problems 716

15 MACHINERY VIBRATION: MONITORING AND DIAGNOSIS 721

15.1 Introduction 721
15.2 Time-Domain Vibration Analysis and Signal Processing 722
Time-Series Averaging, 723
Local Signal Averaging, 727
Signal Enveloping, 727
The Kurtosis Method, 729
The Spike Energy Method, 732
15.3 Frequency-Domain Vibration Analysis and Signal Processing 733
Signal Enhancement with Gating, 733
rpm Spectral Maps (Waterfalls), 734
The Campbell Diagram, 739
Cepstrum Analysis, 739
15.4 Fault Diagnosis 745
Unbalance, 745
Slow Transients: Rubbing, 747
Misalignment, 748
Cracks, 749
Rolling Element Bearing Faults, 750
Gear Faults, 751
Fluid-Induced Instabilites, 753
15.5 Quantitative Diagnosis: Sensitivity Analysis 754
The Eigenvalue Sensitivity Problem, 754
The Inverse Structural Modification Problem, 754
Summary of Equations in Chapter 15 757
References and Further Reading 757
Problems 758

APPENDICES 761

I ALGORITHMIC NOTATION 761

II DISCRETE ELEMENTS 763

III ALGEBRAIC IDENTITIES 772

IV ELEMENTS OF LINEAR ALGEBRA 774

Matrices, 774
Basic Matrix Operations, 776
Eigenvalues and Eignevectors of a Square Matrix, 776
Quadratic Forms and the Positive Definiteness of a Square Matrix, 778
Some Useful Relationships, 778

V TRANSFER MATRICES 779

VI LAPLACE TRANSFORMS 782

VII UNIT CONVERSION AND NOMENCLATURE 786

General Conversion Formulas, 786
Nomenclature, 787

VIII THE VIBLAB PACKAGE 791

IX SUMMARY OF MATHEMATICAL COMMANDS 793

X TABLES OF MATERIAL PROPERTIES USEFUL IN VIBRATION ANALYSIS 799

XI SELECTED VIBRATION BIBLIOGRAPHY 803

ANSWERS TO SELECTED PROBLEMS 810

INDEXES 815

Name Index, 815
Subject Index, 818
Applications Index, 824