CONTENTS

PREFACE ix

THE SI SYSTEM OF UNITS 1

1 OSCILLATORY MOTION 5

1.1 Harmonic Motion 6
1.2 Periodic Motion 9
1.3 Vibration Terminology 12

2 FREE VIBRATION 17

2.1 Vibration Model 17
2.2 Equations of Motion–Natural Frequency 18
2.3 Energy Method 22
2.4 Rayleigh Method: Effective Mass 24
2.5 Principle of Virtual Work 26
2.6 Viscously Damped Free Vibration 28
2.7 Logarithmic Decrement 33
2.8 Coulomb Damping 35

3 HARMONICALLY EXCITED VIBRATION 50

3.1 Forced Harmonic Vibration 50
3.2 Rotating Unbalance 55
3.3 Rotor Unbalance 58
3.4 Whirling of Rotating Shafts 59
3.5 Support Motion 63
3.6 Vibration Isolation 65
3.7 Energy Dissipated by Damping 67
3.8 Equivalent Viscous Damping 70
3.9 Structural Damping 72
3.10 Sharpness of Resonance 74
3.11 Vibration Measuring Instruments 76

4 TRANSIENT VIBRATION 88

4.1 Impulse Excitation 88
4.2 Arbitrary Excitation 90
4.3 Laplace Transform Formulation 93
4.4 Response Spectrum 96
4.5 Finite Difference Numerical Computation 100
4.6 Runge-Kutta Method (*Method* 2) 108

5 INTRODUCTION TO MULTI-DEGREE OF FREEDOM SYSTEMS 120

5.1 Normal Mode Vibration 121
5.2 Coordinate Coupling 125
5.3 Forced Harmonic Vibration 129
5.4 Digital Computation 131
5.5 Vibration Absorber 136
5.6 Centrifugal Pendulum Vibration Absorber 138
5.7 Vibration Damper 140

6 PROPERTIES OF VIBRATING SYSTEMS 155

6.1 Flexibility Matrix 155
6.2 Stiffness Matrix 159
6.3 Stiffness of Beam Elements 161

6.4 Eigenvalues and Eigenvectors 164
6.5 Orthogonal Properties of the Eigenvectors 170
6.6 Repeated Roots 171
6.7 Modal Matrix P 173
6.8 Modal Damping in Forced Vibration 175
6.9 Normal Mode Summation 177

7 LAGRANGE'S EQUATION **188**

7.1 Generalized Coordinates 188
7.2 Virtual Work 193
7.3 Lagrange's Equation 196
7.4 Kinetic Energy, Potential Energy, and Generalized Force 203

8 NORMAL MODE VIBRATION OF CONTINUOUS SYSTEMS **213**

8.1 Vibrating String 214
8.2 Longitudinal Vibration of Rods 216
8.3 Torsional Vibration of Rods 218
8.4 Euler Equation for Beams 221
8.5 Effect of Rotary Inertia and Shear Deformation 224

9 MODE-SUMMATION PROCEDURES FOR CONTINUOUS SYSTEMS **233**

9.1 Mode-Summation Method 233
9.2 Beam Orthogonality Including Rotary Inertia and Shear Deformation 238
9.3 Normal Modes of Constrained Structures 239
9.4 Mode-Acceleration Method 244
9.5 Component Mode Synthesis 246

10 INTRODUCTION TO THE FINITE ELEMENT METHOD **257**

10.1 Element Stiffness and Mass 257
10.2 Stiffness and Mass for the Beam Element 262
10.3 Transformation of Coordinates (Global Coordinates) 265

10.4 Element Stiffness and Element Mass in Global Coordinates 267
10.5 Vibrations Involving Beam Elements 273
10.6 Spring Constraints on Structure 280
10.7 Generalized Force for Distributed Load 282
10.8 Beam Element with One Pinned End 284

11 APPROXIMATE NUMERICAL METHODS 292

11.1 Rayleigh Method 292
11.2 Dunkerley's Equation 299
11.3 Rayleigh-Ritz Method 304
11.4 Method of Matrix Iteration 308
11.5 Calculation of Higher Modes 310

12 NUMERICAL PROCEDURES FOR LUMPED MASS SYSTEMS 319

12.1 Holzer Method 319
12.2 Digital Computer Program for the Torsional System 322
12.3 Myklestad's Method for Beams 325
12.4 Coupled Flexure-Torsion Vibration 329
12.5 Transfer Matrices 331
12.6 Systems with Damping 333
12.7 Geared System 335
12.8 Branched Systems 336
12.9 Transfer Matrices for Beams 338
12.10 Difference Equation 341

13 RANDOM VIBRATIONS 351

13.1 Random Phenomena 351
13.2 Time Averaging and Expected Value 352
13.3 Frequency Response Function 354
13.4 Probability Distribution 357
13.5 Correlation 363
13.6 Power Spectrum and Power Spectral Density 367

13.7 Fourier Transforms 373
13.8 FTs and Response 380

14 NONLINEAR VIBRATIONS **392**

14.1 Phase Plane 393
14.2 Conservative Systems 394
14.3 Stability of Equilibrium 397
14.4 Method of Isoclines 399
14.5 Perturbation Method 401
14.6 Method of Iteration 404
14.7 Self-Excited Oscillations 408
14.8 Runge-Kutta Method 410

APPENDICES

A SPECIFICATIONS OF VIBRATION BOUNDS **419**

B INTRODUCTION TO LAPLACE TRANSFORMATION **421**

C DETERMINANTS AND MATRICES **427**

C.1 Determinant 427
C.2 Matrices 428
C.3 Rules of Matrix Operations 431
C.4 Determination of Eigenvectors 434
C.5 Cholesky's Method of Solution 436

D NORMAL MODES OF UNIFORM BEAMS **438**

ANSWERS TO SELECTED PROBLEMS **449**

INDEX **461**