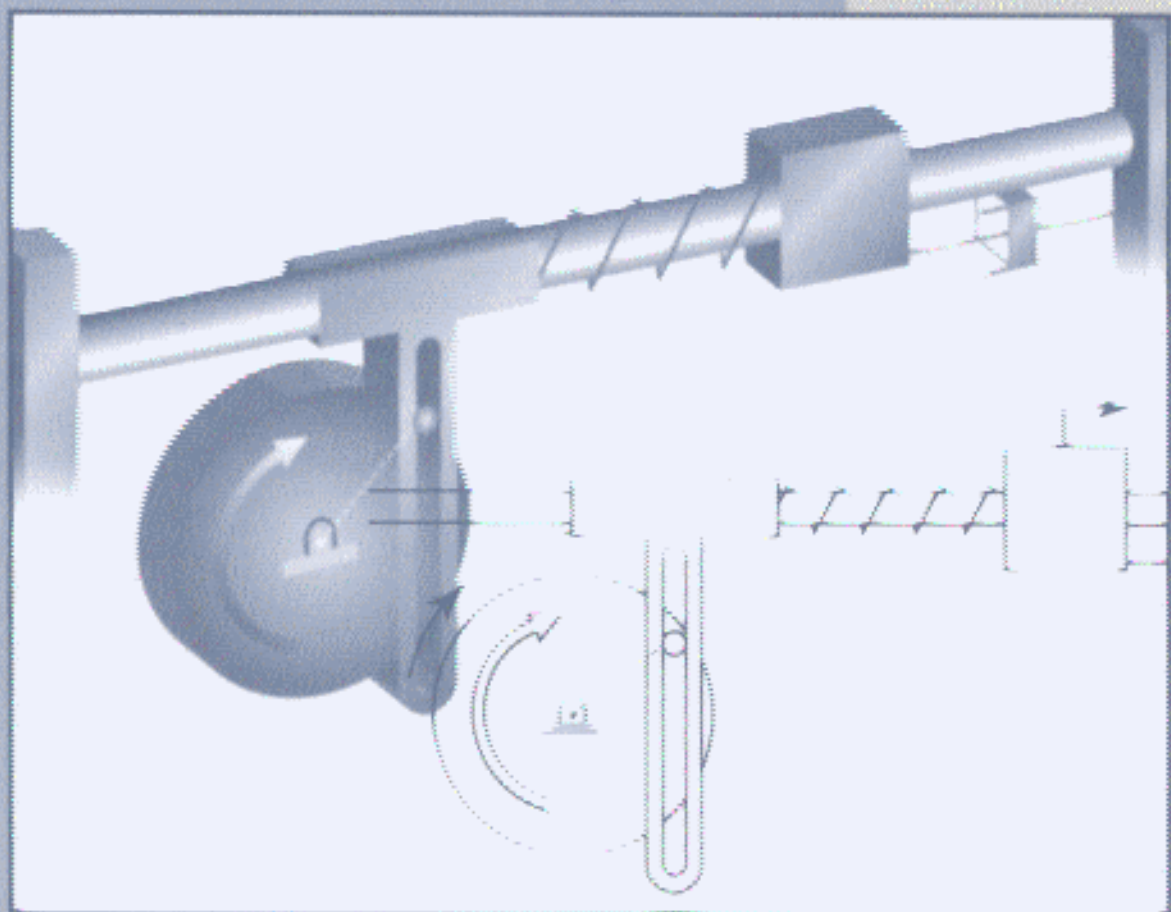


Mechanical and Structural Vibrations

Theory and
Applications



Jerry H. Ginsberg

CHAPTER 1 EQUATIONS OF MOTION FOR DISCRETE SYSTEMS 1

1.1	The Study of Vibrations: An Overview	1
1.2	System Elements	3
1.3	Generalized Coordinates	8
1.4	Newton-Euler Motion Equations	12
1.5	Power Balance Method for Time-Invariant Systems	19
1.5.1	Power Balance Law	20
1.5.2	Linearized Energy and Power	21
1.5.3	Linearized Equations of Motion	24
1.5.4	Implementation	27
	References and Selected Readings	54
	Exercises	54

CHAPTER 2 TRANSIENT RESPONSE OF ONE-DEGREE-OF-FREEDOM SYSTEM 64

2.1	Harmonic Functions	64
2.1.1	Basic Properties	64
2.1.2	Complex Variable Representation	67
2.1.3	Algebraic Operations	69
2.2	Free Vibration	74
2.2.1	Undamped Systems	76
2.2.2	Underdamped Systems	79
2.2.3	Overdamped Systems	88
2.2.4	Critically Damped Systems	90
2.2.5	Coulomb Friction	94
2.3	Transient Response to Basic Excitations	98
2.3.1	Method of Undetermined Coefficients	98
2.3.2	Superposition and Time Delay	100
2.3.3	Pulse Excitation	104
2.3.4	Step and Impulse Responses	108
2.3.5	Shock Spectra	110
	References and Selected Readings	112
	Exercises	112

CHAPTER 3 STEADY-STATE RESPONSE TO HARMONIC EXCITATION 121

3.1	Complex Frequency Response	121
3.2	Power Dissipation	130

3.2.1	Quality Factor of Resonance	131
3.2.2	Structural Damping	135
3.3	Resonant Response	139
3.4	Rotating Imbalance	143
3.4.1	Basic Model	143
3.4.2	Frequency Response	148
3.5	Whirling of Shafts	152
3.6	Force Transmission	154
3.7	Periodic Excitations	155
3.7.1	Complex Fourier Series	155
3.7.2	The Discrete Fourier Transform	159
3.7.3	The Inverse Discrete Fourier Transform	162
3.7.4	Explanation and Implementation of the FFT Algorithm	164
3.7.5	Periodic Response Using FFTs	168
3.7.6	Accelerometers and Seismometers	175
3.8	Transient Response Revisited	181
3.8.1	Convolution Integral	181
3.8.2	FFTs for Transient Response	184
	References and Selected Readings	206
	Exercises	206

CHAPTER 4 MODAL ANALYSIS OF MULTI-DEGREE-OF-FREEDOM SYSTEMS 219

4.1	Background	219
4.2	Eigenvalue Problem—Undamped Systems	223
4.2.1	Natural Frequencies and Modes	223
4.2.2	Orthogonality and Normalization	230
4.2.3	Computerized Implementations	235
4.2.4	Flexibility Coefficients	241
4.2.5	Repeated Natural Frequencies	245
4.2.6	Rigid Body Modes	252
4.3	Modal Equations	256
4.3.1	Coordinate Transformations	256
4.3.2	Modal Coordinates	257
4.3.3	Modal Coordinate Description of Mechanical Energy and Power	260
4.3.4	Free Vibration Response	261
4.3.5	Forced Response	266
4.3.6	Modal Damping	269

4.3.7 Harmonic Steady-State Response	274	7.3 Eigensolutions for Flexure	432
References and Selected Readings	283	7.4 Wave Interpretation of Modes and High-Frequency Asymptotics	441
Exercises	283	7.5 Symmetry and Mode Functions	447
CHAPTER 5 HARMONIC EXCITATION OF MULTI-DEGREE-OF-FREEDOM SYSTEMS	294	7.6 Orthogonality	450
5.1 Frequency Domain Transfer Function	294	7.7 Modal Analysis of Response	456
5.2 Structural Damping and Modal Analysis	297	7.7.1 Modal Equations	456
5.3 Vibration Absorber	301	7.7.2 Steady-State and Transient Response	458
5.4 FFT Techniques	306	7.8 Time-Dependent Boundary Conditions	469
5.4.1 Analysis of Transient Response	306	7.8.1 Mindlin-Goodman Decomposition	469
5.4.2 Experimental Modal Analysis	313	7.8.2 Harmonic Boundary Excitation Wave Solution	474
References and Selected Readings	317	7.9 Timoshenko Beam Theory	482
Exercises	317	7.9.1 Field Equations	482
CHAPTER 6 VIBRATION OF ELASTIC BARS: THE RITZ METHOD AND THE RAYLEIGH RATIO	324	7.9.2 Wave Solutions	487
6.1 Equations of Motion	325	7.9.3 Modal Analysis	490
6.1.1 Axial Displacement	328	References and Selected Readings	498
6.1.2 Torsion of Circular Bars	338	Exercises	498
6.1.3 Flexural Displacement	341	CHAPTER 8 THE FINITE ELEMENT METHOD	508
6.1.4 Implementation and Solution	352	8.1 Interpolating Functions	506
6.2 Eigensolutions	367	8.2 Elemental Matrices	509
6.3 Modal Analysis	367	8.3 Conversion to Global Coordinates	513
6.3.1 Orthogonality of the Mode Functions	367	8.4 Assembly of the Elements	517
6.3.2 Modal Response	371	8.5 Reaction Forces and Constraint Conditions	523
6.3.3 Initial Conditions: The Expansion Theorem	373	References and Selected Readings	528
6.3.4 Free Vibration	375	Exercises	528
6.3.5 Impulse Response	376	CHAPTER 9 SUBSTRUCTURING CONCEPTS	532
6.3.6 Harmonic Steady-State Response	376	9.1 Method of Lagrange Multipliers	532
6.4 Rayleigh Ratio and Convergence Properties	381	9.1.1 Constraint Equations and Reactions	532
6.5 Time-Dependent Boundary Conditions	394	9.1.2 Synthesis of the Equations of Motion	539
6.6 Ritz Method for Discrete Systems	403	9.1.3 Solution Methods	542
References and Selected Readings	406	9.2 Component Mode Synthesis	552
Exercises	406	9.2.1 Relaxation of Constraints	553
CHAPTER 7 FIELD DESCRIPTIONS FOR VIBRATING BARS	414	9.2.2 Component Properties	558
7.1 Derivation of Motion Equations	415	References and Selected Readings	562
7.1.1 Field Equations	415	Exercises	562
7.1.2 Boundary Conditions	420	CHAPTER 10 DAMPED MODAL ANALYSIS: THE STATE SPACE	565
7.2 Eigensolutions for Extension and Torsion	424	10.1 State-Space Equations	565
		10.2 Eigenvalue Problem	567

10.3	Relation to Previous Developments	569
10.4	Orthogonality	575
10.5	Modal Coordinates	580
10.5.1	Free Vibration	581
10.5.2	Impulsive Forces	582
10.5.3	Steady-State Harmonic Vibration	583
10.5.4	Rigid Body Motion	584
10.5.5	Closure	585
	References and Selected Readings	591
	Exercises	591

CHAPTER 11 MODAL ANALYSIS OF GYROSCOPIC SYSTEMS 595

11.1	General Linearized Equations of Motion	595
11.2	Right and Left Eigenvalue Problems	606
11.3	Dynamic Stability	613
11.4	Bi-orthogonality and Modal Equations of Motion	619
11.5	Moving Continuous Systems	627
	References and Selected Readings	641
	Exercises	642

CHAPTER 12 INTRODUCTION TO ROTORDYNAMICS 647

12.1	Elements of a Rotordynamic Model	647
12.2	Effects of Internal and External Damping	650
12.3	Flexible Orthotropic Bearings	656
12.4	Gyroscopic Effects	661
12.5	Flexible Orthotropic Shafts	668
	References and Selected Readings	674
	Exercises	674

APPENDIX A LAGRANGE'S EQUATIONS 677

APPENDIX B TRANSIENT RESPONSES FOR UNDERDAMPED ONE-DEGREE-OF- FREEDOM SYSTEMS 685

APPENDIX C DEFORMATION MODES FOR UNIFORM BARS 686

INDEX 687
