

Contents

<i>Foreword</i>	<i>xix</i>
<i>Preface to the Second Edition</i>	<i>xxi</i>
<i>Preface</i>	<i>xxiii</i>
<i>Acknowledgments</i>	<i>xxix</i>

PART I	SINGLE-DEGREE-OF-FREEDOM SYSTEMS	1
1	<i>Equations of Motion, Problem Statement, and Solution Methods</i>	3
1.1	Simple Structures	3
1.2	Single-Degree-of-Freedom System	7
1.3	Force–Displacement Relation	8
1.4	Damping Force	12
1.5	Equation of Motion: External Force	14
1.6	Mass–Spring–Damper System	19
1.7	Equation of Motion: Earthquake Excitation	23

1.8	Problem Statement and Element Forces	26
1.9	Combining Static and Dynamic Responses	28
1.10	Methods of Solution of the Differential Equation	28
1.11	Study of SDF Systems: Organization	33
	<i>Appendix 1: Stiffness Coefficients for a Flexural Element</i>	33

2 Free Vibration

39

2.1	Undamped Free Vibration	39
2.2	Viscously Damped Free Vibration	48
2.3	Energy in Free Vibration	56
2.4	Coulomb-Damped Free Vibration	57

3 Response to Harmonic and Periodic Excitations

65

Part A: Viscously Damped Systems: Basic Results

66

3.1	Harmonic Vibration of Undamped Systems	66
3.2	Harmonic Vibration with Viscous Damping	72

Part B: Viscously Damped Systems: Applications

85

3.3	Response to Vibration Generator	85
3.4	Natural Frequency and Damping from Harmonic Tests	87
3.5	Force Transmission and Vibration Isolation	90
3.6	Response to Ground Motion and Vibration Isolation	91
3.7	Vibration-Measuring Instruments	95
3.8	Energy Dissipated in Viscous Damping	99
3.9	Equivalent Viscous Damping	103

Part C: Systems with Nonviscous Damping

105

3.10	Harmonic Vibration with Rate-Independent Damping	105
3.11	Harmonic Vibration with Coulomb Friction	109

Part D: Response to Periodic Excitation

113

3.12	Fourier Series Representation	114
3.13	Response to Periodic Force	114
	Appendix 3: Four-Way Logarithmic Graph Paper	118
4	<i>Response to Arbitrary, Step, and Pulse Excitations</i>	125
	Part A: Response to Arbitrarily Time-Varying Forces	125
4.1	Response to Unit Impulse	126
4.2	Response to Arbitrary Force	127
	Part B: Response to Step and Ramp Forces	129
4.3	Step Force	129
4.4	Ramp or Linearly Increasing Force	131
4.5	Step Force with Finite Rise Time	132
	Part C: Response to Pulse Excitations	135
4.6	Solution Methods	135
4.7	Rectangular Pulse Force	137
4.8	Half-Cycle Sine Pulse Force	143
4.9	Symmetrical Triangular Pulse Force	148
4.10	Effects of Pulse Shape and Approximate Analysis for Short Pulses	151
4.11	Effects of Viscous Damping	154
4.12	Response to Ground Motion	155
5	<i>Numerical Evaluation of Dynamic Response</i>	165
5.1	Time-Stepping Methods	165
5.2	Methods Based on Interpolation of Excitation	167
5.3	Central Difference Method	171
5.4	Newmark's Method	174
5.5	Stability and Computational Error	180
5.6	Analysis of Nonlinear Response: Central Difference Method	184
5.7	Analysis of Nonlinear Response: Newmark's Method	184

6	<i>Earthquake Response of Linear Systems</i>	197
6.1	Earthquake Excitation	197
6.2	Equation of Motion	203
6.3	Response Quantities	204
6.4	Response History	205
6.5	Response Spectrum Concept	207
6.6	Deformation, Pseudo-velocity, and Pseudo-acceleration Response Spectra	208
6.7	Peak Structural Response from the Response Spectrum	217
6.8	Response Spectrum Characteristics	222
6.9	Elastic Design Spectrum	228
6.10	Comparison of Design and Response Spectra	238
6.11	Distinction between Design and Response Spectra	240
6.12	Velocity and Acceleration Response Spectra	241
	<i>Appendix 6: El Centro, 1940 Ground Motion</i>	245
7	<i>Earthquake Response of Inelastic Systems</i>	257
7.1	Force–Deformation Relations	258
7.2	Normalized Yield Strength, Yield Strength Reduction Factor, and Ductility Factor	264
7.3	Equation of Motion and Controlling Parameters	265
7.4	Effects of Yielding	266
7.5	Response Spectrum for Yield Deformation and Yield Strength	273
7.6	Yield Strength and Deformation from the Response Spectrum	277
7.7	Yield Strength–Ductility Relation	277
7.8	Relative Effects of Yielding and Damping	279
7.9	Dissipated Energy	280
7.10	Energy Dissipation Devices	283

- 7.11 Inelastic Design Spectrum 288
- 7.12 Applications of the Design Spectrum 295
- 7.13 Comparison of Design and Response Spectra 301

8 Generalized Single-Degree-of-Freedom Systems 305

- 8.1 Generalized SDF Systems 305
- 8.2 Rigid-Body Assemblages 307
- 8.3 Systems with Distributed Mass and Elasticity 309
- 8.4 Lumped-Mass System: Shear Building 321
- 8.5 Natural Vibration Frequency by Rayleigh's Method 328
- 8.6 Selection of Shape Function 332
- Appendix 8: Inertia Forces for Rigid Bodies 336*

PART II MULTI-DEGREE-OF-FREEDOM SYSTEMS 343

9 Equations of Motion, Problem Statement, and Solution Methods 345

- 9.1 Simple System: Two-Story Shear Building 345
- 9.2 General Approach for Linear Systems 350
- 9.3 Static Condensation 367
- 9.4 Planar or Symmetric-Plan Systems: Ground Motion 370
- 9.5 Unsymmetric-Plan Buildings: Ground Motion 375
- 9.6 Symmetric-Plan Buildings: Torsional Excitation 383
- 9.7 Multiple Support Excitation 384
- 9.8 Inelastic Systems 389
- 9.9 Problem Statement 389
- 9.10 Element Forces 390
- 9.11 Methods for Solving the Equations of Motion: Overview 390

10 Free Vibration**401****Part A: Natural Vibration Frequencies and Modes 402**

- 10.1** Systems without Damping 402
- 10.2** Natural Vibration Frequencies and Modes 404
- 10.3** Modal and Spectral Matrices 406
- 10.4** Orthogonality of Modes 407
- 10.5** Interpretation of Modal Orthogonality 408
- 10.6** Normalization of Modes 408
- 10.7** Modal Expansion of Displacements 418

Part B: Free Vibration Response 419

- 10.8** Solution of Free Vibration Equations: Undamped Systems 419
- 10.9** Free Vibration of Systems with Damping 422
- 10.10** Solution of Free Vibration Equations: Classically Damped Systems 426

Part C: Computation of Vibration Properties 428

- 10.11** Solution Methods for the Eigenvalue Problem 428
- 10.12** Rayleigh's Quotient 430
- 10.13** Inverse Vector Iteration Method 430
- 10.14** Vector Iteration with Shifts: Preferred Procedure 435
- 10.15** Transformation of $\mathbf{k}\phi = \omega^2\mathbf{m}\phi$ to the Standard Form 440

11 Damping in Structures**447****Part A: Experimental Data and Recommended Modal Damping Ratios 447**

- 11.1** Vibration Properties of Millikan Library Building 447
- 11.2** Estimating Modal Damping Ratios 452

Part B: Construction of Damping Matrix 454

- 11.3** Damping Matrix 454
- 11.4** Classical Damping Matrix 455
- 11.5** Nonclassical Damping Matrix 463

Part B: Response Spectrum Analysis	555
13.7	Peak Response from Earthquake Response Spectrum 555
13.8	Multistory Buildings with Symmetric Plan 560
13.9	Multistory Buildings with Unsymmetric Plan 572
14	<i>Reduction of Degrees of Freedom</i> 593
14.1	Kinematic Constraints 594
14.2	Mass Lumping in Selected DOFs 595
14.3	Rayleigh–Ritz Method 595
14.4	Selection of Ritz Vectors 599
14.5	Dynamic Analysis Using Ritz Vectors 604
15	<i>Numerical Evaluation of Dynamic Response</i> 609
15.1	Time-Stepping Methods 609
15.2	Analysis of Linear Systems with Nonclassical Damping 611
15.3	Analysis of Nonlinear Systems 618
16	<i>Systems with Distributed Mass and Elasticity</i> 629
16.1	Equation of Undamped Motion: Applied Forces 630
16.2	Equation of Undamped Motion: Support Excitation 631
16.3	Natural Vibration Frequencies and Modes 632
16.4	Modal Orthogonality 639
16.5	Modal Analysis of Forced Dynamic Response 641
16.6	Earthquake Response History Analysis 648
16.7	Earthquake Response Spectrum Analysis 653
16.8	Difficulty in Analyzing Practical Systems 656
17	<i>Introduction to the Finite Element Method</i> 661
	Part A: Rayleigh–Ritz Method 661

- 17.1 Formulation Using Conservation of Energy 661
- 17.2 Formulation Using Virtual Work 665
- 17.3 Disadvantages of Rayleigh–Ritz Method 667

Part B: Finite Element Method 667

- 17.4 Finite Element Approximation 667
- 17.5 Analysis Procedure 669
- 17.6 Element Degrees of Freedom and Interpolation Functions 671
- 17.7 Element Stiffness Matrix 672
- 17.8 Element Mass Matrix 673
- 17.9 Element (Applied) Force Vector 675
- 17.10 Comparison of Finite Element and Exact Solutions 679
- 17.11 Dynamic Analysis of Structural Continua 680

PART III EARTHQUAKE RESPONSE AND DESIGN OF MULTISTORY BUILDINGS 687

18 *Earthquake Response of Linearly Elastic Buildings* 689

- 18.1 Systems Analyzed, Design Spectrum, and Response Quantities 689
- 18.2 Influence of T_1 and ρ on Response 694
- 18.3 Modal Contribution Factors 695
- 18.4 Influence of T_1 on Higher-Mode Response 697
- 18.5 Influence of ρ on Higher-Mode Response 700
- 18.6 Heightwise Variation of Higher-Mode Response 701
- 18.7 How Many Modes to Include 703

19 *Earthquake Response of Inelastic Buildings* 707

- 19.1 Allowable Ductility and Ductility Demand 708
- 19.2 Buildings with “Weak” or “Soft” First Story 713

19.3	Buildings Designed for Code Force Distribution	718
19.4	Limited Scope	728
	<i>Appendix 19: Properties of Multistory Buildings</i>	730
20	<i>Earthquake Dynamics of Base-Isolated Buildings</i>	731
20.1	Isolation Systems	731
20.2	Base-Isolated One-Story Buildings	734
20.3	Effectiveness of Base Isolation	740
20.4	Base-Isolated Multistory Buildings	744
20.5	Applications of Base Isolation	750
21	<i>Structural Dynamics in Building Codes</i>	755
	Part A: Building Codes and Structural Dynamics	756
21.1	<i>International Building Code (United States), 2000</i>	756
21.2	<i>National Building Code of Canada, 1995</i>	758
21.3	<i>Mexico Federal District Code, 1993</i>	762
21.4	<i>Eurocode 8</i>	764
21.5	Structural Dynamics in Building Codes	766
	Part B: Evaluation of Building Codes	772
21.6	Base Shear	772
21.7	Story Shears and Equivalent Static Forces	777
21.8	Overturning Moments	778
21.9	Concluding Remarks	781
A	<i>Frequency-Domain Method of Response Analysis</i>	783
B	<i>Notation</i>	805
C	<i>Answers to Selected Problems</i>	817
	<i>Index</i>	833