

Table of Contents

1 Introduction.....	1
2 A Little Dynamics	4
2.1 Single-Degree-of-Freedom Systems.....	4
2.2 Lagrange's Equations	9
2.3 Reciprocity and Mutual Energy	18
2.4 Modal Synthesis	20
2.5 Energy Considerations.....	20
2.5.1 Minimization of the Average Energy Difference (Hamilton's Principle)	22
2.5.2 The Rayleigh Quotient.....	24
References	25
3 Survey of Wave Types and Characteristics.....	27
3.1 Longitudinal Waves.....	27
3.1.1 Pure Longitudinal Waves	27
3.1.2 Quasi-Longitudinal Waves on Beams and Plates	33
3.2 Transverse Waves.....	39
3.2.1 Transverse Plane Waves	39
3.2.2 Torsional Waves	44
3.3 Bending Waves.....	49
3.3.1 Pure Bending Waves	49
3.3.2 Energy Relations.....	58
3.4 Wave Motions on Beams of Finite Length.....	60
3.4.1 Longitudinal Natural Vibrations.....	61
3.4.2 Natural Vibrations in Bending.....	67
3.5 The General Field Equations	74
3.6 Wave Field at a Free Surface.....	84
3.6.1 Reflection of Plane Waves	84
3.6.2 Excitation of an Elastic Half-Space	93
3.6.3. Surface Waves	96
3.7 Free Plate Waves	99
3.7.1 Boundary Conditions and Types of Solutions	99
3.7.2 Waves with Displacements only Parallel to the Surface	101
3.7.3 Waves with Displacements Perpendicular to the Surface	103

3.7.4 Equations of Motion for Thin Plates from the General Field Equations	109
3.8 Hamilton's Principle for the Derivation of the Equations of Motion.....	120
3.8.1 Fundamentals.....	120
3.8.2 Flat Plate with Shear Stiffness (The Corrected Bending Wave).....	121
3.8.3 Cylindrical Shells	126
3.9 Structure-Borne Sound Intensity	140
3.9.1 Fundamental Equations	140
3.9.2 Intensity in this Plates.....	141
3.9.3 Power Transmission in Thin-Walled Cylindrical Shells	145
References	147
4 Damping.....	149
4.1 Damping Mechanisms and their Mathematical Description.....	149
4.2 Complex Modulus and Wavenumbers.....	153
4.3. Resonant Vibrations of Damped Beams.....	161
4.3.1 Quasi-Longitudinal Waves and Torsional Waves	162
4.3.2 Bending Waves.....	169
4.4. Measurement of Complex Moduli.....	173
4.4.1 Measurements on Small Samples	174
4.4.2 Measurements on Beams	183
4.4.3 Measurements on Other than Beam-Like Samples	190
4.5 Experimental Data	191
4.5.1 Metals	191
4.5.2 Plastics	193
4.5.3 Building Materials	196
4.6 Plates with Attached Layers	197
4.6.1 Plates with Simple, Extensionally Loaded Layers	197
4.6.2 Plates with Multi-Layer Treatments	201
4.6.3 Equations of Motion of Layered Plates	208
4.7 Damping by means of Resonant Systems.....	217
4.7.1 Damping by Thick Layers (Ballast)	223
4.8 Damping at Joints	225
4.8.1 Damping by Relative Motion Normal to the Interface	226
4.8.2 Damping by Relative Motion Tangential to the Interface	230
References	232
5 Impedance and Mobility	236
5.1 Definitions	236
5.2 Measurement of Mobilities (Impedances)	238

5.2.1 Registration of Force and Velocity	238
5.2.2 Comparison with Known Mobilities	240
5.2.3 Other Measurement Methods	242
5.3 Input Mobility of Infinite Rods, Beams and Plates	244
5.3.1 Excitation of Quasi-Longitudinal Waves in Rods	244
5.3.2 Excitation of Bending Waves in Beams	245
5.3.3 Point Mobility of a Homogeneous Plate.....	251
5.4 Wave Impedance, Wave Mobility	256
5.4.1 Calculation of Wave Impedances and Wave Mobilities.....	256
5.4.2 Examples	257
5.4.3 Relation between Wave Mobility and Point Mobility	260
5.4.4 Moment Mobilities	272
5.4.5 Calculation of Impulse Response	275
5.5 Power Transmission to Infinite, Plane Structures.....	277
5.5.1 Determination of Structure-Borne Sound Power.....	277
5.5.2 Relationship with the Point Mobility.....	280
5.5.3 Interpretations and Examples	283
5.6 Summary of Impedance and Mobility Formulae; Approximations	286
5.7 Point-Excitation of Finite Systems	289
5.7.1 General Properties	290
5.7.2 Some Applications.....	294
5.7.3 Power Considerations	298
5.8 Some Specific Applications.....	306
5.8.1 Impact Excitation.....	306
5.8.2 Excitation by Sudden Release of Potential Energy	317
5.8.3 Rough Surfaces as Sources of Structure-Borne Sound.....	319
5.8.4 Parametric Excitation	322
5.8.5 Vibration Transmission from Machinery	326
References	338
 6 Attenuation of Structure-Borne Sound.....	 341
6.1 Material and Cross-Sectional Changes	341
6.1.1 Attenuation of Longitudinal Waves.....	342
6.1.2 Attenuation of Bending Waves.....	344
6.2 Right-Angled Corners and Branches	348
6.2.1 Incident Bending Wave	348
6.2.2 Incident Longitudinal Wave	353
6.2.3 Right Angled Branches with Incident Bending and Longitudinal Waves.....	354
6.3 Elastic Interlayers	359
6.3.1 Attenuation of Longitudinal Waves.....	360

6.3.2 Attenuation of Bending Waves.....	363
6.4 Blocking Masses.....	367
6.4.1 Attenuation of Longitudinal Waves.....	368
6.4.2 Attenuation of Bending Waves – Symmetric Blocking Masses	368
6.4.3 Attenuation of Bending Waves – Eccentric Blocking Masses	373
6.5 Periodic Structures.....	376
6.5.1 Periodic Mass-Spring Systems	376
6.5.2 Attenuation of Longitudinal Waves	380
6.5.3 Periodic Bending Wave-Guide.....	385
6.6 Hamilton's Principle for Transmission Problems.....	392
6.6.1 Procedure	392
6.6.2 An Introductory Example	394
6.6.3 Bending and Longitudinal Waves at an Eccentric Blocking Mass.....	397
6.7 Oblique Incidence.....	402
6.7.1 General Considerations	402
6.7.2 General Consequences of the Boundary Conditions	405
6.7.3 Examples	409
6.7.4 Application of Hamilton's Principle.....	420
6.8 Parallel Plates	422
6.8.1 Continuous Coupling by Elastic Interlayers	422
6.8.2 Point-Like Sound Bridges	427
6.9 Statistical Energy Analysis (SEA).....	430
6.9.1 Analogies to Statistical Room Acoustics.....	430
6.9.2 Energy Flow between Linearly Coupled Oscillators.....	434
6.9.3 Estimation of Coupling Loss Factors	437
6.9.4 Application	444
References	447
 7 Sound Radiation from Structures	 449
7.1 Measurement of Radiated Power.....	449
7.2 Definition and Measurement of Radiation Efficiency	451
7.3 Radiation Loss Factor	453
7.4 Elementary Radiators	455
7.4.1 Spherical Radiators.....	455
7.4.2 Dipole Radiators and Radiation from Forces	458
7.4.3 Infinite Plates.....	461
7.4.4 Cylindrical Radiators.....	465
7.4.5 Impulsive Sources	469
7.5 Plane, Baffled Radiators	472

7.5.1 The Plane Radiator as a Sum of Point Sources.....	473
7.5.2 Plane Radiators as Sum of Plane Waves	479
7.6 Radiation from Bending Waves.....	483
7.6.1 Semi-infinite plate	483
7.6.3 Modal Radiation	489
7.6.4 Radiation from Externally Excited Bending Waves.....	492
7.6.5 Comparison with Experiments	497
7.6.6 Additional Remarks on Structure-Borne Sound Radiation....	501
7.7 Fluid-Borne Sound Excitation of Structures.....	508
7.7.1 Transmission Loss of Single Leaf Wall.....	508
7.7.2 Double Walls with Sound Bridges	512
7.8 Relation between Radiation and Response.....	515
7.8.1 Reciprocity	515
7.8.2 Response and Radiation in a Reverberant Room	516
7.8.3 Directivity by Excitation and Radiation	519
7.8.4 Sound Transmission above the Critical Frequency	520
7.8.5 Transmission Loss in the Vicinity of the Critical Frequency	524
7.9 Application of Statistical Energy Analysis.....	525
7.9.1 Flanking Transmission	525
7.9.2 Double Walls	528
7.9.3 Multi-Layered Walls with Several Rigid Connections.....	531
References	533
8 Generation and Measurement of Structure-Borne Sound.....	536
8.1 Mechanical Measurement Methods.....	536
8.1.1 Registration of Motion.....	536
8.1.2 Comparison with Known Mobilities	538
8.1.3 Mechanical Transducers as Damped Mass-Spring Systems	541
8.1.4 Interaction of Transducer and Measurement Object	545
8.1.5 Immobile Reference and Rigid Termination	552
8.2 Controllable Sensors	553
8.2.1 Electrical Sensors	553
8.2.2 Optical Sensors	558
8.3 Excitation and Measurement of Structure-Borne Sound	560
8.3.1 Electro-Dynamic Transducers	561
8.3.2 Piezo-Electric Transducers	571
8.3.3 Electro-Static Transducers.....	578
8.3.4 Electro-Magnetic Transducers.....	583
8.3.5 Magnetostrictive Transducers.....	585
8.3.6 Elaboration on Reciprocal Transducers.....	586

XII Table of Contents

8.4 Combined Quantities	589
References	591
List of Symbols and Notation.....	593
Index.....	598