

# Table of Contents

<b>1 Introduction.....</b>	<b>1</b>
<b>2 A Little Dynamics .....</b>	<b>4</b>
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
<b>3 Survey of Wave Types and Characteristics.....</b>	<b>27</b>
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
<b>4 Damping.....</b>	<b>149</b>
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
<b>5 Impedance and Mobility .....</b>	<b>236</b>
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
<b>6 Attenuation of Structure-Borne Sound .....</b>	<b>341</b>
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
<b>7 Sound Radiation from Structures .....</b>	<b>449</b>
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

8.4 Combined Quantities ..... 589

References ..... 591

**List of Symbols and Notation..... 593**

**Index..... 598**

Structure-Borne Sound

Structural Vibrations and Sound Radiation at Audio  
Frequencies

Cremer, L.; Heckl, M.; Petersson, B.A.T.

2005, XII, 608 p., Hardcover

ISBN: 978-3-540-22696-3