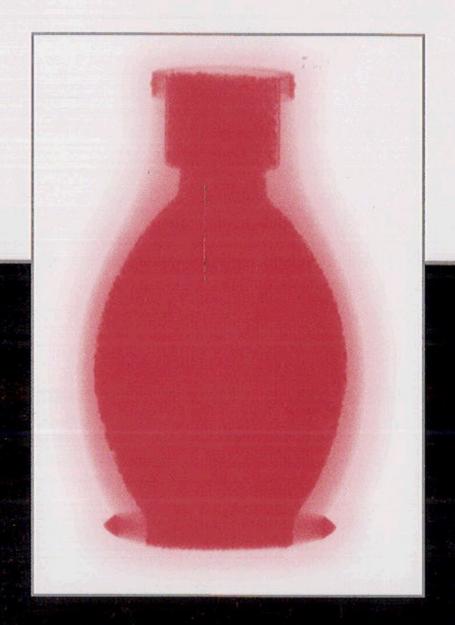
## INTRODUCTION TO

## ACOUSTICS



ROBERT D. FINCH

## **Contents**

| Preface   |   |
|-----------|---|
| Chapter 1 | Vibration 1   |
| 1.1       | Phasors 1   |
|           | 1.1.1 Kinematics of Harmonic Motion 1                   |
|           | 1.1.2 Phasor Representation of Oscillatory Quantities 5 |
|           | 1.1.3 Superposition of Oscillations 8                   |
|           | 1.1.4 Dynamics and Energy of Harmonic Motion 11         |
| 1.2       | Single Degree of Freedom Oscillators 13                 |
|           | 1.2.1 Mass Loaded Spring 13                             |
|           | 1.2.2 Elasticity 15                                     |
|           | 1.2.3 Pneumatic Springs 17                              |
|           | 1.2.4 Stiffness of Mechanical Elements 20               |
|           | 1.2.5 Damping 26  |
| 1.3       | Forced Oscillation 30                                   |
|           | 1.3.1 Equation of Motion 30                             |
|           | 1.3.2 Impedance 33                                      |
|           | 1.3.3 Resonance 35                                      |
|           | 1.3.4 Energy and Phase in Forced Oscillations 37        |
|           | 1.3.5 Transmissibility and Vibration Isolation 40       |
|           | 1.3.6 Electromechanical Analogies 42                    |
| 1.4       | Two Degree of Freedom Oscillators 45                    |
|           | 1.4.1 Natural Modes 45                                  |
|           | 1.4.2 Forced Oscillation 48                             |
| 1.5       | Multidegree of Freedom Systems 51                       |
|           | 1.5.1 Natural Modes 51                                  |
|           | 1.5.2 Examples of Multidegree of Freedom Systems 53     |

xiii

| 1.6   | Vibration of a One-Dimensional Continuum: Waves 1.6.1 Dynamics of a Transmission Line 57 1.6.2 One-Dimensional Waves 60 1.6.3 Energy Transport in a Progressive Wave 64 1.6.4 Sound Pressure Level 66 1.6.5 Transmission and Reflection at a Boundary 69 References and Further Reading 72 Problems 72  |
|---|---|
| Chapter 2   | Linear Systems 75   |
| 2.1   | Fourier Analysis 75   |
| 2.2   | Complex Form of Fourier Series 82   |
| 2.3   | Fourier Integral Theorem 83   |
| 2.4   | Pulses and Wavetrains 86  |
| 2.5   | Phase and Group Velocity 90   |
| 2.6   | The Laplace Transform 91  |
| 2.7   | Simple Results with Laplace Transforms 94   |
| 2.8   | Transients: Impulse Response and Convolution 96   |
| 2.9   | Use of Laplace Transforms in Solving Equations 99   |
| 2.10  | Stability 101   |
| 2.11  | Transfer Functions of Simple Systems 102  |
| 2.12  | Linear Electromechanical Transducer 111   |
|   | References and Further Reading 115  |
|   | Problems 115  |
| Chapter 3   | Waves in Fluids 119   |
| 3.1   | Radiation in Three Dimensions 119   |
|   |   |
| 3.2   | Solutions of the Wave Equation 125  |
| 3.2<br>3.3  | <del>*</del>  |
|   | Intensity of Spherical Waves 129  |
| 3.3   | Intensity of Spherical Waves 129  |
| 3.3<br>3.4  | Intensity of Spherical Waves 129<br>Simple Source or Monopole 130   |
| 3.3<br>3.4<br>3.5   | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132   |
| 3.3<br>3.4<br>3.5<br>3.6                                      | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135  |
| 3.3<br>3.4<br>3.5<br>3.6                                      | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140   |
| 3.3<br>3.4<br>3.5<br>3.6                                      | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141  |
| 3.3<br>3.4<br>3.5<br>3.6                                      | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141 3.7.2 Refraction of Plane Waves at a Plane Boundary 141 3.7.3 Reflection of Spherical Waves on a Plane Surface 143 3.7.4 Reflection of Spherical Waves at a Concave  |
| 3.3<br>3.4<br>3.5<br>3.6                                      | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141 3.7.2 Refraction of Plane Waves at a Plane Boundary 141 3.7.3 Reflection of Spherical Waves on a Plane Surface 143 3.7.4 Reflection of Spherical Waves at a Concave Spherical Surface 144  |
| 3.3<br>3.4<br>3.5<br>3.6<br>3.7                               | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141 3.7.2 Refraction of Plane Waves at a Plane Boundary 141 3.7.3 Reflection of Spherical Waves on a Plane Surface 144 3.7.4 Reflection of Spherical Waves at a Concave Spherical Surface 144 3.7.5 The Thin Lens 146  |
| 3.3<br>3.4<br>3.5<br>3.6<br>3.7                               | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141 3.7.2 Refraction of Plane Waves at a Plane Boundary 141 3.7.3 Reflection of Spherical Waves on a Plane Surface 14 3.7.4 Reflection of Spherical Waves at a Concave Spherical Surface 144 3.7.5 The Thin Lens 146 Rectilinear Propagation, the Zone Plate, and Diffraction 148  |
| 3.3<br>3.4<br>3.5<br>3.6<br>3.7                               | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141 3.7.2 Refraction of Plane Waves at a Plane Boundary 141 3.7.3 Reflection of Spherical Waves on a Plane Surface 144 3.7.4 Reflection of Spherical Waves at a Concave Spherical Surface 144 3.7.5 The Thin Lens 146 Rectilinear Propagation, the Zone Plate, and Diffraction 148 Fresnel's Formulation of Huygens' Principle 155   |
| 3.3<br>3.4<br>3.5<br>3.6<br>3.7<br>3.8<br>3.9<br>3.10         | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141 3.7.2 Refraction of Plane Waves at a Plane Boundary 141 3.7.3 Reflection of Spherical Waves on a Plane Surface 14 3.7.4 Reflection of Spherical Waves at a Concave Spherical Surface 144 3.7.5 The Thin Lens 146 Rectilinear Propagation, the Zone Plate, and Diffraction 148 Fresnel's Formulation of Huygens' Principle 155 Kirchoff Radiation Theory 159  |
| 3.3<br>3.4<br>3.5<br>3.6<br>3.7<br>3.8<br>3.9<br>3.10<br>3.11 | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141 3.7.2 Refraction of Plane Waves at a Plane Boundary 141 3.7.3 Reflection of Spherical Waves on a Plane Surface 14 3.7.4 Reflection of Spherical Waves at a Concave Spherical Surface 144 3.7.5 The Thin Lens 146 Rectilinear Propagation, the Zone Plate, and Diffraction 148 Fresnel's Formulation of Huygens' Principle 155 Kirchoff Radiation Theory 159 Rayleigh—Sommerfeld Formulation of Radiation 161 |
| 3.3<br>3.4<br>3.5<br>3.6<br>3.7<br>3.8<br>3.9<br>3.10         | Intensity of Spherical Waves 129 Simple Source or Monopole 130 The Dipole or Doublet Source 132 The Linear Array 135 Huygens' Principle 140 3.7.1 Reflection of a Plane Wave at a Plane Boundary 141 3.7.2 Refraction of Plane Waves at a Plane Boundary 141 3.7.3 Reflection of Spherical Waves on a Plane Surface 14 3.7.4 Reflection of Spherical Waves at a Concave Spherical Surface 144 3.7.5 The Thin Lens 146 Rectilinear Propagation, the Zone Plate, and Diffraction 148 Fresnel's Formulation of Huygens' Principle 155 Kirchoff Radiation Theory 159  |

| 3.14<br>3.15 | Piston Radiator: Radiation Impedance 169 Diffraction Around a Circular Obstacle 171 References and Further Reading 172 Problems 172 |
|--------------|---|
| Chapter 4    | Pipes and Horns 176   |
| 4.1          | Webster's Equation 176  |
| 4.2          | Propagation in Pipes 177  |
| 4.3          | Impedance Transformation by a Tube 180  |
| 4.4          | Standing Wave Ratio 182   |
| 4.5          | Salmon Horns 186  |
| 4.6          | Properties of Infinite Horns 188  |
| 4.7          | Finite Horns: Impedance Transformation 189  |
| 4.8          | Solid Horns 192   |
| 4.9          | Sinusoidal Horns 194  |
|              | References and Further Reading 196<br>Problems 196  |
| Chapter 5    | Audio Frequency Generators 198  |
| 5.1          | Introduction 198  |
| 5.2          | Direct Radiator Loudspeaker 198   |
| 5.3          | Typical Direct Radiator Parameters 201  |
| 5.4          | Impedance Loops   205   |
| 5.5          | Improving on the Typical Speaker 208  |
| 5.6          | Effect of Voice Coil Parameters 209   |
| 5.7          | Use of a Baffle 210   |
| 5.8          | Loudspeaker Cabinets 211  |
| 5.9          | Horn Loudspeakers 214   |
| 5.10         | Maximizing Efficiency: General Remarks 215  |
| 5.11         | Maximizing Efficiency: Tubular Couplers 216   |
|              | References and Further Reading 218  |
|              | Problems 218  |
| Chapter 6    | Sensors: Microphones and Accelerometers 220   |
| 6.1          | Introduction 220  |
| 6.2          | Equivalent Circuit of Reversible Microphones 221  |
| 6.3          | Electrodynamic (Moving Coil) Microphone 222   |
| 6.4          | Condenser (Capacitor) Microphones 224   |
| 6.5          | Vibration Sensors 227   |
| 6.6          | The Seismometer 228   |
| 6.7          | Accelerometers 231  |
| 6.8          | New Transducers 232   |
|              | References and Further Reading 233  |
|              | Problems 233  |

| Chapter 7   | Piezoelectric Transducers 235   |
|---|---|
| 7.1<br>7.2<br>7.3<br>7.4<br>7.5<br>7.6<br>7.7<br>7.8<br>7.9<br>7.10         | Postulates of the Electromagnetic Theory Dipoles 239 Polarization 241 Energy of Polarization 246 Mechanisms of Polarization 247 Maxwell's Equations in a Dielectric 249 Kelvin's Theory of Piezoelectricity 251 Distributed Piezoelectric Systems 253 Thickness Vibrations of Piezoelectric Plates 253 Effects of Damping 261   |
| 7.11  | Low Frequency Limit: Coupling Factor 262  |
| 7.12  | Equivalent Circuits Valid Near Resonance 266  |
| 7.13<br>7.14  | Resonance: Admittance Loops 268 Transducers for Echo Sounding 272   |
| 7.14  | Conclusion 275  |
| 7.13  | References and Further Reading 276 Problems 277   |
| Chapter 8   | Instrumentation and Signal Processing 279   |
| 8.1<br>8.2<br>8.3<br>8.4<br>8.5<br>8.6<br>8.7<br>8.8<br>8.9<br>8.10<br>8.11 | Acoustic Signals 279 Digital Signals 284 Impulse Response and Convolution 291 Amplification and Electronics 297 Basic Digital Circuit Elements 302 Signal Processing Electronics 304 The Discrete Time Fourier Transform 309 Sampling of Continuous Time Signals 314 The Fast Fourier Transform 317 Windowing 320 Correlation Functions 323 Homomorphic Digital Signal Processing 325 References and Further Reading 326 Problems 326 |
| Chapter 9   | Basic Acoustic Measurements 328   |
| 9.1   | Acoustic Parameters 328   |
| 9.2<br>9.3  | Reciprocity Calibration 330 Directivity 333   |
| 9.3<br>9.4  | Particle Velocity 334   |
| 9.5   | Density Fluctuation 335   |
| 9.6   | Intensity 337   |
| 9.7   | Speed of Sound 340  |
| 9.8   | Acoustic Impedance 342  |

|  | References and Further Reading 347 Problems 347   |
|--|---|
| Chapter 10   | Plane Waves in Large Enclosures 349   |
| 10.1<br>10.2<br>10.3<br>10.4<br>10.5<br>10.6   | Modes of a Tube with Rigid Caps 349 Energy in Plane Standing Waves 352 Transmission Through Three Media 354 Plane Waves in Three Dimensions 359 Rectangular Waveguide 361 Modes of a Rectangular Enclosure 364 References and Further Reading 367 Problems 368  |
| Chapter 11   | Series Solutions and Scattering 369   |
| 11.1<br>11.2<br>11.3<br>11.4<br>11.5<br>11.6<br>11.7<br>11.8<br>11.9<br>11.10                            | The Method of Frobenius 369 Legendre's Equation 370 Bessel's Equation 372 Series Solutions of the Wave Equation 375 Scattering from a Sphere 378 Scattering by Soft Particles 381 The Behavior of Rigid Particles Under Radiation Pressure 383 Scattering by Bubbles 384 Scattering in Multiple Bubble Systems 386 Radiation Pressure on Bubbles 391 References and Further Reading 391 Problems 392  |
| Chapter 12   | Vibration of Structural Elements 394  |
| 12.1<br>12.2<br>12.3<br>12.4<br>12.5<br>12.6<br>12.7<br>12.8<br>12.9<br>12.10<br>12.11<br>12.12<br>12.13 | Historical Notes 394 Measurement of Elasticity 395 The Wave Equation for a String 396 A String of Finite Length 400 The Wave Equation for a Membrane 401 Forced Vibrations of a Membrane 403 Longitudinal Waves in a Rod 406 Shear and Torsional Waves in Rods 407 The Statics of Bending of Beams 409 The Dynamics of Bending: Flexural Vibrations 412 Natural Flexural Modes of a Beam 414 Response of a Beam to an Applied Force 418 Structural Acoustics 422 References and Further Reading 424 |
| 12.4<br>12.5<br>12.6<br>12.7<br>12.8<br>12.9<br>12.10<br>12.11<br>12.12                                  | A String of Finite Length 400 The Wave Equation for a Membrane 401 Forced Vibrations of a Membrane 403 Longitudinal Waves in a Rod 406 Shear and Torsional Waves in Rods 407 The Statics of Bending of Beams 409 The Dynamics of Bending: Flexural Vibrations 412 Natural Flexural Modes of a Beam 414 Response of a Beam to an Applied Force 418 Structural Acoustics 422  |

9.9 Attenuation 343

**Chapter 13** Propagation in Solids

| 13.1<br>13.2<br>13.3<br>13.4<br>13.5<br>13.6<br>13.7<br>13.8<br>13.9<br>13.10<br>13.11 | Elasticity of Extended Media 426 Strain Tensor Ellipsoid 431 Transformation of Coordinates 433 Generalized Form of Hooke's Law 435 Energy of Elastic Deformation 437 Isotropic Media 440 Young's Modulus, Poisson's Ratio, and Bulk Modulus 443 Dynamics of an Elastic Medium: The Navier Equation 446 Plane Waves in an Infinite Solid Isotropic Medium 451 Propagation in Bounded Solids 452 Surface Waves 460 Propagation in a Plate 466 References and Further Reading 471 Problems 471 |
|--|---|
| Chapter 14   | Damping, Attenuation, and Absorption 473  |
| 14.1<br>14.2<br>14.3<br>14.4<br>14.5<br>14.6<br>14.7<br>14.8<br>14.9                   | The Navier–Stokes Equation 473 Viscous Attenuation of Sound 476 Heat Conduction as a Source of Attenuation in Fluids Sound Absorption by the Atmosphere 484 Attenuation in Water 486 Absorption of Sound in Fluid-Filled Pipes 487 Sound Absorption in Rooms 489 Damping in Solids 492 Damping Nomenclature for Solids 494 References and Further Reading 496 Problems 497  |
| Chapter 15   | Nonlinear Acoustics 499   |
| 15.1<br>15.2<br>15.3<br>15.4<br>15.5<br>15.6   |   |
| Chapter 16   | Noise Control 536   |
| 16.1<br>16.2<br>16.3   | The Auditory System 536 Measurements on the Ear 545 Hearing Aids and Prostheses for the Ear 548   |

426

| 16.4       | The Voice 550   |
|------------|---|
| 16.5       | Effects of Noise on Humans 551                            |
| 16.6       | Noise Measurement and Criteria 553                        |
| 16.7       | Outdoor Sound 559   |
| 16.8       | Treatment at Source 562                                   |
| 16.9       | Treatment of the Transmission Path 564                    |
| 16.10      | Hearing Protection 567                                    |
|            | References and Further Reading 567                        |
|            | Problems 569  |
| Chapter 17 | Acoustic Systems 572                                      |
| 17.1       | Systems Theory 572  |
| 17.2       | Ranging and Detection Systems 577                         |
| 17.3       | Imaging Systems 579                                       |
| 17.4       | Recognition Systems 588                                   |
| 17.5       | Recognition Using Artificial Neural Nets 598              |
| 17.6       | Information Theory and Model-Based Systems 603            |
| 17.7       | Systems for Speech and Hearing 615                        |
|            | 17.7.1 Speech Production 615                              |
|            | 17.7.2 Speech Perception 618                              |
| 17.8       | Musical Acoustics 620                                     |
| 17.9       | Evolution of Acoustic Systems 624                         |
|            | References and Further Reading 626                        |
|            | Problems 627  |
| Appendice  | s   |
| A          | Greek Alphabet 629  |
| В          | Basic Physical and Mathematical Constants 630             |
| · C        | Definitions 631   |
| D          | Units 632   |
| E          | Bessel Functions and Directivity and Impedance Functions  |
|            | for a Piston 633  |
| F          | Some Useful Results from Vector Analysis 635              |
| G          | Notes on Matrices 636                                     |
| Н          | Properties of Solids 638                                  |
| I          | Properties of Fluids 639                                  |
| J          | Absorption Coefficients at Various Frequencies 640        |
| K          | Acceptable Ambient Sound Levels for Unoccupied Spaces 641 |
|            | •   |

Index

643