CONTENTS

PREFACE xv

ACKNOWLEDGMENTS xvii

INTRODUCTION 1

Prelude and Basic Definitions / 1
The Advantages of Using Ultrasound in Medicine / 2
A General Statement on Safety / 4
Some Common Applications of Ultrasound / 5
What Is It that We Need to Know? / 6
References / 7

1 WAVES—A GENERAL DESCRIPTION 9

1.1 General Definitions of Waves—A Qualitative Description / 9
1.2 General Properties of Waves—A Qualitative Description / 12
1.2.1 Interference and the Superposition Principle / 12
1.2.2 Reflection and Transmission of Waves / 13
1.2.3 Diffraction / 15
1.2.4 Standing Waves / 15

1.3 Mechanical One-Dimensional Waves / 17
1.4 The Wave Function / 19
1.5 The Wave Equation / 20
1.6 Harmonic Waves / 20
1.6.1 Equivalent Presentations / 22
1.7 Group Waves / 22
1.8 Wave Velocity / 23
1.9 Standing Waves (a Mathematical Description) / 24
1.10 Spherical Waves / 25
1.11 Cylindrical Waves / 27
1.12 The Wave Equation in a Nonhomogeneous Medium / 29
1.12.1 The Born Approximation / 32
1.12.2 The Rytov Approximation / 32
References / 33

2 WAVES IN A ONE-DIMENSIONAL MEDIUM 35
2.1 The Propagation Speed of Transverse Waves in a String / 35
2.2 Vibration Frequencies for a Bounded String / 37
2.3 Wave Reflection (Echo) in a One-Dimensional Medium / 41
2.4 Special Cases / 43
2.5 Wave Energy in Strings / 45
2.6 Propagation of Longitudinal Waves in an Isotropic Rod or String / 47
2.7 A Clinical Application of Longitudinal Waves in a String / 51
References / 53

3 ULTRASONIC WAVES IN FLUIDS 55
3.1 Waves in Fluids / 55
3.2 Compressibility / 56
3.3. Longitudinal Waves in Fluids / 57
3.4 The Wave Energy / 61
3.5 Intensity / 62
3.6 Radiation Pressure / 64
3.7 A Perfect Reflector / 68
References / 72

4 PROPAGATION OF ACOUSTIC WAVES IN SOLID MATERIALS 75

4.1 Introduction to the Mechanics of Solids / 75
4.1.1 Stress / 75
4.1.2 Strain / 76
4.1.3 Special Issues to Be Noted when Investigating Wave Propagation in Solids / 76
4.2 The Elastic Strain / 77
4.2.1 Strain Properties / 80
4.3 Stress / 81
4.4 Hooke's Law and Elastic Coefficients / 83
4.5 The Wave Equation for an Elastic Solid Material / 84
4.6 Propagation of a Harmonic Planar Wave in a Solid Material / 86
4.6.1 Special Case #1 / 89
4.6.2 Special Case #2 / 89
4.6.3 Special Case #3 / 90
References / 92

5 ATTENUATION AND DISPERSION 93

5.1 The Attenuation Phenomenon / 93
5.2 Explaining Attenuation with a Simple Model / 95
5.3 Attenuation Dependency on Frequency / 97
5.4 The Complex Wave Number / 101
5.5 Speed of Sound Dispersion / 102
5.6 The Nonlinear Parameter B/A / 103
References / 104

6 REFLECTION AND TRANSMISSION 107

6.1 The Acoustic Impedance / 107
6.1.1 The Relation Between Particle Velocity and Pressure / 107
6.1.2 An Exemplary Function φ / 109
6.1.3 Definition of the Acoustic Impedance / 109
6.1.4 The Relation Between the Impedance and the Wave Intensity / 111
6.2 Snell's Law / 112
6.3 Reflection and Transmission from Boundaries Separating Two Fluids (or Solids with No Shear Waves) / 115
6.3.1 Critical Angles / 115
6.3.2 Reflection and Transmission Coefficients / 115
6.3.3 The Matching Layer / 118

6.4 Reflection from a Free Surface in Solids (Mode Conversion) / 120
6.5 Reflection and Transmission from a Liquid–Solid Boundary / 125
6.5.1 Case #1: From a Fluid to a Solid / 125
6.5.2 Case #2: From a Solid to a Fluid / 128
6.5.3 An Exemplary Application / 129
References / 130

7 ACOUSTIC LENSES AND MIRRORS 133
7.1 Optics / 133
7.2 Optics and Acoustics / 138
7.3 An Ellipsoidal Lens / 141
7.4 Spherical Lenses / 143
7.4.1 Bi-Concave Lens / 146
7.4.2 Focal Point Properties / 146
7.5 Zone Lenses / 148
7.6 Acoustic Mirrors (Focusing Reflectors) / 150
References / 152

8 TRANSDUCERS AND ACOUSTIC FIELDS 153
8.1 Piezoelectric Transducers / 153
8.2 The Acoustic Field / 158
8.3 The Field of a Point Source / 159
8.4 The Field of a Disc Source / 160
8.4.1 Near Field and Far Field / 161
8.4.2 The Acoustic Far (Off Axis) Field / 163
8.5 The Field of Various Transducers / 168
8.5.1 The Field of a Ring Source / 168
8.5.2 The Field of a Line Source / 168
8.5.3 The Field of a Rectangular Source / 171
8.6 Phased-Array Transducers / 173
8.6.1 The General Field from an Array Source / 173
8.6.2 The Field of a Linear Phased Array / 173
8.6.3 Far-Field Approximation for a Linear Phased Array / 175
8.6.4 Grating Lobes for a Linear Phased Array / 175
8.6.5 Beam Steering with a Linear Phased Array / 176

8.6.6 Maximal Steering Angle for a Linear Phased Array / 179
8.6.7 Beam Forming with a Linear Phased Array / 181
8.7 Annular Phased Arrays / 182
8.7.1 Steering the Focal Point of an Annular Array / 185
8.7.2 The Bessel Beam / 187
References / 189

9 ULTRASONIC IMAGING USING THE PULSE-ECHO TECHNIQUE 191

9.1 Basic Definitions in Imaging / 191
9.1.1 Image and Data Acquisition / 191
9.1.2 Image Contrast / 193
9.1.3 Signal-to-Noise Ratio / 193
9.1.4 Resolution / 195
9.2 The "A-Line" / 197
9.2.1 The Simple Model / 197
9.2.2 Extending the Model / 199
9.3 Scatter Model for Soft Tissues / 201
9.3.1 The Speckle Texture / 204
9.4 Time Gain Compensation / 205
9.5 Basic Pulse-Echo Imaging (B-Scan) / 206
9.5.1 Conversion to Gray Levels / 207
9.5.2 M-Mode Imaging / 212
9.5.3 Spatial Mapping—The Simple Model / 213
9.5.4 Deconvolution Methods / 217
9.6 Advanced Methods for Pulse-Echo Imaging / 218
9.6.1 Second Harmonic Imaging / 218
9.6.2 Multifrequency Imaging / 220
9.6.3 Image Compounding / 221
9.6.4 Three-Dimensional Imaging / 223
9.6.5 Semi-invasive Imaging / 225
9.6.5.1 Trans-esophageal Echo / 225
9.6.5.2 Intra-vaginal Imaging / 226
9.6.5.3 Trans-rectal Imaging / 226
9.6.6 Invasive Imaging / 227
9.6.6.1 Intravascular Ultrasound / 227
9.6.6.2 Intraventricular Echo / 229
9.6.6.6 Laparoscopic Ultrasonic Imaging / 229
References / 230

10 SPECIAL IMAGING TECHNIQUES **233**
10.1 Acoustic Impedance Imaging—Impediography / 233
10.2 Elastography / 236
10.3 Tissue Speckle Tracking / 243
10.4 Through-Transmission Imaging / 245
10.4.1 Acoustic Projection Imaging / 247
10.5 Vibro-acoustic Imaging / 250
10.6 Time Reversal / 252
10.7 Ultrasonic Computed Tomography / 254
10.7.1 Basic Computed Tomography Principles / 254
10.7.2 Spiral Computed Tomography / 259
10.7.3 Diffractive Tomography / 260
10.8 Contrast Materials / 262
10.9 Coded Excitations / 265
References / 267

11 DOPPLER IMAGING TECHNIQUES **271**
11.1 The Doppler Effect / 271
11.2 Velocity Estimation / 274
11.3 Frequency Shift Estimation / 276
11.4 Duplex Imaging (Combined B-Scan and Color Flow Mapping) / 279
References / 284

12 SAFETY AND THERAPEUTIC APPLICATIONS **287**
12.1 Effects Induced by Ultrasound and Safety / 287
12.1.1 Thermal Effects / 287
12.1.2 Cavitation Bubbles / 292
12.1.3 Additional Effects / 293
12.2 Ultrasonic Physiotherapy / 295
12.3 Lithotripsy / 296
12.3.1 Principles of Operation / 297
12.4 Hyperthermia HIFU and Ablation / 301
12.5 Drug Delivery / 305
12.6 Gene Therapy / 307
12.7 Cosmetic Applications / 309
References / 310

APPENDIX A: TYPICAL ACOUSTIC PROPERTIES OF TISSUES **313**
Table A.1: Typical Density, Speed of Sound, and Acoustic Impedance Values / 313
Table A.2: Typical Attenuation and B/A Values / 314

APPENDIX B: EXEMPLARY PROBLEMS **315**

APPENDIX C: ANSWERS TO EXEMPLARY PROBLEMS **341**

INDEX **367**