

CONTENTS

PREFACE XI

ACKNOWLEDGMENTS XIII

1

INTRODUCTION

- 1.1 The Beginnings 1
- 1.2 Understanding Sound 2
- 1.3 Representations of Sound 3
- 1.4 Sounds Classical and Sounds Quantum 5
- 1.5 Comparisons between Light and Ultrasound 6
- 1.6 The Adiabatic Idealization 7
- 1.7 Common Sense Is Unsound 8
- 1.8 Scope of This Work 9
- 1.9 How to Use This Book 9

2

WATER

- 2.1 Measurement of Sound Velocity 11
 - 2.1.1 *Introduction* 11
 - 2.1.2 *Accuracy and Errors* 14
 - 2.1.2.1 Temperature 15
 - 2.1.2.2 Acoustical Delays 15
 - 2.1.2.3 Impedance 16
 - 2.1.2.4 The Control of Reverberation with Buffer Rods 18
 - 2.1.2.5 Acoustical Bonds 19
 - 2.1.2.6 Power Levels 19
 - 2.1.2.7 Diffraction and Phase Cancellation 20
 - 2.1.2.8 Timing Errors Due to Trigger Point Variation 23
 - 2.1.2.9 Measuring Group Velocity 24
 - 2.1.3 *Calibration* 25
- 2.2 The Dependence of Velocity of Sound on Density and Compressibility 25
 - 2.2.1 *The Velocity of Sound in Mixtures and Suspensions* 26
 - 2.2.2 *The Velocity of Sound in Air/Water Mixtures* 28
 - 2.2.3 *The Importance of Removing Air from Samples* 29
 - 2.2.4 *The Effects of Temperature on Propagation in Water* 29
 - 2.2.5 *The Effects of Pressure on Propagation in Water* 31
 - 2.2.6 *Sound Velocity in Equidensity Dispersions* 31
- 2.3 The Relationship between Velocity and Attenuation—Conditions of High Attenuation 33
- 2.4 The Compressibility of Solute Molecules 34
 - 2.4.1 *Introduction* 34
 - 2.4.1.1 Empirical and Semiempirical Methods 34
 - 2.4.1.2 Concentrations 35
 - 2.4.2 *Determining Partial Volumes* 36
 - 2.4.2.1 The Method of Intercepts 36
 - 2.4.3 *Apparent Molar Quantities* 37
 - 2.4.3.1 Apparent Specific Volume 37
 - 2.4.3.2 Apparent Compressibility 38
 - 2.4.3.3 Concentration Increments 39
 - 2.4.4 *The Dilute Limit* 39
 - 2.4.4.1 Partial Specific Volume and Partial Specific Adiabatic Compressibility 40
 - 2.4.5 *Sound Velocity and Concentration—The Urick Equation* 40
 - 2.4.6 *Determining the Compressibility of Solute Molecules—a Summary* 42
 - 2.4.7 *Experimental Data on Compressibility and Its Interpretation* 44
 - 2.4.7.1 Protein 44

3

MULTIPHASE MEDIA

- 3.1 Apparatus 47
- 3.2 Determining Composition in the Absence of Phase Changes 49
 - 3.2.1 Alcohol 50
 - 3.2.2 Sugar 51
 - 3.2.3 Concentration of a Dispersed Phase in a Colloidal Phase 52
 - 3.2.4 Analysis of Edible Oils and Fats 52
 - 3.2.5 Cell Suspensions 54
 - 3.2.6 Temperature Scanning 54
- 3.3 Following Phase Transitions 54
 - 3.3.1 General Comments 54
 - 3.3.2 Attenuation Changes 56
 - 3.3.3 Crystallizing Solids 57
 - 3.3.4 Crystallization in Colloidal Systems 59
- 3.4 Determination of Solid Fat Content 60
 - 3.4.1 Introduction 60
 - 3.4.2 General Method 61
 - 3.4.2.1 Region I 61
 - 3.4.2.2 Region III 62
 - 3.4.2.3 Region II 63
 - 3.4.3 Margarine 65
 - 3.4.4 Chocolate 65
 - 3.4.5 Accuracy 68
 - 3.4.6 Anomalies Close to the Melting Point 69
 - 3.4.7 Comparison with Dilatometry and Pulsed Nuclear Magnetic Resonance 70
 - 3.4.8 Solid Content and Particle Size 72
- 3.5 Crystal Nucleation 72
 - 3.5.1 Crystal Nucleation Rates 72
 - 3.5.2 Ice 74
- 3.6 The Solution-Emulsion Transition and Emulsion Inversion 75
 - 3.6.1 Emulsion Inversion 76
- 3.7 Determination of Emulsion Stability by Ultrasound Profiling 76
 - 3.7.1 Introduction 76
 - 3.7.2 History 77
 - 3.7.3 The Leeds Profiler 78
 - 3.7.4 Interpretation of Ultrasound Velocity Profiles 80
 - 3.7.4.1 Renormalization 81
 - 3.7.4.2 Limits of Applicability of Renormalization Method 83
 - 3.7.5 Examples of Profiling 84
- 3.8 Summary 90

4

SCATTERING OF SOUND

- 4.1 Theories of Sound 91
- 4.2 A Comparison of Electromagnetic and Acoustic Propagation 92
- 4.3 Scattering Theory 93
 - 4.3.1 *Why Scattering Theory?* 93
 - 4.3.2 *What Is Scattering? Assumptions of Scattering Theory* 94
 - 4.3.2.1 Long Wavelength Limit 99
 - 4.3.2.2 Low Attenuation 100
 - 4.3.2.3 Plane Wave 100
 - 4.3.2.4 Scattering Is Weak 100
 - 4.3.2.5 Random Distribution of Particles 100
 - 4.3.2.6 Adiabatic Approximation 100
 - 4.3.2.7 Navier–Stokes’ Form for the Momentum Equation 101
 - 4.3.2.8 Thermal Stresses Neglected 102
 - 4.3.2.9 No Changes in Phase 102
 - 4.3.2.10 Linearization of Equations 102
 - 4.3.2.11 Temperature Variations 102
 - 4.3.2.12 System Is Static 102
 - 4.3.2.13 Particles Are Spherical 102
 - 4.3.2.14 Infinite Time Irradiation 103
 - 4.3.2.15 Pointlike Particles 103
 - 4.3.2.16 No Overlap of Thermal and Shear Waves 103
 - 4.3.2.17 No Interactions between Particles 103
 - 4.3.2.18 Lack of Self-Consistency 103
 - 4.3.3 *A Description of Weak Scattering* 104
 - 4.3.3.1 Wave Potentials 104
 - 4.3.3.2 Modes in a Pure Liquid 106
 - 4.3.3.3 Thermoelastic Scattering 109
 - 4.3.3.4 Viscoinertial Scattering 110
 - 4.3.3.5 Scattered Waves Combine within the Transducer 110
 - 4.3.4 *Plane Wave Incident on a Single Particle* 111
 - 4.3.4.1 Introduction 111
 - 4.3.4.2 Spherical Harmonics 111
 - 4.3.4.3 Boundary Conditions 112
 - 4.3.5 *Scattering by Many Particles* 116
 - 4.3.5.1 Introduction 116
 - 4.3.5.2 Multiple Scattering Theories 116
 - 4.3.6 *Numerical Calculations Using Scattering Theory* 118
 - 4.3.6.1 Particle Size Distribution and Change in Phase 118
 - 4.3.7 *The Results of Scattering Theory* 118
 - 4.3.8 *Simplified Scattering Coefficients* 120
 - 4.3.9 *Working Equations* 124

- 4.3.9.1 The Urick Equation 124
- 4.3.9.2 The Multiple Scattering Result 124
- 4.3.9.3 The Modified Urick Equation 125
- 4.3.9.4 Experimental Determination of the Scattering Coefficients 127
- 4.3.10 *Multiple Dispersed Phases* 129
- 4.3.11 *MathCad Calculation Results* 130
- 4.3.12 *Experimental Validation of Acoustic Scattering Theory* 133
- 4.4 Scattering from Bubbles 137

5

ADVANCED TECHNIQUES

- 5.1 Particle Sizing 141
 - 5.1.1 *Introduction* 141
 - 5.1.2 *Review* 142
 - 5.1.3 *Theoretical Limitations of Acoustic Particle Sizing* 143
 - 5.1.4 *Relaxation Effects* 144
 - 5.1.5 *Ultrasonic Methods of Particle Sizing* 145
 - 5.1.5.1 Simultaneous Measurement of Velocity and Attenuation 145
 - 5.1.5.2 Determination of Particle Size from Velocity and Attenuation 145
 - 5.1.5.3 Bandwidth and Signal-to-Noise Ratio 147
 - 5.1.5.4 A Particle Sizing Apparatus—Pulsed Method 148
 - 5.1.5.5 Continuous-Wave Interferometer 148
 - 5.1.5.6 Commercial Particle Sizing Apparatus 149
 - 5.1.5.7 Electroacoustics 150
 - 5.1.5.8 The Future—Measurement Systems 152
- 5.2 Propagation in Viscoelastic Materials 152
 - 5.2.1 *Introduction* 152
 - 5.2.2 *Measuring Aggregation in Viscoelastic Materials* 156
 - 5.2.2.1 Introduction 156
 - 5.2.2.2 Detecting Aggregation with Ultrasound Profiling 157
 - 5.2.2.3 Computer Modeling 158
 - 5.2.2.4 Aggregation of Casein 159
 - 5.2.3 *Frequency-Dependent Ultrasound Profiling* 161
 - 5.2.4 *Particle Size Effects in Ultrasound Profiling* 162
- 5.3 Bubbles and Foams 163
- 5.4 Automation and Computer Tools 163
 - 5.4.1 *The Computer as Controller* 165
 - 5.4.2 *Windows* 165
 - 5.4.3 *Prototyping* 167
 - 5.4.4 *RS232C* 168
 - 5.4.5 *IEEE Bus* 168
 - 5.4.6 *Instrument Programming* 169

5.4.7	<i>Oscilloscope</i>	169
5.4.7.1	Fourier Analysis	169
5.4.8	<i>Timer-Counter</i>	172
5.4.9	<i>The UVM</i>	173
5.4.10	<i>Transducer Excitation</i>	173
5.4.11	<i>Cabling</i>	173
5.4.12	<i>Calibration</i>	174
5.4.13	<i>Sample Changer</i>	174
5.4.14	<i>Temperature Control</i>	174
5.4.15	<i>Data Storage and Analysis</i>	174
5.4.16	<i>Conclusion</i>	175

APPENDIX A

Basic Theory 177

A.1	The Isotropic Elastic Solid	178
A.2	The Pure Newtonian Fluid	179
A.3	Mixture of Two Pure Newtonian Fluids	179
A.4	Viscoplastic Materials	179

APPENDIX B

MathCad Solutions of the Explicit Scattering Expressions 181

GLOSSARY 185

BIBLIOGRAPHY 191

INDEX 205