BASICS OF BIOMEDICAL ULTRASOUND FOR ENGINEERS

HAIM AZHARI



WILEY A JOHN WILEY & SONS, INC., PUBLICATION

BASICS OF BIOMEDICAL ULTRASOUND FOR ENGINEERS

BASICS OF BIOMEDICAL ULTRASOUND FOR ENGINEERS

HAIM AZHARI



WILEY A JOHN WILEY & SONS, INC., PUBLICATION Copyright © 2010 John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey Published simultaneously in Canada

Copyright for the Hebrew version of the book and distribution rights in Israel are held by Michlol, Inc.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at http://www.wiley.com/go/permission.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Azhari, Haim, 1955-

Basics of biomedical ultrasound for engineers / Haim Azhari.

p. cm.

Includes bibliographical references and index.

Summary: "Basics of Biomedical Ultrasound for Engineers is a structured textbook for university engineering courses in biomedical ultrasound and for researchers in the field. This book offers a tool for building a solid understanding of biomedical ultrasound, and leads the novice through the field in a step-by-step manner. The book begins with the most basic definitions of waves, proceeds to ultrasound in fluids, and then delves into solid ultrasound, the most complicated kind of ultrasound. It encompasses a wide range of topics within biomedical ultrasound, from conceptual definitions of waves to the intricacies of focusing devices, transducers, and acoustic fields"—Provided by publisher.

ISBN 978-0-470-46547-9 1. Ultrasonics in medicine. 2. Ultrasonics. I. Title. R857.U48A94 2009 616.07'54-dc22

2009025404

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

To the memory of Elad Grenadier, who was killed by terrorists on July 17, 2002, at the age of 21. And to the memory of his father and my friend, Dr. Ehud Grenadier. Blessed be their souls.

CONTENTS

PRE	EFAC	E		xv			
ACKNOWLEDGMENTS							
		ICTION		1			
Prel	lude a	nd Basi	c Definitions / 1				
The	Adva	ntages o	of Using Ultrasound in Medicine / 2				
AC	Benera	l Staten	nent on Safety / 4				
Son	ne Cor	nmon A	applications of Ultrasound / 5				
What	at Is It	t that W	e Need to Know? / 6				
Ref	erence	es / 7					
1	WAVES—A GENERAL DESCRIPTION						
	1.1		al Definitions of Waves—A Qualitative ption / 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 / 201.6.1 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

- 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

- 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

35

PROPAGATION OF ACOUSTIC WAVES IN SOLID MATERIALS 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

4.1

- 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

- The Attenuation Phenomenon / 93 5.1
- 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**

- 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
- Reflection and Transmission from Boundaries Separating 6.3 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

75

107

- X CONTENTS
 - 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

- 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

- 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

153

- 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

- 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

- 10.1 Acoustic Impedance Imaging—Impediography / 233
- 10.2 Elastography / 236
- 10.3 Tissue Speckle Tracking / 243
- 10.4 Through-Transmission Imaging / 24510.4.1 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

- 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

- 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

271

APPENDIX A: TYPICAL ACOUSTIC PROPERTIES OF TISSUES Table A.1: Typical Density, Speed of Sound, and Acoustic Impedance Values / 313 Table A.2: Typical Attenuation and <i>B/A</i> Values / 314	313
APPENDIX B: EXEMPLARY PROBLEMS	315
APPENDIX C: ANSWERS TO EXEMPLARY PROBLEMS	341

I	Ν	D	Ε	Х