

# Contents

<b>1</b>	<b>Symmetry Properties of Acoustic Fields</b>	<b>1</b>
1.1	Introduction	1
1.2	Sound Propagation in Solids	2
1.2.1	Derivation of Linear Wave Equation of Motion and Its Solutions	2
1.2.2	Symmetries in Linear Acoustic Wave Equations and the New Stress Field Equation	3
1.3	Use of Gauge Potential Theory to Solve Acoustic Wave Equations	4
1.4	Gauge Theory Formulation of Sound Propagation in Solids	6
1.4.1	Translational Symmetry	6
1.4.2	Introduction of Covariant Derivative to the Infinitesimal Amplitude Sound Wave Equation	7
1.4.3	Introduction of Covariant Derivative to the Large Amplitude Sound Wave Equation	8
1.4.4	Local Rotational Symmetry	8
1.5	Symmetry Is the Theoretical Framework of Acoustical Metamaterial	8
1.5.1	Rotational Symmetry and Theory of Elasticity	9
1.6	Local Gauge Invariance	9
1.7	Covariant Derivative	10
1.8	Discovery of Anisotropy as a Form of Local Symmetry	11
1.9	Role of Symmetry Properties of Acoustic Field in the Design of a Phononic Structure	12
1.10	Phonon as a Goldstone Mode	13
1.11	Symmetry Property of Turbulence Field	13
1.12	Time Reversal Symmetry in Acoustics	15
	References	15

<b>2</b>	<b>Negative Refraction and Acoustical Cloaking</b>	<b>17</b>
2.1	Introduction	17
2.2	Limitation of Veselago's Theory	18
2.2.1	Introduction	18
2.2.2	Gauge Invariance of Homogeneous Electromagnetic Wave Equation	19
2.2.3	Gauge Invariance of Acoustic Field Equations	20
2.2.4	Acoustical Cloaking	21
2.2.5	Gauge Invariance of Nonlinear Homogeneous Acoustic Wave Equation	22
2.2.6	My Important Discovery of Negative Refraction Is a Special Case of Coordinate Transformations or a Unified Theory for Negative Refraction and Cloaking	22
2.2.7	Conclusions	23
2.3	Multiple Scattering Approach to Perfect Acoustic Lens	24
2.4	Acoustical Cloaking	29
2.4.1	Introduction	29
2.4.2	Derivation of Transformation Acoustics	30
2.4.3	Application to a Specific Example	34
2.5	Acoustic Metamaterial with Simultaneous Negative Mass Density and Negative Bulk Modulus	35
2.6	Acoustical Cloaking based on Nonlinear Coordinate Transformations	39
2.7	Acoustical Cloaking of Underwater Objects	41
2.8	Extension of Double Negativity to Nonlinear Acoustics	43
	References	44
<b>3</b>	<b>Basic Mechanisms of Sound Propagation in Solids for Negative Materials</b>	<b>47</b>
3.1	Methods to Treat Multiple Scattering in Conventional Solids	47
3.2	$T$ -Matrix of Multiple Scattering	47
3.3	Application of $T$ -Matrix to Multiple Scattering in Acoustical Metamaterials	49
3.4	Low-Frequency Resonances Giving Rise to Locally Negative Parameters	50
3.5	Acoustic Scatterers with Locally Negative Parameters	50
3.6	Multiple Scattering of Acoustic Waves in the Low-Frequency Limit	53
3.7	Multiple Scattering Effects: The $\Delta$ Factor	53
3.8	Suitability of the $T$ -Matrix Method to Multiple Scattering in Acoustic Metamaterials	57
3.9	Diffraction	57
3.10	Diffraction by Negative Inclusion	58

3.11	Theory of Diffraction by Negative Inclusion . . . . .	59
3.11.1	Formulation of Forward Problem of Diffraction Tomography . . . . .	59
3.11.2	Modelling Diffraction Procedure in a Negative Medium . . . . .	64
3.11.3	Results of Numerical Simulation . . . . .	65
3.11.4	Points to Take Care of During Numerical Simulation . . . . .	72
3.12	Refraction . . . . .	73
	References . . . . .	74
<b>4</b>	<b>Artificial Elasticity . . . . .</b>	<b>77</b>
4.1	Elastic Stiffness and Compliance . . . . .	77
4.2	Symmetry Properties of Stress Field and Particle Velocity Field . . . . .	78
4.2.1	Symmetries between the Particle Velocity Field Acoustic Equation of Motion and the Stress Field Acoustic Equation of Motion . . . . .	80
4.3	Rotation Invariance of the Stress Field and Particle Velocity Field for an Isotropic Solid . . . . .	81
4.4	Reflection Symmetry as a Special Case of Rotational Symmetry . . . . .	81
4.5	Form Invariance of the Particle Velocity Field Acoustic Equation of Motion . . . . .	82
4.6	Gauge Invariance of Nonlinear Homogeneous Acoustic Wave Equation . . . . .	83
4.7	Acoustic Metamaterial with Simultaneous Negative Mass Density and Negative Bulk Modulus-Demonstration of Artificial Elasticity . . . . .	84
4.8	The New Field of Artificial Elasticity . . . . .	88
	References . . . . .	88
<b>5</b>	<b>Artificial Piezoelectricity . . . . .</b>	<b>89</b>
5.1	What Is Piezoelectricity? . . . . .	89
5.2	Piezoelectric Constitutive Relations . . . . .	91
5.3	Coupled Acoustic Field Equations and Maxwell's Equations . . . . .	91
5.4	The Stiffened Christoffel Equation for Piezoelectricity . . . . .	92
5.5	Application of Metamaterial to Acoustic Resonator . . . . .	93
5.6	Application of Metamaterial to Acoustic Waveguide . . . . .	96
5.7	Piezoelectricity as Second Order Phase Transition . . . . .	98
5.8	Artificial Piezoelectricity . . . . .	102
5.9	Fabrication of Artificial Piezoelectricity . . . . .	102
	References . . . . .	104

<b>6</b>	<b>Acoustic Diode</b>	107
6.1	Nonlinear Acoustics based on the Metamaterial	107
6.1.1	Principles	107
6.1.2	Nonlinear Acoustic Metamaterials for Sound Attenuation Applications	109
6.2	Acoustic Diode Enabling One-Way Sound Transmission	110
6.3	Application of Acoustic Diode to Acoustical Imaging	113
6.4	Theoretical Framework of the Acoustic Diode [9]	114
6.4.1	Introduction	114
6.4.2	Physics of Acoustic Diode	115
	References	122
<b>7</b>	<b>Energy Harvesting and Phononics</b>	125
7.1	Introduction—Technological Application of Phononic Networks	125
7.2	What Is Phononic Crystal?	126
7.3	Elastodynamics of Artificial Structure	128
7.3.1	Introductory Remarks	128
7.3.2	Fundamental Equations and Governing Principles	129
7.3.3	The Discrete to the Continuum: Taking Limits	131
7.3.4	Evolution versus Conservation: The Microscopic E.O.M. versus the Variational Principle	134
7.3.5	Broken Symmetry and Polarizations of the Vector Phonon	137
7.3.6	Concluding Remarks on Elastodynamics from a Symmetry Breaking Perspective	140
7.4	Development of a Universal Design Framework: Mathematical Structure	141
7.4.1	Introductory Remarks	141
7.4.2	Generalization of Avoided Crossings and Perturbation Theory	143
7.4.3	Nonlocality: The Effect of the Lattice and its Interactions	146
7.4.4	Nonlocality: The Effect of the Lattice and its Interactions	148
7.4.5	Local Principles: The Variational Principle from a Geometric Viewpoint	150
7.4.6	Groups and Representations: Nonsymmorphicity and Wyckoff Positioning	152
7.4.7	Classifications of Lattices: Physical Topology of Phononic Structures	153

7.5	Designing Dispersion Relation for Phononic Metamaterials I: Avoided Crossings . . . . .	166
7.5.1	Introductory Remarks . . . . .	166
7.5.2	From Crystals to “Resonant” Metamaterials . . . . .	167
7.5.3	Meso-scale Phononic Metacrystal: Polarization- Specific Spectral Gaps . . . . .	170
7.6	Designing Dispersion Relations Phononic Metamaterials II: A Polychromatic Nonsymmorphic Phononic Crystal . . . . .	171
7.6.1	Introduction . . . . .	171
7.6.2	Global Symmetry: Nonsymmorphicity and Sticking Bands . . . . .	172
7.7	Thermoelectrics and Engineering Thermal Conductivity . . . . .	180
7.8	Phononic Metamaterial Networks and Information Processing . . . . .	182
7.9	Current and Future Work . . . . .	183
	References . . . . .	184
<b>8</b>	<b>Local Resonant Structures . . . . .</b>	<b>187</b>
8.1	Introduction . . . . .	187
8.2	Background of Phononic Crystals . . . . .	188
8.3	Theory of Phononic Crystals—The Multiple Scattering Theory (MST) . . . . .	189
8.3.1	Details of Calculation . . . . .	192
8.3.2	Discussion of Results . . . . .	192
8.4	Multiple Scattering Approach to Perfect Acoustic Lens . . . . .	194
8.5	Acoustic Metamaterials in a Broader Sense Beyond the Phononic Crystals (Ma and Sheng [31]) . . . . .	199
8.6	Demonstration of Local Resonance Using the Spring-Mass Model and Dynamic Effective Mass [31] . . . . .	200
8.6.1	Effective Mass Dispersion between Two Resonances . . . . .	201
8.6.2	Effective Bulk Modulus and Spatial Symmetry of the Resonances [31] . . . . .	202
8.6.3	Doubly Negative Mass Density and Bulk Modulus . . . . .	203
8.7	Membrane-Type Acoustic Metamaterials [31] . . . . .	203
8.7.1	Normal Displacement Decomposition and Relationship to Propagative and Evanescent Modes . . . . .	204
8.7.2	Effective Mass Density and Impedance of the Membrane Resonator . . . . .	205
8.7.3	Effective Bulk Modulus of Two Coupled Membrane Resonators and Double Negativity . . . . .	206

8.8	Super-Resolution and Focusing Beyond the Diffraction Limit [31] . . . . .	208
8.8.1	Resolution Limit and the Evanescent Waves . . . . .	208
8.8.2	To Defeat the Diffraction Limit . . . . .	208
8.8.3	Acoustic Superlens . . . . .	210
8.8.4	Acoustic Hyperlens [31] . . . . .	211
8.9	Coordinate Transformations . . . . .	212
8.9.1	My Important Discovery of Negative Refraction is a Special Case of Coordinate Transformations or a Unified Theory for Negative Refraction and Cloaking . . . . .	212
8.9.2	Acoustical Cloaking . . . . .	214
8.9.3	Zero-Index Medium [31]. . . . .	221
8.10	Space-Coiling and Acoustic Metasurfaces [31] . . . . .	221
8.10.1	Incurring Large Phase Delays Within a Small Space . . . . .	221
8.10.2	Phase Manipulation with Acoustic Metasurfaces [31] . . . . .	222
8.11	Absorption [31] . . . . .	223
8.12	Sound Insulation Materials as Application of Complex Local Resonant Structures. . . . .	225
8.12.1	Introduction . . . . .	225
8.12.2	Sound Insulation . . . . .	226
8.12.3	Application of Acoustic Metamaterials to Sound Insulation [126] . . . . .	226
8.12.4	Modelling Methodology of the Localized Resonances Structures (LRS) . . . . .	229
8.12.5	Experimental Methods of the Localized Resonances Structures (LRS). . . . .	229
8.12.6	Plane Wave Testing . . . . .	229
8.12.7	Diffuse Field Testing . . . . .	230
8.12.8	Results. . . . .	231
8.12.9	Discussion . . . . .	231
8.12.10	Conclusion . . . . .	233
8.13	Emerging New Directions and Outlooks. . . . .	233
8.13.1	Elastic and Mechanical Metamaterials [31]. . . . .	233
8.13.2	Acoustic Metamaterials as Rapidly Developing Field with Tremendous Potential . . . . .	234
	References . . . . .	235

<b>9</b>	<b>Application of Acoustic Metamaterial to Time-Reversal Acoustics</b>	243
9.1	Time-Reversal Symmetry Property of Acoustic Field-Basic Principle of Time-Reversal Acoustics	243
9.2	Experimental Implementation of Time-Reversal Acoustics	244
9.3	Ultrasonic Focusing in Inhomogeneous Media	245
9.3.1	Adaptative Time-Delay Focusing Techniques	245
9.3.2	The Time-Reversal Cavity	247
9.3.3	Time-Reversal Mirror	248
9.3.4	Focusing with a Time-Reversal Mirror	248
9.3.5	Signal Processing used in Time-Reversal Method	249
9.3.6	The Iterative Time-Reversal Mode—an Automatic Target Selection	249
9.4	Some Practical Applications of Time-Reversal Acoustics	250
9.5	Sub-wavelength Focusing Using Far Field Time-Reversal for Electromagnetic Waves	252
9.6	Extension of Above Concept to Acoustics	253
	References	256
<b>10</b>	<b>Underwater Acoustical Cloaking</b>	259
10.1	Acoustical Cloaking	259
10.2	Propagation Theory	260
10.3	Reflection and Scattering from the Sea Surface	261
10.4	Reflection and Scattering from the Sea Bottom	262
10.5	Sea Bottom—Reflection Loss	262
10.6	Westervelt Equation	264
10.6.1	Coordinate Transformations on the Westervelt Equation	265
10.7	A Practical Example of Underwater Acoustical Cloaking	269
10.7.1	Principle of Underwater Acoustic Cloaking	269
10.7.2	Geometric Structure of the Underwater Acoustic Cloak	270
10.7.3	Experimental Procedure	271
10.8	Application of Underwater Acoustical Cloaking	275
	References	275
<b>11</b>	<b>Seismic Metamaterials</b>	277
11.1	Introduction	277
11.2	Electromagnetics Cloaking Principles for Seismic Metamaterials	278
11.3	Acoustical Cloaking Principles for Seismic Metamaterials	278
11.4	Seismic Cloak Would Minimize Earthquake Damage	279
11.4.1	Transformation Seismology	279
11.5	A Practical Example of a Seismic Cloak	281

11.6	Seismic Waveguide Made of Metamaterials . . . . .	282
11.6.1	Introductory Theory on Seismic Waves . . . . .	282
11.6.2	Negative Modulus . . . . .	283
11.6.3	Seismic Attenuator . . . . .	286
	References . . . . .	287
<b>12</b>	<b>Application of Acoustic Metamaterials to Finite Amplitude Sound</b>	
	<b>Wave . . . . .</b>	<b>289</b>
12.1	Introduction . . . . .	289
12.2	Acoustical Cloaking . . . . .	290
12.3	Acoustic Radiation Force . . . . .	291
12.4	Application of Acoustical Metamaterials to Force of Levitation [41] in the Presence of General Relativity and Gravitational Force . . . . .	294
12.4.1	Modelling of the Proposed Levitation System [41] . . .	295
12.4.2	Computation of the Acoustic Levitation Force . . . . .	296
12.5	Conclusions . . . . .	298
	References . . . . .	298
<b>13</b>	<b>Acoustical Imaging on a Curvilinear Spacetime . . . . .</b>	<b>301</b>
13.1	Introduction . . . . .	301
13.2	The Usual Applications of the Theory of General Relativity . . .	302
13.3	Vibrography . . . . .	302
13.4	Elasticity Imaging . . . . .	304
	Reference . . . . .	305
<b>14</b>	<b>Transport Theory is Key Foundation of Theoretical Metamaterials Design—Metamaterial is Artificial Phase Transition . . . . .</b>	<b>307</b>
14.1	Transport Theory, Transport Properties and Discovery of Metamaterial is in Fact Artificial Phase Transition . . . . .	307
14.2	Discovery of Metamaterial is Artificial Phase Transition and Singularity Behaviour of the Transport Properties of Metamaterials at the Critical Point of Phase Transition . . . . .	308
14.3	Use of Transport Properties to Explore New Forms of Metamaterials . . . . .	310
14.3.1	Artificial Elasticity . . . . .	311
14.3.2	Artificial Magnetism . . . . .	311
14.3.3	Artificial High Temperature Superconductivity . . . . .	311
14.3.4	Artificial Piezoelectricity . . . . .	312
14.3.5	Artificial Ferromagnetism . . . . .	312
14.4	Metamaterial as Artificial Phase Transition as Breakthrough to a New World of Artificial Materials . . . . .	312
14.5	Conclusions . . . . .	313
	References . . . . .	313



<http://www.springer.com/978-981-10-6375-6>

New Acoustics Based on Metamaterials

Gan, W.S.

2018, XVI, 313 p. 69 illus., 25 illus. in color., Hardcover

ISBN: 978-981-10-6375-6