

# Contents

<b>1</b>	<b>Comfort for the Computationally Crippled . . . . .</b>	<b>1</b>
1.1	The Five Most Powerful Math Techniques . . . . .	2
1.1.1	Taylor Series . . . . .	2
1.1.2	The Product Rule or Integration by Parts . . . . .	5
1.1.3	Logarithmic Differentiation . . . . .	6
1.2	Equilibrium, Stability, and Hooke's Law . . . . .	7
1.2.1	Potentials and Forces . . . . .	9
1.2.2	A Simple Pendulum . . . . .	11
1.3	The Concept of Linearity . . . . .	13
1.4	Superposition and Fourier Synthesis . . . . .	15
1.5	Convenience (Complex) Numbers . . . . .	20
1.5.1	Geometrical Interpretation on the Argand Plane . . . . .	22
1.5.2	Algebraic Operations with Complex Numbers . . . . .	23
1.5.3	Integration and Differentiation of Complex Exponentials . . . . .	25
1.5.4	Time Averages of Complex Products (Power) . . . . .	25
1.6	Standard (SI) Units and Dimensional Homogeneity . . . . .	27
1.7	Similitude and the Buckingham $\Pi$ -Theorem (Natural Units) . . . . .	28
1.7.1	Three Simple Examples . . . . .	28
1.7.2	Dimensionless Groups . . . . .	31
1.7.3	Windscreen Noise* . . . . .	31
1.7.4	Similitude Summary . . . . .	34
1.8	Precision, Accuracy, and Error Propagation . . . . .	35
1.8.1	Random Errors (Noise) and Relative Uncertainty . . . . .	36
1.8.2	Normal Error Function or the Gaussian Distribution . . . . .	38
1.8.3	Systematic Errors (Bias) . . . . .	40
1.8.4	Error Propagation and Covariance . . . . .	43

1.8.5	Significant Figures . . . . .	45
1.9	Least-Squares Fitting and Parameter Estimation . . . . .	45
1.9.1	Linear Correlation Coefficient . . . . .	47
1.9.2	Relative Error in the Slope . . . . .	51
1.9.3	Linearized Least-Squares Fitting . . . . .	52
1.9.4	Caveat for Data Sets with Small $N^*$ . . . . .	55
1.9.5	Best Fit to Models with More Than Two Adjustable Parameters . . . . .	56
1.10	The Absence of Rigorous Mathematics . . . . .	58
	Talk Like an Acoustician . . . . .	58
	Exercises . . . . .	59
	References . . . . .	65

## Part I Vibrations

<b>2</b>	<b>The Simple Harmonic Oscillator . . . . .</b>	<b>69</b>
2.1	The Undamped Harmonic Oscillator . . . . .	70
2.1.1	Initial Conditions . . . . .	72
2.2	The Lumped Element Approximation . . . . .	74
2.2.1	Series and Parallel Combinations of Several Springs . . . . .	75
2.2.2	A Characteristic Speed . . . . .	76
2.3	Energy . . . . .	78
2.3.1	The Virial Theorem . . . . .	79
2.3.2	Rayleigh's Method . . . . .	80
2.3.3	Gravitational Offset . . . . .	81
2.3.4	Adiabatic Invariance . . . . .	84
2.4	Damping and Free Decay . . . . .	86
2.4.1	Viscous Damping and Mechanical Resistance . . . . .	87
2.4.2	Free-Decay Frequency and Quality Factor . . . . .	88
2.4.3	Critical Damping . . . . .	89
2.4.4	Thermal Equilibrium and Fluctuations . . . . .	90
2.4.5	Frictional (Coulomb) Damping* . . . . .	96
2.5	Driven Systems . . . . .	97
2.5.1	Force-Driven SHO . . . . .	98
2.5.2	Power Dissipation, the Decibel, and Resonance Bandwidth . . . . .	102
2.5.3	Resonance Tracking and the Phase-Locked Loop* . . . . .	104
2.5.4	Transient Response . . . . .	108
2.5.5	The Electrodynamic Loudspeaker . . . . .	110
2.5.6	Electrodynamic (Moving Coil) Microphone . . . . .	115
2.5.7	Displacement-Driven SHO and Transmissibility . . . . .	117
2.6	Vibration Sensors . . . . .	120

2.7	Coupled Oscillators . . . . .	122
2.7.1	Two Identical Masses with Three Identical Springs . . . . .	123
2.7.2	Coupled Equations for Identical Masses and Springs . . . . .	124
2.7.3	Normal Modes and Normal Coordinates . . . . .	126
2.7.4	Other Initial Conditions . . . . .	127
2.7.5	General Solutions for Two Masses and Three Springs . . . . .	128
2.7.6	Driven Oscillators, Level Repulsion, and Beating . . . . .	129
2.7.7	String of Pearls . . . . .	131
2.8	The Not-So-Simple (?) Harmonic Oscillator . . . . .	137
	Talk Like an Acoustician . . . . .	138
	Exercises . . . . .	138
	References . . . . .	151
<b>3</b>	<b>String Theory . . . . .</b>	<b>153</b>
3.1	Waves on a Flexible String . . . . .	154
3.2	Pulse Reflections at a Boundary and the Utility of Phantoms . . . . .	159
3.3	Normal Modes and Standing Waves . . . . .	162
3.3.1	Idealized Boundary Conditions . . . . .	163
3.3.2	Consonance and Dissonance* . . . . .	167
3.3.3	Consonant Triads and Musical Scales* . . . . .	168
3.4	Modal Energy . . . . .	171
3.4.1	Nature Is Efficient . . . . .	173
3.4.2	Point Mass Perturbation . . . . .	176
3.4.3	Heavy Chain Pendulum (Nonuniform Tension)* . . . . .	177
3.5	Initial Conditions . . . . .	180
3.5.1	Total Modal Energy . . . . .	183
3.6	“Imperfect” Boundary Conditions . . . . .	184
3.6.1	Example: Standing-Wave Modes for $M/m_s = 5$ . . . . .	187
3.6.2	An Algebraic Approximation for the Mass-Loaded String . . . . .	188
3.6.3	The Resistance-Loaded String* . . . . .	190
3.7	Forced Motion of a Semi-infinite String . . . . .	192
3.8	Forced Motion of a Finite String . . . . .	194
3.8.1	Displacement-Driven Finite String . . . . .	195
3.8.2	Mass-Loaded String in the Impedance Model* . . . . .	198
3.8.3	Force-Driven Finite String . . . . .	198
3.8.4	An Efficient Driver/Load Interaction* . . . . .	199

3.9 “I’ve Got the World on a String...”: Summary . . . . . 200  
 Talk Like an Acoustician . . . . . 204  
 Exercises . . . . . 204  
 References . . . . . 208

**4 Elasticity of Solids . . . . . 211**

4.1 Hooke, Young, Poisson, and Fourier . . . . . 212

4.2 Isotropic Elasticity . . . . . 214

4.2.1 Bulk Modulus . . . . . 214

4.2.2 Modulus of Unilateral Compression . . . . . 216

4.2.3 Shear Modulus . . . . . 218

4.2.4 Two Moduli Provide a Complete  
 (Isotropic) Description . . . . . 220

4.3 Real Springs . . . . . 220

4.3.1 Solids as Springs . . . . . 221

4.3.2 Flexure Springs . . . . . 228

4.3.3 Triangularly Tapered Cantilever Spring . . . . . 234

4.3.4 Buckling . . . . . 236

4.3.5 Torsional Springs . . . . . 239

4.3.6 Coil Springs . . . . . 241

4.4 Viscoelasticity . . . . . 244

4.4.1 Maxwell (Relaxation Time) Model . . . . . 245

4.4.2 Standard Linear Model (SLM)  
 of Viscoelasticity . . . . . 249

4.4.3 Complex Stiffnesses and Moduli\* . . . . . 251

4.4.4 Kramers–Kronig Relations . . . . . 254

4.5 Rubber Springs . . . . . 257

4.5.1 Effective Modulus . . . . . 258

4.5.2 Rubber-to-Glass Transition (Type I and Type II  
 Rubbers) . . . . . 259

4.5.3 Transmissibility of Rubberlike Vibration  
 Isolators . . . . . 262

4.6 Anisotropic (Crystalline) Elasticity\* . . . . . 268

4.7 There Is More to Stiffness Than Just “*k*” . . . . . 271  
 Talk Like an Acoustician . . . . . 272  
 Exercises . . . . . 272  
 References . . . . . 276

**5 Modes of Bars . . . . . 279**

5.1 Longitudinal Waves in Thin Bars . . . . . 280

5.1.1 Longitudinal Waves in Bulk Solids . . . . . 284

5.1.2 The Quartz Crystal Microbalance . . . . . 285

5.1.3 Bodine’s “Sonic Hammer” . . . . . 288

5.2 Torsional Waves in Thin Bars . . . . . 291

5.3	Flexural Waves in Thin Bars . . . . .	293
5.3.1	Dispersion . . . . .	294
5.3.2	Flexural Wave Functions . . . . .	297
5.3.3	Flexural Standing-Wave Frequencies . . . . .	298
5.3.4	Flexural Standing-Wave Mode Shapes . . . . .	300
5.3.5	Rayleigh Waves* . . . . .	305
5.4	Resonant Determination of Elastic Moduli . . . . .	306
5.4.1	Mode-Selective Electrodynamical Excitation and Detection . . . . .	308
5.4.2	Bar Sample Size and Preparation* . . . . .	310
5.4.3	Measured Resonance Spectra . . . . .	311
5.4.4	Effective Length Correction for Transducer Mass . . . . .	313
5.4.5	Modes of a Viscoelastic Bar . . . . .	318
5.4.6	Resonant Ultrasound Spectroscopy* . . . . .	322
5.5	Vibrations of a Stiff String . . . . .	325
5.6	Harmonic Analysis . . . . .	330
	Talk Like an Acoustician . . . . .	331
	Exercises . . . . .	331
	References . . . . .	333
<b>6</b>	<b>Membranes, Plates, and Microphones . . . . .</b>	<b>335</b>
6.1	Rectangular Membranes . . . . .	337
6.1.1	Modes of a Rectangular Membrane . . . . .	338
6.1.2	Modal Degeneracy . . . . .	341
6.1.3	Density of Modes . . . . .	344
6.2	Circular Membranes . . . . .	348
6.2.1	Series Solution to the Circular Wave Equation . . . . .	349
6.2.2	Modal Frequencies and Density for a Circular Membrane . . . . .	353
6.2.3	Mode Similarities Illustrating Adiabatic Invariance . . . . .	356
6.2.4	Normal Modes of Pie-Shaped Wedges and Annular Membranes . . . . .	358
6.2.5	Effective Piston Area for a Vibrating Membrane . . . . .	360
6.2.6	Normal Mode Frequencies of Tympani . . . . .	362
6.2.7	Pressure-Driven Circular Membranes . . . . .	365
6.3	Response of a Condenser Microphone . . . . .	368
6.3.1	Optimal Backplate Size and Optimal Open-Circuit Sensitivity . . . . .	371
6.3.2	Limits on Polarizing Voltages and Electrostatic Forces . . . . .	373
6.3.3	Electret Condenser Microphone . . . . .	376

- 6.4 Vibrations of Thin Plates . . . . . 380
  - 6.4.1 Normal Modes of a Clamped Circular Plate . . . . . 382
- 6.5 Flatland . . . . . 384
- Talk Like an Acoustician . . . . . 385
- Exercises . . . . . 385
- References . . . . . 390

**Part II Waves in Fluids**

- 7 Ideal Gas Laws . . . . . 395**
  - 7.1 Two Ways of Knowing: Phenomenology and Microscopics . . . . . 397
    - 7.1.1 Microscopic Models . . . . . 398
    - 7.1.2 Phenomenological Models . . . . . 401
    - 7.1.3 Adiabatic Equation of State for an Ideal Gas . . . . . 405
    - 7.1.4 Adiabatic Temperature Change . . . . . 406
  - 7.2 Specific Heats of Ideal Gases . . . . . 407
    - 7.2.1 Monoatomic (Inert) Gases . . . . . 408
    - 7.2.2 Polyatomic Gases . . . . . 409
  - 7.3 The Fundamental Equations of Hydrodynamics . . . . . 412
    - 7.3.1 The Continuity Equation . . . . . 413
    - 7.3.2 The Navier–Stokes (Euler) Equation . . . . . 413
    - 7.3.3 Entropy Conservation Equation . . . . . 416
    - 7.3.4 Closure with the Equation of State . . . . . 417
  - 7.4 Flashback . . . . . 418
  - Talk Like an Acoustician . . . . . 419
  - Exercises . . . . . 419
  - References . . . . . 422
- 8 Nondissipative Lumped Elements . . . . . 423**
  - 8.1 Oscillations About Equilibrium . . . . . 425
  - 8.2 Acoustical Compliance and the Continuity Equation . . . . . 427
    - 8.2.1 The Continuity Equation . . . . . 428
    - 8.2.2 Linearized Continuity Equation . . . . . 430
    - 8.2.3 Acoustical Compliance . . . . . 433
    - 8.2.4 The Gas Spring . . . . . 434
  - 8.3 Hydrostatic Pressure . . . . . 435
  - 8.4 Inertance and the Linearized Euler Equation . . . . . 437
    - 8.4.1 The Venturi Tube . . . . . 437
    - 8.4.2 The Linearized Euler Equation . . . . . 439
    - 8.4.3 Acoustical Inertance . . . . . 441
    - 8.4.4 Acoustical Mass . . . . . 442
  - 8.5 The Helmholtz Resonance Frequency . . . . . 442
    - 8.5.1 Helmholtz Resonator Network Analysis . . . . . 445
    - 8.5.2 A 500 mL Boiling Flask . . . . . 448

8.6	DELTAEC Software . . . . .	451
8.6.1	Download DELTAEC . . . . .	452
8.6.2	Getting Started with DELTAEC (Thermophysical Properties) . . . . .	453
8.6.3	Interpreting planewave.in . . . . .	454
8.6.4	Running planewave.in . . . . .	458
8.6.5	Finding the Resonance Frequencies of planewave.in . . . . .	460
8.6.6	State Variable Plots (*.sp) . . . . .	461
8.6.7	Modifying planewave.in to Create Flask500.in . . . . .	462
8.6.8	Interpreting the *.out File . . . . .	463
8.6.9	The RPN Target . . . . .	465
8.6.10	Power Flow and Dissipation in the 500 mL Boiling Flask . . . . .	467
8.6.11	An “Effective Length” Correction . . . . .	468
8.6.12	Incremental Plotting and the *.ip File . . . . .	469
8.6.13	So Much More Utility in DELTAEC . . . . .	474
8.7	Coupled Helmholtz Resonators . . . . .	474
8.8	The Bass-Reflex Loudspeaker Enclosure . . . . .	477
8.8.1	Beranek’s Box Driven by a Constant Volume Velocity . . . . .	479
8.8.2	Loudspeaker-Driven Bass-Reflex Enclosure* . . . . .	480
8.9	Lumped Elements . . . . .	485
	Talk Like an Acoustician . . . . .	486
	Exercises . . . . .	486
	References . . . . .	492
<b>9</b>	<b>Dissipative Hydrodynamics . . . . .</b>	<b>495</b>
9.1	The Loss of Time Reversal Invariance . . . . .	496
9.2	Ohm’s Law and Electrical Resistivity . . . . .	498
9.3	Thermal Conductivity and Newton’s Law of Cooling . . . . .	499
9.3.1	The Thermal Boundary Layer . . . . .	502
9.3.2	Adiabatic Compression Within a Bounded Volume . . . . .	506
9.3.3	Energy Loss in the Thermal Boundary Layer* . . . . .	507
9.3.4	Adiabatic vs. Isothermal Propagation in an Ideal Gas . . . . .	508
9.4	Viscosity . . . . .	510
9.4.1	Poiseuille Flow in a Pipe of Circular Cross-Section . . . . .	511
9.4.2	The Viscous Boundary Layer . . . . .	513
9.4.3	Viscous Drag in the Neck of a Helmholtz Resonator . . . . .	515
9.4.4	Quality Factors for a Helmholtz Resonator . . . . .	517

- 9.5 Kinetic Theory of Thermal and Viscous Transport\* . . . . . 521
  - 9.5.1 Mean Free Path . . . . . 521
  - 9.5.2 Thermal Conductivity of an Ideal Gas . . . . . 522
  - 9.5.3 Viscosity of an Ideal Gas . . . . . 525
  - 9.5.4 Prandtl Number of an Ideal Gas and Binary Gas Mixtures . . . . . 526
- 9.6 Not a Total Loss . . . . . 528
- Talk Like an Acoustician . . . . . 529
- Exercises . . . . . 529
- References . . . . . 532
- 10 One-Dimensional Propagation . . . . . 533**
  - 10.1 The Transition from Lumped Elements to Waves in Fluids\* . . . . . 534
  - 10.2 The Wave Equation . . . . . 537
    - 10.2.1 General Solutions to the Wave Equation . . . . . 539
  - 10.3 The Dispersion Relation (Phase Speed) . . . . . 540
    - 10.3.1 Speed of Sound in Liquids . . . . . 541
    - 10.3.2 Speed of Sound in Ideal Gases and Gas Mixtures . . . . . 542
  - 10.4 Harmonic Plane Waves and Specific Acoustic Impedance . . . . . 545
  - 10.5 Acoustic Energy Density and Intensity . . . . . 546
    - 10.5.1 Decibel Scales . . . . . 548
    - 10.5.2 Superposition of Sound Levels (The Rule for Adding Decibels) . . . . . 552
    - 10.5.3 Anthropomorphic Frequency Weighting of Sound Levels . . . . . 552
  - 10.6 Standing Waves in Rigidly Terminated Tubes . . . . . 554
    - 10.6.1 Quality Factor in a Standing-Wave Resonator . . . . . 556
    - 10.6.2 Resonance Frequency in Closed–Open Tubes . . . . . 558
  - 10.7 Driven Plane Wave Resonators . . . . . 559
    - 10.7.1 Electroacoustic Transducer Sensitivities . . . . . 561
    - 10.7.2 The Principle of Reciprocity . . . . . 562
    - 10.7.3 In situ Reciprocity Calibration . . . . . 564
    - 10.7.4 Reciprocity Calibration in Other Geometries\* . . . . . 567
    - 10.7.5 Resonator–Transducer Interaction . . . . . 568
    - 10.7.6 Electrodynamical Source Coupling Optimization . . . . . 575
  - 10.8 Junctions, Branches, and Filters . . . . . 577
    - 10.8.1 Abrupt Discontinuities and the Acoustic Admittance . . . . . 577
    - 10.8.2 Tuned Band-Stop Filter . . . . . 579
    - 10.8.3 Stub Tuning . . . . . 581



10.9	Quasi-One-Dimensional Propagation (Horns) . . . . .	582
10.9.1	Exponential Horn . . . . .	582
10.9.2	Salmon Horns* . . . . .	587
10.9.3	Horns of Finite Length . . . . .	588
	Talk Like an Acoustician . . . . .	591
	Exercises . . . . .	591
	References . . . . .	599
<b>11</b>	<b>Reflection, Transmission, and Refraction . . . . .</b>	<b>603</b>
11.1	Normal Incidence . . . . .	604
11.1.1	Three Media . . . . .	609
11.1.2	An Impedance-Matching Layer . . . . .	611
11.2	Snell’s Law and Fermat’s Principle . . . . .	611
11.2.1	Total Internal Reflection . . . . .	614
11.2.2	The Rayleigh Reflection Coefficient . . . . .	616
11.3	Constant Sound Speed Gradients . . . . .	618
11.3.1	Constant Gradient’s Equivalence to Solid Body Rotation . . . . .	619
11.3.2	Sound Channels . . . . .	623
11.3.3	Propagation Delay* . . . . .	626
11.3.4	Under Ice Propagation . . . . .	627
11.3.5	Sound Focusing . . . . .	628
	Talk Like an Acoustician . . . . .	630
	Exercises . . . . .	630
	References . . . . .	632
<b>12</b>	<b>Radiation and Scattering . . . . .</b>	<b>635</b>
12.1	Sound Radiation and the “Event Horizon” . . . . .	638
12.2	Spherically Diverging Sound Waves . . . . .	641
12.2.1	Compact Monopole Radiation Impedance . . . . .	642
12.2.2	Compact Monopole Acoustic Transfer Impedance . . . . .	645
12.2.3	General Multipole Expansion* . . . . .	646
12.3	Bubble Resonance . . . . .	647
12.3.1	Damping of Bubble Oscillations . . . . .	649
12.4	Two In-phase Monopoles . . . . .	652
12.4.1	The Method of Images . . . . .	656
12.5	Two Out-of-Phase Compact Sources (Dipoles) . . . . .	660
12.5.1	Dipole Radiation . . . . .	663
12.5.2	Cardioid (Unidirectional) Radiation Pattern . . . . .	667
12.5.3	Pressure Gradient Microphones . . . . .	669
12.5.4	The DIFAR Directional Sonobuoy . . . . .	672
12.6	Translational Oscillations of an Incompressible Sphere . . . . .	673
12.6.1	Scattering from a Compact Density Contrast . . . . .	675
12.6.2	Scattering from a Compact Compressibility Contrast . . . . .	678

- 12.6.3 Scattering from a Single Bubble or a Swim Bladder . . . . . 680
- 12.6.4 Multiple Scattering in the Effective Medium Approximation . . . . . 681
- 12.7 *N*-Element Discrete Line Array . . . . . 684
  - 12.7.1 Beam Steering and Shading . . . . . 687
  - 12.7.2 Continuous Line Array . . . . . 690
- 12.8 Baffled Piston . . . . . 692
  - 12.8.1 Rayleigh Resolution Criterion . . . . . 696
  - 12.8.2 Directionality and Directivity . . . . . 697
  - 12.8.3 Radiation Impedance of a Baffled Piston . . . . . 700
  - 12.8.4 On-Axis Near-Field Pressure from a Baffled Piston . . . . . 702
- Talk Like an Acoustician . . . . . 706
- Exercises . . . . . 706
- References . . . . . 714
- 13 Three-Dimensional Enclosures . . . . . 717**
  - 13.1 Separation of Variables in Cartesian Coordinates . . . . . 718
    - 13.1.1 Rigid-Walled Rectangular Room . . . . . 719
    - 13.1.2 Mode Characterization . . . . . 721
    - 13.1.3 Mode Excitation . . . . . 722
    - 13.1.4 Density of Modes . . . . . 723
  - 13.2 Statistical Energy Analysis . . . . . 725
    - 13.2.1 The Sabine Equation . . . . . 728
    - 13.2.2 Critical Distance and the Schroeder Frequency . . . . . 731
  - 13.3 Modes of a Cylindrical Enclosure . . . . . 734
    - 13.3.1 Pressure Field and Normal Modes within a Rigid Cylinder . . . . . 734
    - 13.3.2 Modal Density Within a Rigid Cylinder . . . . . 742
    - 13.3.3 Modes of a Rigid-Walled Toroidal Enclosure . . . . . 745
    - 13.3.4 Modal Degeneracy and Mode Splitting . . . . . 747
    - 13.3.5 Modes in Nonseparable Coordinate Geometries . . . . . 749
  - 13.4 Radial Modes of Spherical Resonators . . . . . 753
    - 13.4.1 Pressure-Released Spherical Resonator . . . . . 754
    - 13.4.2 Rigid-Walled Spherical Resonator . . . . . 755
  - 13.5 Waveguides . . . . . 756
    - 13.5.1 Rectangular Waveguide . . . . . 757
    - 13.5.2 Phase Speed and Group Speed . . . . . 759
    - 13.5.3 Driven Waveguide . . . . . 761
    - 13.5.4 Cylindrical Waveguide . . . . . 762
    - 13.5.5 Waveguide Attenuation from Thermoviscous Boundary Losses . . . . . 764
  - Talk Like an Acoustician . . . . . 765
  - Exercises . . . . . 766
  - References . . . . . 775

**14 Attenuation of Sound** . . . . . 779

14.1 An Almost Correct Expression for Viscous Attenuation . . . . . 781

14.2 Bulk Thermoviscous Attenuation in Fluids . . . . . 784

14.3 Classical Thermoviscous Attenuation . . . . . 789

14.4 The Time-Dependent Equation of State . . . . . 790

14.5 Attenuation due to Internal Relaxation Times . . . . . 793

14.5.1 Relaxation Attenuation in Gases . . . . . 795

14.5.2 Relaxation Attenuation in Fresh and Salt  
Water . . . . . 799

14.6 Transmission Loss . . . . . 800

14.6.1 Short and Very Short Wavelengths . . . . . 802

14.6.2 Very Long Wavelengths . . . . . 803

14.7 Quantum Mechanical Manifestations in Classical  
Mechanics . . . . . 803

Talk Like an Acoustician . . . . . 804

Exercises . . . . . 805

References . . . . . 808

**Part III Extensions**

**15 Nonlinear Acoustics** . . . . . 813

15.1 Surf’s Up . . . . . 815

15.1.1 The Grüneisen Parameter . . . . . 817

15.1.2 The Virial Expansion and  $B/A$  . . . . . 819

15.1.3 Anomalous Distortion\* . . . . . 820

15.1.4 The Gol’dberg Number . . . . . 824

15.1.5 Stable Sawtooth Waveform Attenuation . . . . . 825

15.2 Weak Shock Theory and Harmonic Distortion . . . . . 827

15.2.1 The Order Expansion . . . . . 827

15.2.2 The Earnshaw Approximation . . . . . 828

15.2.3 Higher Harmonic Generation (the Hargrove  
Construction) . . . . . 829

15.3 The Phenomenological Model . . . . . 832

15.3.1 The (Nondissipative) Nonlinear Wave  
Equation . . . . . 833

15.3.2 Geometrical Resonance (Phase Matching) . . . . . 834

15.3.3 Intermodulation Distortion and the Parametric  
End-Fire Array . . . . . 835

15.3.4 Resonant Mode Conversion . . . . . 839

15.4 Nonzero Time-Averaged Effects . . . . . 843

15.4.1 The Second-Order Pressure in an Adiabatic  
Compression . . . . . 844

15.4.2 The Bernoulli Pressure . . . . . 847

15.4.3 The Rayleigh Disk . . . . . 849

15.4.4 Radiation Pressure . . . . . 851

- 15.4.5 Acoustic Levitation in Standing Waves . . . . . 853
- 15.4.6 Adiabatic Invariance and the Levitation Force . . . . . 855
- 15.4.7 Levitation Superstability (“Acoustic Molasses”) . . . . . 861
- 15.5 Beyond the Linear Approximation . . . . . 865
- Talk Like an Acoustician . . . . . 866
- Exercises . . . . . 866
- References . . . . . 870
  
- Appendix A Useful Constants and Conversion Factors . . . . . 873**
- Appendix B Resonator Quality Factor . . . . . 875**
- Appendix C Bessel Functions of the First Kind . . . . . 879**
- Appendix D Trigonometric Functions . . . . . 883**
- Appendix E Hyperbolic Functions . . . . . 885**
- Index . . . . . 889**



<http://www.springer.com/978-3-319-49976-5>

Understanding Acoustics

An Experimentalist's View of Acoustics and Vibration

Garrett, S.L.

2017, XXXI, 896 p. 401 illus., 81 illus. in color.,

Hardcover

ISBN: 978-3-319-49976-5