

# Contents

Introduction .....	xix
<b>1 Fundamentals of Sound .....</b>	<b>1</b>
Simple Harmonic Motion and the Sine Wave .....	2
Sound in Media .....	3
Particle Motion .....	4
Propagation of Sound .....	5
Speed of Sound .....	7
Wavelength and Frequency .....	7
Complex Waveforms .....	8
Harmonics .....	8
Phase .....	10
Partials .....	13
Octaves .....	13
Spectrum .....	15
Key Points .....	18
<b>2 Sound Levels and the Decibel .....</b>	<b>19</b>
Ratios versus Differences .....	19
Expressing Numbers .....	20
Logarithms .....	21
Decibels .....	21
Reference Levels .....	23
Logarithmic and Exponential Forms Compared .....	24
Acoustic Power .....	25
Using Decibels .....	26
Measuring Sound-Pressure Level .....	29
Sine-Wave Measurements .....	30
Electrical, Mechanical, and Acoustical Analogs .....	32
Key Points .....	32
<b>3 Sound in the Free Field .....</b>	<b>35</b>
The Free Field .....	35
Sound Divergence .....	35
Sound Intensity in the Free Field .....	36
Sound Pressure in the Free Field .....	37
Free-Field Sound Divergence .....	37
Sound Fields in Enclosed Spaces .....	39
Hemispherical Field and Propagation .....	39
Key Points .....	41



<b>4</b>	<b>The Perception of Sound</b>	<b>43</b>
	Sensitivity of the Ear	43
	Ear Anatomy	44
	The Outer Ear—Pinna	45
	A Demonstration of Directional Cues	45
	The Outer Ear—Auditory Canal	45
	The Middle Ear	46
	The Inner Ear	48
	Stereocilia	49
	Loudness versus Frequency	50
	Loudness Control	52
	Area of Audibility	52
	Loudness versus Sound-Pressure Level	53
	Loudness and Bandwidth	55
	Loudness of Impulses	57
	Audibility of Loudness Changes	58
	Pitch versus Frequency	58
	An Experiment in Pitch	59
	The Missing Fundamental	60
	Timbre versus Spectrum	60
	Localization of Sound Sources	60
	Binaural Localization	63
	Law of the First Wavefront	63
	The Franssen Effect	64
	The Precedence (Haas) Effect	64
	Perception of Reflected Sound	65
	The Cocktail-Party Effect	67
	Aural Nonlinearity	68
	Subjective versus Objective Evaluation	68
	Occupational and Recreational Hearing Loss	69
	Key Points	71
<b>5</b>	<b>Signals, Speech, Music, and Noise</b>	<b>73</b>
	Sound Spectrograph	73
	Speech	74
	Vocal Tract Molding of Speech	77
	Formation of Voiced Sounds	77
	Formation of Unvoiced Sounds	77
	Frequency Response of Speech	78
	Directionality of Speech	79
	Music	79
	String Instruments	79
	Wind Instruments	81
	Nonharmonic Overtones	82
	Dynamic Range of Speech and Music	82
	Power in Speech and Music	83



Frequency Range of Speech and Music .....	84
Auditory Area of Speech and Music .....	84
Noise .....	86
Noise Measurements .....	87
Random Noise .....	88
White and Pink Noise .....	89
Signal Distortion .....	91
Harmonic Distortion .....	92
Resonance .....	95
Audio Filters .....	96
Key Points .....	99
<b>6 Reflection .....</b>	<b>101</b>
Specular Reflections .....	101
Flutter Echoes .....	103
Doubling of Pressure at Reflection .....	104
Reflections from Convex Surfaces .....	104
Reflections from Concave Surfaces .....	105
Reflections from Parabolic Surfaces .....	105
Whispering Galleries .....	105
Standing Waves .....	107
Corner Reflectors .....	107
Mean Free Path .....	108
Perception of Sound Reflections .....	108
The Effect of Single Reflections .....	108
Perception of Spaciousness, Images, and Echoes .....	111
Effect of Angle of Incidence, Signal Type, and Spectrum on Audibility of Reflection .....	111
Key Points .....	112
<b>7 Diffraction .....</b>	<b>115</b>
Diffraction and Wavefront Propagation .....	115
Diffraction and Wavelength .....	116
Diffraction by Obstacles .....	116
Diffraction by Apertures .....	119
Diffraction by a Slit .....	120
Diffraction by a Zone Plate .....	120
Diffraction around the Human Head .....	120
Diffraction by Loudspeaker Cabinet Edges .....	120
Diffraction by Various Objects .....	124
Key Points .....	124
<b>8 Refraction .....</b>	<b>125</b>
The Nature of Refraction .....	125
Refraction in Solids .....	126
Refraction in the Atmosphere .....	127
Refraction in Enclosed Spaces .....	130



	Refraction in the Ocean .....	130
	Key Points .....	131
<b>9</b>	<b>Diffusion</b> .....	<b>133</b>
	The Perfectly Diffuse Sound Field .....	133
	Evaluating Diffusion in a Room .....	134
	Steady-State Measurements .....	134
	Decay Beats .....	135
	Exponential Decay .....	135
	Spatial Uniformity of Reverberation Time .....	136
	Geometrical Irregularities .....	139
	Absorbent in Patches .....	140
	Concave Surfaces .....	140
	Convex Surfaces: The Polycylindrical Diffuser .....	140
	Plane Surfaces .....	142
	Key Points .....	142
<b>10</b>	<b>Comb-Filter Effects</b> .....	<b>143</b>
	Comb Filters .....	143
	Superposition of Sound .....	143
	Tonal Signals and Comb Filters .....	144
	Comb Filtering of Music and Speech Signals .....	146
	Comb Filtering of Direct and Reflected Sound .....	147
	Comb Filters and Critical Bands .....	151
	Comb Filters in Multichannel Playback .....	152
	Controlling Comb Filtering .....	153
	Reflections and Spaciousness .....	153
	Comb Filters in Microphone Placement .....	154
	Comb-Filter Effects in Practice: Six Examples .....	154
	Estimating Comb-Filter Response .....	157
	Key Points .....	159
<b>11</b>	<b>Reverberation</b> .....	<b>161</b>
	Growth of Sound in a Room .....	161
	Decay of Sound in a Room .....	163
	Idealized Growth and Decay of Sound .....	163
	Calculating Reverberation Time .....	164
	Sabine Equation .....	165
	Eyring-Norris Equation .....	167
	Air Absorption .....	168
	Measuring Reverberation Time .....	168
	Impulse Sources .....	169
	Steady-State Sources .....	169
	Measuring Equipment .....	170
	Measurement Procedure .....	171
	Reverberation and Normal Modes .....	171
	Analysis of Decay Traces .....	173



Mode Decay Variations	173
Frequency Effect	175
Reverberation Characteristic	175
Reverberation Time Variation with Position	176
Decay Rate and the Reverberant Field	176
Acoustically Coupled Spaces	178
Electroacoustically Coupled Spaces	178
Eliminating Decay Fluctuations	179
Influence of Reverberation on Speech	179
Influence of Reverberation on Music	180
Optimum Reverberation Time	181
Bass Rise of Reverberation Time	184
Initial Time-Delay Gap	185
Listening Room Reverberation Time	185
Artificial Reverberation	186
Examples of Reverberation Time Calculations	188
Key Points	190
<b>12 Absorption</b>	<b>193</b>
Dissipation of Sound Energy	193
Absorption Coefficients	194
Reverberation Chamber Method	196
Impedance Tube Method	196
Tone-Burst Method	198
Mounting of Absorbents	200
Mid/High-Frequency Absorption by Porosity	201
Glass-Fiber Low-Density Materials	201
Glass-Fiber High-Density Boards	203
Glass-Fiber Acoustical Tile	204
Effect of Thickness of Absorbent	205
Effect of Airspace behind Absorbent	205
Effect of Density of Absorbent	205
Open-Cell Foams	206
Drapes as Sound Absorbers	208
Carpet as Sound Absorber	210
Effect of Carpet Type on Absorbance	212
Effect of Carpet Underlay on Absorbance	212
Carpet Absorption Coefficients	213
Sound Absorption by People	213
Sound Absorption in Air	215
Panel (Diaphragmatic) Absorbers	215
Polycylindrical Absorbers	220
Polycylindrical Absorber Construction	222
Bass Traps: Low-Frequency Absorption by Resonance	223
Helmholtz (Volume) Resonators	224
Perforated Panel Absorbers	227



Slat Absorbers .....	231
Placement of Materials .....	231
Reverberation Time of Helmholtz Resonators .....	231
Reducing Room Modes with Absorbers .....	234
Increasing Reverberation Time .....	236
Absorption Module Design .....	236
Key Points .....	238
<b>13 Modal Resonances .....</b>	<b>241</b>
Early Experiments and Examples .....	241
Resonance in a Pipe .....	242
Indoor Reflections .....	244
Two-Wall Resonance .....	246
Frequency Regions .....	247
Room-Mode Equation .....	249
Mode Calculations—An Example .....	250
Experimental Verification .....	253
Mode Decay .....	254
Mode Bandwidth .....	255
Mode Pressure Plots .....	260
Mode Density .....	263
Mode Spacing and Timbral Defects .....	264
Audibility of Timbral Defects .....	265
Optimal Room Proportions .....	266
Bonello Criterion .....	269
Splaying Room Surfaces .....	269
Nonrectangular Rooms .....	270
Controlling Problem Modes .....	273
Simplified Axial-Mode Analysis .....	273
Key Points .....	275
<b>14 Schroeder Diffusers .....</b>	<b>277</b>
Experimentation .....	277
Reflection Phase-Grating Diffusers .....	278
Quadratic Residue Diffusers .....	279
Primitive Root Diffusers .....	280
Performance of Diffraction-Grating Diffusers .....	281
Reflection Phase-Grating Diffuser Applications .....	283
Flutter Echo .....	287
Application of Fractals .....	289
Diffusion in Three Dimensions .....	292
Diffusing Concrete Blocks .....	293
Measuring Diffusion Efficiency .....	293
Comparison of Gratings with Conventional Approaches .....	295
Key Points .....	297
<b>15 Adjustable Acoustics .....</b>	<b>299</b>
Draperies .....	299



	Portable Absorptive Panels .....	300
	Hinged Panels .....	303
	Louvered Panels .....	303
	Absorptive/Diffusive Adjustable Panels .....	304
	Variable Resonant Devices .....	305
	Rotating Elements .....	306
	Modular Low-Frequency Absorptive Devices .....	308
	Key Points .....	311
<b>16</b>	<b>Sound Isolation and Site Selection .....</b>	<b>313</b>
	Propagation through Barriers .....	314
	Approaches to Noise Control .....	314
	Airborne Noise .....	315
	Transmission Loss .....	316
	Effect of Mass and Frequency .....	317
	Coincidence Effect .....	318
	Separation of Mass .....	319
	Porous Materials .....	319
	Sound Transmission Class .....	320
	Structureborne Noise .....	322
	Noise Transmitted by Diaphragmatic Action .....	323
	Noise and Room Resonances .....	323
	Site Selection .....	323
	The Noise Survey .....	325
	Assessment of Environmental Noise .....	328
	Measurement and Testing Standards .....	329
	Recommended Practices .....	330
	Noise Measurements and Construction .....	332
	Floor Plan Considerations .....	334
	Designing within a Frame Structure .....	335
	Designing within a Concrete Structure .....	335
	Key Points .....	335
<b>17</b>	<b>Sound Isolation: Walls, Floors, and Ceilings .....</b>	<b>337</b>
	Walls as Effective Noise Barriers .....	337
	The Role of Porous Absorbers .....	338
	The Mass Law and Wall Design .....	339
	Separation of Mass in Wall Design .....	342
	Wall Design Summary .....	345
	Improving an Existing Wall .....	350
	Flanking Sound .....	351
	Gypsum Board Walls as Sound Barriers .....	351
	Masonry Walls as Sound Barriers .....	352
	Weak Links .....	355
	Summary of Wall STC Ratings .....	356
	Floating Floors .....	358
	Floating Walls and Ceilings .....	360
	Resilient Hangers .....	361



	Floor/Ceiling Construction .....	362
	Case Study of Footfall Noise .....	363
	Floor/Ceiling Structures and Their IIC Performance .....	365
	Floor/Ceilings in Frame Buildings .....	365
	Floor Attenuation with Concrete Layers .....	366
	Plywood Web versus Solid Wood Joists .....	368
	Key Points .....	370
<b>18</b>	<b>Sound Isolation: Windows and Doors .....</b>	<b>371</b>
	Single-Pane Windows .....	372
	Double-Pane Windows .....	373
	Acoustical Holes in Glass: Mass-Air-Mass Resonance .....	374
	Acoustical Holes in Glass: Coincidence Resonance .....	376
	Acoustical Holes in Glass: Standing Waves in the Cavity .....	377
	Glass Mass and Spacing .....	378
	Dissimilar Panes .....	380
	Laminated Glass .....	380
	Plastic Panes .....	380
	Slanting the Glass .....	381
	Third Pane .....	381
	Cavity Absorbent .....	381
	Thermal Glass .....	381
	Example of an Optimized Double-Pane Window .....	381
	Construction of an Observation Window .....	382
	Proprietary Observation Windows .....	385
	Sound-Isolating Doors .....	386
	Sound Locks .....	390
	Composite Partitions .....	390
	Key Points .....	392
<b>19</b>	<b>Noise Control in Ventilating Systems .....</b>	<b>393</b>
	Selection of Noise Criteria .....	393
	Fan Noise .....	396
	Machinery Noise and Vibration .....	398
	Air Velocity .....	401
	Natural Attenuation .....	402
	Duct Lining .....	403
	Plenum Silencers .....	405
	Proprietary Attenuators .....	406
	Reactive Silencers .....	407
	Tuned Silencers .....	408
	Duct Location .....	408
	ASHRAE .....	409
	Active Noise Control .....	410
	Key Points .....	411
<b>20</b>	<b>Acoustics of Listening Rooms and Home Theaters .....</b>	<b>413</b>
	Playback Criteria .....	413



26	Planning the Playback Room	415
	Acoustical Treatment of Playback Rooms	416
	Peculiarities of Small-Room Acoustics	416
	Room Size and Proportion	417
	Reverberation Time	417
	Low-Frequency Considerations	417
	Modal Anomalies	421
	Control of Modal Resonances	421
	Bass Traps for Playback Rooms	421
	Mid/High-Frequency Considerations	423
	Identification and Treatment of Reflection Points	425
	Lateral Reflections and Control of Spaciousness	426
	Loudspeaker Placement	427
	Listening Room Plan	428
	Home-Theater Plan	431
	Controlling Early Reflections	433
	Other Treatment Details	434
	Key Points	437
<b>21</b>	<b>Acoustics of Home Studios</b>	<b>439</b>
	Home Acoustics: Modes	439
	Home Acoustics: Reverberation	440
	Home Acoustics: Noise Control	440
	Home Studio Budget	441
	Home Studio Treatment	442
	Home Studio Plan	444
	Recording in the Home Studio	446
	Garage Studio	448
	Key Points	449
<b>22</b>	<b>Acoustics of Small Recording Studios</b>	<b>451</b>
	Ambient Noise Requirements	451
	Acoustical Characteristics of Small Studios	452
	Direct and Indirect Sound	452
	Role of Room Treatment	452
	Room Modes and Room Volume	454
	Mode Analysis for Different Room Sizes	454
	Reverberation Time	456
	Reverberation in Small Rooms	456
	Optimal Reverberation Time	457
	Diffusion	457
	Noise	458
	Small Studio Design Example	458
	Absorption Design Goal	458
	Proposed Room Treatment	459
	Key Points	463



<b>23</b>	<b>Acoustics of Large Recording Studios</b> .....	<b>465</b>
	Design Criteria of a Large Studio .....	466
	Floor Plan .....	466
	Wall Sections .....	466
	Section D-D .....	467
	Section E-E .....	469
	Sections F-F and G-G .....	470
	Studio Treatment .....	470
	Drum Booth .....	472
	Vocal Booth .....	473
	Sound-Lock Corridor .....	475
	Reverberation Time .....	475
	Key Points .....	477
<b>24</b>	<b>Acoustics of Control Rooms</b> .....	<b>479</b>
	Initial Time-Delay Gap .....	479
	Live End-Dead End .....	481
	Specular Reflections versus Diffusion .....	482
	Low-Frequency Resonances in Control Rooms .....	484
	Initial Time-Delay Gaps in Practice .....	485
	Loudspeaker Placement, Reflection Paths, and Near-Field Monitoring .....	485
	The Reflection-Free-Zone Control Room .....	487
	Control-Room Frequency Range .....	489
	Outer Shell and Inner Shell of the Control Room .....	490
	Design Criteria of a Control Room .....	490
	Design Example 1: Control Room with Rectangular Walls .....	491
	Design Example 2: Double-Shell Control Room with Splayed Walls ...	493
	Design Example 3: Single-Shell Control Room with Splayed Walls ...	494
	Key Points .....	496
<b>25</b>	<b>Acoustics of Isolation Booths</b> .....	<b>499</b>
	Applications .....	499
	Design Criteria .....	500
	Isolation Requirements .....	501
	The Small-Room Problem .....	501
	Design Example 1: Traditional Isolation Booth .....	502
	Axial Modes .....	503
	Reverberation Time .....	503
	Design Example 2: Isolation Booth with Cylindrical Traps .....	505
	Acoustical Measurements .....	510
	Reverberation Time .....	510
	Design Example 3: Isolation Booth with Diffusers .....	512
	Reverberation Time .....	514
	Evaluation and Comparison .....	515
	Live End-Dead End Isolation Booth .....	519
	Key Points .....	519



<b>26</b>	<b>Acoustics of Audiovisual Postproduction Rooms</b> .....	<b>521</b>
	Design Criteria .....	521
	Design Example 1: Small Postproduction Room .....	522
	Appraisal of Room Resonances .....	522
	Proposed Treatment .....	522
	Design Example 2: Large Postproduction Room .....	526
	Appraisal of Room Resonances .....	526
	Monitor Loudspeakers and Early Sound .....	526
	Late Sound .....	530
	Proposed Treatment .....	531
	Workbench .....	534
	Mixing Engineer's Workstation .....	534
	Video Display and Lighting .....	535
	Key Points .....	536
<b>27</b>	<b>Acoustics of Teleconference Rooms</b> .....	<b>537</b>
	Design Criteria .....	537
	Shape and Size of the Room .....	538
	Floor Plan .....	539
	Ceiling Plan .....	539
	Elevation Views .....	540
	Reverberation Time .....	541
	Key Points .....	543
<b>28</b>	<b>Acoustics of Large Halls</b> .....	<b>545</b>
	Design Criteria .....	546
	Reverberation and Echo Control .....	546
	Air Absorption .....	548
	Hall Design for Speech .....	549
	Volume .....	549
	Hall Geometry .....	549
	Absorption Treatment .....	551
	Ceiling, Walls, and Floor .....	551
	Speech Intelligibility .....	552
	Speech Frequencies and Duration .....	552
	Subject-Based Measures .....	552
	Analytical Measures .....	552
	Concert Hall Acoustical Design .....	554
	Reverberation .....	554
	Clarity .....	555
	Brilliance .....	555
	Gain .....	555
	Seating Capacity .....	556
	Volume .....	556
	Diffusion .....	557
	Spaciousness .....	557
	Apparent Source Width .....	557



Initial Time-Delay Gap .....	557
Bass Ratio and Warmth .....	558
Concert Hall Architectural Design .....	558
Balcony .....	558
Ceiling and Walls .....	559
Raked Floor .....	560
Virtual Image Source Analysis .....	560
Hall Design Procedure .....	562
Case Studies .....	562
Postscript .....	564
Key Points .....	565
<b>A Overview of TDS and MLS Analysis .....</b>	<b>569</b>
<b>B Room Auralization .....</b>	<b>575</b>
<b>C Selected Absorption Coefficients .....</b>	<b>587</b>
<b>Bibliography .....</b>	<b>589</b>
<b>Glossary .....</b>	<b>605</b>
<b>Index .....</b>	<b>619</b>