

# CONTENTS

## Part I *Sound and Hearing*

1. OUR SONIC ENVIRONMENT	3
Sounds in Nature	4
Sounds in the Ocean	5
Communication and Language	7
Acoustics in Antiquity	9
Early Measurements Relating to Sound	11
Telephony	13
Radio Broadcasting	15
Sounds of Music	16
Infrasonic to Ultrasonic	18
2. SOUND CHARACTERIZATION	21
Sound Sources	21
Sound Waves	22
Frequency and Wavelength	26
Velocity of Sound	27
Molecular Velocity and Displacement	29
Velocity of Sound in Common Materials	33
Sound Intensity	33
Sound Pressure	34
The Decibel Scale	35
<i>Sound Pressure Level, 38</i>	
<i>Features of the Decibel Scale, 38</i>	
<i>Power Level, 41</i>	
<i>Intensity Level, 41</i>	

Sound Wave Interaction Phenomena	43
<i>Dissipation of Energy</i> , 43	
<i>Reflection</i> , 44	
<i>Diffraction</i> , 45	
<i>Refraction</i> , 46	
<i>Superposition or Interference</i> , 47	
Sound Spectra	50
<i>Line Spectra</i> , 50	
<i>Continuous Spectra</i> , 50	
<i>Bandwidth</i> , 50	
Noise	51
Fourier Representation of a Sound Wave	53
3. SOUND PROPAGATION IN THE ATMOSPHERE	56
Properties of the Atmosphere	56
Sound Propagation in the Open Air	58
<i>The Inverse Square Law</i> , 58	
<i>Intensity from Line Sources</i> , 59	
Air Absorption	61
Effect of Wind and Temperature	63
Effect of Clouds, Fog, and Smoke	69
Effect of Ground Cover	70
Echoes and Thunder	70
The Doppler Effect	73
<i>General Formula for the Doppler Effect</i> , 77	
<i>Doppler Effect Phenomena</i> , 78	
Speed of Exceedingly Loud Sounds	79
4. SOUND IN ENCLOSED SPACES	82
Sound Fields	82
Growth of a Sound Field	86
Reverberation Time	87
Standing Waves	90
Absorption in Acoustic Materials	92
<i>Absorption Coefficients</i> , 94	
<i>Noise Reduction Coefficients (NRC)</i> , 94	
General Noise Reduction in Rooms	94
Transmission of Sound from Exterior Sources	97
<i>Transmission Loss</i> , 98	
<i>The Mass Law</i> , 99	
<i>Leaks and Flanking</i> , 102	

5. AUDITORY PERCEPTION	105
Anatomy of the Ear	105
<i>The External Ear</i> , 105	
<i>Middle Ear</i> , 107	
<i>The Inner Ear</i> , 108	
Cochlear Potentials	111
Cochlear Frequency Response	111
Threshold of Hearing	114
Upper Limit of Hearing	115
The Ear as a Frequency Analyzer	116
Critical Bandwidth	117
Response to Transient Phenomena	119
Channel Capacity of the Ear	119
Persistence of Hearing	120
Auditory Fatigue	121
Masking	122
Localization in Space	125
The Precedence (Haas) Effect	126
6. SUBJECTIVE PARAMETERS OF HEARING	129
Loudness	129
<i>Loudness Level Contours (Phons)</i> , 130	
<i>The Sone Scale</i> , 130	
Loudness Index, Annoyance, and Perceived Noise Level	132
Loudness Level and Duration Time	138
Pitch	139
<i>Units of Pitch—Mels</i> , 140	
Pitch and Intensity	140
Minimum Perceptible Change in Pitch	143
Pitch and Duration Time	144
Perceived Pitch of a Musical Sound	146
Aural Harmonics and Combination Tones	146
The Phenomenon of Beats	149
The Concept of Volume	153
7. INSTRUMENTATION FOR SOUND ANALYSIS	155
Microphones	155
Sound Level Meter	158
Noise Exposure Monitor	159
Personnel Noise Monitor	160

xvi Contents

Octave-Band Analyzers	161
$\frac{1}{3}$ Octave-Band Analyzers	163
Narrow Band Analyzers	163
Real Time Analyzers	165
Tape Recorders	167
Digital Data Systems	169
Oscilloscopes	169
Reverberation Time Apparatus	170
Field-Type Acoustic Wattmeter	171
Vibration Transducers	171
Stroboscopes	172
Audiometers	173

**Part II Noise Control**

8. NOISE AS A SOCIETAL PROBLEM	179
The Impact of Urbanization	180
Growth of Noise Sources	180
Conflict in Societal Goals	182
Legal Considerations	184
9. TRAFFIC AND VEHICULAR NOISE	190
Transportation Noise	190
Automobiles	192
Truck Noise	197
Vehicle Speed and Weight	203
Expressway Noise Profiles	205
Roads as Line Sources	207
Noise vs. Traffic Density	211
Effects of Road Surface, Gradients, and Intersections	212
Attenuation by Barriers	214
Traffic Noise Index (TNI)	216
Rail Transit Systems	217
Hovercraft	219
Recreational Vehicles	220
<i>Motorcycles</i> , 221	
<i>Snowmobiles</i> , 224	
<i>Motorboats</i> , 225	

10. AIRCRAFT NOISE	228
Aircraft Noise as a Systems Problem	228
Propeller Aircraft	232
Helicopter Noise Spectra	232
Jet Noise	234
Subjective Response to Aircraft Noise	238
<i>Effective Perceived Noise Level (EPNL)</i> , 238	
<i>Noise and Number Index (NNI)</i> , 240	
<i>Composite Noise Rating (CNR)</i> , 243	
<i>Noise Exposure Forecast (NEF)</i> , 243	
<i>Community Noise Equivalent Level (CNEL)</i> , 247	
Noise Contours Near Airports	247
<i>Takeoff and Landing Patterns</i> , 247	
<i>Noise Under Air Route Corridors</i> , 249	
Certification of New Aircraft	251
Community Reaction to Airport Noise	253
Sonic Booms	254
<i>Nature of the Sonic Boom</i> , 254	
<i>Ground Exposure Pattern</i> , 254	
<i>Frequency Spectrum of N-Waves</i> , 257	
Near-Sonic Transports	258
Rocket-Powered Vehicles	260
11. INDUSTRIAL NOISE CONTROL	262
Planning for Noise Control	262
Audiometric Testing and Personnel Protection	263
Construction Noise	264
Noise Control in Manufacturing Plants	266
<i>In-Plant Noise Sources</i> , 267	
<i>Directivity of Sound Pattern</i> , 270	
<i>Operator and Machine Enclosures</i> , 271	
<i>Vibration Isolation</i> , 273	
<i>Noise Reduction with Acoustic Materials</i> , 274	
Noise Levels in Industrial Plant Environs	278
Industrial Products	281
<i>Transformer Noise</i> , 281	
<i>Fan Noise</i> , 282	
<i>Pumps and Motors</i> , 286	
<i>Power Equipment Specifications</i> , 287	
<i>Gears and Bearings</i> , 288	
<i>The Development of "Quiet" Components</i> , 289	

xviii Contents

Consumer Products	290
Noise Control in Process Plants	292
Power Plant Noise Control	295
Noise Control in Offices	299
<i>Noise Criterion (NC)</i> , 300	
<i>Preferred Noise Criterion (PNC)</i> , 302	
12. LEGAL ASPECTS OF NOISE ABATEMENT	304
National Environmental Policy Act	304
Environmental Protection Agency	305
Federal Aviation Administration	306
Airport and Airways Development Act	308
Federal-Aid Highway Act	309
Walsh-Healey Public Contracts Act	309
Occupational Safety and Health Act	312
The Clean Air Act	313
Noise Control Act of 1972	315
State Statutes	316
Regulation of Vehicular Noise	318
Regulation of Public Utilities	322
Local Regulation of Machine Noise	323
Noise Nuisance Ordinances	324
A "Model" City Ordinance	326
International Efforts Toward Noise Control	329
13. COMMUNITY PLANNING	337
Factors Affecting Community Response to Noise	337
Land Use and Zoning	339
Highway Planning	341
Land Use Surrounding Airports	344
Recreational Areas	346
Utilities and Municipal Services	348
Architectural Planning	351
<i>Site Utilization</i> , 352	
<i>Building Design</i> , 355	
Building Codes	358
Environmental Noise—A New Rating Scheme ( $L_{eq}$ )	359
Conservative Levels of Community Noise	360

**Part III *Speech, Music, and Physio-psychological Effects of Sound***

14. THE SOUNDS OF SPEECH	365
The Vocal Apparatus	365
Acoustic Power of Speech	367
Speech Formants	369
Speech Intelligibility and Bandwidth	372
Acoustical Correlates of Emotion in Speech	375
Parameters Relating to the Intelligibility of Speech Sounds	376
<i>Signal-to-Noise Ratio, 376</i>	
<i>Talker-Listener Distance, 377</i>	
<i>Articulation Index, 379</i>	
<i>Effect of Reverberation, 380</i>	
<i>Speech Interference Level, 380</i>	
Communication in "Open Plan" Rooms and Landscaped Offices	381
The Voice Contour Spectrograph	386
Potential Use of the Voice Spectrograph for Legal Purposes	387
Generation of Speech Sounds by Computer	390
15. MUSICAL ACOUSTICS	393
Intervals	393
Musical Scales	395
The Tempered Scale	397
The Standard of Pitch	399
Harmonics and Transients	400
Fundamental Frequency Range of Musical Instruments	403
Acoustic Power of Instruments	403
Harmonic Spectra of Instruments	406
<i>Stringed Instruments, 406</i>	
<i>Brass Instruments, 411</i>	
<i>Woodwinds, 412</i>	
<i>Organ Pipes, 415</i>	
<i>Bells and Carillons, 418</i>	
<i>The Human Voice, 421</i>	
Chorus Effect of an Instrumental Ensemble	422
Tonality	423
Absolute Pitch	425

16. AUDITORIUMS AND CONCERT HALLS	427
The Evolution of Architectural Acoustics	427
The Sound Field in an Auditorium	429
Acoustic Criteria for Speech	432
Acoustic Criteria for Music	436
Basic Hall Shapes	440
Classic Concert Halls	443
Air Absorption in Large Halls	447
Electronic Enhancement of Reverberation	450
J. F. Kennedy Center for the Performing Arts	452
Band Shells and “Open” Auditoriums	454
17. PHYSIOLOGICAL AND PSYCHOLOGICAL EFFECTS OF SOUND	460
General Physiological Effects	460
Effect of Noise on Sleep	462
Hearing Loss	464
<i>Presbycusis</i> , 464	
<i>Temporary Threshold Shift</i> , 466	
<i>Permanent Threshold Shift</i> , 468	
<i>Acoustic Trauma</i> , 472	
Psychological Response to Noise	472
Effect of Noise on Performance	474
<i>Manual Tasks</i> , 475	
<i>Decision Making</i> , 476	
Effect of “Startle”	477
Aftereffects of Noise	479
Effect of Music on Performance	480
Music and Employee Attitudes	482
Acoustic Options	483
<b>Appendix: Expansion of a Function in a Fourier Series</b>	<b>489</b>
<b>Index</b>	<b>493</b>