Contents

Foreword xv
Preface xvii
Acknowledgments xix
About the Author xxi
List of Acronyms xxiii

CHAPTER 1

Vehicle Acoustics and Understanding of Noise 1

1.1. Typical Frequencies Related to Vehicle Noise 2
1.2. Fundamentals of Acoustics 4
1.2.1 Waves 6
1.2.2 Mathematical Description of Sound Waves 8
1.3. Propagation of Waves 10
1.3.1 Spherical Wave 10
1.3.2 Cylindrical Wave 11
1.3.3 Plane Wave 12
1.4 Sound Power and Sound Intensity 12
1.5 Levels and Decibels 13
1.5.1 Reference Values 15
1.5.2 Adding and Subtracting Decibels 16
1.5.2.1 Adding Decibels 16
1.5.2.2 Subtracting Decibels 17
1.5.3 More on Changes in Decibel Values 17
1.6 Frequency 17
1.6.1 Constant Bandwidth Frequency 18
1.6.2 Constant Percent Bandwidth Frequency 19
1.7 Perception of Sound and Weighting Curves 23
1.8 Performance Descriptors in Sound Package Development Work 24
References 27
Additional Reading 28

CHAPTER 2
Instrumentation and Test Facilities 31

2.1 Performance Characteristics of Instruments 32
2.1.1 Frequency Response 32
2.1.2 Dynamic Range 32
2.1.3 Crest Factor 33
2.1.4 Response Time 34
2.2 Sound Measurements 34
2.2.1 Selection of a Microphone 35
2.2.1.1 Free-Field Microphone 35
2.2.1.2 Random Incidence Microphone 36
2.2.1.3 Pressure Microphone 36
2.2.2 Sound Level Meter 38
2.2.3 Sound Intensity Probe 39
2.2.4 Binaural Measurement System 39
2.2.5 Near-Field Acoustic Holography and Beamforming 40
2.3 Vibration Measurements 42
2.3.1 Accelerometers 44
2.3.2 Impedance Head 46
2.3.3 Laser Vibrometer 47
2.4 Test Facilities 48
2.4.1 Reverberation Room 48
2.4.1.1 Diffusers 50
2.4.2 Anechoic or Hemi-anechoic Room 51
2.4.2.1 Wedge Absorber 53
2.4.2.2 Flat Panel Absorber 54
References 56
Additional Reading 57

CHAPTER 3
Hearing Parameters 59

3.1 Hearing Sound 60
3.2 Equal Loudness Level Contour 62
3.2.1 Loudness Level (Phon) 63
3.2.2 Loudness (Sone) 64
3.3 Loudness of Complex Sounds 64

3.4 Additional Metrics 66
3.4.1 Sharpness 66
3.4.2 Booming 67
3.4.3 Roughness and Fluctuation Strength 68
3.5 Articulation Index 68
References 70

CHAPTER 4
Vehicle Noise Sources and Solutions 73

4.1 Vehicle Noise Sources 73
4.1.1 Propulsion System Noises Related to ICE Vehicles 74
4.1.1.1 Engine Noise 74
4.1.1.2 Transmission Noise 75
4.1.1.3 Cooling System 77
4.1.1.4 Intake Noise 78
4.1.1.5 Exhaust Noise 78
4.1.2 Propulsion System Noises Related to EVs 78
4.1.2.1 Motor Noise 79
4.1.2.2 Gear Reduction System Noise 80
4.1.2.3 Inverter Noise 80
4.1.3 Brake Noise 80
4.1.4 Road Noise 82
4.1.5 Tire Noise 83
4.1.6 Wind Noise 85
4.1.6.1 Wind Flutter 85
4.1.6.2 Windrush 85
4.1.7 Relative Spectral Distribution between ICE and EV 86
4.2 Some Specialty Noises 86
4.2.1 Climate Control (HVAC) Noise 86
4.2.2 Power Accessory Noise 88
4.3 The Noise System 88
4.3.1 Source-Path-Receiver System 90
4.4 Noise Control Design Approach: Source, Path, and Receiver 92
4.4.1 Noise Control at the Source 93

4.4.2 Noise Control along the Path 94
4.4.2.1 Materials for Airborne Noise Control 94
4.4.2.2 Materials for Structure-Borne Noise Control 95
4.4.3 Noise Control at the Receiver 97
References 97
Additional Reading 98

CHAPTER 5
Sound Absorber 101

5.1 Sound Absorption Materials and Their Applications 102
5.1.1 Typical Materials 102
5.1.2 Typical Absorber Applications 102
5.2 Acoustical Descriptor of an Absorber 103
5.2.1 Sound Absorption Coefficients 105
5.2.1.1 Normal Incidence Sound Absorption Coefficient 105
5.2.1.2 Random Incidence Sound Absorption Coefficient 106
5.2.1.3 Statistical (Energy) Sound Absorption Coefficient 106
5.3 How Does It Work 106
5.3.1 Various Factors Effecting Sound Absorption 107
5.4 Particle Velocity and Thickness 110
5.4.1 Thickness, Density, and Air Gap 111
5.5 How Sound Is Absorbed 113
5.5.1 Porosity 113
5.5.2 Airflow Resistivity 114
5.5.3 Tortuosity 115
5.5.4 Viscous Length 116
5.5.5 Thermal Length 117
5.5.6 Predicting Sound Absorption Performance 117
5.6 Absorber Surface Treatment 118
5.6.1 Film 119
5.6.2 Film with an Opening: Helmholtz Resonator 122
5.6.3 Perforated Film with Absorber Backing 123
5.6.4 Scrim 125
References 128
Additional Reading 129

CHAPTER 6
Sound Barrier 131

6.1 Barrier Materials and Their Applications 132
6.1.1 Typical Materials 132
6.1.2 Typical Barrier Applications 132
6.2 Acoustical Descriptor of a Barrier 133
6.3 How Does It Work 134
6.3.1 Nonporous 135
6.3.2 Limp 135
6.3.3 Massive 136
6.4 Sound Transmission Loss Performance 136
6.4.1 Region I: Stiffness and Resonance-Controlled Region 136
6.4.2 Region II: Mass-Controlled Region 137
6.4.3 Region III: Coincidence and Stiffness-Controlled Region 138
6.5 Mass Law Performance of a Panel 140
6.5.1 Normal Incidence 142
6.5.2 Grazing Incidence 142
6.5.3 Random Incidence 142
6.5.4 Field Incidence 143
6.6 Sound Transmission Loss of Single Wall Constructions 146
6.7 Sound Transmission Loss of Double Wall Constructions 147
6.7.1 Coupled Mass Region 149
6.7.2 Double Wall Resonance Point 149
6.7.3 Transition Region 150
6.7.4 Intercept Point 150
6.7.5 Double-Wall Decoupled Region 151
6.8 Effect of Holes in a Barrier 151
6.9 Dissipative System 154
References 157
Additional Reading 158

CHAPTER 7
Vibration Damper 161

7.1 Damping Materials and Their Applications 162
7.1.1 Typical Materials 162
7.1.2 Typical Damper Applications 162

7.2 Acoustical Descriptor of a Damper 163
7.3 How Does It Work 167
7.3.1 Polymers 167
7.3.2 Viscoelasticity 168
7.3.3 Behavior of Viscoelastic Materials 170
7.3.4 How to Determine the Glass Transition Temperature 174
7.4 Damping Treatments 177
References 183
Additional Reading 184

CHAPTER 8
Case Studies 187

8.1 Engine Compartment Sound Package Treatments 190
8.2 Vehicle Interior Sound Absorption Treatments 193
8.2.1 Floor Carpet Pile 195
8.2.2 Headliner 195
8.2.3 Seats 199
8.3 Vehicle Interior Sound Insulation Treatments 201
8.3.1 Dashmat 201
8.3.1.1 Barrier Decoupler Dashmat 202
8.3.1.2 Dissipative Dashmat 202
8.3.2 Floor Carpet 204
8.3.2.1 Barrier Decoupler Floor Carpet 204
8.3.2.2 Dissipative Floor Carpet 205
8.3.3 Door System 206
8.3.4 Backlight Trim Panel 211
8.4 Vehicle Interior Vibration Treatments 212
8.4.1 Laminated Panels 213
8.4.2 Laminated Glass 217
8.5 Passthroughs 219
8.6 Noise Control Patches 222
8.7 Body Cavity Fillers 223
References 227

CHAPTER 9

Test Methods 231

9.1 Standards and Specifications 232
9.1.1 Standards 232
9.1.2 Specifications 232
9.2 Different Test Methods 233
9.3 Airflow Resistance Tests 233
9.4 Sound Absorption Tests 235
9.4.1 Normal Incidence Sound Absorption Test 236
9.4.1.1 Roving Microphone and Standing Wave Ratio Method 237
9.4.1.2 Two-Microphone Method 240
9.4.1.3 Results of Normal Incidence Sound Absorption Tests 242
9.4.2 Random Incidence Sound Absorption Test 242
9.4.3 Differences between Normal and Random Incidence Sound Absorption Tests 246
9.5 Sound Transmission Loss Tests 246
9.5.1 Normal Incidence STL Test 247
9.5.2 Field Incidence STL Test 249
9.5.2.1 Correlation Factor Based Measurement 249
9.5.2.2 Two Reverberation Room Based Measurement 251
9.5.2.3 Sound Intensity Based Measurement 252
9.5.3 IL Tests for Body Cavity Filler Materials 252
9.6 Vibration Damping Tests 253
9.6.1 Complex Modulus Test (Oberst Bar Test) 254
9.6.1.1 System Performance Based Measurement 255
9.6.1.2 Material Property Evaluation Based Measurement 257
9.6.2 Mechanical Impedance Test (CenterPoint Test) 258
9.7 A Few Other Material Testing Methods 260
9.7.1 Apamat and Acoustic Gravelometer 260
9.7.2 Panel Damping Measurement 260
9.8 Component Level Tests 264
9.8.1 Airborne Noise Test 264
9.8.2 Structure-Borne Noise Test 266
9.9 Vehicle Level Tests 266
9.9.1 Engine Noise Test 267
9.9.2 Road Noise Test 268
9.9.3 Wind Noise Test 269
References 269
Additional Reading 271

CHAPTER 10

Closing the Loop 273

10.1 Speed of Sound with Temperature, Humidity, and Barometric Pressure 273

10.2 Addition and Subtraction of Decibels 274
10.2.1 Mathematical Approach 275
10.2.2 Nomogram Approach 275
10.2.3 Shortcut Approach 275

10.3 Test Facilities 277
10.3.1 Facility Site Selection 277
10.3.2 Design Goals for Testing Needs and Requirements 277
10.3.3 Laboratory Layout and Dimensions 278
10.3.4 HVAC and Mechanical Equipment System Design 278

10.4 Designing a Reverberation Room 279
10.4.1 Cutoff Frequency 279
10.4.2 Schroeder Frequency 279
10.4.3 Room Dimensions 280
10.4.4 Normal Modes 281

10.5 Size of Anechoic and Hemi-anechoic Rooms 281

10.6 Reduced Frequency Nomogram 282

10.7 Some Thoughts on Statistical Energy Analysis 284

10.8 How to Develop Acoustic Targets for Sound Package Treatments 287

10.9 Testing of Passthroughs 287

References 288
Additional Reading 290

Index 291