

Contents

Acronyms	V
Operators	VII
Notation	VII
Symbols	VIII
Special Terms	X
1. Introduction	1
1.1. History	1
1.2. Scope	3
1.3. Outline	4
2. Fundamentals	5
2.1. Coordinate Systems	5
2.2. Basic Acoustics	6
2.2.1. Sound Field Equations	6
2.2.2. Point Sources, Reflection and Image Sources	7
2.2.3. Diffraction and Scattering	8
2.2.4. Directivity	9
2.3. Fourier Transform	11
2.3.1. Fourier Transform of Time Signals	11
2.3.2. Fourier Transform of Time Discrete Signals	12
2.3.3. Discrete Fourier Transform	13
2.4. Measurement Theory	14
2.4.1. Dirac Impulse	14
2.4.2. LTI-Systems	15
2.4.3. Measurement Chain	19
2.4.4. Ambient Noise	21
2.5. Measurement Signals	22
2.5.1. Sweeps	23
2.5.2. Perfect Sequences	31
2.5.3. Quasi-Parallel Sweeps	32
2.5.4. System Identification using Adaptive Filters	37

2.5.5. Orthogonal Expansion	42
2.6. Error Assessment	43
2.6.1. Deviation	43
2.6.2. Correlation	43
2.6.3. Vector 2-Norm	45
2.7. Room Acoustic Parameters	45
2.7.1. Reverberation Time	45
2.7.2. Early Decay Time	46
2.7.3. Early- and Late-Arriving Energy	47
2.7.4. Inter-Aural Cross Correlation	48
2.8. Geometric Room Acoustic Simulation Methods	48
2.8.1. Stochastic Ray Tracing	49
2.8.2. Image Source Model	52
3. Spherical Signal Processing	57
3.1. Spherical Wave Fields	57
3.1.1. Spherical Wave Equation	58
3.1.2. Associated Legendre Functions	59
3.1.3. Spherical Harmonics	61
3.1.4. Spherical Wave Spectrum	63
3.1.5. Spherical Bessel Functions	64
3.1.6. Boundary Value Problems of Spherical Wave Fields	65
3.2. Manipulation of Spherical Wave Fields	73
3.2.1. Rotation	73
3.2.2. Translation	76
3.3. Special Functions and Properties	78
3.3.1. Completeness and Dirac on a Sphere	79
3.3.2. Spherical Convolution	79
3.3.3. Addition Theorem	80
3.3.4. Cross-Correlation in the Spherical Wave Spectrum	80
3.3.5. Order Truncation	81
3.3.6. Order Low-Pass Filter	84
3.3.7. Vibrating Polar Cap	89
3.3.8. Discontinuities	91
3.4. Discretely Sampled Spherical Wave Fields	94
3.4.1. The Discrete Spherical Wave Spectrum	94
3.4.2. Matrix Formulations	95
3.4.3. Linear Equation Sensitivity and Error Propagation	96
3.4.4. Matrix Inversions	98

3.5.	Exact Spherical Sampling Schemes	106
3.5.1.	Hyper-Interpolation Sampling Scheme	106
3.5.2.	Quadrature Equiangular Sampling Scheme	107
3.5.3.	Gaussian Quadrature Sampling Scheme	109
3.6.	Not Exact Spherical Sampling Schemes	113
3.6.1.	Regular Equiangular Sampling Scheme	113
3.6.2.	HEALPix Sampling Scheme	114
4.	Source Directivity and Directional Room Impulse Responses	119
4.1.	Artificial Source Directivity Generation	121
4.1.1.	Adaption of Real Sources	121
4.1.2.	Spherical Wave Spectrum Domain Designed Sources	122
4.1.3.	Order Limitation	123
4.1.4.	Analysis of Generated Sources	129
4.2.	Simulation Settings and Parameters	135
4.2.1.	Simulation Methods	135
4.2.2.	Simulated Sources	135
4.2.3.	Simulation Rooms	136
4.3.	Validation	141
4.3.1.	Source Validation	141
4.3.2.	Room Model Verification	143
4.4.	Simulation Results	147
4.4.1.	Small Seminar Room	147
4.4.2.	Medium Concert Hall	148
4.4.3.	Large Auditorium	149
4.5.	Measurement Comparison	156
4.6.	Conclusion	157
5.	Directional Room Impulse Response Measurement	159
5.1.	fDRIR Measurement	159
5.2.	Directivity Measurement	161
5.2.1.	Common Directivity Measurement Errors	162
5.3.	Directivity Transformation	164
5.3.1.	Measurement Instrument Directivity	165
5.3.2.	Excitation Point Distribution	166
5.3.3.	Unwanted Order Compensation	166
5.3.4.	Directivity Basis Inversion	167
5.4.	Sequential fDRIR Synthesis Method	172
5.4.1.	Directional Room Impulse Response Measurement	172
5.4.2.	Temperature Drift in DRIR Measurements	174

Contents

5.4.3. Directivity and DRIR Measurement Signals	175
5.4.4. Directional Room Impulse Response Superposition	181
5.5. Directional Room Impulse Response Measurement Systems	187
5.5.1. Order-Frequency Target Range	187
5.5.2. Measurement Instrument Directivity	187
5.5.3. Excitation Point Distribution	188
5.5.4. MIMO Measurements	190
5.5.5. Application	191
5.6. Conclusion	193
6. Conclusion and Outlook	195
A. Simulation Material Coefficients	199
A.1. Small Seminar Room	199
A.2. Medium Concert Hall	201
A.3. Large Auditorium	203
Bibliography	205
CV	215
Publications	217
Acknowledgements	221