

Contents

<i>Preface</i>	vii
<i>Acknowledgments</i>	xv
1. Analysis and Synthesis of Musical Instrument Sounds	1
<i>James W. Beauchamp</i>	
1 Analysis/Synthesis Methods.....	2
1.1 Harmonic Filter Bank (Phase Vocoder) Analysis/Synthesis.....	3
1.1.1 Frequency Deviation and Inharmonicity.....	3
1.1.2 Heterodyne-Filter Analysis Method.....	5
1.1.2.1 Window Functions.....	5
1.1.2.2 Harmonic Analysis Limits.....	10
1.1.2.3 Synthesis from Harmonic Amplitudes and Frequency Deviations.....	12
1.1.3 Signal Reconstruction (Resynthesis) and the Band-Pass Filter Bank Equivalent.....	12
1.1.4 Sampled Signal Implementation.....	13
1.1.4.1 Analysis Step.....	14
1.1.4.2 Synthesis Step.....	17
1.1.4.2.1 Piecewise Constant Amplitudes and Frequencies.....	20
1.1.4.2.2 Piecewise Linear Amplitude and Frequency Interpolation.....	20
1.1.4.2.3 Piecewise Quadratic Interpolation of Phases.....	21
1.1.4.2.4 Piecewise Cubic Interpolation of Phases.....	23
1.2 Spectral Frequency-Tracking Method.....	26
1.2.1 Frequency-Tracking Analysis.....	27
1.2.2 Frequency-Tracking Algorithm.....	29
1.2.3 Fundamental Frequency (Pitch) Detection.....	33

1.2.4	Reduction of Frequency-Tracking Analysis to Harmonic Analysis	36
1.2.5	Frequency-Tracking Synthesis	37
1.2.5.1	Frequency-Tracking Additive Synthesis	37
1.2.5.2	Residual Noise Analysis/Synthesis	39
1.2.5.3	Frequency-Tracking Overlap-Add Synthesis	40
2	Analysis Results Using SNDAN	42
2.1	Analysis File Data Formats	43
2.2	Phase-Vocoder Analysis Examples for Fixed-Pitch Harmonic Musical Sounds	44
2.2.1	Spectral Centroid	45
2.2.2	Spectral Envelopes	50
2.2.3	Spectral Irregularity	55
2.3	Phase-Vocoder Analysis of Sounds with Inharmonic Partial	58
2.3.1	Inharmonicity of Slightly Inharmonic Sounds: The Piano	60
2.3.2	Measurement of Tones with Widely Spaced Partial: The Chime	62
2.3.3	Measurement of a Sound with Dense Partial: The Cymbal	66
2.3.4	Spectrotemporal Incoherence	67
2.3.5	Inverse Spectral Density: Cymbal, Chime, and Timpani	69
2.4	Frequency-Tracking Analysis of Harmonic Sounds	75
2.4.1	Frequency-Tracking Analysis of Steady Harmonic Sounds	75
2.4.2	Frequency-Tracking Analysis of Vibrato Sounds: The Singing Voice	75
2.4.3	Frequency-Tracking Analysis of Variable-Pitch Sounds	81
3	Summary	82
	References	86

2. **Fundamental Frequency Tracking and Applications to Musical Signal Analysis** 90

Judith C. Brown

1	Introduction to Musical Signal Analysis in the Frequency Domain	90
2	Calculation of a Constant-Q Transform for Musical Analysis	93
2.1	Background	93
2.2	Calculations	96
2.3	Results	

3	Musical Fundamental-Frequency Tracking Using a Pattern-Recognition Method	99
3.1	Background	99
3.2	Calculations	100
3.3	Results	101
4	High-Resolution Frequency Calculation Based on Phase Differences	103
4.1	Introduction	103
4.2	Results Using the High-Resolution Frequency Tracker	104
5	Applications of the High-Resolution Pitch Tracker	105
5.1	Frequency Ratios of Spectral Components of Musical Sounds	105
5.1.1	Background	106
5.1.2	Calculation	107
5.1.3	Results	107
5.1.3.1	Cello	108
5.1.3.2	Alto Flute	110
5.1.4	Discussion	110
5.2	Perceived Pitch Center of Bowed String Instrument Vibrato Tones	111
5.2.1	Background	111
5.2.2	Experimental Method	112
5.2.2.1	Sound Production and Manipulation	112
5.2.2.2	Listening Experiments	112
5.2.3	Results	113
5.2.3.1	Experiment 1: NonProfessional-Performer Listeners	113
5.2.3.2	Experiment 2: Graduate-Level and Professional Violinist Listeners	114
5.2.3.3	Experiment 3: Determination of JND for Pitch	114
6	Summary and Conclusions	116
	Appendix A: An Efficient Algorithm for the Calculation of a Constant-Q Transform	116
	Appendix B: Single-Frame Approximation—Calculation of Phase Change for a Hop Size of One Sample	117
	References	119
3.	Beyond Traditional Sampling Synthesis: Real-Time Timbre Morphing Using Additive Synthesis <i>Lippold Haken, Kelly Fitz, and Paul Christensen</i>	122
1	Introduction	122
2	Additive Synthesis Model	123
2.1	Real-Time Synthesis	124

2.2	Envelope Parameter Streams.....	125
2.3	Noise Envelopes.....	125
3	Additive Sound Analysis.....	125
3.1	Sinusoidal Analysis.....	125
3.2	Noise-Enhanced Sinusoidal Analysis.....	125
3.3	Spectral Reassignment.....	128
3.3.1	Time Reassignment.....	128
3.3.2	Frequency Reassignment.....	130
3.3.3	Spectral-Reassignment Summary.....	130
4	Navigating Source Timbres: Timbre Control Space.....	131
4.1	Creating a New Timbre Control Space.....	135
4.2	Timbre Control Space with More Control Dimensions.....	135
4.3	Producing Intermediate Timbres: Timbre Morphing.....	135
4.4	Weighting Functions for Real-Time Morphing.....	136
4.5	Time Dilation Using Time Envelopes.....	136
4.6	Morphed Envelopes.....	137
4.7	Low-Amplitude Partial.....	138
5	New Possibilities for the Performer: The Continuum Fingerboard.....	139
5.1	Previous Work.....	140
5.2	Mechanical Design of the Playing Surface.....	141
6	Final Summary.....	142
	References.....	142

4. A Compact and Malleable Sines+Transients+Noise Model for Sound 145

Scott N. Levine and Julius O. Smith III

1	Introduction.....	145
1.1	History of Sinusoidal Modeling.....	146
1.2	Audio Signal Models for Data Compression and Transformation.....	148
1.3	Chapter Overview.....	149
2	System Overview.....	150
2.1	Related Current Systems.....	150
2.2	Time-Frequency Segmentation.....	151
2.3	Reasons for the Different Models.....	151
3	Multiresolution Sinusoidal Modeling.....	152
3.1	Analysis Filter Bank.....	154
3.2	Sinusoidal Parameters.....	155
3.2.1	Sinusoidal Tracking.....	155
3.2.2	Masking.....	155
3.2.3	Sinusoidal Trajectory Elimination.....	157
3.2.4	Sinusoidal Trajectory Quantization.....	158
3.3	Switched Phase Reconstruction.....	158
3.3.1	Cubic-Polynomial Phase Reconstruction.....	160

3.3.2	Phaseless Reconstruction.....	160
3.3.3	Phase Switching.....	161
4	Transform-Coded Transients.....	161
4.1	Transient Detection.....	162
4.2	A Simplified Transform Coder.....	163
4.3	Time-Frequency Pruning.....	164
5	Noise Modeling.....	164
5.1	Bark-Band Quantization.....	165
5.2	Line-Segment Approximation.....	166
6	Applications.....	167
6.1	Sinusoidal Time-Scale Modification.....	170
6.2	Transient Time-Scale Modification.....	170
6.3	Noise Time-Scale Modification.....	170
7	Conclusions.....	170
8	Acknowledgment.....	171
	References.....	171
5.	Spectral Envelopes and Additive + Residual Analysis/Synthesis	175
	<i>Xavier Rodet and Diemo Schwarz</i>	
1	Introduction.....	175
2	Spectral Envelopes and Source-Filter Models.....	178
2.1	Source-Filter Models.....	178
2.2	Source-Filter Models Represented by Spectral Envelopes.....	181
2.3	Spectral Envelopes and Perception.....	184
2.4	Source and Spectrum Tilt.....	186
2.5	Properties of Spectral Envelopes.....	187
3	Spectral Envelope Estimation Methods.....	188
3.1	Requirements.....	190
3.2	Autoregression Spectral Envelope.....	190
3.2.1	Disadvantage of AR Spectral Envelope Estimation.....	193
3.3	Cepstrum Spectral Envelope.....	194
3.3.1	Disadvantages of the Cepstrum Method.....	196
3.4	Discrete Cepstrum Spectral Envelope.....	197
3.5	Improvements on the Discrete Cepstrum Method.....	200
3.5.1	Regularization.....	200
3.5.2	Stochastic Smoothing (the Cloud Method).....	200
3.5.3	Nonlinear Frequency Scaling.....	202
3.6	Estimation of the Spectral Envelope of the Residual Signal.....	204
4	Representation of Spectral Envelopes.....	205
4.1	Requirements.....	205
4.2	Filter Parameters.....	206

4.3	Frequency Domain Sampled Representation	206
4.4	Geometric Representation	207
4.5	Formants	208
4.5.1	Formant Wave Functions	208
4.5.2	Basic Formants	209
4.5.3	Fuzzy Formants	209
4.5.4	Discussion of Formant Representation	210
4.6	Comparison of Representations	210
5	Transcoding and Manipulation of Spectral Envelopes	211
5.1	Transcodings	211
5.1.1	Converting Formants to AR-Filter Coefficients	211
5.1.2	Formant Estimation	211
5.2	Manipulations	212
5.3	Morphing	212
5.3.1	Shifting Formants	213
5.3.2	Shifting Fuzzy Formants	214
5.3.3	Morphing Between Well-Defined Formants	215
5.3.4	Summary of Formant Morphing	215
6	Synthesis with Spectral Envelopes	216
6.1	Filter Synthesis	216
6.2	Additive Synthesis	217
6.3	Additive Synthesis with the FFT^{-1} Method	217
7	Applications	218
7.1	Controlling Additive Synthesis	218
7.2	Synthesis and Transformation of the Singing Voice	219
8	Conclusions	220
9	Summary	220
	Appendix: List of Symbols	221
	References	222

6. A Comparison of Wavetable and FM Data Reduction Methods for Resynthesis of Musical Sounds 228

Andrew Horner

1	Introduction	228
2	Evaluation of Wavetable and FM Methods	229
3	Comparison of Wavetable and FM Methods	231
3.1	Generalized Wavetable Matching	232
3.2	Wavetable-Index Matching	232
3.3	Wavetable-Interpolation Matching	234
3.4	Formant-FM Matching	236
3.5	Double-FM Matching	237
3.6	Nested-FM Matching	238
4	Results	240
4.1	The Trumpet	241

4.2	The Tenor Voice	243
4.3	The Pipa	245
5	Conclusions	245
	Acknowledgments	247
	References	247
7.	The Effect of Dynamic Acoustical Features on Musical Timbre	250
	<i>John M. Hajda</i>	
1	Introduction	250
2	Global Time-Envelope and Spectral Parameters	251
2.1	Saliency of Partitioned Time Segments	251
2.2	Relational Timbre Studies	258
2.2.1	Temporal Envelope	260
2.2.2	Spectral Energy Distribution	261
2.2.3	Spectral Time Variance	262
3	The Experimental Control of Acoustical Variables	263
4	Conclusions and Directions for Future Research	267
	References	268
8.	Mental Representation of the Timbre of Complex Sounds	272
	<i>Sophie Donnadieu</i>	
1	Timbre: A Problematic Definition	272
2	The Notion of Timbre Space	274
2.1	Continuous Perceptual Dimensions	274
2.1.1	Spectral Attributes of Timbre	274
2.1.2	Temporal Attributes of Timbre	281
2.1.3	Spectrotemporal Attributes of Timbre	283
2.2	The Notion of Specificities	285
2.3	Individual and Group Listener Differences	286
2.4	Evaluating the Predictive Power of Timbre Spaces	290
2.4.1	Perceptual Effects of Sound Modifications	290
2.4.2	Perception of Timbral Intervals	290
2.4.3	The Role of Timbre in Auditory Streaming	292
2.4.4	Context Effects	294
2.5	Verbal Attributes of Timbre	296
2.5.1	Semantic Differential Analyses	296
2.5.2	Relations Between Verbal and Perceptual Attributes or Analyses of Verbal Protocols	296
3	Categories of Timbre	297
3.1	Studies of the Perception of Causality of Sound Events	299
3.2	Categorical Perception: A Speech-Specific Phenomenon	301

3.2.1	Definition of the Categorical Perception Phenomenon.....	301
3.2.2	Musical Categories: Plucking and Striking vs Bowing.....	302
3.2.2.1	Are the Same Feature Detectors Used for Speech and Nonspeech Sounds?.....	303
3.2.2.2	Categorical Perception in Young Infants.....	304
3.2.2.3	The McGurk Effect for Timbre.....	305
3.2.3	Is There a Perceptual Categorization of Timbre?.....	306
4	Conclusions.....	312
	References.....	313
	<i>Index</i>	320