

Table of Contents

1. Introduction	1
1.1 Basic Physical Principles	1
1.2 Acoustical Waveform Examples	3
1.3 Speech Analysis and Synthesis Models	5
1.4 The Linear Prediction Model	10
1.5 Organization of Book	16
2. Formulations	18
2.1 Historical Perspective	18
2.2 Maximum Likelihood	20
2.3 Minimum Variance	23
2.4 Prony's Method	25
2.5 Correlation Matching	31
2.6 PARCOR (Partial Correlation)	32
2.6.1 Inner Products and an Orthogonality Principle	35
2.6.2 The PARCOR Lattice Structure	38
3. Solutions and Properties	42
3.1 Introduction	42
3.2 Vector Spaces and Inner Products	44
3.2.1 Filter or Polynomial Norms	46
3.2.2 Properties of Inner Products	47
3.2.3 Orthogonality Relations	48
3.3 Solution Algorithms	50
3.3.1 Correlation Matrix	51
3.3.2 Initialization	53
3.3.3 Gram-Schmidt Orthogonalization	54
3.3.4 Levinson Recursion	55
3.3.5 Updating $A_m(z)$	56
3.3.6 A Test Example	57
3.4 Matrix Forms	58
4. Acoustic Tube Modeling	60
4.1 Introduction	60
4.2 Acoustic Tube Derivation	61
4.2.1 Single Section Derivation	63
4.2.2 Continuity Conditions	65

4.2.3 Boundary Conditions	68
4.3 Relationship between Acoustic Tube and Linear Prediction	71
4.4 An Algorithm, Examples, and Evaluation	77
4.4.1 An Algorithm	78
4.4.2 Examples	80
4.4.3 Evaluation of the Procedure	82
4.5 Estimation of Lip Impedance	84
4.5.1 Lip Impedance Derivation	84
4.6 Further Topics	88
4.6.1 Losses in the Acoustic Tube Model	88
4.6.2 Acoustic Tube Stability	90
 5. Speech Synthesis Structures	92
5.1 Introduction	92
5.2 Stability	93
5.2.1 Step-up Procedure	94
5.2.2 Step-down Procedure	95
5.2.3 Polynomial Properties	98
5.2.4 A Bound on $ F_m(z) $	99
5.2.5 Necessary and Sufficient Stability Conditions	101
5.2.6 Application of Results	102
5.3 Recursive Parameter Evaluation	103
5.3.1 Inner Product Properties	103
5.3.2 Equation Summary with Program	110
5.4 A General Synthesis Structure	113
5.5 Specific Speech Synthesis Structures	117
5.5.1 The Direct Form	118
5.5.2 Two-Multiplier Lattice Model	118
5.5.3 Kelly-Lochbaum Model	121
5.5.4 One-Multiplier Models	123
5.5.5 Normalized Filter Model	123
5.5.6 A Test Example	126
 6. Spectral Analysis	129
6.1 Introduction	129
6.2 Spectral Properties	130
6.2.1 Zero Mean All-Pole Model	130
6.2.2 Gain Factor for Spectral Matching	130
6.2.3 Limiting Spectral Match	132
6.2.4 Non-uniform Spectral Weighting	134
6.2.5 Minimax Spectral Matching	136
6.3 A Spectral Flatness Model	139
6.3.1 A Spectral Flatness Measure	139
6.3.2 Spectral Flatness Transformations	141
6.3.3 Numerical Evaluation	142
6.3.4 Experimental Results	143
6.3.5 Driving Function Models	144

6.4 Selective Linear Prediction	146
6.4.1 Selective Linear Prediction (SLP) Algorithm	148
6.4.2 A Selective Linear Prediction Program	149
6.4.3 Computational Considerations	150
6.5 Considerations in Choice of Analysis Conditions	151
6.5.1 Choice of Method	151
6.5.2 Sampling Rates	153
6.5.3 Order of Filter	154
6.5.4 Choice of Analysis Interval	156
6.5.5 Windowing	157
6.5.6 Pre-emphasis	158
6.6 Spectral Evaluation Techniques	159
6.7 Pole Enhancement	161
7. Automatic Formant Trajectory Estimation	164
7.1 Introduction	164
7.2 Formant Trajectory Estimation Procedure	165
7.2.1 Introduction	165
7.2.2 Raw Data from $A(z)$	167
7.2.3 Examples of Raw Data	169
7.3 Comparison of Raw Data from Linear Prediction and Cepstral Smoothing	172
7.4 Algorithm 1	176
7.5 Algorithm 2	180
7.5.1 Definition of Anchor Points	181
7.5.2 Processing of Each Voiced Segment	181
7.5.3 Final Smoothing	183
7.5.4 Results and Discussion	184
7.6 Formant Estimation Accuracy	185
7.6.1 An Example of Synthetic Speech Analysis	185
7.6.2 An Example of Real Speech Analysis	187
7.6.3 Influence of Voice Periodicity	188
8. Fundamental Frequency Estimation	190
8.1 Introduction	190
8.2 Preprocessing by Spectral Flattening	191
8.2.1 Analysis of Voiced Speech with Spectral Regularity	191
8.2.2 Analysis of Voiced Speech with Spectral Irregularities	193
8.2.3 The STREAK Algorithm	197
8.3 Correlation Techniques	199
8.3.1 Autocorrelation Analysis	200
8.3.2 Modified Autocorrelation Analysis	201
8.3.3 Filtered Error Signal Autocorrelation Analysis	203
8.3.4 Practical Considerations	206
8.3.5 The SIFT Algorithm	206

9. Computational Considerations in Analysis	212
9.1 Introduction	212
9.2 Ill-Conditioning	213
9.2.1 A Measure of Ill-Conditioning	214
9.2.2 Pre-emphasis of Speech Data	216
9.2.3 Prefiltering before Sampling	216
9.3 Implementing Linear Prediction Analysis	217
9.3.1 Autocorrelation Method	217
9.3.2 Covariance Method	219
9.3.3 Computational Comparison	220
9.4 Finite Word Length Considerations	222
9.4.1 Finite Word Length Coefficient Computation	223
9.4.2 Finite Word Length Solution of Equations	224
9.4.3 Overall Finite Word Length Implementation	225
 10. Vcoders	227
10.1 Introduction	227
10.2 Techniques	229
10.2.1 Coefficient Transformations	229
10.2.2 Encoding and Decoding	233
10.2.3 Variable Frame Rate Transmission	235
10.2.4 Excitation and Synthesis Gain Matching	239
10.2.5 A Linear Prediction Synthesizer Program	242
10.3 Low Bit Rate Pitch Excited Vcoders	245
10.3.1 Maximum Likelihood and PARCOR Vcoders	246
10.3.2 Autocorrelation Method Vcoders	249
10.3.3 Covariance Method Vcoders	255
10.4 Base-Band Excited Vcoders	260
 11. Further Topics	263
11.1 Speaker Identification and Verification	263
11.2 Isolated Word Recognition	265
11.3 Acoustical Detection of Laryngeal Pathology	267
11.4 Pole-Zero Estimation	271
11.5 Summary and Future Directions	275
 References	278
Subject Index	285