

Advanced Phase-Lock Techniques

Contents

<i>Preface</i>	<i>xvii</i>
Chapter 1	
<i>Phase-Locked Systems—A High-Level Perspective</i>	1
1.1 Phase-Locked Loop Basics	1
1.1.1 Some PLL History	2
1.2 Continuous-Time Control System Perspective for PLLs (High SNR)	2
1.3 Time-Sampled PLL Systems (High SNR)	8
1.4 Estimation Theoretic Perspective (Low SNR) for PLLs	14
1.4.1 PLL as a Minimum Mean-Square-Error (MMSE) Estimator	17
1.4.2 PLL as a Maximum-Likelihood (ML) Estimator	18
1.4.3 PLL as a Maximum A Posteriori (MAP)-Based Estimator	19
1.4.4 Performance Limits from the Cramer-Rao Bound	21
1.4.5 Optimal Mean-Square-Error Tracking: Kalman Filtering	22
1.5 Summary	23
References	25
Selected Bibliography	26
Chapter 2	
<i>Design Notes</i>	27
2.1 Summary of Classic Continuous-Time Type-2 Second-Order PLL Design Equations	27
2.2 Continuous-Time Type-2 Fourth-Order PLLs	40
2.3 Discretized PLLs	40
2.3.1 Integration Methods	40
2.3.2 Closed-Form Discrete-Time PLL Solutions	42
2.3.3 Higher-Order Differentiation Formulas.....	44
2.4 Hybrid PLLs Incorporating Sample-and-Holds	45
2.4.1 Ideal Type-1 with Zero-Order Sample-and-Hold	45
2.4.2 Ideal Type-2 with Zero-Order Sample-and-Hold	46
2.5 Communication Theory	47
2.5.1 Graphical Bit Error Rate and Symbol Error Rate Results	49
2.5.2 BPSK Bit Error Rate	49
2.5.3 QPSK Bit Error Rate	50
2.5.4 16-QAM Symbol Error Rate	51
2.5.5 64-QAM Symbol Error Rate	52

2.5.6 256-QAM Symbol Error Rate	53
2.5.7 8-PSK Symbol Error Rate	54
2.5.8 16-PSK Symbol Error Rate	55
2.6 Spectral Relationships	56
2.7 Trigonometry	58
2.8 Laplace Transforms.....	59
2.9 z-Transforms	60
2.10 Probability and Stochastic Processes	62
2.11 Numerical Simulation.....	64
2.11.1 DSP Windows	66
2.11.2 Polynomial-Based Interpolation	67
2.11.3 Raised-Cosine-Based Interpolation	68
2.11.4 Fourth-Order Runge-Kutta Numerical Integration	68
2.12 Calculus.....	68
2.13 Butterworth Lowpass Filters	69
2.14 Chebyshev Lowpass Filters.....	69
2.15 Constants	70
References.....	70
 Chapter 3	
<i>Fundamental Limits</i>	<i>71</i>
3.1 Phase Modulation and Bessel Functions.....	71
3.2 Hilbert Transforms.....	73
3.3 Cauchy-Schwarz Inequality	78
3.4 RF Filtering Effects on Frequency Stability.....	78
3.5 Chebyshev Inequality	81
3.6 Chernoff Bound.....	81
3.7 Cramer-Rao Bound	83
3.7.1 CR Bound for Sine Wave in AWGN.....	85
3.7.2 Phase Estimation for Sine Wave in AWGN	89
3.7.3 CR Bound for Bit-Time Estimation.....	89
3.8 Eigenfilters (Optimal Filters).....	90
3.9 Fano Broadband Matching Theorem.....	93
3.10 Leeson-Scherer Phase Noise Model.....	94
3.11 Thermal Noise Limits	94
3.12 Nyquist Sampling Theorem	95

3.13 Paley-Wiener Criterion	97
3.14 Parseval's Theorem	97
3.15 Poisson Sum.....	97
3.16 Time-Bandwidth Product.....	98
3.16.1 Gabor Limit for Deterministic Signals	98
3.16.2 Time-Frequency Resolution for Deterministic Signals	99
3.16.3 Time-Frequency Resolution Limits for Stochastic Signals	99
3.17 Matched-Filters for Deterministic Signals in Additive White Gaussian Noise (AWGN).....	100
3.18 Weak Law of Large Numbers.....	101
References.....	103
Appendix 3A: Maximum-Likelihood Frequency Estimator	104
Appendix 3B: Phase Probability Density Function for Sine Wave in AWGN	105
Chapter 4	
Noise in PLL-Based Systems.....	109
4.1 Introduction.....	109
4.2 Sources of Noise	109
4.2.1 Semiconductor Noise Sources	109
4.2.2 Quantization Noise	116
4.2.3 Other Sources of Noise.....	118
4.3 Power Spectral Density Concept for Continuous-Time Stochastic Signals.....	118
4.4 Power Spectral Density for Discrete-Time Sampled Systems.....	120
4.4.1 Example Results for Time-Sampled Noise.....	121
4.4.2 DAC and ADC Quantization Noise.....	124
4.4.3 Power Spectral Densities Refinements	125
4.4.4 Windowing Functions for Power Spectral Density Estimation	125
4.4.5 Stationary Versus Cyclostationary Processes	131
4.5 Phase Noise First Principles.....	131
4.5.1 Discrete Spurious Contaminations	131
4.6 Random Phase Noise	132
4.6.1 Phase Noise Spectrum Terminology	135
4.6.2 Time-Domain Phase Noise Terminology	138
4.6.3 Modeling Phase Noise Processes	141
4.7 Noise Impression on Time and Frequency Sources	142
4.7.1 Noise Equipartition with AM and PM Noise	142
4.7.2 Noise in Linear Two-Port Networks	142
4.7.3 Noise in Dividers.....	145
4.7.4 Macroscopic Noise Modeling in PLLs	146
References.....	148

Appendix 4A: Review of Stochastic Random Processes	150
4A.1 Wide-Sense Stationarity	151
4A.2 Probability Density Functions	151
4A.3 Characteristic Function.....	154
4A.4 Cumulative Probability Distribution Function	155
4A.5 Creation of Sample Sequences Exhibiting an Arbitrary Probability Density	155
4A.6 Power Spectral Density	156
4A.7 Linear Filtering of WSS Processes	157
4A.8 Equivalent Noise Bandwidth	158
References	158
Appendix 4B: Accurate Noise Modeling for Computer Simulations	158
4B.1 Noise Modeling for $1/f^\alpha$ Processes with $0 < \alpha < 2$	159
References	166
Appendix 4C: Creating Arbitrary Noise Spectra in a Digital Signal Processing Environment	167
References	170
Appendix 4D: Noise in Direct Digital Synthesizers	171
4D.1 Traditional DDS General Concepts	171
4D.2 Phase Truncation and Related Spurious Effects	173
4D.3 DDS Output C/N	173
References	174
Chapter 5	
System Performance	175
5.1 System Performance Overview	175
5.2 Integrated Phase Noise	176
5.3 Local Oscillators for Receive Systems	176
5.3.1 Close-In Phase Noise Effects	179
5.3.2 Large Frequency Offset Phase Noise Effects	183
5.4 Local Oscillators for Transmit Systems	186
5.4.1 Close-In Phase Noise Effects	186
5.4.2 Large Frequency Offset Phase Noise Effects	187
5.5 Local Oscillator Phase Noise Impact on Digital Communication Error Rate Performance	188
5.5.1 Uncoded BPSK Bit Error Rate Performance	189
5.5.2 Uncoded QPSK Bit Error Rate Performance.....	190
5.5.3 Symbol Error Rate for Square QAM Signal Constellations	190
5.5.4 Phase-Modulated Signals M -PSK	194
5.6 Phase Noise Effects on OFDM Systems	197
5.6.1 Channel Estimation Errors Due to Phase Noise	201
5.7 Phase Noise Effects on Spread-Spectrum Systems	205

5.8 Phase Noise Impact for More Advanced Modulation Waveforms	205
5.8.1 Euclidean Distance Measures	205
5.8.2 Forward Error Correction Coding Benefits	207
5.9 Clock Noise Impact on DAC Performance	207
5.10 Clock Noise Impact on ADC Performance	209
5.10.1 ADC Example with Rectangular Interfering Spectrum	210
References	212
Appendix 5A: Image Suppression and Error Vector Magnitude	212
Appendix 5B: Channel Capacity and Cutoff Rate	214
5B.1 Channel Capacity	215
References	222
 Chapter 6	
<i>Fundamental Concepts for Continuous-Time Systems</i>	223
6.1 Continuous Versus Discrete Time	223
6.2 Basic Continuous-Time Phase-Locked Loops	223
6.3 Additional Results for the Ideal Type-2 PLL	228
6.3.1 Natural Frequency ω_n	228
6.3.2 Damping Factor	232
6.4 Loop Filters	233
6.4.1 Single-Ended Versus Differential	234
6.5 More Complicated Loop Filters	235
6.5.1 One Additional Real Pole in Loop Filter	235
6.5.2 Additional RC Lowpass Filter Section	240
6.5.3 Cascading Two RC Lowpass Sections	243
6.6 Type-3 PLL	244
6.6.1 Close Equivalence for the Type-3 PLL with the Ideal Type-2 PLL	246
6.7 Haggai Constant Phase Margin Loop (9 dB per Octave)	251
6.8 Pseudo-Continuous Phase Detector Models	259
6.8.1 Tri-State Voltage-Based Charge-Pump	259
6.8.2 Tri-State Charge-Pump Detector—Current-Based	263
6.8.3 Zero-Order Sample-and-Hold	266
6.8.4 Digital Feedback Dividers	268
6.8.5 Modeling Time Delays in Continuous Systems	270
6.9 Stability Analysis	272
6.9.1 Nyquist Stability Criterion	272
6.9.2 Measures of System Stability: Gain and Phase Margins	273
6.10 Transient Response Evaluation for Continuous-Time Systems	274
6.10.1 Exact Method—Partial Fractions	275
6.10.2 Exact Method—System of Differential Equations	276
6.10.3 Exact Method—State-Transition Matrix Method	278

6.10.4 Exact Method—Corrington	279
6.10.5 Approximate Method—Integration Formula Substitution.....	281
6.10.6 Approximate Method—Line Integration.....	281
6.10.7 Approximate Method—FFT.....	281
6.10.8 Approximate Method—Poisson Sum.....	282
6.10.9 Approximate Method—Companion Models	282
References.....	283
Appendix 6A: Simplification of Linear Systems	284
References.....	286
Appendix 6B: Bandwidth Considerations for Continuous-Time Modeling of Time-Sampled Systems.....	287
6B.1 Appearance of $\exp(-sT_s/2)$ Factor.....	290
6B.2 Pole-Zero Excess and the Poisson Sum Formula.....	290
Reference	290
Appendix 6C: Christiaan Huygens and Phase-Locked Pendulum Clocks	293
Appendix 6D: Admittance Matrix Methods for Analyzing Complex Loop Filters ...	293
Chapter 7	
<i>Fundamental Concepts for Sampled-Data Control Systems</i>	<i>295</i>
7.1 Sampled Signal Basics	295
7.2 Relationships Between Continuous-Time and Discrete-Time Signal Representations.....	296
7.2.1 Additional Insights for Sampled Signals	297
7.3 Sampled-Time PLL.....	300
7.4 Stability Assessment for Sampled Systems.....	303
7.5 Time-Domain Response.....	304
7.6 Closed-Form Results for Sampled PLLs	305
7.6.1 Ideal Type-1 with Sample-Hold	305
7.6.2 Ideal Type-2 PLL with Sample-Hold	309
7.6.3 Type-2 Third-Order with Charge-Pump Phase Detector	313
7.6.4 Type-2 Fourth-Order with Charge-Pump Phase Detector	317
7.7 Pseudo-Continuous Versus Sampled System Analysis.....	319
7.8 Noise in Sampled Systems	320
7.8.1 Reference-Referred Noise	321
7.8.2 VCO-Referred Noise	324
References.....	325
Appendix 7A: Additional Closed-Form Results for Sampled PLLs	326

Chapter 8

Fractional-N Frequency Synthesizers	327
8.1 A Brief History of Fractional-N Synthesis	327
8.2 Analog-Based Fractional-N Synthesis	333
8.3 Δ-Σ Modulator Fundamentals	333
8.3.1 Quantization	336
8.3.2 Oversampling Rate	337
8.3.3 Noise Shaping.....	337
8.3.4 Signal Transfer Function	341
8.3.5 Δ - Σ Modulator Stability	342
8.3.6 Phase Error Probability Density Functions.....	344
8.4 Δ-Σ Frequency Synthesis Architectures	346
8.4.1 Single-Stage Δ - Σ Modulator Architectures	346
8.4.2 Multi-Stage Modulator Architectures	355
8.5 Single-Bit Versus Multiple-Bit Output Δ-Σ Modulators	359
8.6 Combating Discrete Spurious Tones	363
8.6.1 Spur Reduction Using Dithering	364
8.6.2 Spur Reduction Using Chaos.....	364
8.6.3 Irrational Initial Condition.....	365
8.6.4 Limit-Cycles	365
8.7 Δ-Σ Fractional-N Caveats to Avoid	369
8.7.1 Load Pulling and Pushing on VCO	369
8.7.2 Time Delay Variations	369
8.7.3 Charge-Pump Nonlinearities	370
8.7.4 Loop Filter Requirements.....	376
8.8 Final Recommendations	377
References.....	377

Chapter 9

Oscillators	381
9.1 Linear Oscillator Theory.....	381
9.1.1 Control System Perspective.....	381
9.1.2 Negative-Resistance Oscillator.....	383
9.2 Oscillator Configurations.....	389
9.2.1 RC Oscillators	389
9.2.2 Ring Oscillators	394
9.2.3 Bridge Oscillators.....	395
9.2.4 LC Oscillators.....	403
9.2.5 Oscillator Summary.....	406
9.2.6 Oscillator ALC	408
9.2.7 Best Oscillator Design Practices.....	410
9.3 Oscillator Usage in Phase-Locked Loops.....	416

9.3.1 VCO Coarse-Tuning Methods.....	416
9.3.2 VCO Fine-Tuning Methods.....	417
9.3.3 VCO Gain Compensation.....	421
9.4 Oscillator Impairments	423
9.4.1 Load-Pulling.....	423
9.4.2 Injection-Locking	425
9.4.3 Oscillator-Pushing.....	426
9.4.4 Post-Tuning Drift	426
9.5 Classical Phase Noise Models.....	429
9.5.1 Leeson's Model	429
9.5.2 Haggai Phase Noise Model	430
9.5.3 Ring Oscillator Phase Noise Model.....	433
9.6 Nonlinear Oscillators and Noise	439
References.....	440
Selected Bibliography	442
 <i>Chapter 10</i>	
<i>Clock and Data Recovery</i>	<i>443</i>
10.1 Clock and Data Recovery Basics	443
10.2 Signaling Waveforms.....	444
10.3 Intersymbol Interference.....	447
10.3.1 Zero Intersymbol Interference	448
10.4 Bit Error Rate	451
10.5 Optimal Timing Recovery Methods.....	455
10.5.1 Cramer-Rao Bound Limits	455
10.5.2 Estimation Theory-Based Timing-Error Metrics.....	455
10.5.3 Hardware-Based Timing-Error Metrics.....	471
10.6 Bit Error Rate Including Time Recovery	476
10.6.1 Clock Recovery Using First-Order Markov Modeling	477
10.6.2 Computing Transition-Probabilities for CDR Applications	482
10.6.3 Mean-Time to First-Slip	486
10.6.4 Applying First-Order Markov Modeling to Real PLLs	488
10.6.5 Conventional Approach to Timing-Recovery Analysis.....	490
10.6.6 Connecting Phase Tracking Performance with CDR BER Performance	491
10.7 Final Thoughts	491
References.....	492
Appendix 10A: BER Calculation Using the Gil-Pelaez Theorem.....	493
References.....	494
<i>Acronyms and Abbreviations</i>	<i>495</i>
<i>List of Symbols.....</i>	<i>499</i>

<i>About the Author</i>	501
<i>Index</i>	503

