PHASELOCK TECHNIQUES

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Third Edition

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To Benjamin

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PREFACE

The first edition of this book was published in 1966 and the second in 1979. Phaselock was an unimaginably exotic subject in 1966, with limited applications and few practitioners. Now phaselock is a mature subject: myriads of phaselock loops are ensconced in the world's electronic devices; numerous applications include phaselock loops; large numbers of practitioners deal with phaselock. No other books on phaselock loops existed when the first edition was published, but more than 20 exist today. Why is a third edition justified at this time?

In 1966, a simple, short introduction to the basics of the subject was needed for an audience for whom phaselock was strange and new. Today, phaselock loops are firmly established in the mainstream of electronics engineering. Much new information on phaselock loops has accumulated over the years, and several topics once thought important have proved to be ephemeral. Experience has taught me that certain explanations would be better presented from revised viewpoints.

There is no need for another introductory text; that function is well served by a number of the books listed in Section 1.3 and probably others as well. Instead, this book reexamines the traditional phaselock topics in greater depth than previously. In addition, much new material has been included, some of it never before published. Examples of additions include revised and expanded material on transfer functions, two chapters related to phase noise, two chapters related to digital phaselock loops, a chapter on charge-pump phaselock loops, expanded material on phase detectors, and a chapter on anomalous phaselocking.

As in the earlier editions, only minimal space has been devoted to circuits. The book is concerned with underlying principles, which remain valid despite technology advances, not with implementations, which change drastically as technology changes. Several parts of the second edition have been omitted: the chapters on

optimization and synchronization, and the mathematical appendix. Formal optimization has not proved to be as important to design as was earlier anticipated; instead, a designer is much more likely to perform a trade-off among the few parameters available in a practical phaselock loop. The mathematical appendix has been omitted on the premise that the level of mathematics presented here should be comfortable for all electrical engineering graduates. Synchronization (recovery of carrier and clock from data signals), a major discipline of its own, was deemed to have grown too large to cover adequately in a book on phaselock loops. See Section 17.1 for a brief guide to synchronization.

Simulation is another absent topic. Information presented in several chapters is based on simulations, certain kinds of new data can be gathered only by simulation, and simulation is crucial for design and verification of integrated circuits. Nonetheless, the book does not tell how to conduct simulations of phaselock loops. That topic deserves a separate book of its own; it is too extensive to include here.

Many thousands of articles and books on phaselock have appeared worldwide over the years, far too many to cite individually. Although many pertinent references have been cited in the individual chapters of the book, it is not possible to discover every valuable publication written on each topic. Nor, after many years of work on the subject, is it possible always to remember who originated every technique that is presented. I apologize in advance to anyone who may have been slighted; the omission is not deliberate.

Several guidelines have been followed in selecting reference citations for each chapter: The reference is to an original work; wherever possible, the reference appeared in a public, archival publication; the reference treats lasting principles rather than transitory details of implementation. A reader will observe a preponderance of citations to IEEE publications and to books published in the United States. This choice reflects the omnipresence of IEEE publications and also the contents of my personal library.

I want to thank my many clients over the years who have afforded me the opportunities to learn so much about such a fascinating subject.

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NOTATION

A	Amplitude
B_i	Bandwidth (Hz) of an input bandpass filter
B_L	Noise bandwidth (Hz) of a PLL
b	Number of bits in a digital word
b	Ratio of frequency of a pole to frequency of a zero
f	Frequency (Hz)
f	Transform variable of Fourier transforms
f_c	Comparison frequency (Hz) at a phase detector
f_{ck}	Clock frequency (Hz)
f_m	Frequency (Hz) of modulation
f_s	Sampling frequency (Hz), $= 1/t_s$
Δf	Peak frequency deviation (Hz)
Δf	Frequency offset (Hz) from a carrier
δf	Frequency increment (Hz) in a quantized-tuning oscillator
D	Delay (sample intervals)
$E(f)$	$= E(s)\|_{s=j2\pi f}$
$E(s)$	Closed-loop error transfer function of a PLL
$F(s)$	Transfer function of a loop filter
FP$[x]$	Fractional part of x
$G(s)$	Open-loop transfer function of a PLL
$H(f)$	$= H(s)\|_{s=j2\pi f}$
$H(s)$	Closed-loop system transfer function of a PLL
Im$[x]$	Imaginary part of x
IP$[x]$	Integer part of x
i	Subscript denoting "input"

i	An integer
$J_n(x)$	Bessel function of the first kind, order n, and argument x
j	$\sqrt{-1}$
K	Loop gain (rad/sec) of a PLL
K'	Normalized (dimensionless) loop gain, $= K\tau_2$
K_d	Gain (V/rad or A/rad) of a phase detector
K_{DC}	DC gain (rad/sec) of a PLL
K_i	Gain coefficient in analog PLL, $i = 1, 2, \ldots$
K_m	Gain (V^{-1}) of a multiplier
K_o	Gain (rad/sec·V) of a VCO
K_p	Gain (V/cycle) of a phase detector $= 2\pi K_d$
K_v	Gain (Hz/V) of a VCO, $= K_o/2\pi$
k	An integer
$L\{x\}$	Laplace transform of x
$\mathcal{L}(f)$	Normalized one-sided RF spectrum of a signal
m, M	An integer
$m(t)$	Modulation waveshape
N_0	One-sided spectrum (V^2/Hz) of white noise
n, N	An integer
$n(t)$	Noise voltage (V)
$n_c(t)$, $n_s(t)$	Baseband quadrature components of bandpass noise (V)
o	Subscript denoting "output" or "oscillator"
$P_{\mathrm{RF}}(f)$	Spectrum analyzer representation of the one-sided spectral density of an RF signal
P_s	Signal power (W)
p	Normalized Laplace variable, $= s\tau_2$
Q	Quality factor of a resonator
Q	Number of quantization levels
Q	Division ratio
$\mathrm{Re}[x]$	Real part of x
$r(t)$	Received signal
$s = \sigma + j\omega$	Transform complex variable of a Laplace transform
SNR	Signal-to-noise ratio
SNR_L	Signal-to-noise ratio in PLL noise bandwidth $2B_L$
t	Time (sec)
t_s	Sampling interval (sec), $= 1/f_s$
$u_c[n]$	Sample-n control input (dimensionless) to an NCO
$u_d[n]$	Sample-n output (dimensionless) of a digital phase detector
V_o	Peak output voltage (V) of a VCO
V_s	Peak voltage (V) of an input signal
$v_c(t)$, $V_c(s)$	VCO control voltage (V)
$v_d(t)$, $V_d(s)$	Phase detector output (V)
$W_{n'}(f)$	One-sided spectral density (rad^2/Hz) of the equivalent noise out of a phase detector

$W_{\theta no}(f)$	One-sided spectral density of the VCO phase (rad^2/Hz) due to the noise input to a PLL
$W_{\mathrm{RF}}(f)$	Measured one-sided spectral density (V^2/Hz) of an RF signal
$W_{vo}(f)$	Theoretical one-sided spectral density (V^2/Hz) of an oscillator output
$W_{\phi}(f)$	One-sided baseband spectrum (rad^2/Hz) of phase noise
z	Transform variable of z-transforms

Greek Symbols

α	Signal suppression factor (dimensionless) in a limiter
β	Modulation index (rad) of angle modulation
γ	Crest factor of a signal
$\varepsilon[n]$	Sample n of phase (cycles)
ζ	Damping factor of a second-order PLL
θ	Phase angle (rad)
θ_a	Steady-state phase error (rad) due to frequency-ramp input
θ_e	Phase error (rad) between an input signal and a VCO, $= \theta_i - \theta_o$
θ_i	Phase angle (rad) of an input signal
θ_{no}	Fluctuation of VCO phase (rad) caused by noise
θ_o	VCO phase (rad)
θ_v	Steady-state phase error (static phase error; loop stress) due to frequency offset
$\Delta\theta$	Phase deviation (rad)
$\Delta\theta$	Amplitude (rad) of phase step
κ	Loop gain (dimensionless) in a digital PLL
κ_d	Gain (rad^{-1}) of a digital phase detector
κ_i	Gain coefficient in a digital PLL, $i = 1, 2, \ldots$
κ_o	Gain (rad) of a NCO
κ_p	Gain (cycle^{-1}) of a digital phase detector, $= 2\pi\kappa_d$
κ_v	Gain (cycles) of an NCO, $= \kappa_o/2\pi$
Λ	Rate of change (rad/sec^2) of frequency, $= d\omega/dt$
ρ	Signal-to-noise ratio
σ_x	Standard deviation of x
τ	Timing error (sec)
τ	Delay (sec)
τ_i	Time constant (sec), $i = 1, 2, \ldots$
τ_2	Time constant (sec) of stabilizing zero in a type 2 PLL
$\phi(t)$	Phase noise (rad)
ψ	Angle (rad) around a unit circle
ψ	Normalized frequency (dimensionless), $= \omega t_s$
$\psi(s)$	Phase (rad) of a transfer function
ψ_{gc}	Normalized unity-gain crossover frequency $\omega_{gc}t_s$ of open-loop transfer function of sampled PLL, $\lvert G(e^{j\psi_{gc}})\rvert = 1$

ω	Angular frequency (rad/sec), $= 2\pi f$
ω_c	Comparison frequency (rad/sec) at a phase detector, $= 2\pi f_c$
ω_{gc}	Unity-gain crossover frequency (rad/sec) of open-loop transfer function, $\lvert G(j\omega_{gc})\rvert = 1$
ω_m	Modulating frequency (rad/sec)
ω_n	Natural frequency (rad/sec) of a second-order PLL
ω_π	Phase crossover frequency (rad/sec), $\text{Arg}[G(j\omega_\pi)] = -\pi$
$\Delta\omega$	Frequency offset or frequency step (rad/sec)
$\Delta\omega_H$	Hold-in limit (rad/sec) of a PLL
$\Delta\omega_L$	Lock-in limit (rad/sec) of a PLL
$\Delta\omega_P$	Pull-in limit (rad/sec) of a PLL