Index

actuators, 61, 65
aliasing, 49, 105, 159, 162, 165, 166, 168
analog multipliers, 14
analog-to-digital converter (ADC), 157–159
delay, 163
low-latency, 164
pipelined, 163
quantization, 159
successive-approximation, 163
analysis equation
discrete time Fourier transform, 49
Fourier series, 25
Fourier transform, 27
anti-aliasing filter, 159
aperiodic signals, 26
approximation, art of, 92

bandwidth ($\omega_h$)
second-order system, 98
Black’s formula, 69, 78, 80, 83
block diagrams, 55, 58
rules governing, 58

Bode plots, 126
accuracy in hand analysis, 126
and Nyquist plots, 127, 134
and phase margin, 138, 144
in discrete time, 146
of loop transmissions, 116
of pure delays, 142
boundary conditions, 155, 157

capacitance
physical meaning of, 2
capacitor, 1, 7, 11, 14
charged with imaginary voltage, 19
constitutive law, 2
discharge, 1, 2, 6
in superposition discussion, 15
in time invariance discussion, 15
voltage, 4
Cauchy’s principle of the argument, 119, 120, 122, 125
accounting, 123
change of variables, 160, 166, 167
characteristic equation, 9, 17, 20, 36
closed-loop, 81
compensation, 76, 77, 108
and poles in right-half plane, 76
and root locus, 81
definition of, 76
discrete time, 165, 169
dominant pole, 107, 108
gain vs. dynamics, 77
lag, 108–110
lead, 108, 110
PID, 111
complex conjugates, 20
complex numbers, 9
algebraic necessity of, 11
and Euler’s relation, 42
as vectors, 42
geometrical picture of, 42
in the Z-transform, 50
logarithm of, 9
polar form of, 9
subtraction of, 42
to describe purely real quantities, 11
complex plane, 42, 44, 45
conformal mapping, 117, 118
not to scale, 117
conjugate symmetry, 22, 128, 134
definition of, 21
contour integral, 35, 50, 165–167
convolution, 15
discrete time, 50
integral, 32, 47
sum, 32
cross-modulation, 18
cross-modulation terms, 14
cruise control system, 56, 61, 138
dynamics of, 63
damping
heavy, 94
light, 94
damping ratio (ζ), 96, 102
delay, 70
and convergence for adaptive predistorters, 171
digital filters, 170
D contour, 124, 125
curved part, 126
poles on, 152
damping
heavy, 94
light, 94
damping ratio (ζ), 96, 102
delay, 70
and convergence for adaptive predistorters, 171
digital filters, 170
D contour, 124, 125
curved part, 126
poles on, 152
damping
heavy, 94
light, 94
damping ratio (ζ), 96, 102
delay, 70
and convergence for adaptive predistorters, 171
digital filters, 170
D contour, 124, 125
curved part, 126
poles on, 152
damping
effectiveness of, 19
equality of, 21
eigenfunctions, 18
eigenvalues, 147, 150
eigenvectors, 19, 147, 150
eigencircles
definition of, 119
elements, 120
negative, 120
equilibrium
definition, 67
stable, 67
unstable, 67
equations
first-order, 8, 12
higher-order, 8
second-order, 8, 9
exponential
as eigenfunctions of LTI systems, 18, 47
convenience of, 21
Fourier transform of, 29
imaginary parts, 19
exponentials
and roots of characteristic equations, 17
differentiating, 17, 18
exponentials, complex, 19, 20, 23, 24, 28, 33,
47
time invariance, 15
CT vs. DT, 49
in continuous time, 49
in discrete time, 50
and frequency domain methods, 22
and phasors, 21
and transfer functions, 18
as eigenfunctions of LTI systems, 18, 47
convenience of, 21
Fourier transform of, 29
imaginary parts, 19
fourier transform of, 29
imaginary parts, 19
error
in feedback systems, 56
Euler’s relation, 9, 11, 20, 42
error
in feedback systems, 56
Euler’s relation, 9, 11, 20, 42
in difference equations, 49
in differential equations, 17
in ZIRs and ZSRs, 16
special place in LTI systems, 15, 17, 18, 28

feedback
fundamental advantage, 57
final value theorem, 44, 45
Fourier series, 23, 25
Fourier transform, 15, 27, 29, 33
and differential equations, 33, 34
and impulse response, 33
in discrete time, 49
inverse, 29, 46
meaning of, 23
of first derivative, 33
of higher-order derivatives, 34
vs. Laplace transform, 35, 36
frequency domain methods, 15

gain, 77, 86
and lag compensation, 108
and lead compensation, 108
and PID control, 112
and root locus, 78, 89
at high frequencies, 107, 109, 110
at low frequencies, 107, 109, 110
block, 59
DC, 71
frequency-independent, 77, 81
prioritized in different frequency ranges, 108
variation of in forward path, 71
gain reduction, 105–107
is bad, 107
granularity
in nature, 3
greed
and bandwidth, 137
Green’s functions, 15

harmonics, 24

impulse response, 15
continuous time, 32
contributions of each pole, 39
discrete time, 50
driven RC circuit, 37, 38
driving with train of impulses vs. continuous drive, 40
Fourier transform of, 33

linearity and time invariance, 47
multiple poles, 39
slow systems, 33
Z-transform of, 50
impulses, 29
and Laplace transform integration limits, 35
and slow-responding systems, 40
and unilateral Laplace transform, 35
behavior under integral, 30
continuous time, 30
discrete time, 50
Fourier transform of, 33
importance of area, 31
Laplace transform of, 37
shape, 30
superposition of time-delayed, 31, 32
inductor, 11
current, 11, 19
initial value theorem, 44, 46
integrals, 28
and calculus of residues, 35
and impulses, 30
convolution, 15
definition of, 27
integration by parts, 33, 34, 45
integrators, 67, 83
and dominant pole compensation, 107
discrete time, 170
intermodulation terms, 14

Laplace transform, 15, 35–37
and differential equations, 36
and impulse response, 37
bilateral, 19
definition, 35
inverse, 35, 37, 46
lower integration limit, 35
of unit step, 38
one-sided, 19
table of inverse transforms, 35, 46
vs. Fourier transform, 35
least-squares fit, 5
linear algebra, 147, 149
linear operator, 13
linear phase
and delay, 73
linearity, 13–18, 21, 32, 47
linearization, 5
loop transmission, 66, 82, 83
and delay, 70
and fundamental oscillation condition, 74
Index

loop transmission (Cont.)
definition of, 66
getting sign right, 174
importance of, 67, 69, 70
in closed-loop transfer function, 70
normalized, 152
sign convention, 66
magnitude peaking ($M_p$), 98
matrices, 147, 150
measurement limits, 30
memoryless system, 32
mixers, 14
mixing term, 14
multiplier, 60
music, 23
musicians, 23, 24
natural frequency ($\omega_n$), 96
noncausal system, 13
nonlinear systems, 13, 14, 51
approximated as linear systems, 51
nonlinearity, 14
numerical fit, 12
Nyquist plots, 125, 128, 134, 142
and Bode plots, 127
and delay, 142
degree of stability, 138, 139
half, 134
public address system, 179
singularities on the $j\omega$ axis, 152
Nyquist stability criterion, 116, 137
accounting, 132, 134
and Cauchy’s principle of the argument, 119
and conformal mapping, 117
and phase margin, 138, 144
definition, 123
harmony with root locus, 132
in discrete time, 146
lack of nuance, 138
summary, 125
oscillation
and the loop transmission, 74
as resonance, 155
fundamental condition, 74, 75, 107
wrong intuition, 151
public address system, 180
oscillators
and closed-loop poles, 70
definition, 74

Index

ideal, 81
unintended, 74
oversampling, 159, 165, 168
and real-time control, 163
overtones, 24
partial fraction expansion, 38, 39
partials, 24
percentage overshoot ($P_0$), 97
periodic signals, 23, 25, 26
phase margin, 116, 137, 138
advantages of, 138
and characteristics of second-order systems, 145
and degree of stability, 138
definition of, 143
reading off a Bode plot, 144
surprising result, 152
phase response
as a frequency-dependent delay, 73
phasors, 21, 22
technique, 21
PID control, 111
and poles and zeros, 112
pole-zero diagram, 75, 80, 81, 84, 91, 94
delay, 117
in discrete time, 100
poles, 36, 86
and compensation, 81
and impulse response, 39
and speed of response, 36, 38
and the D contour, 124
and the fundamental oscillation condition, 74
at the origin, 43, 86, 90, 112
closed-loop, 70, 79, 80, 83, 85, 89
conjugate pairs, 87, 90
definition of, 37
dominance of, 91, 93
dominant, 40, 91, 92, 107
effect on sinusoids, 43, 44
fast, 39
geometric view of, 40, 44, 83, 87
in pole-zero diagrams, 75
in right-half plane, 76, 90
lightly damped, 43
multiple, 39
number of, 86
of an oscillator, 74
on root locus, 80, 81
open-loop, 83
Index

real, 43
right-half plane (RHP), 39, 70, 75, 174
slow, 39
small \( k \) in root locus, 86
unmodeled, 106, 134
widely spaced, 89, 92, 126
polynomial, 4, 6, 17, 18, 39
and computational hardware, 5
equation, 17
expansions, 5
fitting, 5
roots of, 17
positive feedback, 132
predistortion
adaptive, 171
public address system, 175
pulses, rectangular, 31
quadratic formula, 9
residues, calculus of, 35
resistor, 1, 2
resolution limit, 30
resonance, 155, 157
Riemann sum, 27
right-half plane (RHP), 75, 93
and the Nyquist stability criterion, 122
definition of, 75
rise time \( (t_r) \), 97
root locus, 76, 79
and compensation strategy, 83, 89, 91, 105
and delay, 117
and numerical values of \( k \), 89
and phase response, 73
angle condition, 83, 89
arrow directions on loci, 85
definition, 79
drawing to scale, 89
first example, 81
in discrete time, 99, 101
limitations of, 137
list of rules, 85
magnitude condition, 83, 85
usefulness of, 81
roots
nondistinct, 17
of characteristic equation, 17, 20
of transfer function numerator, 39
repeated, 39
sampling, 159
fast, 163, 164
slow, 169
theoretical minimum rate, 165
second-order systems, 93
canonical transfer function, 96
forest vs. trees, 99
parameters to describe, 93
sensors, 61, 65, 105
settling time \( (t_{s2\%}) \), 97
shorthand, 3, 7, 10, 28, 51, 93, 99, 149
sinc function, 162–164
singularities, 37
geometric view of, 40
phase contribution, 72
sinusoids, 20–22, 29, 31, 33, 42, 43
and impulses, 33
and LTI systems, 21
and periodic signals, 23
and phasors, 21
and the Fourier transform, 30
complex, 25
effect of poles on, 43, 44
nondecaying, 43
of infinite extent, 152
purely real, 20
with very small separation, 30
speed of sound, 177
squarer, 13, 14
stability margins, 138
state variables, 11, 15–17, 148–150
step response, 39, 45
strategy
compensation, 83
conservative, 106
control, 105
summing junction, 59
superposition, 13–15, 22, 25, 31, 74, 155
synthesis equation
discrete time Fourier transform, 49
Fourier series, 25
Fourier transform, 27
Taylor expansion, 12
timbre, 24
time constant, 40
time invariance, 15, 32, 47
time step, 5, 40, 48
transfer function, 18, 23, 33
and frequency response, 26
and impulse response, 33
<table>
<thead>
<tr>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>transfer function (Cont.)</td>
</tr>
<tr>
<td>and step response, 38</td>
</tr>
<tr>
<td>discrete time, 49, 50</td>
</tr>
<tr>
<td>general form of, 39, 41</td>
</tr>
<tr>
<td>geometric view of singularities, 40, 42</td>
</tr>
<tr>
<td>of a driven RC circuit, 37, 38</td>
</tr>
<tr>
<td>poles of, 36</td>
</tr>
<tr>
<td>symbol for, 29</td>
</tr>
<tr>
<td>transform methods, 35</td>
</tr>
<tr>
<td>undersampling, 159</td>
</tr>
<tr>
<td>unit step function, 38</td>
</tr>
<tr>
<td>definition of, 37</td>
</tr>
<tr>
<td>Laplace transform of, 38</td>
</tr>
<tr>
<td>unity crossover frequency, 164</td>
</tr>
<tr>
<td>unity-gain feedback loop, 78</td>
</tr>
<tr>
<td>vectors, 41, 43, 44</td>
</tr>
<tr>
<td>as representing complex numbers, 42</td>
</tr>
<tr>
<td>subtraction of, 41</td>
</tr>
<tr>
<td>viscous resistance, 63</td>
</tr>
<tr>
<td>Z-transform, 15, 50, 167</td>
</tr>
<tr>
<td>inverse, 50, 166</td>
</tr>
<tr>
<td>of unit delay, 169</td>
</tr>
<tr>
<td>zero-input response (ZIR), 16, 20</td>
</tr>
<tr>
<td>zero-order hold (ZOH), 160</td>
</tr>
<tr>
<td>and half-sample delay, 162</td>
</tr>
<tr>
<td>and Laplace transform, 168</td>
</tr>
<tr>
<td>zero-state response (ZSR), 16, 18, 20–22, 34</td>
</tr>
<tr>
<td>zeros, 40, 42</td>
</tr>
<tr>
<td>and compensation, 81</td>
</tr>
<tr>
<td>and the D contour, 124</td>
</tr>
<tr>
<td>at infinity, 86</td>
</tr>
<tr>
<td>definition of, 39</td>
</tr>
<tr>
<td>dominant, 92</td>
</tr>
<tr>
<td>effect on sinusoids, 43</td>
</tr>
<tr>
<td>geometric view of, 40, 44, 83, 87</td>
</tr>
<tr>
<td>in PID control, 112</td>
</tr>
<tr>
<td>in pole-zero diagrams, 75</td>
</tr>
<tr>
<td>on root locus, 86</td>
</tr>
<tr>
<td>widely spaced, 126</td>
</tr>
</tbody>
</table>