Index

A-to-D converter, *see* Analog-to-digital (A-to-D) converter
Accumulator system, 418
Adder, 170
Adding a constant to a signal, 61–62
Advanced signal, 148n1
Alias, 107–108
  folded, 108
  principal, 108–110, 115, 118–119
Aliasing, 109, 111–112, 114, 121, 128–129, 132, 134, 224–227, 312
  (folding) distortion, 313
  due to under-sampling, 115–116
  folding due to under-sampling, 116–118
  time, 299, 302
AM broadcast system, 61
AM radio, 54, 58, 61, 96
Amplitude, 9, 12, 14, 23, 195
  complex, 25, 28–29
  function, 215–216
  and phase plots, 217
Amplitude modulation, 58–61
  beat note, 55–58
  spectrum, 59–60
Analog signals, 102–103, 109, 117, 139, 145, 225
Analog-to-digital (A-to-D) converter, 7, 11, 104, 151, 281
Angle function, 26, 86–89
Angle of complex number, 22
Angle function of cosine, 86
Argument of complex number, 22
Associative property of convolution, 182–183
Audio system, 7–8
Autocorrelation function, 258
Average value, 78, 149

Bandedges, 270–271
Bandlimited interpolation, 127
Bandlimited signal, 79, 102, 128, 247–250, 262, 311–312, 517
  continuous-time, 311–314
  ideal, 247–248
  reconstruction, 102
Bandpass filter, 263–264, 379–381
Band-reject filter, 264
Bandwidth, 60–61, 79
  3-dB, 448–450
  of pulse wave, 513, 516–517
  of spectrum, 60–61
Beat note, 55–58
Beating of tones in music, 57
Block-diagram notation, 170
Block diagrams, 7
  of FIR systems, 170–174, 354–355
  of IIR systems, 408–412

C-major scale, 83
  spectrogram, 84
Carrier
  frequency, 58, 61
  signal, 58
Cartesian form, 22–23, 29, 471 (*See also* Rectangular form)
Cascade connection, 182, 212, 361, 363
Cascaded LTI systems, 182–184, 212–214, 361–362
Causal filter, 151–152
Causality, 151
Centralized averager, 187
Center frequency, 55
Chirp signals, 85–89
Colon operator, 493–494
Commutative property of convolution, 166–167
Complex amplitude, 25, 28–29
Complex exponential, 22–24, 475,
  orthogonality, 285, 509–510
  signals, 23–25
Complex numbers, 22–23, 469–490
  addition, 29, 476–477
  conjugate, 477
  definition, 470–474
  division, 476–477
  multiplication, 476–477
  notation, 471–474
  represented as vector, 469
Complex powers, 484–485
Complex roots, 363, 439, 484–485
Conjugate of complex number, 27–28, 477
Conjugate symmetry property, 52, 65–66, 206
Continuous-time signals, 3, 5–6, 8–9, 148, 302, 307
  bandlimited, 311–312
  filtering sampled, 224–229
  Fourier series for, 309
  sample of, 103–104, 109
  sinusoidal signals, 105
  spectrum representation of, 110–111, 116, 128
Continuous-time systems, 147, 225
Continuous-to-discrete (C-to-D) converter, 6–7, 104, 128 (*See also* Sampling)
Convolution, 164
  associative property, 182
  commutative property, 166–167, 180–181
  computing the output of, 162
  derivation of, 179–180
  distributive property, 182
  identity element, 181
  of impulses, 181
  length of, 163
  and LTI systems, 178–182
  in MATLAB, 164
  MATLAB GUI for, 167
  sum formula, 179–180
  and the z-transform, 358–360
Cooley, 289n5
Cosine modulation property, 336
Cosine signals (waves), 9–10
Cubic spline interpolation, 124–125
Cutoff frequency of ideal filter, 260
Cyclic frequency, 15

DC, 17
  coefficient, 518–519
  component, 51, 62–63, 76, 78, 211, 515, 522, 524
  of Fourier series, 78–79
  power converters, 75–76
  term, 58, 100
  value, 62, 76, 78–80, 221, 517

Deconvolution, 364
Definition of z-transform, 348–350
Delay-compensated running-average filter, 186
Delayed signal, 171, 358
Delay system, 206–207
Delta function, 158
DeMoivre's formula, 485
Derivative, 13, 36
of angle function, 86–87
of Fourier series, 508–511
of FWRS, 80
of HWRS, 521
of sine plus DC, 64–65
of triangular wave, 528–529
DFT, *see* Discrete Fourier transform
Difference equation, 150
Difference frequency, 55, 57–58
Digital-to-analog (D-to-A) converter, 7, 112, 115, 121, 123, 126
Direct current, 17n3, 51n3
Direct form FIR structure, 171
Direct form I structure, 408–409
Direct form II structure, 409–411
Dirichlet form, 215n5, 215, 216
Discrete convolution evaluation of, 358
Discrete Fourier Series (DFS), 308–310
Discrete Fourier transform, 281–338
of complex exponential, 287–288
computation of, 288–289
conjugate symmetry of, 292–294
convolution property, 304–306
definition of, 283
frequency response plotting, 295–296
inherent periodicity of, 298–302
inverse, 284–285
L-point, 294
matrix form of, 289–290
negative frequencies of, 291–292
N-point, 294–295
pairs, 286
periodicity of, 298–301
properties, 290–294, 301–304
of real cosine signal, 296–297
of shifted impulse, 286
table of pairs, 307
table of properties, 308
time-dependent, 325–328
zero padding, 303
z-transform and, 367–369
Discrete-time cosine signal, 105, 109
Discrete-time filtering, 28
Discrete-time Fourier transform (DTFT), 239–280
bandlimited, 247–250
of a complex exponential, 253
convolution and, 255–257
definition of, 241
existence of, 245
forward, 241
frequency shift and, 253
inverse, 246–247, 250
L-point rectangular pulse, 243, 254
linearity of, 242, 252
periodicity of, 241
properties of, 251–259, 274
of a pulse, 243
of a right-sided exponential sequence, 244
of a shifted impulse sequence, 241–242
of a sinc function, 248–250
spectrum interpretation, 250–251
table of pairs, 273
table of properties, 273
time delay and, 252
uniqueness of, 243
of windows, 319–320
Discrete-time frequency ($\hat{\omega}$), 105
Discrete-time signal, 103
Discrete-time systems, 148–149
Discrete-to-continuous (D-to-C) converter, 7, 111–112, 115–116, 118, 120–129, 134, 224, 226–229
Discrete-to-continuous conversion, 121–127
interpolation with pulses, 121–127
oversampling in, 125–127
Domains, *see* Three domains
Doppler radar, 538–543
Dow-Jones industrial average, 184
DSP First toolbox, 84n15
DTFT, *see* Discrete-time Fourier transform (DTFT)
Dual-tone multi-frequency (DTMF) signals, 90
Dummy index of summation, 258, 285, 365
Dummy variable of integration, 75, 246

Echo, 539
Effective frequency response, 224–225
Elliptic filter, 454–456
Energy spectrum, 257
autocorrelation function and, 257–259
Envelope, 56–57, 287
Envelope detector, 59
Euler's formula, 23, 475–476
inverse, 27–28, 476
Factoring z-polynomials, 363
Fast Fourier Transform (FFT), 289, 323, 326, 328, 334–338
derivation of, 334–337
operation count of, 337
Feed-forward coefficients, 395–396
Feed-forward difference equation, 147, 171
Feedback coefficients, 395
Feedback systems, 394
FFT, *see* Fast Fourier Transform
Filter design, 265
cutoff frequency, 269
practical filters, 266
passband defined 268–269
passband ripple, 268
passband edge, 268
stopband defined 269–270
stopband ripple, 270
stopband edge, 269
transition width, 270
windowed sinc, 266–267
Filter length, 155
Filters (*See also* Filtering)
bandpass, 379–381
complex bandpass, 379
linear-phase, 384–386
practical bandpass, 381–384
Filtering, 8, 337
convolution property of, 257

discrete-time, 28
filter design and, 264–273
FIR, 156–158, 168, 184–187, 264–265
ideal bandpass, 263
ideal highpass, 262–263
ideal lowpass, 261–262
IIR, 395
interpretation of delay, 226–229
inverse, 364
running-sum, 214–223
of sampled continuous-time signals, 224–229
unit-step response, 165–166
Finite Fourier sum, 80, 283
Finite impulse response (FIR) system, 147, 394
Finite-length signal, 149
Finite number of sinusoids, 54
FIR filter, 154–156, 168, 184–187, 264–265
block diagrams for, 170–174
and convolution, 161
frequency response of, 195–196
implementation of, 169–170
FIR filtering, *see* FIR filter
examples of, 156–159, 184–187
First-difference system, 207–209
FM signals, 86 (*See also* Frequency modulation)
Folded aliases, 108
Folding frequency, 119
Fourier, Jean-Baptiste, 39
Fourier analysis, 75
full-wave rectified sine (FWRS), 75–80
half-wave rectified sine (HWRS), 521–524
pulse wave, 514–518
triangular wave, 518–521
Fourier analysis integral, 75, 507
Fourier series, 74–80, 507–543
approximation error, 80
coefficients, 75
convergence of, 531–538
DC value of, 78–79
derivation, 508–511
full-wave rectified sine, 75–80
Gibb's phenomenon, 535–536
half-wave rectified sine (HWRS), 521–524
operations on, 524–531
orthogonality, 285, 534
Parseval's theorem for, 533
pulse wave, 514–518
spectrum, 78–80
square wave, 515
synthesis equation, 250, 513
triangular wave, 518–521
Fourier series integral, 83, 307, 508–511
Fourier synthesis, 74–75, 79, 508
finite, 513
Fourier synthesis summation, 508
Fourier transform
discrete, *see* Discrete Fourier transform
discrete time, *see* Discrete-time Fourier transform (DTFT)
fast, *see* Fast Fourier Transform
short-time discrete, 326
Fourier transform pairs, 272–273, 307
Fourier transforms and LTI systems, 346
Frequency
cyclic, 15
instantaneous, 85–89
radian, 15
Frequency division multiplexing, 61
Frequency modulation (FM)
angle function, 86
chirp signal, 85–89
instantaneous frequency, 86
spectrogram of, 89
Frequency resolution, 330–333
Frequency response
of cascaded LTI systems, 212–214
effective, 224
graphical representation of, 206–223
formula for, 197
of an LTI FIR filter, 196
plotting the, 215–218
properties of, 203–206
of second-order IIR filter, 446–450
sinusoidal, of FIR systems, 195–197
steady-state and transient responses, 201–203
superposition and, 198–201
Frequency scaling, 112
Frequency selective filters, 259–264
Frequency shifting property, 58, 66
Doppler shift, 540–541
property, 253–254, 308, 529–531
Frequency-domain, 39, 51, 239–240
Frequency-domain approach, 201
Frequency-domain representation, 51, 239–240, 242, 246, 322–323
Full-wave rectified sine (FWRS), 75–80
finite synthesis of, 79–80
spectrum of, 78–80
Fundamental frequency, 67, 313
Fundamental period, 67, 76, 512, 526
of discrete-time sinusoid, 311–312

Gain, 196, 200, 210, 372, 382–383, 453
of LTI system, 196
Geometric series, 214, 243–244
Gibbs phenomenon, 535

Half-wave rectified sine (HWRS), 521
finite synthesis of, 523
Fourier series, 522
spectrum of, 524
Hamming, Richard, 265n9
Hamming window, 265–269
Hann, Julius von, 318n10
Hann window, 318–321
Harmonic frequency, 67
Hertz, Heinrich, 16n2
Hertz, unit of frequency, 16
Highpass filter, 207, 262–263

Ideal continuous-to-discrete (C-to-D) converter, 6–7, 104, 111–114, 128, 224, 227
Ideal discrete-to-continuous (D-to-C) converter, 7, 111–112, 120–129, 134, 224
Ideal filters, 259–264, 382
bandpass, 263–264
band-reject, 264
highpass, 262–263
lowpass, 260–262

Ideal reconstruction, 111–113
IIR digital filters, 394–456
  block diagrams for, 408–412
  definition, 395
  difference equation for, 395–396
  frequency response of, 420–423
  impulse response of, 399–401
  linearity and time invariance of, 398–399
  poles and zeros for, 412–416
  response to finite-length input, 401–402
  stability of, 416–420
  system function of, 405–408
Image smoothing example, 220–223
Imaginary part, 22
Implementation structures, 409
Impulse in MATLAB, 455
Impulse response, 159–161
  finite, 147
  first-order IIR system, 399–401
  unit, 158–161
Impulse response sequence, 159–161
Initial rest conditions, 397, 399
Inner product, 494–495
Instantaneous frequency, 86–89
Interpolation, 103, 112
  cubic spline, 124–125
  ideal bandlimited, 127
  linear, 20–21, 123–124
  with pulses, 121
  zero-order hold, 122–123
Interpretation of delay, 226–229
Inverse z-transform, 349
Inverse discrete Fourier transform (DFT), 284–286, 335
Inverse DTFT, 246–247, 250
Inverse Euler formulas, 27–28, 50, 55
Inverse filtering, 364

L-point rectangular window, 264, 318
L-point running averager, 227
L-point running sum filter, 214
L^{th} root of unity, 377 (*See also* roots of unity)
Left-sided exponential signal, 272
Line spectra, 52
Linear combination, 50, 54, 179, 240, 247, 351, 399
Linear FM signals, 86
Linear interpolation, 20
Linear phase filters, 207, 266–267, 384–386
Linear time-invariant (LTI) systems, 160, 174–178
Linearity, 147, 174, 176–178
  of DFT, 296–297, 308
  of DTFT, 242, 247, 252, 255, 274
  and time-invariant IIR filters, 398–399
  of z-transform, 351
Linearly swept frequency, 85–86
Local spectrum, 318, 323, 328
Lowpass filter, 209–211, 260–262, 454–456
LTI systems, 174–184, 212–214, 257, 353–354
  cascade, 182–184, 212–214
  causal, 417, 419
  convolution and, 178–180
  derivation of convolution sum, 179–180
  properties of, 175–177, 180–182

Magnitude, 22, 196–200, 207–208, 219
  of complex number, 22
  squared spectrum, 258
Main lobe, 217, 266, 320
MATLAB, 491–506
  array multiplication, 495
  colon operator, 493–494
  debugging, 501–502
  figure windows, 496
  functions, 498
  help command, 492
  M-file, 499–502
  multiple plots, 497
  phasors, demo, 33
  plotting, 496–497
  pointwise array operations, 495
  printing, 497
  programming constructs, 497
  reshape matrix, 447
  scripts, 498–499
  `spectrogram`, 83–84
  vectorizing, 504–505
  `zvect`, `zcat`, `zprint`, 488
MATLAB built-in functions, 498
MATLAB help, 492
MATLAB GUI
  `con2dis`, 120
  `dconvdemo`, 168
  `DLTIdemo`, 229
  `filterdesign`, 271–272
  `fourierseries`, 80
  `Sine Drill`, 18
  `zdrill`, 23, 479–480
MATLAB programming, 502–506
MATLAB scripts, 498–499
MATLAB variables, 492–496
Matrix multiplication, 494–495
MP3 compression, 7
Modulating signal, 59
Modulo-N arithmetic, 302
Multipath fading, 47–48
Multiplier, 169–170
Music notation, 81–82
Musical scale, 10

Narrowband spectrogram, 395
n-domain, 347–349, 351, 368
Negative frequency, 26, 28
Newton's second law, 35
Noise, 156
Noncausal filter, 152, 219
Nonlinear systems, 177
Non-periodic signal, 72–73
Normalized radian frequency, 15
Nulling, 237
Nulling filters, 372–373
Nyquist, Harry, 111n6
Nyquist rate, 111

Octave, 82
$\hat{\omega}$-domain, 347, 349
One-dimensional continuous-time system, 5
Orthogonality property, 285, 509–510
Outer product, 495
Output-signal, 5

Over-sampling, 114–115, 125–127

Parseval's Theorem, 257, 259, 537
Partial fraction expansion, 428
Passband, 268
Period, 10, 15–17, 67
Periodic signal, 54, 67–72
Periodicity of $H(e^{j\hat{\omega}})$, 205
PeZ GUI, 452–454
Phase, 9, 14
Phase change in complex amplitudes of spectrum
    delayed cosine, 64
    derivative of sine plus DC, 64–65
Phase shift, 24, 196
Phasor, 25
    addition, 28–34
    MATLAB demo of, 33
    rotating, 26–27
Physics of tuning fork, 34–37
Piano keyboard, 82
Pixel, 220
Plots and graphics, 496–497
Pointwise array operations, 495–496
Polar form, 22–23, 208–209, 217
    of complex number, 22–23, 472
    of complex roots, 439
Poles of $H(z)$, 369–376, 412–413
Pole-zero plot, 370–371
Polynomial division, 162n11
Polynomial multiplication, 164
Positive frequency, 26
Principal aliases, 110, 112, 115
Principal value, 19, 217
Principle of superposition, 176
Property of the spectrum representation, 61
Properties of z-transform, 358, 368, 428
Pulse Wave, 514
    Fourier series, 515
    spectrum of, 516
    finite synthesis of, 517–518
    time scaling of, 526–527
    sinusoidal multiplication of, 530

Radian frequency, 9, 15
Radix-2, 335
Rational function, 347, 353
Real part, 22, 131, 206, 471
Receiver, 540, 542
Reconstruction, 102–103, 111, 124–129, 134
    cubic spline, 124
    GUI, 120–121
    ideal, 127
    linear, 123
    spectrum view of, 112
    zero-order hold, 123n10
Rectangular form, 22, 31
    of complex number, 22, 471–472
Rectangular window, 264–265
Recursive filter, 394 (*See also* IIR digital filters)
Reducing modulo 2π, 19
Region of convergence, 353, 407
Resolution of the spectrogram, 322–323
Riemann integral, 251
Right-sided exponential signal, 244
Roots of unity, 485–486
Rotating disk, 133
Rotating phasor, 25–27
Running-average filter, 149–153
Running-average filtering, 156–158
    smoothing an image, 220–223
Running-sum filtering, 214–219

Sample spacing, 19–20
Sampling, 3–4, 6, 19–21, 102–105 (*See also* C-to-D conversion)
    aliasing and, 109
    bandlimited periodic signals, 311–314
    frequency-domain, 294–296
    oversampling, 114–115, 125–127
    reconstruction GUI, 120–121
    sinusoidal signals, 105–107
    spectrum view, 113–118
    under-sampling, 115–118
Sampling frequency, *see* Sampling rate
Sampling period, 3, 19, 103
Sampling rate, 104
Sampling theorem, 110–111, 128–129, 299
Sampler, 6
Scale factor, 61
Second-order IIR filters, 435–452
Shannon, Claude, 111n6
Shannon sampling theorem, 110–111, 122, 128–129
Shannon/Nyquist sampling theorem, 111
Short-time discrete Fourier transform, 326
Sidelobes, 216–217, 320–321, 516
Signal, 1–2
    continuous-time, 3
    cosine, 12–14
    discrete-time, 3, 5
    sine, 12–14
    speech, 1–4
    two-dimensional, 3–4
    video, 1–2, 4
Sinc function, 127, 248–250
Sinc signal, energy of, 258
Sine-cubed signal, 71–72
Sine and cosine functions, review of, 12–14
Sinusoidal amplitude modulation
    AM spectrum, 59–60
    amplitude modulation, 54, 58–59
    beat note waveform, 55–57
    concept of bandwidth, 60–61
    multiplication of sinusoids, 54
Sinusoidal response of FIR systems, 195–196
Sinusoidal steady-state component, 433
Sinusoid-in gives sinusoid-out, 194, 257
Sinusoids, 9
    period of, 10, 15–17
    phase and time-shift of, 17–19
    plotting of, 15, 19–21
    sampling, 19–21
    tuning fork experiment, 10–12
Sinusoids, spectrum of sum of, 50–54
    analysis *vs* synthesis, 53–54
    graphical plot, 52–53
    notation change, 52
Smoothing an image, 220–223
spectgr, 84n15

Specgram, 84
Spectral components, 50, 68
Spectral line, 52
Spectrogram, 81, 322–334
  analysis, 83–85, 281
  display of, 328
  frequency resolution in, 330–333
  interpretation of, 328–330
  of chirp, 85–87, 90, 119
  of a linear-FM signal, 89
  MATLAB, 333–334
  music notation and the, 81–83
  piano, 90
  of a sampled periodic signal, 307–317
  of simple sounds, 55, 90
Spectrum representation, 49–89
  adding signals, 62–63
  bandwidth of, 60–61
  complex amplitudes of, 64
  DC component, 51
  definition, 50n1, 51
  of a discrete-time signal, 109–110
  frequency shifting behavior, 65–66
  of full-wave rectified sine (FWRS), 78–80
  of half-wave rectified sine (HWRS), 524
  non-periodic signal, 72–73
  operations on, 61–67
  plot of, 52–53
  of a product, 55
  of a pulse wave, 516
  scaling or adding constant, 61–62
  of sum of sinusoids, 50–54
  of sum of two equal-amplitude sinusoids, 56
  time-frequency, 81–85
  of a triangular wave, 520
  two-sided, 51
Spectrum analysis of periodic signals, 314–317
Spectrum of discrete-time signal, 109–110
Square wave, 72, 515
  bipolar, 525
  zero-one, 525
Square-law system, 174–175
Squarer system, 5
Stability, 403
  general definition of, 403
  mathematical condition for, 403, 417, 419
  from pole location, 416
  region of convergence and, 418–420
  steady-state response and, 431–433
Stable systems, 416
Steady-state part, 202
Steady-state response, 431–435
Step response, 403
  first-order IIR system, 402–404
Stepped frequency, 83
Stopband, 269
Strobe, 129–134
  demonstration, 129–134
  spectrum interpretation, 133–134
Suddenly applied input, 201–202, 397, 399, 432–433, 435
Superposition, 358, 428
  frequency response, 198–201
  principle of, 176
  property of DTFT, 252, 274
  property of z-transform, 358, 428
Support of a sequence, 149, 154
Synthesis procedure, 53–54
Synthetic polynomial multiplication, 183, 214
Synthetic vowel, 68–70
System function $H(z)$
  of cascade, 361
  of FIR filter, 356
  of IIR filter, 405
Systems
  as building blocks, 7–8
  cascading, 361–363
  definition, 1
  discrete-time, 148–149
  FIR, 194–197
  IIR, 416–420, 436–440
  linear time-invariant, 174–184, 212–214, 257, 353–354
  mathematical representation of, 5–6
  unit-delay, 354

Three Domains
  for FIR, 347–348, 364–369
  for IIR, 425–426
  movie, 376–377
  PeZ GUI, 377, 387, 452–454
Time aliasing, 299, 302
Time-delay property of z-transforms, 351–352
Time-dependent discrete Fourier transform, 325–328 (*See also* Spectrogram)
Time-domain, 201
  chirp signal, 87
  convolution, 358
  DTFT, 273–274
  DFT, 304, 307–308
  operations, 61
  representation, 51, 53, 56, 75, 240, 349, 354
  response, 396–398
  signal, 110, 258
  of under-sampling, 117
Time-flip system, 175–176
Time–frequency spectrum, 81–85 (*See also* Spectrogram)
  analysis, 83–84
  stepped-frequency waveforms, 83
Time invariance, 175–176
Time shift (delay), 17–19
  effect on spectrum, 64
  property of DFT, 301–302
  property of DTFT, 252
  property of z-transform, 351–352
Time-windowing, 343
Transient response
  of FIR filter, 201–203
  of IIR filter, 433–435
Transition region, 202, 383
Transmitter, 83
Transposed form
  of FIR filter, 173
  of IIR filter, 411–412
Triangular wave, 518
  finite synthesis of, 520–521
  Fourier series, 519
  spectrum of, 520
Trigonometric identities, 14

Tukey, 289n5
Tuning fork, 10–12
  physics of, 34–37
Two-sided spectrum, 51

Unit circle, 366–367
Unit delay, 169, 352, 354
  operator, 169, 354
  property of the z-transform, 352
  system, 354
Unit impulse response, 159–161
Unit impulse sequence, 158–159
Unit impulse signal, *see* unit-impulse sequence
Unit-step, 165–166
Unstable, 403
  system, 416, 418

von Hann, Julius, 318n10
Vowel signal, *see* Synthetic vowel

Weighted running average, 153
Windowing, 264–266, 317–322
Writing a MATLAB function, 499

z-domain, 364–366, 368
`zdrill` GUI, 479
z-plane, 353, 358n4, 366–370
z-transform
  basic properties, 351–352
  convolution and the, 358–364
  definition, 348–350
  DFT and, 367–369
  domains, *see* Three Domains
  general formula, 352–353
  inverse, 349–350, 426–431
  linear systems and, 353–357
  linearity of, 351
  of FIR filter, 355
  of impulse response, 355–356
  as an operator, 358
  pair, 349
  poles and zeros, 369–377, 412–416
  polynomial roots, 356–358, 363
  properties, 368
  region of convergence, 353
  of a signal, 350
  of second-order filters, 435–446
  superposition property of, 358, 428
  table of, 427
  time-delay property of, 351–352
  unit circle and, 366–367
  z^{-1} operators, 354
Zero-order hold, 122–123
  interpolation, 122–123
  reconstruction, 123n10
Zero padding, 294–296
Zeros, 369–371
  of FIR linear-phase systems, 385–386
  of $H(z)$, 369–371