

# Index

- Adder, 639
- Additivity property, 73, 76
- Aliasing, 402
- Alternation theorem, 696
- Amplitude modulation, 66–67
- Amplitude response, 167–169, 170–171, 172
- Amplitude spectrum, 167–169, 170–171, 172
- Analog signals, 6
- Analog to digital (A/D) conversion, 649, 393, 526
- Aperiodic signals, 9, 193, 475
- Approximate bandwidth, 322
- Arithmetic overflow, 654
- Audio, 754
  - formats, 755
  - spectral analysis, 756
  - filtering, 759
  - compression, 765, 770
- Autocorrelation function, 748, 751
  
- Bandpass filter, 624, 688, 735
- Bandstop filter, 624, 691, 736
- Bandwidth, 322, 413, 539
  - approximate, 418
  - transition, 674, 676
- Baseband signal, 393
- Bilateral Laplace transform, 261, 262–266
- Bilateral z-transform, 567
- Bilinear transformation, 728–733
- Binary code, 412
- Bit, 9, 71, 415
- Block diagram, 62–63, 76, 307–311, 382, 385
- Block diagram representation, 63, 307–311
- Bode plots, 245–246, 250–251, 636
- Bounded-input bounded-output (BIBO)
  - stability, 88–90, 128–130, 298–305, 452, 601–606, 737–739
- Break frequency, *see* corner frequency
- Butterworth filter, 321, 328–338, 364, 718
- Butterfly operation, 556, 557
  
- Carrier, 67, 369
- Causal signal, 31, 266
- Causal system, 84–85, 93, 127, 136, 204, 665
- CCD camera, 415
- Characteristic equation, 107, 110, 273, 294, 346, 597
- Characteristic roots, 294–295
- Charge coupled device (CCD), 3–5
- Circular reflection, 442
- Compact disc (CD), 413
- Complex frequency, 28–31, 261, 306
- Complex frequency plane, 250, 271
- Complex numbers, 3–5, 797–805
  - arithmetical operations of, 798
  - graphical interpretation, 801
  - polar representation, 801
  - set of, 218
- Continuous-time filter, 320–364
- Continuous-time FT to DTFT, 526
- Continuous-time system, 6–8, 84
  - forced response of, 107
  - frequency response of, 203, 351
  - Laplace-transform analysis of, 285–286
  - natural response of, 106
  - realization of, 307
  - stability of, 88, 128, 298–305
  - time-domain analysis of, 116–124
  - transfer function of, 181, 229, 237–239, 285
  - zero-input response of, 106–112
  - zero-state response of, 106–112
- Control system, 306, 368
  - stability considerations in, 458
- Convolution, 116–127, 430–451
  - circular (or periodic), 431, 439, 500
  - graphical, 118–125, 848
  - properties of, 125–127, 448
- Convolution property
  - of DTFT, 498, 502
  - of DFT, 549

- of DTFS, 504
- of z-transform, 589
- Convolution sum
  - graphical procedure of, 432
  - properties of, 448
  - sliding tape method of, 436
- Corner (break) frequency, 332
- Cut-off frequency, 321, 622
  - normalized, 675
- Damping ratio, 69, 377
- Decibel, 246, 671
- Decimation (downsampling), 41, 584
- Decimation-in-time algorithm, 553
- Decomposition property, 182, 193
- Delay element, 638
- Demodulation of AM, 371–374
- DFT, *see* discrete Fourier transform
- Difference equation, 63, 70–72, 423, 455
  - iterative solution of, 423
  - linear, 431
  - z-transform solution of, 594–595
- Differential equation, 63, 64–67
  - time-domain solution of, 106–111, 131–135
  - classical solution of, 108, 806
  - Laplace transform solution of, 288–293
- Digital audio, 754
  - filtering, 759, 850
- Digital communication, 20, 70
- Digital filters, 621–660
  - advantages of, 621
  - nonrecursive, 625, 665–712
  - recursive, 626, 713–742
- Digital signals, 8
- Digital to analog (D/A) conversion, 393
- Dirac, Paul Adrien, 32
- Dirichlet conditions, 178
- Discrete Fourier transform (DFT), 525–560, 531
  - properties of, 547–551
- Discrete Fourier transform
  - as matrix multiplication, 535
  - basis functions of, 537
  - spectrum analysis using, 538
  - computational complexity of, 551
- Discrete-time Fourier series (DTFS), 465–475
  - spectrum, 483
- Discrete-time Fourier transform, 475–482
  - existence of, 484
  - of periodic functions, 485
  - equations, 477
  - existence of, 482
  - properties of, 491–505
  - spectrum, 483
  - Table, 481
- Discrete-time processing, 393
- Discrete-time signals, 6, 30, 34
- Discrete-time sinusoid, 27
- Discrete-time systems, 62–63, 69–72, 393
  - forced response of, 424
  - frequency response of, 506
  - natural response of, 424
  - realization of, 638–651
  - stability of, 601–605
  - time-domain analysis of, 422–460
  - transfer function of, 499, 596
  - z-transform analysis of, 594–609
  - zero-input response of, 424
  - zero-state response of, 424
- Distortionless transmission, 627
- Downsampling (decimation), 41
- DPCM, 767
- DTFT, *see* Discrete-time Fourier transform
- Dual tone multifrequency (DTMF), 621
- Duality property, 226
- Dynamic systems, 83
- Energy signals, 17–20
- Envelop detector, 374
- Euler formula, 11, 801
- Even function, 21–24
- Everlasting exponential, 28–31
- Exponential Fourier series, 163–179
- Fast Fourier transform (FFT), 553–558
  - radix-2 algorithm, 553–556
  - bit-reversal for, 558
- Feedback systems, 308
- Fidelity, 412
- Filter realization
  - direct form, 640, 644, 646
  - cascaded form, 640, 647
  - linear phase form, 641
  - parallel form, 649
  - transposed form, 642
- Filters, 322–367, 621–742
  - allpass, 260, 304–305
  - analog, *see* continuous-time filter
  - bandpass, 322, 357–361, 624, 688–691, 735
  - bandstop, 322–323, 361–364, 624, 691–693, 736
  - butterworth, 321, 328–338, 351, 718–728, 731–733
  - causal, 592, 632
  - chebyshev, 321, 338–349, 351
  - digital, 621
  - elliptic, 321, 349–352, 714, 734–736
  - FIR, 625
  - frequency transformation in, 352–364
  - group delay of, 628
  - highpass, 321–322, 353–357, 623, 684–688, 734

- Filters (*cont.*)
  - ideal, 321–324, 622–625
  - IIR, 625
  - linear phase, 629, 665
  - lowpass, 321, 327–352, 622, 666–684
  - non-ideal, 632
  - phase delay of, 628
  - realization, 638
  - recursive, 86, 338
  - passband of, 321, 511, 622–625, 634
  - stopband of, 321, 511, 622–625, 634
- Final value theorem, 287–288, 593
- Finite impulse response, 625
- Finite precision representation, 652
- FIR, *see* finite impulse response
- FIR filters
  - linear phase, 629
  - Type 1–4, 630
  - optimal, 693
- Forced response, 107, 424
- Fourier, Jean-Baptiste-Joseph, 152
- Fourier integral, 196
- Fourier series, 141–182
  - dirichlet conditions for, 178
  - exponential, 163–176
  - Symmetry conditions in, 156–158
  - trigonometric, 153–163
- Fourier spectra
  - of CTFT, 197, 205–208
  - of discrete-time Fourier series, 471
  - of exponential CTFS, 167–169
  - of DTFT, 478–479
- Fourier transform
  - continuous-time, 193–251
  - discrete-time, 475–517
  - duality property of, 226–227
  - existence of, 231–233, 482
  - frequency-convolution property of, 227–230
  - frequency-shifting property of, 222–223
  - linearity, 216–219, 492
  - numerical computation of, 247–250
  - properties of, 491–505
  - scaling property of, 219–220, 493
  - short-time, 748
  - table of, 217, 481
  - time convolution property of, 227–230, 498
  - time differentiation property of, 224–225
  - time integration property of, 225
  - time shifting property of, 221–222, 493
- Frequency division multiplexing (FDM), 369
- Frequency-differentiation property
  - of DTFT, 497
  - of z-transform, 588
- Frequency-domain analysis
  - of continuous-time systems, 227–230, 237–246
  - of discrete-time systems, 498–502, 506–514
- Frequency resolution, 542, 749, 757
- Frequency response, 245, 506, 606, 623, 707
- Frequency sampling, 529
- Frequency shifting property
  - of CTFT, 222–223
  - of DTFT, 495
  - of DTFS, 504
- Frequency spectrum, 245, 471, 483
- Fundamental frequency, 10
- Gate function, 25, 208
- Generalized function, 255
- Gibbs phenomenon, 158, 688
- Hamming window, 669
- Hanning window, 669
- Harmonic frequency, 13
- Heaviside, Oliver, 815
- Heaviside formula, 210, 815
- Hermitian Symmetry Property
  - of DFT, 548
  - of DTFS, 504
  - of DTFT, 491
- Highpass filter, 623, 780
  - design methods, 684, 706
- Homogeneity property, 73
- Ideal filter, 321–324, 622–625
- IIR, *see* infinite impulse response
- Image, 771
  - formats, 772
  - spectral analysis, 773
  - filtering, 777
  - compression, 782
- Impulse function, 32–34, 426
- Impulse invariance method, 715–728
- Impulse response, 98, 103, 113–116, 427, 623
  - of ideal filters, 625, 632, 672, 675
- Infinite impulse response, 625
- Initial conditions, 64, 423, 594
- Initial value theorem, 287–288, 593
- Instantaneous frequency, 750
- Instantaneous (memoriless) systems, 83–84, 127
- Integration table, 795–796
- Interpolation, 41–43, 399, 584
  - zero-order hold, 407
- Inverse discrete Fourier transform, 531
- Inverse Fourier transform, 209–210, 477
- Inverse Laplace transform, 273–276

- Inverse z-transform, 574
  - partial fraction method, 575
  - power series method, 580
- JPEG format, 421, 787
- Laplace, Pierre-Simon, 262
- Laplace transform, 261–311
  - bilateral, 262–266
  - existence, 271
  - frequency-convolution property of, 284–287
  - frequency-shifting property of, 280–281
  - inverse, 273–276
  - linearity property of, 276–278
  - region of convergence, 271, 295–298
  - scaling property of, 278–279
  - table of, 270
  - time convolution property of, 284–287
  - time differentiation property of, 281–282
  - time integration property of, 282–284
  - time shifting property of, 279–280
  - unilateral, 266–269
- Leakage, 543
- Left half plane (LHP), 301
- Legendre polynomials, 185
- L'Hopital's rule, 795
- Linear phase, 629, 665
- Linear system, 73–79
- Linear time-invariant system, 103–137, 423
- Linearity property
  - of DTFT, 492, 505
  - of DTFS, 492, 504
  - of DFT, 549
  - of z-transform, 582
- Lower sidebands, 371
- Lowpass filter, 622, 778
  - design methods, 674, 680, 715
- Magnitude response, 508, 623
- Magnitude spectrum, 471, 483
- Main lobe, 671
- Marginally stable system, 302–303, 604
- MATLAB, 829
  - control statements, 838
  - elementary operations, 840
  - plotting functions, 842
  - user interface, 851
- Maximally flat response, 324
- Mean, 751
- Mean square error, 785
- Memoryless system, 83–84, 127, 452
- Minimax optimization, 696
- Modulation, 66–67, 70–72, 369–373
- MP3 player, 421
- Multiplexing, frequency-division, 369
- Multipliers, 639
- Natural frequencies, 95, 344
- Natural response, 107, 424
- Noncausal signals, 31
- Noncausal system, 84–85, 93, 127, 136
- Nyquist sampling rate, 247, 397
- Odd function, 21–24
- Operators, differential, 106
- Orthogonal signal set, 142–149
- Orthogonal vector set, 142
- Orthogonality
  - in complex signals, 143
  - property, 465
- Orthonormal set, 144, 465
- Parks-McClellan algorithm, 698
- Parseval's theorem
  - for discrete Fourier transform, 550
  - for Fourier series, 170–171, 184
  - for Fourier transform, 230–231, 253
  - for discrete-time Fourier series, 504
  - for discrete-time Fourier transform, 503
- Partial fraction expansion
  - for CTFT, 209–211, 820
  - for DTFT, 500, 814, 825
  - for Laplace transform, 273, 814–822
  - for z-transform, 575, 826–828
- Passband of a filter, 320, 321–323, 622, 634
- Period of a CT signal, 9–15
- Period of a DT signal, 9–15
- Periodic reflection, 442
- Periodic signal, continuous-time, 9–15
- Periodic signal, discrete-time, 9–15
- Periodicity property
  - of DTFT, DTFS, 491
  - of DFT, 548
- Periodogram, 752
- Phase response, 245–246, 351, 508
- Phase spectrum, 245–246, 351, 471, 483
- Picket fence effect, 543
- Picture element (pixel), 415
- Polar plot, 801
- Power spectral density, 751
- Poles, 294–295, 597, 612
  - first-order, 815
  - higher-order, 820
- Power Series, 794
- Power signals, 17–20
- Probabilistic signals, 20–21
- Pulse code modulation (PCM), 412

- Quantization, 410–413
  - uniform/nonuniform, 410
  - error, 411
- Random signals, 20–21, 750
  - spectral analysis, 756, 773
- Rectangular window, 666
- Recursive filter, 657
- Region of convergence, 263–266, 295–298, 573
- Right half plane (PHP), 301
- Ripple Control parameter, 679
- Ripples, 668
- Round-off errors, 654
- Sampling rate (frequency), 247
- Sampling, 393
  - interval, 395
  - rate, 395, 397
  - impulse-train, 395
  - pulse-train, 405
    - bandpass, 418
    - sawtooth wave, 419
  - theorem, 247, 397
- Scaling property, 126, 173–174, 219–220, 278–279, 493
- Series summation, 794
- Shape control parameter, 679
- Shift operator, 638
- Sidebands, 371
- Sidelobes, 177, 671
- Short-time FT, 748
- Signals, 3
  - analog, 8–9
  - aperiodic, 9–15
  - continuous-time, 6–8
  - digital, 8–9
  - discrete-time, 6–8
  - energy, 16–20
  - energy of, 16
  - essential bandwidth of, 322
  - periodic, 9–15
  - power, 16–20
  - power of, 16
    - orthogonal representation of, 142–149
- Signum (sign) function,  $\text{sgn}(t)$ , 25–27
- Sinc function, 27–28
- Sinusoids, continuous-time, 10–11, 27, 29–30
- Sinusoids, discrete-time, 11–12, 27
- Spectral estimation, 746
- Spectral folding, *see* aliasing
- Spectrogram, 752
- Spectrum
  - magnitude, 167–169, 170–171
  - phase, 245–246, 351
- Stability, 88–90
  - analysis, 601, 453, 737
  - bounded-input, bounded-output (BIBO), 88–90, 128–130, 298–305, 601
  - marginal, 302–304, 604
- Steady-state response, 107, 109, 137, 608
- Stopband, 320, 321–323, 623, 634
  - attenuation, 676
- Superposition principle, 73, 113
- Symmetry conditions in Fourier series, 169–170
- Systems
  - block-diagram of, 63, 307–311
  - causal, 84–85, 93, 127, 452
  - characteristic equation of, 107, 273, 294, 346, 575
  - classification of, 72–90
  - continuous-time, 73
  - control, 306, 368
  - discrete-time, 73, 422
  - dynamic, 83–84
  - feedback, 308
  - finite memory, 84
  - frequency response of, 245, 506, 606, 628
  - invertible, 130–131, 454
  - linear, 73–79
  - LTIC, 103
  - LTID, 422
  - marginally stable, 302–303, 604
  - memoryless, 83–84, 127, 452
  - overdamped, 376
  - realization of
  - response to sinusoid input, 150–152, 239–240
  - stability, 88–90, 128, 298–305, 452
  - time-domain analysis of, 103–137
  - time-invariance, 79–83
  - transform analysis of, 180–182, 237–246, 305–307
  - underdamped, 376
  - unstable, 88–90, 128, 298–305
- Time-differencing property
  - of DTFT, 496
  - of DTFS, 504
  - of z-transform, 587
- Time-differentiation property
  - of CTFS, 174
  - of CTFT, 224–225
  - of Laplace transform, 281–282
- Time-domain analysis
  - of continuous-time systems, 118–126
  - of discrete-time systems, 422–460
- Time integration property, 174, 225, 282–284
- Time-invariant system, 79–83
- Time inversion, 172

- Time reversal property, 172
- Time scaling property
  - of CTFS, 173
  - of CTFT, 219–220
  - of Laplace transform, 278–279
  - of DTFT, 493
  - of DTFS, 504
  - of z-transform, 584
- Time shifting, 35–39
- Time shifting property
  - of CTFS, 171
  - of CTFT, 221–222
  - of DFT, 549
  - of DTFS, 504
  - of DTFT, 493
  - of Laplace transform, 279–280
  - of z-transform, 585
- Time-summation property
  - of DTFT, 498
  - of DTFS, 504
  - of z-transform, 592
- Transfer function, 181, 237–239, 285, 622–625, 723
- Transition bandwidth, 634, 671, 676
  - normalized, 676
- Trigonometric Fourier series, 153–162
- Trigonometric identities, 793
- Underdamped system, 376
- Unilateral Laplace transform, 266–272
- Unilateral z-transform, 579
- Unit impulse function, 32–35
- Unit impulse response of a system, 113–116
- Unstable system, 88–90, 128–130, 298–305, 453, 602
- Upsampling (interpolation), 41–44, 493
- Vectors, 142
- Width property of convolution, 126, 449
- Window function
  - Bartlett/triangular, 669
  - Blackman, 669
  - Hamming, 669
  - Hanning, 669
  - Kaiser, 671, 678
  - rectangular, 666
- Zero-input response, 106–111, 424, 807
- Zero-order hold, 407
- Zero-padding, 546
- Zero-state response, 106–111, 424, 810
- Zeros, 294–295, 597
- z-transform, 565
  - bilateral, 567
  - convolution property, 589
  - inverse, 574
  - shifting property of, 585
  - linearity property of, 582
  - region of convergence of, 573
  - Table of, 572
  - Unilateral, 569