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Fast Fourier Transform: Algorithms and Applications

Springer

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Preface

This book presents an introduction to the principles of the fast Fourier transform (FFT). It covers FFTs, frequency domain filtering, and applications to video and audio signal processing.

As fields like communications, speech and image processing, and related areas are rapidly developing, the FFT as one of the essential parts in digital signal processing has been widely used. Thus there is a pressing need from instructors and students for a book dealing with the latest FFT topics.

This book provides a thorough and detailed explanation of important or up-to-date FFTs. It also has adopted modern approaches like MATLAB examples and projects for better understanding of diverse FFTs.

Fast Fourier transform (FFT) is an efficient implementation of the discrete Fourier transform (DFT). Of all the discrete transforms, DFT is most widely used in digital signal processing. The DFT maps a sequence either in the time domain or in the spatial domain into the frequency domain. The development of the DFT originally by Cooley and Tukey [A1] followed by various enhancements/modifications by other researchers has provided the incentive and the impetus for its rapid and widespread utilization in a number of diverse disciplines. Independent of the Cooley-Tukey approach, several algorithms such as prime factor, split radix, vector radix, split vector radix, Winograd Fourier transform, and integer FFT have been developed. The emphasis of this book is on various FFTs such as the decimation-in-time FFT, decimation-in-frequency FFT algorithms, integer FFT, prime factor DFT, etc.

In some applications such as dual-tone multi-frequency detection and certain pattern recognition, their spectra are skewed to some regions that are not uniformly distributed. With this basic concept we briefly introduce the nonuniform DFT (NDFT), dealing with arbitrarily spaced samples in the Z-plane, while the DFT deals with equally spaced samples on the unit circle with the center at the origin in the Z-plane.

A number of companies provide software for implementing FFT and related basic applications such as convolution/correlation, filtering, spectral analysis, etc. on various platforms. Also general-purpose DSP chips can be programmed to implement the FFT and other discrete transforms.

This book is designed for senior undergraduate and graduate students, faculty, engineers, and scientists in the field, and self-learners to understand FFTs and directly apply them to their fields, efficiently. It is designed to be both a text and a reference. Thus examples, projects and problems all tied with MATLAB, are provided for grasping the concepts concretely. It also includes references to books and review papers and lists of applications, hardware/software, and useful websites. By including many figures, tables, bock diagrams and graphs, this book helps the reader understand the concepts of fast algorithms readily and intuitively. It provides new MATLAB functions and MATLAB source codes.

The material in this book is presented without assuming any prior knowledge of FFT. This book is for any professional who wants to have a basic understanding of the latest developments in and applications of FFT. It provides a good reference for any engineer planning to work in this field, either in basic implementation or in research and development.

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Organization of the Book

Chapter 1 introduces various applications of the discrete Fourier transform. Chapter 2 is devoted to introductory material on the properties of the DFT for the equally spaced samples. Chapter 3 presents fast algorithms to be mainly categorized as decimation-in-time (DIT) or decimation-in-frequency (DIF) approaches. Based on these, it introduces fast algorithms like split-radix, Winograd algorithm and others. Chapter 4 is devoted to integer FFT which approximates the discrete Fourier transform. One-dimensional DFT is extended to the two-dimensional signal and then to the multi-dimensional signal in Chapter 5. Applications to filtering are presented in this chapter. Variance distribution in the DFT domain is covered. It also introduces how we can diagonalize a circulant matrix using the DFT matrix. Fast algorithms for the 2-D DFT are covered in Chapter 6. Chapter 7 is devoted to introductory material on the properties of nonuniform DFT (NDFT) for the none-qually spaced samples. Numerous applications of the FFT are presented in Chapter 8. Appendix A covers performance comparison of discrete transforms. Appendix B covers spectral distance measures of image quality. Appendix C covers Integer DCTs. DCTs and DSTs are derived in Appendix D (DCT – discrete cosine transform, DST – discrete sine transform). Kronecker products and separability are briefly covered in Appendix E. Appendix F describes mathematical relations. Appendices G and H include MATLAB basics and M files. The bibliography contains lists of references to books and review papers, software/hardware, and websites. Numerous problems and projects are listed at the end of each chapter.

Arlington, TX K.R. Rao
August 2010

Contents

Abbreviations

AAC	Advanced audio coder, AAC-LD (low delay) AAC-LC (low complexity)
AC, AC-2, AC-3	Audio coder
ACATS	FCC advisory committee on advanced television service
ACM	Association for computing machinery
ADSL	Asymmetric digital subscriber line
AES	Audio engineering society
ANN	Artificial neural network
ANSI	American National Standards Institute
APCCAS	IEEE Asia-Pacific Conference on Circuits and Systems
ASIC	Application specific integrated circuit
ASPEC	Adaptive spectral perceptual entropy coding of high quality music signals
ASSP	Acoustics, speech, and signal processing
ATC	Adaptive transform coding
ATRAC	Adaptive transform acoustic coding
ATSC	Advanced television systems committee
AVC	Advanced video coding, MPEG-4 AVC (MPEG-4 Part 10)
AVS	Audio video standard
BER	Bit error rate
BF	Butterfly
BIFORE	Binary Fourier representation
BPF	Band pass filter
BRO	Bit reversed order
BV	Basis vector
CAS	Circuits and systems
CBT	Complex BIFORE transform
CCETT	*Centre Commun d'Etudes de Télédiffusion et Télécommuications* in French (Common Study Center of Telediffusion and Telecommunications)

CD	Compact disc
CDMA	Code division multiple access
CE	Consumer electronics
CELP	Code-excited linear prediction
CF	Continuous flow
CFA	Common factor algorithms
CGFFT	Conjugate gradient FFT
CICC	Custom integrated circuits conference
CIPR	Center for image processing research
CMFB	Cosine modulated filter bank
CODEC	Coder and decoder
COFDM	Coded orthogonal frequency division multiplex
CM	Circulant matrix
CR	Compression ratio
CRT	Chinese reminder theorem
CSVT	Circuits and systems for video technology
DA	Distributed arithmetic
DAB	Digital audio broadcasting
DCC	Digital compact cassette
DCT	Discrete cosine transform
DEMUX	Demultiplexer
DF	Decision feedback
DFT	Discrete Fourier transform
DHT	Discrete Hartley transform
DIS	Draft International Standard
DMT	Discrete multitone modulation
DOS	Disc operating systems
DOT	Discrete orthogonal transform
DPCM	Differential pulse code modulation
D-PTS	Decomposition partial transmit sequence
DSP	Digital signal processing/processor
DST	Discrete sine transform
DTMF	Dual-tone multifrequency. DTMF signals/tones are used for telephone touch keypads [B40]
DTT	Discrete trigonometric transform
DVB-T	Digital video broadcasting standard for terrestrial transmission, using COFDM modulation
DVD	Digital video/versatile disc
DWT	Discrete wavelet transform
ECCTD	Biennial European Conference on Circuit Theory and Design
EDN	Electrical design news
EECON	Electrical Engineering Conference of Thailand
EEG	Electroencephalograph
EKG	Electrocardiograph, ECG

EMC	Electromagnetic compatibility, IEEE transactions on
EURASIP	European Association for Signal Processing
EUSIPCO	European Signal Processing Conference
FAQ	Frequently asked questions
FCC	The Federal Communications Commission
FFT	Fast Fourier transform
FIR	Finite impulse response
FMM	Fast multipole method
FPGA	Field programmable gate array
FRAT	Finite radon transform
FRExt	Fidelity range extensions
FRIT	Finite ridgelet transform
FSK	Frequency shift keying
FTP	File transfer protocol
FUDCuT	Fast uniform discrete curvelet transform
FxpFFT	Fixed point FFT
GDFHT	Generalized discrete Fourier Hartley transform
GDFT	Generalized DFT
GLOBECOM	IEEE Global Telecommunications Conference
GZS	Geometrical zonal sampling
H.263	Standard for visual communication via telephone lines
HDTV	High-definition television
HPF	High pass filter
HT	Hadamard transform
HTTP	Hyper text transfer protocol
HVS	Human visual sensitivity
Hz	Hertz cycles/sec, or cycles/meter
IASTED	The International Association of Science and Technology for Development
IBM	International business machines
IC	Integrated circuit(s)
ICA	Independent component analysis
ICASSP	IEEE International Conference on Acoustics, Speech, and Signal Processing
ICC	IEEE International Conference on Communications
ICCE	IEEE International Conference on Consumer Electronics
ICCS	IEEE International Conference on Circuits and Systems
ICECS	International Conference on Electronics, Circuits and Systems
ICIP	IEEE International Conference on Image Processing
ICME	IEEE International Conference on Multimedia and Expo
ICSPAT	International Conference on Signal Processing Applications and Technology
IDFT	Inverse DFT
IEC	International Electrotechnical Commission

IEEE	The Institute of Electrical and Electronics Engineers
IEICE	Institute of Electronics, Information and Communication Engineers
IFFT	Inverse FFT
IGF	Inverse Gaussian filter
IJG	Independent JPEG group
ILPM	Inverse LPM (log polar mapping)
IMTC	IEEE Instrumentation and Measurement Technology Conference
IntFFT	Integer FFT
IP	Image processing / intellectual property
IRE	Institute of radio engineers
IS	International standard
IS&T	The Society for Imaging Science and Technology
ISCAS	IEEE International Symposium on Circuits and Systems
ISCIT	IEEE International Symposium on Communications and Information Technologies
ISDN	Integrated services digital network
ISO	International Organization for Standardization
ISPACS	IEEE International Symposium on Intelligent Signal Processing and Communication Systems
IT	Information theory
JPEG	Joint photographic experts group
JSAC	Journal on selected areas in communications, IEEE
JTC	Joint technical committee
KLT	Karhunen−Loève transform
LAN	Local area networks
LC	Low complexity
LMS	Least mean square
LO	Lexicographic ordering
LPF	Low pass filter
LPM	Log polar mapping
LPOS	Left point of symmetry
LS	Least square, lifting scheme
LSI	Linear shift invariant
LUT	Look up tables
LW	Long window
MCM	Multichannel carrier modulation
MD	MiniDisc
MDCT	Modified discrete cosine transform
MDST	Modified discrete sine transform
ML	Maximum likelihood/multiplierless
MLS	Maximum length sequence
MLT	Modulated lapped transform
MMSE	Minimum mean square error

MoM	The method of moments
MOPS	Million operations per second
MOS	Mean opinion score
MOV	Model output variable
MPEG	Moving picture experts group
MR	Mixed radix
MRI	Magnetic resonance imaging
ms	Millisecond
M/S	Mid/side, middle and side, or sum and difference
MSB	Most significant bit
MUSICAM	Masking pattern universal subband integrated coding and multiplexing (MPEG-1 Level 2, MP2)
MUX	Multiplexer
MVP	Multimedia video processor
MWSCAS	Midwest Symposium on Circuits and Systems
NAB	National Association of Broadcasters
NBC	Nonbackward compatible (with MPEG-1 audio)
NMR	Noise-to-mask ratio
NNMF	Nonnegative matrix factorization
NTC	National telecommunications conference
OCF	Optimum coding in the frequency domain
OEM	Original equipment manufacturer
OFDM	Orthogonal frequency-division multiplexing
ONB	Orthonormal basis
PAC	Perceptual audio coder
PAMI	Pattern analysis and machine intelligence
PAPR	Peak-to-average power ratio
PC	Personal computer
PCM	Pulse code modulation
PDPTA	International Conference on Parallel and Distributed Processing Techniques and Applications
PE	Perceptual entropy
PFA	Prime factor algorithm
PFM	Prime factor map
PoS	Point of symmetry
PQF	Polyphase quadrature filter
PR	Perfect reconstruction
PRNG	Pseudorandom number generator
P/S	Parallel to serial converter
PSF	Point spread function
PSK	Phase shift keying
PSNR	Peak-to-peak signal-to-noise ratio
QAM	Quadrature amplitude modulation
QMF	Quadrature mirror filter

QPSK	Quadrature phase-shift keying
RA	Radon transform
RAM	Random access memory
RELP	Residual excited linear prediction
RF	Radio frequency
RFFT	Real valued FFT
RI	Ridgelet transform
RMA	Royal Military Academy of Belgium
RPI	Rensselear Polytechnic Institute
RPOS	Right point of symmetry
R−S	Reed Solomon
RST	Rotation, scaling and translation
SDDS	Sony dynamic digital sound
SEPXFM	Stereo-entropy-coded perceptual transform coder
SIAM	Society for Industrial and Applied Mathematics
SiPS	Signal processing systems
SMPTE	Society of Motion Picture and Television Engineers
SMR	Signal-to-mask ratio
SNR	Signal to noise ratio
SOPOT	Sum-of-powers-of-two
SP	Signal processing
S/P	Serial to parallel converter
SPIE	Society of Photooptical and Instrumentation Engineers
SPS	Symmetric periodic sequence
SR	Split radix
SS	Spread spectrum
SSST	Southeastern Symposium on System Theory
STBC	Space-time block code
SW	Short window
TDAC	Time domain aliasing cancellation
T/F	Time-to-frequency
UDFHT	Unified discrete Fourier-Hartley transform
USC	University of Southern California
VCIP	SPIE and IS&T visual communications and image processing
VCIR	Visual communication and image representation
VLSI	Very large scale integration
VSP	Vector signal processor
WD	Working draft
WHT	Walsh-Hadamard transform
WLAN	Wireless LAN
WMV	Window media video
WPMC	International Symposium on Wireless Personal Multimedia Communications