

The Fast Fourier Transform and Its Applications

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Abstract—The advent of the fast Fourier transform method has greatly extended our ability to implement Fourier methods on digital computers. A description of the algorithm and its programming is given here and followed by a theorem relating its operands, the finite sample sequences, to the continuous functions they often are intended to approximate. An analysis of the error due to discrete sampling over finite ranges is given in terms of aliasing. Procedures for computing Fourier integrals, convolutions and lagged products are outlined.

HISTORICAL BACKGROUND

THE FAST Fourier transform algorithm has an interesting history which has been described in [3]. Time does not permit repeating this history here in detail. The essentials are, however, that until the recent publication of fast Fourier transform methods, computer programs were using up hundreds of hours of computer time with procedures requiring something proportional to N^3 operations to compute Fourier transforms of N data points. It is not surprising then that the "new" methods requiring a number of operations proportional to $N \log N$ received considerable attention and led to revisions in computer programs and in problem-solving techniques using Fourier methods. It was discovered later that the base 2 form of the fast Fourier transform algorithm had been published many years ago by Runge and König [10] and by Stumpff [12], [13]. These are authors whose works are widely read and their papers certainly were used by those computing Fourier series. How then could these important algorithms have gone unnoticed? The answer is that the papers of Runge, König, and Stumpff described primarily how one could use *symmetries* of the sine-cosine functions to reduce the amount of computation by factors of 4, 8, or even more. Relatively small portions of these papers mentioned the *successive doubling* algorithm which permitted one to take two Fourier analyses of N -point samples of data and combine them in N operations to obtain an analysis of a $2N$ -point sampling of the same data. Successive application of this algorithm obviously yields an N -point Fourier analysis in $\log_2 N$ doublings, and therefore, takes $N \log_2 N$ operations. Thus, while the computational method using *symmetries* reduced the proportionality factor in the KN^3 operations required to transform an N -point sequence, the method based on the doubling algorithm took a number of operations proportional to $N \log_2 N$.

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It is most likely that with the relatively small values of N used in pre-electronic computer days, the former methods were easier to use and took fewer operations. Consequently, the methods requiring $N \log N$ operations were neglected. With the arrival of electronic computers capable of doing calculations of Fourier transforms with large values of N , the $N \log N$ methods were overlooked and the well-known hand calculator methods were programmed for the computers. Perhaps there is something to be learned from this experience, namely, that there may exist numerical methods in the older literature which should be reappraised whenever computing devices undergo radical changes.

FAST FOURIER ALGORITHMS

In the interest of coherent presentation, the definitions and procedures utilized herein will be developed in blocks and shown as figures. Thus, the discrete Fourier series is defined in Fig. 1 with $A(\pi)$ being a sequence which gives the complex Fourier amplitudes as a function of frequency π . The $X(j)$, $j=0, 1, \dots, N-1$ are regarded here as a complex sequence, and in a problem may represent a sampling of a signal at N sampling points. Also,

$$W_N = \exp \left\{ \frac{2\pi i}{N} \right\} = \cos \frac{2\pi}{N} + i \sin \frac{2\pi}{N}$$

is the principle N th root of unity and if we substitute the expression for W_N in terms of sines and cosines, we obtain the perhaps more familiar sine-cosine Fourier series. Complex Fourier series is employed for ease of notation and derivation of formulas. One should note next the inversion formula in Fig. 1, giving the $A(\pi)$'s in terms of the $X(j)$'s. Since $A(\pi)$ is also a Fourier series, an algorithm or a program for computing the $A(\pi)$'s from the $X(j)$'s can be used to compute the $X(j)$'s from the $A(\pi)$'s. Since $W_N^N = 1$, the exponent of W_N is to be interpreted modulo N . This leads to an essential property of the sequences $X(j)$ and $A(\pi)$, i.e., that they are periodic functions of j and π , respectively, with period N .

It is shown in Fig. 2 that when N is a product, $N=rs$, the Fourier series can be calculated in a two-stage process. This is done just as though the sequences $A(\pi)$ and $X(j)$ were defined on two-dimensional $r \times s$ arrays with the array indices (j_1, j_2) and (π_1, π_2) being defined as shown. When we substitute for j and π in W_N^{jn} , and jn is reduced modulo N , it is found that the series can be

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Lectures on the Fourier Transform and Its Applications Brad G. Osgood, 2019-01-18 This book is derived from lecture notes for a course on Fourier analysis for engineering and science students at the advanced undergraduate or beginning graduate level Beyond teaching specific topics and techniques all of which are important in many areas of engineering and science the author's goal is to help engineering and science students cultivate more advanced mathematical know how and increase confidence in learning and using mathematics as well as appreciate the coherence of the subject He promises the readers a little magic on every page The section headings are all recognizable to mathematicians but the arrangement and emphasis are directed toward students from other disciplines The material also serves as a foundation for advanced courses in signal processing and imaging There are over 200 problems many of which are oriented to applications and a number use standard software An unusual feature for courses meant for engineers is a more detailed and accessible treatment of distributions and the generalized Fourier transform There is also more coverage of higher dimensional phenomena than is found in most books at this level *Fourier Analysis and Its Applications* Anders Vretblad, 2006-04-18

The classical theory of Fourier series and integrals as well as Laplace transforms is of great importance for physical and technical applications and its mathematical beauty makes it an interesting study for pure mathematicians as well I have taught courses on these subjects for decades to civil engineering students and also mathematics majors and the present volume can be regarded as my collected experiences from this work There is of course an unsurpassable book on Fourier analysis the treatise by Katznelson from 1970 That book is however aimed at mathematically very mature students and can hardly be used in engineering courses On the other end of the scale there are a number of more or less cookbook styled books where the emphasis is almost entirely on applications I have felt the need for an alternative in between these extremes a text for the ambitious and interested student who on the other hand does not aspire to become an expert in the field There do exist a few texts that fulfill these requirements see the literature list at the end of the book but they do not include all the topics I like to cover in my courses such as Laplace transforms and the simplest facts about distributions **Practical Signal Processing And Its Applications: With Solved Homework Problems** Sharad R Laxpati, Vladimir Goncharoff, 2017-12-15 This textbook gives a fresh approach to an introductory course in signal processing Its unique feature is to alternate chapters on continuous time analog and discrete time digital signal processing concepts in a parallel and synchronized manner This presentation style helps readers to realize and understand the close relationships between continuous and discrete time signal processing and lays a solid foundation for the study of practical applications such as the analysis and design of analog and digital filters The compendium provides motivation and necessary mathematical rigor It generalizes the Fourier transform to Laplace and Z transforms applies these transforms to linear system analysis covers the time and frequency domain analysis of differential and difference equations and presents practical applications of these techniques to convince readers of their usefulness

MATLAB examples are provided throughout and over 100 pages of solved homework problems are included in the appendix

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Quaternion and Clifford Fourier Transforms and Wavelets Eckhard Hitzer, Stephen J. Sangwine, 2013-06-24 Quaternion and Clifford Fourier and wavelet transformations generalize the classical theory to higher dimensions and are becoming increasingly important in diverse areas of mathematics physics computer science and engineering This edited volume presents the state of the art in these hypercomplex transformations The Clifford algebras unify Hamilton's quaternions with Grassmann algebra A Clifford algebra is a complete algebra of a vector space and all its subspaces including the measurement of volumes and dihedral angles between any pair of subspaces Quaternion and Clifford algebras permit the systematic generalization of many known concepts This book provides comprehensive insights into current developments and applications including their performance and evaluation Mathematically it indicates where further investigation is required For instance attention is drawn to the matrix isomorphisms for hypercomplex algebras which will help readers to see that software implementations are within our grasp It also contributes to a growing unification of ideas and notation across the expanding field of hypercomplex transforms and wavelets The first chapter provides a historical background and an overview of the relevant literature and shows how the contributions that follow relate to each other and to prior work The book will be a valuable resource for graduate students as well as for scientists and engineers

Engineering Optics Keigo Iizuka, 2019-04-30 The expanded 4th edition of this classic optics text is aimed at those wishing to apply their knowledge of optics to engineering problems and provides a sound introduction to the basic principles of optics for engineering students. It describes fundamental material including Fourier optics, diffraction theory, geometrical optics and lenses and goes on to cover important topics such as optical signal processing, holography, tomography, optical communication, electro and acousto-optic devices, integrated optics, 3D imaging and optical distance measurement. Comprehensively updated throughout, this new edition features a major additional section on optical measurement techniques including chapters on scanning methods, structured light, pattern projection methods, depth measurement using a microscope, coherent as well as incoherent interferometry and distance mapping using CCD cameras. Fully illustrated, the text includes numerous practical examples together with worked exercises and end of chapter problem sets. From the reviews of the third edition: 'It is intended not only for the physics and engineering students who want to acquire the basic principles of optics but also for researchers and engineers who use optics in their research and/or professional activity. For all these people this book will be a valuable source of scientific information.' *Optica Applicata*. Iizuka managed to intermingle lively and exciting ideas, humorous and enthusiastic presentations, eye-catching and tasteful cartoons, significant backbone, optics materials and even some frontier state-of-the-art optics information. I did not have a dull moment reading this book. It has a very attractive style, educational yet entertaining. *IEEE Circuits and Devices Magazine*. I found this book most helpful in demonstrating an effective teaching approach that was especially suited for engineering students. The examples and problem sets at the end of each chapter are also helpful to students and instructors. Overall, it is a delightful book and I would definitely recommend it to students starting out on the path of exploring optical technologies and educators who want to enlighten young engineers fascinated by optics.

Optics and Photonics News Basic System Analysis S K Pandey, 2011 The book *Basic System Analysis* is written especially for the students of III semester of Electrical Electronics Engineering (EN) of all Engineering Colleges of Maha Maya Technical University, Noida and Gautam Buddha Technical University, Lucknow. It also meets the needs of those readers who want to gain sound understanding of Basic System Analysis.

Explorations in the Mathematics of Data Science Simon Foucart, Stephan Wojtowytsch, 2024-09-12 This edited volume reports on the recent activities of the new Center for Approximation and Mathematical Data Analytics (CAMDA) at Texas A M University. Chapters are based on talks from CAMDA's inaugural conference held in May 2023 and its seminar series as well as work performed by members of the Center. They showcase the interdisciplinary nature of data science, emphasizing its mathematical and theoretical foundations, especially those rooted in approximation theory.

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