Fundamentals of Signals and Systems

This innovative textbook provides a solid foundation in both signal processing and systems modeling using a building block approach. The authors show how to construct signals from fundamental building blocks (or basis functions), and demonstrate a range of powerful design and simulation techniques in MATLAB®, recognizing that signal data are usually received in discrete samples, regardless of whether the underlying system is discrete or continuous in nature.

The book begins with key concepts such as the orthogonality principle and the discrete Fourier transform. Using the building block approach as a unifying principle, the modeling, analysis and design of electrical and mechanical systems are then covered, using various real-world examples. The design of finite impulse response filters is also described in detail.

Containing many worked examples, homework exercises, and a range of MATLAB laboratory exercises, this is an ideal textbook for undergraduate students of engineering, computer science, physics, and other disciplines.

Accompanying the text is a CD containing the MATLAB m-files for MATLAB generated figures, examples, useful utilities and some interesting demonstrations. The files can be easily modified to solve other related problems.

Further resources for this title including solutions, lecture slides, additional problems and labs, are available at www.cambridge.org/9780521849661.

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A building block approach

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521849661

First published 2006

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this publication is available from the British Library

ISBN-13 978-0-521-84966-1 hardback
ISBN-10 0-521-84966-7 hardback

Cambridge University Press
0521849667 - Fundamentals of Signals and Systems: A Building Block Approach
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Preface

This text results from a new approach to teaching the sophomore engineering course entitled *Introduction to Engineering Systems* at Harvey Mudd College. Since the course is required of all students regardless of major, the goal is to provide a clear understanding of concepts, tools, and techniques that will be beneficial in engineering, physics, chemistry, mathematics, biology, and computer science. Cha, Rosenberg, and Dym's *Fundamentals of Modeling and Analyzing Engineering Systems*,[1] written specifically for this course and providing an excellent introduction to the modeling and analysis of systems from a wide variety of disciplines, was used for several years. This text complements that text's focus on modeling with a strong emphasis on representation of continuous-time and discrete-time signals in both the time and frequency domains, modeling of mechanical and electrical systems, and the design of finite impulse response (FIR) discrete filters. *Fundamentals of Modeling and Analyzing Engineering Systems* and this text can be used together in a two-semester sequence to provide a thorough introduction to both signal processing and modeling, or selected topics from both can be used as the basis for a one-semester course. The sampling theorem, continuous-to-discrete and discrete-to-continuous converters, the discrete Fourier transform (DFT) and its computation with the fast Fourier transform (FFT) are explained in detail. Students are introduced to MATLAB and get hands-on experience with a series of laboratory assignments that illustrate and apply the theory. Single variable calculus is the only essential background although some knowledge of differential equations, linear algebra, and vector spaces is helpful. The materials covered in this text have

[1] *Fundamentals of Modeling and Analyzing Engineering Systems* by P. D. Cha, J. J. Rosenberg and C. L. Dym, Cambridge University Press, UK, 2000.

grown out of lectures given primarily to sophomores at Harvey Mudd College. These notes have been classroom-tested over a period of six semesters.

Engineers, scientists, and mathematicians are increasingly faced with acquiring, processing, interpreting, and extracting information from data, which are usually provided as a series of discrete samples, independent of whether the original underlying signals and systems were continuous or discrete in nature. Discrete-time techniques are used almost exclusively for simulating both continuous-time and discrete-time systems. Effective use of modern analysis, design, and simulation tools such as MATLAB require a clear understanding of the underlying theory as well as a good bit of practice with applications.

We begin by developing representations of continuous-time signals as functions and discrete-time signals as sequences (Chapter 1). We then explore various transformations such as shifts, reversal, compression, and expansion for continuous-time signals. We also cover upsampling and downsampling for discrete-time signals. Next, the construction of complicated signals from basic building blocks is introduced using the orthogonality principle (Chapter 2). This provides the foundation and context for the later focus on complex exponentials and the Fourier series. By starting with the generally applicable approach of minimizing the integrated squared error through the use of the orthogonality principle, the student is given a much deeper understanding and appreciation for a broad class of applications, including the use of Walsh functions in cellular phones to various series expansions using a variety of building blocks or basis functions. The difference between the orthogonality principle and orthogonal basis functions is carefully explained. An appendix provides a natural development of basis functions starting with the familiar three-dimensional vectors.

Complex exponentials as building blocks provide the foundation for the development of the spectrum of a continuous-time signal. Its importance in characterizing and extracting information from signals leads naturally to the need for numerical techniques to compute the spectrum of complicated signals produced by phenomena such as earthquakes, space photographs or communication systems. This, in turn, leads to the discrete Fourier transform and its efficient computation using the fast Fourier transform algorithm. While we do not derive the fast Fourier transform algorithm, the text describes its use in considerable detail and laboratory exercises provide the opportunity for students to explore practical applications.

Continuous-time and discrete-time signals are connected via the sampling theorem (Chapter 3). The spectrum of a discrete-time signal provides the basis for exploring the phenomena of aliasing and folding, which must be fully understood in order to correctly acquire, process, analyze and interpret data. The behavior of continuous-to-discrete (analog-to-digital) and discrete-to-continuous (digital-to-analog) converters is explored as the culmination of the first part of the text.

The next major division of the text is devoted to the lumped element modeling of mechanical and electrical systems (Chapters 4 and 5). We start with the basic elements (building blocks) for mechanical systems consisting of springs, dampers, and masses. First-order and second-order governing equations are developed and canonical forms are defined for both the translational and rotational systems. Parallel and series combinations of elements as well as the division of force and displacement are covered. A parallel development for electrical systems leads naturally to the force–current and velocity–voltage analogs. Solution of first-order and second-order differential governing equations is introduced, transient response specifications are defined that are used in system design, and a state space approach is formulated as an alternative means to analyze the free and forced responses of a system (Chapter 6).

Frequency response builds on the concept of the complex exponential building blocks that are covered in the first part of the text (Chapter 7). The complex exponentials also serve as the eigenfunctions of linear time-invariant systems, and the concept of frequency response provides the bridge between signals and systems. Bode plots of first-order and second-order factors are developed. The complex exponential building blocks and the concept of frequency response are then used to define impedance and its application in combining various elements of mechanical and electrical systems.

An introduction to the analysis and design of finite-impulse response filters forms the final major part of the text (Chapter 8). The ease with which arbitrary frequency response functions can be implemented is developed as another application of the Fourier series and demonstrated with a whimsical example. A series of applications from a variety of disciplines then follows, providing the student with an appreciation of the power and scope of the concepts, tools, and techniques developed throughout the text (Chapter 9). The text concludes with a short transition section designed to relate the fundamentals to concepts covered in more advanced texts (Chapter 10).

This text offers numerous special features that distinguish itself from other texts on signals and systems, and they are summarized in the following:

- A rigorous development of the construction of signals from building blocks (basis functions) via the orthogonality principle is given.
- The building block approach to develop a clear understanding of the spectra of both continuous-time and discrete-time signals as well as the frequency responses of continuous-time and discrete-time systems all without the use of the continuous-time impulse, Fourier transform, or Laplace transform is used.
- A solid understanding of the use of the FFT in extracting information from signals and determining the response of electrical and mechanical systems to realistic inputs is provided.
- Signal processing and systems modeling are treated on equal footing. Electrical engineering departments usually teach systems with primary emphasis on signal processing while mechanical engineering departments put the primary emphasis on dynamic modeling and control. In order to cover all of the desired topics, this text does not include the control of dynamical systems. This is a conscious decision the authors made in order to present a complete end-to-end analysis from characterizing the input signal, to modeling the physical system, to determining the response or output of the system to arbitrary inputs.
- A thorough treatment of the modeling of complicated mechanical and electrical systems is provided. The analogy between lumped mechanical and electrical systems is introduced in detail.
- Detailed examples of characterizing both simple and realistic (complicated) input signals, modeling physical systems, and determining their response to these inputs are provided. Most modeling texts focus extensively on how to describe the physical system and determine its response to classical inputs such as impulse, step, and sinusoid. In addition to these standard inputs, this text shows how complicated inputs can be represented using simple building blocks, thus allowing the determination of the response of systems to realistic inputs.

Finally, seven MATLAB laboratory exercises are included at the end of the text to allow students to gain a deeper understanding and mastery of the topics covered in the text. We hope that the use of computational software will enhance the learning experience and stimulate the students' interest in signals and systems.

Acknowledgments

The creation of this text was truly a team effort. As part of the teaching team Professor David Harris diligently took notes on his laptop during the authors' lectures and carefully edited them. Without these notes as a basis or building blocks, the writing of the text may never have gotten off the ground. In addition, David wrote the MATLAB-based laboratory exercises and created the review that is part of Chapter 10. Professors Lori Bassman, Mary Cardenas, David Harris, Elizabeth Orwin, Jennifer Rossmann, and Qimin Yang have all taught parts of the course over the past three years and contributed significantly to the final form and content of the text. Professor Anthony Bright, our department chair, gave us unwavering support and encouragement and allowed us to use his introduction to MATLAB that is the basis of Laboratory Exercise 1. Paul Nahin, a former colleague and long-time friend of the second author gave inspiration through his wide-ranging books from science fiction to a truly innovative blend of science technology, and history, as well as encouragement when this text was just an idea. During his senior year, student Warren Katzenstein provided support in developing the initial drafts of the text and figures. We also want to acknowledge the hundreds of students who have contributed through their questions, evaluations, and comments. Finally, we want to acknowledge the moral support of our families, who have all shared the joy and pain of the writing of this text. In particular, the first author would like to thank his Dad, Mom, brother Paul and sister Pauline, the second author his wife Janet, son Tim, and daughter Karen who always encouraged him but wondered if he would ever actually write a book.

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