PREFACE

MOTIVATION

I wrote the first edition because I love the mathematical beauty of signal and system analysis. That has not changed. The motivation for the second edition is to improve the book based on my own experience using the book in classes and also by responding to constructive criticisms from students and colleagues.

AUDIENCE

This book is intended to cover a two-semester course sequence in the basics of signal and system analysis during the junior or senior year. It can also be used (as I have used it) as a book for a quick one-semester master's-level review of transform methods as applied to linear systems.

CHANGES FROM THE FIRST EDITION

Since writing the first edition I have used it, and my second book, *Fundamentals of Signals and Systems*, in my classes. Also, in preparation for this second edition I have used drafts of it in my classes, both to test the effects of various approaches to introducing new material and to detect and (I hope) correct most or all of the errors in the text and exercise solutions. I have also had feedback from reviewers at various stages in the process of preparing the second edition. Based on my experiences and the suggestions of reviewers and students I have made the following changes from the first edition.

- In looking at other well-received books in the signals and systems area, one finds that the notation is far from standardized. Each author has his/her preference and each preference is convenient for some types of analysis but not for others. I have tried to streamline the notation as much as possible, eliminating, where possible, complicated and distracting subscripts. These were intended to make the material precise and unambiguous, but in some cases, instead contributed to students' fatigue and confusion in reading and studying the material in the book. Also, I have changed the symbols for continuous-time harmonic functions so they will not so easily be confused with discrete-time harmonic functions.
- Chapter 8 of the first edition on correlation functions and energy and power spectral density has been omitted. most junior-level signals and systems courses do not cover this type of material, leaving it to be covered in courses on probability and stochastic processes.
- Several appendices from the printed first edition have been moved to the book's website, www.mhhe.com/roberts. This, and the omission of Chapter 8 from the first edition, significantly reduce the size of the book, which, in the first edition, was rather thick and heavy.
- I have tried to "modularize" the book as much as possible, consistent with the need for consecutive coverage of some topics. As a result the second edition has 16 chapters instead of 12. The coverages of frequency response, filters, communication systems and state-space analysis are now in separate chapters.

- The first ten chapters are mostly presentation of new analysis techniques, theory and mathematical basics. The last six chapters deal mostly with the application of these techniques to some common types of practical signals and systems.
- The second edition has more examples using MATLAB® than the first edition and MATLAB examples are introduced earlier than before.
- Instead of introducing all new signal functions in the chapters on signal description I introduced some there, but held some derived functions until the need for them arose naturally in later chapters.
- In Chapter 4 on system properties and system description, the discussion of mathematical models of systems has been lengthened.
- In response to reviewers' comments, I have presented continuous-time convolution first, followed by discrete-time convolution. Even though continuous-time convolution involves limit concepts and the continuous-time impulse, and discrete-time convolution does not, the reviewers felt that the students' greater familiarity with continuous-time concepts would make this order preferable.
- More emphasis has been placed on the importance of the principle of orthogonality in understanding the theoretical basis for the Fourier series, both in continuous and discrete time.
- The coverage of the bilateral Laplace and z transforms has been increased.
- There is increased emphasis on the use of the discrete Fourier transform to approximate other types of transforms and some common signal-processing techniques using numerical methods.
- Material on continuous-time angle modulation has been added.
- The "comb" function used in the first edition, defined by

$$\mathrm{comb}(t) = \sum_{n=-\infty}^{\infty} \delta(t-n) \quad \text{and} \quad \mathrm{comb}_{N_0}[n] = \sum_{m=-\infty}^{\infty} \delta[n - mN_0]$$

in which a single impulse is represented by $\delta(t)$ in continuous time and by $\delta[n]$ in discrete time, has been replaced by a "periodic impulse" function. The periodic impulse is represented by $\delta_T(t)$ in continuous time and by $\delta_N[n]$ in discrete time where T and N are their respective fundamental periods. They are defined by

$$\delta_T(t) = \sum_{n=-\infty}^{\infty} \delta(t-nT) \quad \text{and} \quad \delta_N[n] = \sum_{m=-\infty}^{\infty} \delta(n-mN).$$

The continuous-time comb function is very elegant mathematically, but I have found from my experience in my own classes that its simultaneous time-scaling and impulse-strength scaling under the change of variable $t \to at$ confuses the students. The periodic impulse function is characterized by having the spacing between impulses (the fundamental period) be a subscript parameter instead of being determined by a time-scaling. When the fundamental period is changed the impulse strengths do not change at the same time, as they do in the comb function. This effectively separates the time and impulse-strength scaling in continuous time and should relieve some confusion among students who are already challenged by

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the abstractions of various other concepts like convolution, sampling and integral transforms. Although simultaneous time and impulse-strength scaling do not occur in the discrete-time form, I have also changed its notation to be analogous to the new continuous-time periodic impulse.

OVERVIEW

The book begins with mathematical methods for describing signals and systems, in both continuous and discrete time. I introduce the idea of a transform with the continuous-time Fourier series, and from that base move to the Fourier transform as an extension of the Fourier series to aperiodic signals. Then I do the same for discrete-time signals. I introduce the Laplace transform both as a generalization of the continuous-time Fourier transform for unbounded signals and unstable systems and as a powerful tool in system analysis because of its very close association with the eigenvalues and eigenfunctions of continuous-time linear systems. I take a similar path for discrete-time systems using the z transform. Then I address sampling, the relation between continuous and discrete time. The rest of the book is devoted to applications in frequency-response analysis, communication systems, feedback systems, analog and digital filters and state-space analysis. Throughout the book I present examples and introduce MATLAB functions and operations to implement the methods presented. A chapter-by-chapter summary follows.

CHAPTER SUMMARIES

CHAPTER 1

Chapter 1 is an introduction to the general concepts involved in signal and system analysis without any mathematical rigor. It is intended to motivate the student by demonstrating the ubiquity of signals and systems in everyday life and the importance of understanding them.

CHAPTER 2

Chapter 2 is an exploration of methods of mathematically describing continuous-time signals of various kinds. It begins with familiar functions, sinusoids and exponentials and then extends the range of signal-describing functions to include continuous-time singularity functions (switching functions). Like most, if not all, signals and systems textbooks, I define the unit step, the signum, the unit impulse and the unit ramp functions. In addition to these I define a unit rectangle and a unit periodic impulse function. The unit periodic impulse, along with convolution, provides an especially compact way of mathematically describing arbitrary periodic signals.

After introducing the new continuous-time signal functions, I cover the common types of signal tranformations, amplitude scaling, time shifting, time scaling, differentiation and integration and apply them to the signal functions. Then I cover some characteristics of signals that make them invariant to certain transformations, evenness, oddness and periodicity, and some of the implications of these signal characteristics in signal analysis. The last section is on signal energy and power.

CHAPTER 3

Chapter 3 follows a path similar to Chapter 2 except applied to discrete-time signals instead of continuous-time signals. I introduce the discrete-time sinusoid and exponential and comment on the problems of determining the period of a discrete-time sinsuoid. This is the student's first exposure to some of the implications of sampling. I define some discrete-time signal functions analogous to continuous-time singularity functions. Then I explore amplitude scaling, time-shifting, time scaling, differencing and accumulation for discrete-time signal functions, pointing out the unique implications and problems that occur, especially when time scaling discrete-time functions. The chapter ends with definitions and discussion of signal energy and power for discrete-time signals.

CHAPTER 4

This chapter addresses the mathematical decription of systems. First I cover the most common forms of classification of systems, homogeneity, additivity, linearity, time-invariance, causality, memory, static nonlinearity and invertibility. By example I present various types of systems that have, or do not have, these properties and how to prove various properties from the mathematical description of the system.

CHAPTER 5

This chapter introduces the concepts of impulse response and convolution as components in the systematic analysis of the response of linear, time-invariant systems. I present the mathematical properties of continuous-time convolution and a graphical method of understanding what the convolution integral says. I also show how the properties of convolution can be used to combine subsystems that are connected in cascade or parallel into one system and what the impulse response of the overall system must be. Then I introduce the idea of a transfer function by finding the response of an LTI system to complex sinusoidal excitation. This section is followed by an analogous coverage of discrete-time impulse response and convolution.

CHAPTER 6

This is the beginning of the student's exposure to transform methods. I begin by graphically introducing the concept that any continuous-time periodic signal with engineering usefulness can be expressed by a linear combination of continuous-time sinusoids, real or complex. Then I formally derive the Fourier series using the concept of orthogonality to show where the signal description as a function of discrete harmonic number (the harmonic function) comes from. I mention the Dirichlet conditions to let the student know that the continuous-time Fourier series applies to all *practical* continuous-time signals, but not to all *imaginable* continuous-time signals.

Then I explore the properties of the Fourier series. I have tried to make the Fourier series notation and properties as similar as possible and analogous to the Fourier transform, which comes later. The harmonic function forms a "Fourier series pair" with the time function. In the first edition I used a notation for harmonic function in which lowercase letters were used for time-domain quantities and uppercase letters for their harmonic functions. This unfortunately caused some confusion because continuous and discrete-time harmonic functions looked the same. In this edition I have changed the harmonic function notation for continuous-time signals to make it easily distinguishable. I also have a section on the convergence of the Fourier series illustrating the Gibb's phenomenon at function discontinuities. I encourage students to use tables and properties to find harmonic functions and this practice prepares them for a similar process in finding Fourier transforms and later Laplace and z transforms.

The next major section of Chapter 6 extends the Fourier series to the Fourier transform. I introduce the concept by examining what happens to a continuous-time Fourier series as the period of the signal approaches infinity and then define and derive the continuous-time Fourier transform as a generalization of the continuous-time Fourier series. Following that I cover all the important properties of the continuous-time Fourier transform. I have taken an "ecumenical" approach to two different notational conventions that are commonly seen in books on signals and systems, control systems, digital signal processing, communication systems and other applications of Fourier methods such as image processing and Fourier optics: the use of either cyclic frequency, f or radian frequency, ω. I use both and emphasize that the two are simply related through a change of variable. I think this better prepares students for seeing both forms in other books in their college and professional careers.

CHAPTER 7

This chapter introduces the discrete-time Fourier series (DTFS), the discrete Fourier transform (DFT) and the discrete-time Fourier transform (DTFT), deriving and defining them in a manner analogous to Chapter 6. The DTFS and the DFT are almost identical. I concentrate on the DFT because of its very wide use in digital signal processing. I emphasize the important differences caused by the differences between continuous and discrete time signals, especially the finite summation range of the DFT as opposed to the (generally) infinite summation range in the CTFS. I also point out the importance of the fact that the DFT relates a finite set of numbers to another finite set of numbers, making it amenable to direct numerical machine computation. I discuss the fast Fourier transform as a very efficient algorithm for computing the DFT. As in Chapter 6, I use both cyclic and radian frequency forms, emphasizing the relationships between them. I use F and Ω for discrete-time frequencies to distinguish them from f and ω, which were used in continuous time. Unfortunately, some authors reverse these symbols. My usage is more consistent with the majority of signals and systems texts. This is another example of the lack of standardization of notation in this area. The last major section is a comparison of the four Fourier methods. I emphasize particularly the duality between sampling in one domain and periodic repetition in the other domain.

CHAPTER 8

This chapter introduces the Laplace transform. I approach the Laplace transform from two points of view, as a generalization of the Fourier transform to a larger class of signals and as result that naturally follows from the excitation of a linear, time-invariant system by a complex exponential signal. I begin by defining the bilateral Laplace transform and discussing significance of the region of convergence. Then I define the unilateral Laplace transform. I derive all the important properties of the Laplace transform. I fully explore the method of partial-fraction expansion for finding inverse transforms and then show examples of solving differential equations with initial conditions using the unilateral form.

CHAPTER 9

This chapter introduces the z transform. The development parallels the development of the Laplace transform except applied to discrete-time signals and systems. I initially define a bilateral transform and discuss the region of convergence. Then I define a unilateral transform. I derive all the important properties and demonstrate the inverse transform using partial-fraction expansion and the solution of difference equations with initial conditions. I also show the relationship between the Laplace and z transforms, an important idea in the approximation of continuous-time systems by discrete-time systems in Chapter 15.

CHAPTER 10

This is the first exploration of the correspondence between a continuous-time signal and a discrete-time signal formed by sampling it. The first section covers how sampling is usually done in real systems using a sample-and-hold and an A/D converter. The second section starts by asking the question of how many samples are enough to describe a continuous-time signal. Then the question is answered by deriving the sampling theorem. Then I discuss interpolation methods, theoretical and practical, the special properties of bandlimited periodic signals. I do a complete development of the relationship between the CTFT of a continuous-time signal and DFT of a finite-length set of samples taken from it. Then I show how the DFT can be used to approximate the CTFT of an energy signal or a periodic signal. The next major section explores the use of the DFT in numerically approximating various common signal processing operations.

CHAPTER 11

This chapter covers various aspects of the use of the CTFT and DTFT in frequency response analysis. The major topics are ideal filters, Bode diagrams, practical passive and active continuous-time filters and basic discrete-time filters.

CHAPTER 12

This chapter covers the basic principles of continuous-time communication systems, including frequency multiplexing, single- and double-sideband amplitude modulation and demodulation, and angle modulation. There is also a short section on amplitude modulation and demodulation in discrete-time systems.

CHAPTER 13

This chapter is on the application of the Laplace transform including block diagram representation of systems in the complex frequency domain, system stability, system interconnections, feedback systems including root-locus, system responses to standard signals, and lastly standard realizations of continuous-time systems.

CHAPTER 14

This chapter is on the application of the z transform including block diagram representation of systems in the complex frequency domain, system stability, system interconnections, feedback systems including root-locus, system responses to standard signals, sampled-data systems and standard realizations of discrete-time systems.

CHAPTER 15

This chapter covers the analysis and design of some of the most common types of practical analog and digital filters. The analog filter types are Butterworth, Chebyshev Types I and II and Elliptic (Cauer) filters. The section on digital filters covers the most common types of techniques for simulation of analog filters, including impulse- and step-invariant, finite difference, matched z transform, direct substitution, bilinear z transform, truncated impulse response and Parks-McClellan numerical design.

CHAPTER 16

This chapter covers state-space analysis in both continuous-time and discrete-time systems. The topics are system and output equations, transfer functions, transformations of state variables and diagonalization.

APPENDICES

There are seven appendices on useful mathematical formulas, tables of the four Fourier transforms, Laplace transform tables and z transform tables.

CONTINUITY

The book is structured so as to facilitate skipping some topics without loss of continuity. Continuous-time and discrete-time topics are covered alternately and continuous-time analysis could be covered without reference to discrete time. Also, any or all of the last six chapters could be omitted in a shorter course.

REVIEWS AND EDITING

This book owes a lot to the reviewers, especially those who really took time and criticized and suggested improvements. I am indebted to them. I am also indebted to the many students who have endured my classes over the years. I believe that our relationship is more symbiotic than they realize. That is, they learn signal and system analysis from me and I learn how to teach signal and system analysis from them. I cannot count the number of times I have been asked a very perceptive question by a student that revealed not only that the students were not understanding a concept but that I did not understand it as well as I had previously thought.

WRITING STYLE

Every author thinks he has found a better way to present material so that students can grasp it and I am no different. I have taught this material for many years and through the experience of grading tests have found what students generally do and do not grasp. I have spent countless hours in my office one-on-one with students explaining these concepts to them and, through that experience, I have found out what needs to be said. In my writing I have tried to simply speak directly to the reader in a straightforward conversational way, trying to avoid off-putting formality and, to the extent possible, anticipating the usual misconceptions and revealing the fallacies in them. Transform methods are not an obvious idea and, at first exposure, students can easily get bogged down in a bewildering morass of abstractions and lose sight of the goal, which is to analyze a system's response to signals. I have tried (as every author does) to find the magic combination of accessibility and mathematical rigor because both are important. I think my writing is clear and direct but you, the reader, will be the final judge of whether that is true.

EXERCISES

Each chapter has a group of exercises along with answers and a second group of exercises without answers. The first group is intended more or less as a set of “drill” exercises and the second group as a set of more challenging exercises.

SUPPLEMENTS

Professors can benefit from McGraw-Hill’s COSMOS electronic solutions manual. COSMOS enables instructors to generate a limitless supply of problem material for assignment, as well as transfer and integrate their own problems into the software. Contact your McGraw-Hill sales representative for additional information.

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CONCLUDING REMARKS

As I indicated in the preface to the first edition, I welcome any and all criticism, corrections and suggestions. All comments, including ones I disagree with and ones that disagree with others, will have a constructive impact on the next edition because they point out a problem. If something does not seem right to you, it probably will bother others also and it is my task, as an author, to find a way to solve that problem. So I encourage you to be direct and clear in any remarks about what you believe should be changed and not to hesitate to mention any errors you may find, from the most trivial to the most significant.

I wish to thank the following reviewers for their invaluable help in making the second edition better.

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Michael J. Roberts, Professor
Electrical and Computer Engineering
University of Tennessee at Knoxville
mjr@utk.edu