国外电子与通信教材系列

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——基于MATLAB和Mathematica的设计方法

Filter Design for Signal Processing Using MATLAB and Mathematica

英文版

Miroslav D. Lutovac
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Prentice Hall

PHEI
電子工業出版社
Publishing House of Electronics Industry
www.phei.com.cn

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内容简介

模拟和数字滤波器设计在电子工程、应用数学和计算机科学领域都是非常重要的内容。本书将滤波器理论与实践相结合，展示了过去几年里算法和设计的新发展，其中包括成熟的滤波器算法和MATLAB、Mathematica算法的实现。本书分为两个部分，第一部分讲述了常规滤波器的设计技术，展示了一些新算法并进行了案例研究。第二部分讨论了现代设计方法的理论。本书有三个特点：一是可以方便地获取关于模拟和数字滤波器设计的最新知识；二是滤波器设计方面的大量案例研究；三是对椭圆函数滤波器的独特讲解。我们为读者提供了一整套软件工具（Mathematica 手册和 MATLAB 脚本），这对解决滤波器设计问题将很有帮助。

本书适合作为高等院校电子工程及相关专业本科高年级学生和研究生的教材和教学参考书。

版权贸易合同登记号：图字：01-2002-3805

图书在版编目（CIP）数据

信号处理滤波器设计——基于MATLAB和Mathematica的设计方法（英文版）/卢特威（Lutovac, M. D.）等著；-北京：电子工业出版社，2002.9

（国外电子与通信教材系列）

书名原文：Filter Design for Signal Processing: Using MATLAB and Mathematica

ISBN 7-5053-7977-1

Ⅰ.信… Ⅱ.卢… Ⅲ.信号处理-滤波器-设计-高等学校-教材-英文 Ⅳ. TN713

中国版本图书馆CIP数据核字（2002）第065183号

责任编辑：杜 萌
印 刷 者：北京东光印刷厂
出版发行：电子工业出版社 http://www.phei.com.cn
北京市海淀区万寿路173信箱 邮编：100036
经 销：各地新华书店
开 本：787×980 1/16 印张：49.25 字数：1135千字
版 次：2002年9月第1版 2002年9月第1次印刷
定 价：69.00元

序

2001年7月间，电子工业出版社的领导同志邀请各高校十几位通信领域方面的老师，商量引进国外教材问题。与会同志对出版社提出的计划十分赞同，大家认为，这对我国通信事业、特别是对高等院校通信学科的教学工作会很有好处。

教材建设是高校教学建设的主要内容之一。编写、出版一本好的教材，意味着开设了一门好的课程，甚至可能预示着一个崭新学科的诞生。20世纪40年代MIT林肯实验室出版的一套28本雷达丛书，对近代电子学科、特别是对雷达技术的推动作用，就是一个很好的例子。

我国领导部门对教材建设一直非常重视。20世纪80年代，在原教委教材编审委员会的领导下，汇集了高等院校几百位富有教学经验的专家，编写、出版了一大批教材；很多院校还根据学校的特点和需要，陆续编写了大量的讲义和参考书。这些教材对高校的教学工作发挥了极好的作用。近年来，随着教学改革不断深入和科学技术的飞速进步，有的教材内容已比较陈旧、落后，难以适应教学的要求，特别是在电子学和通信技术发展神速、可以讲是日新月异的今天，如何适应这种情况，更是一个必须认真考虑的问题。解决这个问题，除了依靠高校的老师和专家撰写新的符合要求的教科书外，引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，是会有好处的。

一年多来，电子工业出版社为此做了很多工作。他们成立了一个“国外电子与通信教材系列”项目组，选派了富有经验的业务骨干负责有关工作，收集了230余种通信教材和参考书的详细资料，调来了100余种原版教材样书，依靠由20余位专家组成的出版委员会，从中精选了40多种，内容丰富，覆盖了电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等方面，既可作为通信专业本科生和研究生的教学用书，也可作为有关专业人员的参考材料。此外，这批教材，有的翻译为中文，还有部分教材直接影印出版，以供教师用英语直接授课。希望这些教材的引进和出版对高校通信教学和教材改革能起一定作用。

在这里，我还要感谢参加工作的各位教授、专家、老师与参加翻译、编辑和出版的同志们。各位专家认真负责、严谨细致、不辞辛劳、不怕琐碎和精益求精的态度，充分体现了中国教育工作者和出版工作者的良好美德。

随着我国经济建设的发展和科学技术的不断进步，对高校教学工作会不断提出新的要求和希望。我想，无论如何，要做好引进国外教材的工作，一定要联系我国的实际。教材和学术专著不同，既要注意科学性、学术性，也要重视可读性，要深入浅出，便于读者自学；引进的教材要适应高校教学改革的需要，针对目前一些教材内容较为陈旧的问题，有目的地引进一些先进的和正在发展中的交叉学科的参考书；要与国内出版的教材相配套，安排好出版英文原版教材和翻译教材的比例。我们努力使这套教材能尽量满足上述要求，希望它们能放在学生们的课桌上，发挥一定的作用。

最后，预祝“国外电子与通信教材系列”项目取得成功，为我国电子与通信教学和通信产业的发展培土施肥。也恳切希望读者能对这些书籍的不足之处、特别是翻译中存在的问题，提出意见和建议，以便再版时更正。

吴佑寿

中国工程院院士、清华大学教授

“国外电子与通信教材系列”出版委员会主任

出 版 说 明

进入21世纪以来，我国信息产业在生产和科研方面都大大加快了发展速度，并已成为国民经济发展的支柱产业之一。但是，与世界上其他信息产业发达的国家相比，我国在技术开发、教育培训等方面都还存在着较大的差距。特别是在加入WTO后的今天，我国信息产业面临着国外竞争对手的严峻挑战。

作为我国信息产业的专业科技出版社，我们始终关注着全球电子信息技术的发展方向，始终把引进国外优秀电子与通信信息技术教材和专业书籍放在我们工作的重要位置上。在2000年至2001年间，我社先后从世界著名出版公司引进出版了40余种教材，形成了一套“国外计算机科学教材系列”，在全国高校以及科研部门中受到了欢迎和好评，得到了计算机领域的广大教师与科研工作者的充分肯定。

引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，将有助于我国信息产业培养具有国际竞争能力的技术人才，也将有助于我国国内在电子与通信教学工作中掌握和跟踪国际发展水平。根据国内信息产业的现状、教育部《关于“十五”期间普通高等教育教材建设与改革的意见》的指示精神以及高等院校老师们反映的各种意见，我们决定引进“国外电子与通信教材系列”，并随后开展了大量准备工作。此次引进的国外电子与通信教材均来自国际著名出版商，其中影印教材约占一半。教材内容涉及的学科方向包括电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等，其中既有本科专业课程教材，也有研究生课程教材，以适应不同院系、不同专业、不同层次的师生对教材的需求，广大师生可自由选择和自由组合使用。我们还将与国外出版商一起，陆续推出一些教材的教学支持资料，为授课教师提供帮助。

此外，“国外电子与通信教材系列”的引进和出版工作得到了教育部高等教育司的大力支持和帮助，其中的部分引进教材已通过“教育部高等学校电子信息科学与工程类专业教学指导委员会”的审核，并得到教育部高等教育司的批准，纳入了“教育部高等教育司推荐——国外优秀信息科学与技术系列教学用书”。

为做好该系列教材的翻译工作，我们聘请了清华大学、北京大学、北京邮电大学、东南大学、西安交通大学、天津大学、西安电子科技大学、电子科技大学等著名高校的教授和骨干教师参与教材的翻译和审校工作。许多教授在国内电子与通信专业领域享有较高的声望，具有丰富的教学经验，他们的渊博学识从根本上保证了教材的翻译质量和专业学术方面的严格与准确。我们在此对他们的辛勤工作与贡献表示衷心的感谢。此外，对于编辑的选择，我们达到了专业对口；对于从英文原书中发现的错误，我们通过与作者联络、从网上下载勘误表等方式，逐一进行了修订；同时，我们对审校、排版、印制质量进行了严格把关。

今后，我们将进一步加强同各高校教师的密切关系，努力引进更多的国外优秀教材和教学参考书，为我国电子与通信教材达到世界先进水平而努力。由于我们对国内外电子与通信教育的发展仍存在一些认识上的不足，在选题、翻译、出版等方面的工作中还有许多需要改进的地方，恳请广大师生和读者提出批评及建议。

电子工业出版社

FOREWORD

The basics of filter design theory have not changed for over half a century. Thus, irrespective of whether the prevailing or available technology favors a particular kind of filter realization; e.g., passive LCR, active RC, digital, or switched-capacitor, the initial steps from filter specifications to actual design are based on the fundamental work of such pioneers as O.J. Zobel, R.M. Foster, W. Cauer, O. Brune, S. Darlington, and many others. The resulting design theories, foremost among them insertion-loss theory, have resulted in an almost ritualistic procedure for the preliminaries of a filter design. This consists of transforming the given specifications; e.g., maximum-passband and minimum- stopband loss, transition-frequency band, impedance level, and so on, into either a transfer function in s or z (depending on whether the filter is to operate in continuous or discrete time), or into an LC filter structure. In doing so, the designer has the choice of filter type; e.g., Chebyshev, Butterworth, Elliptic, Bessel, and many more, this choice being determined by such factors as the filter order (which is generally related to the filter cost), group delay, inband ripple, band-edge selectivity, ease of tuning, and various other application-dependent requirements. Having made these decisions, and taken into account the given specifications, the filter designer then either consults a book of filter tables, or a corresponding computer program, and obtains the above-mentioned transfer function or filter topology. At this point, the "preliminary design ritual" ends and the designer must either make some difficult choices in terms of available technology, or comply with the technological demands of the system to be designed; i.e., IC design, discrete-component active RC or LC design, digital signal processor (DSP), monolithic crystal, surface acoustic wave (SAW), mechanical, and so on.

This book on Advanced Filter Design by M.D. Lutovac, D.V. Tosic and B.L. Evans does away with what I have called the "preliminary design ritual," and opens up completely new vistas in basic filter design, regardless of the technology. The authors show that the conventional filter types (e.g., Butterworth, Chebyshev, Elliptic) are not unique solutions to a given set of specifications; much rather they are special cases of a *continuum of solutions*, all of which, while satisfying the specifications, permit tradeoffs to be made between a variety of optimizations that were considered inaccessible and unachievable in the past. Thus, where, for example, the poles and zeros of an elliptic filter, meeting certain gain and phase demands, were considered immutable in the past, this book can provide a new set of poles and zeros (with possibly an increased order by one or, rarely, two) which they call the "minimum Q" solution, whose poles lie not on an ellipse but on a semicircle (as with a Butterworth filter) and *whose dominant pole Q is significantly lower than that of the original elliptic filter.* Minimum pole Q, of course, implies lower sensitivity to component tolerances and, as a rule, lower thermal noise. However, this is only one of the many optimization options that this remarkable book supplies. It can provide a variety of different solutions (still meeting specs, of course, and with barely an increase in filter order). Thus, for example, it can provide a solution for minimal deviation from linear phase, or for specified group delay while maintaining minimal filter order, or, in the case of discrete-time filters, for zero-phase, or for a multiplierless elliptic IIR filter structure. These are merely examples of the unprecedented versatility in filter design that this new and unique book supplies. Since the essence of the book is to loosen the rigidity, in terms of options and optimization, that the previous "preliminary design ritual" demanded, it can be used as a new versatile preliminary design routine for any kind of subsequent filter realization—be it, for example. LC, active RC, digital or switched-capacitor. Indeed, the authors demonstrate their new and versatile design technique in conjunction with all of these filter types, and many more.

So how do the authors manage the extraordinary accomplishment of liberating themselves from the old classical preliminary design ritual, and why has this not been done long ago? The answer is simple. Beside some exceptionally elegant and creative mathematical stratagems (e.g., accurate replacement of Jacobi elliptic functions by functions comprising polynomials, square roots, and logarithms), they utilize high-power computer programs and optimization routines that were not previously available. Foremost among these are optimization routines carried out with symbolic analysis by *Mathematica*, and the advance filter design software of MATLAB. The exceptional combination of these highly advanced, modern and sophisticated design programs, together with a remarkable mathematical and algorithmic acumen, and an indepth and profound understanding of classical and modern filtering and signal-processing techniques, has produced in this book a new, and, without exaggeration, revolutionary method of filter design, that will have a pivotal effect on the way filter design is carried out in the future. This does not detract one bit from the monumental achievements of the previous pioneers in network theory and filter design; it merely reflects the fact that the modern computing tools available today, when in the hands of the right experts in mathematics, algorithmics, and network theory, can change dramatically a discipline such as filter theory and design, which was previously considered complete, definitive, and immutable. It is fortunate that the right ingredients come together in the form of these three talented authors, combined with the best that modern computer technology and algorithmics can supply (i.e. MATLAB and *Mathematica*) to produce a book and computer-software for filter design that will change the field in a profound way that could not have been anticipated but a few years ago. With the appearance of this book, filter design may never be the same again.

George S. Moschytz

Zurich

PREFACE

Analog and digital filter design is of great importance throughout engineering, applied mathematics, and computer science. Filters are the staple for designers in the controls, signal processing, and communications fields. They are commonly used in a wide variety of systems, such as chemical processing plants, instrumentation, suspension systems, modems, and digital cellular phones.

When a designer uses conventional techniques and software to design a filter, the designer receives only one possible filter that meets a set of specifications, yet an infinite number of designs may exist. This book develops alternative techniques and software to produce a comprehensive set of designs that meet the specification and represent the infinite design space. Included in the set of designs are filters that have minimal order, minimal quality factors, minimal complexity, minimal sensitivity to pole-zero locations, minimal deviation from a specified group delay, approximate linear phase, and minimized peak overshoot. For digital filters, the design space also includes filters with power-of-two coefficients. These alternative filter designs are crucial when evaluating filters for synthesis in analog circuits, digital hardware, or software.

This book overcomes the gap between filter theory and practice, and it presents new algorithms and designs developed over the last five years. The book includes ready-to-use filter design algorithms and implementations of the algorithms in both MATLAB and *Mathematica*. In order to make the material accessible to both the practitioner and the researcher, we have divided the book into two parts. Part I reviews conventional filter design techniques, presents several new ready-to-use algorithms, and discusses many case studies. The case studies present filters that cannot be designed with conventional techniques but can be designed with advanced methods. Part II discusses the theory underlying the new advanced design methods. The book also contains appendices to show examples of using advanced filter design software in MATLAB and *Mathematica*, and it includes filter design problems for the reader to solve.

In designing analog and digital IIR filters, one generally relies on canned software routines or mechanical procedures that rely on extensive tables. The primary reason for this "black box" approach is that the approximation theory that underlies filter design includes complex mathematics. Unfortunately, the conventional approach returns only one design, and it hides a wealth of alternative filter designs that are more robust when implemented in analog circuits, digital hardware, and software.

In this book, we provide advanced techniques to return multiple designs that meet the user specification. The key observations underlying our advanced filter design are as follows:

- Many designs satisfy the same user specification.
- Butterworth and Chebyshev IIR filters are special cases of elliptic IIR filters.
- Minimum-order filters may not be as efficient to implement as some higher-order filters.

Our approach is to search for a variety of design specifications that satisfies both the user specification and the limitations on the target implementation technology. Our algorithms return the following designs:

- Minimal filter order
    - Maximum stopband loss margin
    - Maximum passband loss margin
    - Minimum transition (conventional design)
    - Maximum transition
- Minimal maximum quality factor
- Minimal implementation cost
- Minimal deviation from specified group delay
- Minimal deviation from linear phase
- Elliptic IIR filters with power-of-two coefficients
- Zero-phase elliptic IIR filters
- Multiplierless elliptic half-band IIR filters
- Multiplierless Hilbert transformers
- Robust low-sensitivity sharp cutoff SC filters

For example, we can design selective elliptic IIR filters for microcontrollers and for other architectures that have fixed-point arithmetic and no hardware multiplier.

The theory underlying our advanced techniques is rooted in Jacobi elliptic functions which we use to approximate the magnitude frequency response of the filter. Jacobi elliptic functions are very complex transcendental functions. For many filter orders, however, we derive closed-form solutions to design elliptic filters that only use polynomials, square roots, and logarithms. This breakthrough allows us to derive precise relationships between the user specification, implementation constraints, and the pole-zero locations of the filter. Thus, *we have transformed the design space for IIR filters from elliptic function approximation theory into polynomial theory, which can be understood by designers with a knowledge of algebra.* In addition, final expressions are simple. Most of elliptic filters can be accurately designed ten to hundred times faster than using the classic approach.

The elliptic approximation is the most frequently used function in the design of IIR filters. In the latter part of this book, we explore many of the properties of elliptic functions such as its nesting property. These properties enable us to automate the design of filters using symbolic algebra. Transfer function poles and zeros are obtained by means of simple formulas, thereby freeing the designer from having to rely on extensive tables or canned computer programs. Symbolic design makes it possible to eliminate redundant variables, decrease the filter order, and simplify and approximate the underlying complex relations prior to the final numeric calculations.

The primary benefit of this book is convenient access to the latest advances in algorithms and software for analog and digital IIR filter design. These advanced techniques can design many types of filters that conventional techniques cannot design. A secondary benefit is a large collection of case studies for filter designs that require advanced techniques. Another benefit is a unique treatment of elliptic function filters.

The book is divided into 13 chapters.

Chapter 1 presents an overview of basic classes of continuous-time and discrete-time signals. We discuss mathematical representations of signals, and introduce the two computer environments, MATLAB and *Mathematica*, which we use to analyze and process signals.

In Chapter 2, we introduce fundamentals of linear system theory and define basic system properties. We present basic definitions and background mathematics that are used in this book. Since many readers are already familiar with this material, our aim is to be logically consistent rather than mathematically rigorous.

In Chapter 3, we review the definition and the salient properties of the most important transforms required by the filter design studied in this book. We focus on the phasor transformation, Fourier series and harmonic analysis, Fourier transformation, Laplace transformation, discrete Fourier transform, and z-transform. Step-by-step procedures for analyzing LTI systems in the transform domain are given.

Chapter 4 is intended to review the basics of classic analog filter design. Classification, salient properties and sensitivity of transfer functions are given. The most important analog filter realizations are presented. A detailed case study is given for realization of various transfer functions.

Chapter 5 reviews basic definitions of analog filter design. It introduces straightforward procedures to map the filter specification into a design space. We search this design space for the optimum solution according to given criteria. We conclude this chapter by an application example in which we design a robust selective analog filter based on commercially available integrated circuits.

In Chapter 6, we present (1) case studies of optimal analog filters that cannot be designed with classic techniques, and (2) the formal, mathematical framework that underlies their solutions. We present detailed step-by-step analog filter design algorithms.

Chapter 7 presents an extensible framework for designing analog filters that exhibit several desired behavioral properties after being realized in circuits. In the framework, we model the constrained non-linear optimization problem as a sequential quadratic programming problem. We derive the differentiable constraints and a weighted differentiable objective function for simultaneously optimizing the behavioral properties of magnitude response, phase response, and peak overshoot and the implementation property of quality factors.

Chapter 8 is intended to review the basics of classic digital IIR filter design. Classification, salient properties and sensitivity of transfer functions in the z-domain are given. The most important digital filter realizations are presented. For each realization we provide complete design equations and procedures that make the design easily applicable to a broad variety of digital filter design problems.

Chapter 9 reviews basic definitions of digital IIR filter design. It introduces straightforward procedures to map the filter specification into a design space. We search this design space for the optimum solution according to given criteria. We conclude this chapter with several important application examples in which we design low-sensitivity selective multiplierless IIR filters, power-of-two IIR filters, half-band IIR filters, 1/3-band filters, narrow-band IIR filters, Hilbert transformers, and zero-phase IIR filters. Each example design is followed by a comprehensive step-by-step procedure for computing the filter coefficients.

In Chapter 10, we present (1) case studies of optimal digital filters that cannot be designed with classic techniques, and (2) the formal, mathematical framework that underlies their solutions. We present detailed step-by-step digital filter design algorithms.

Chapter 11 presents an extensible framework for the simultaneous constrained optimization of multiple properties of digital IIR filters. The framework optimizes the pole-zero locations for behavioral properties of magnitude and phase response, and the implementation property of quality factors, subject to constraints on the same properties. We formulate the constrained nonlinear optimization problem as a sequential quadratic programming problem.

Chapter 12 introduces the basic Jacobi elliptic functions and reviews the most important relations between them. Several related theorems not found in standard textbooks are presented. Various useful approximation formulas are offered to facilitate the derivation of elliptic rational functions. A nesting property of the Jacobi elliptic functions is derived. In this chapter we present a novel approach to the design of elliptic filters in which we use exact closed-form expressions based on the nesting property.

In Chapter 13, we introduce the elliptic rational function as a natural generalization of the Chebyshev polynomial and we bypass mathematical theory of special functions required in the previous chapter. We prefer to give a reader an intuitive feel of the basic properties of the elliptic rational function. Our goal is to build the knowledge of the elliptic rational function using simple algebraic manipulations, even without mentioning the Jacobi elliptic functions.

Problems are included at the ends of chapters. The majority provide important practice with the concepts and techniques presented. Almost all the problems are suitable for solution using *Mathematica* and MATLAB. The book is supported by the following websites which contain the filter design software, *Mathematica* notebooks and MATLAB scripts:

`http://galeb.etf.bg.ac.yu/~lutovac`

`http://iritel.iritel.bg.ac.yu/users/lutovac/www`

There is also a companion website that accompanies this text:

`http://www.prenhall.com/lutovac`

How this book can be used in the classroom?

As the title indicates, the emphasis of this book is upon automating filter design in software (MATLAB and *Mathematica*), rather than upon studying the general filter theory.

Our overall approach to the topic has been guided by the fact that with the recent and anticipated developments in the technologies for filter design and implementation, the importance of having equal familiarity with computer-aided techniques suitable for analyzing and designing both continuous-time and discrete-time filters has increased dramatically.

We seek to leave with each reader (student, instructor, researcher, or practicing engineer) a set of software tools — *Mathematica* notebooks and MATLAB scripts — useful for solving filter design problems of practical importance.

A notable feature of the book is a detailed step-by-step exposure to the filter analysis by transform method, or in the time domain, exemplified by self-contained *Mathematica* notebooks. Students can use these notebooks to (a) automate symbolic filter analysis and design in software, (b) derive closed-form expressions for, say, transfer functions, and (c) gain insight into the relevant filter design parameters and coefficients.

This book was designed for educators who wish to integrate their curriculum with computer-based learning tools. Our goal is to provide an effective and efficient environment for students to learn the theory and problem-solving skills for contemporary filter design. To accomplish this we have used a computer-biased approach in which computer solutions and theory are viewed as mutually reinforcing rather than an either-or proposal.

We believe that students learn most effectively by solving problems following a worked-out problem as a model. Software scripts for running electronic examples (of worked-out problems) can capture the essence of a key concept, and encourage active participation in learning.

Filter analysis and design is a foundation subject for many students, due to its direct engineering applications, especially in electrical engineering. The concepts which it embodies, and the analytical techniques which it employs, are valid far outside the boundaries of electrical engineering.

The subject of filter design is an extraordinarily rich one, and a variety of approaches can be taken in structuring an introductory or advanced filter design course. This text provides a broad treatment of filter design and analysis, and contains sufficient material for a one-semester or two-semester course on the subject. Students using this book are assumed to have a basic background in calculus, complex numbers, and differential equations.

A typical one-semester introductory filter design course at a sophomore-junior level using this book could comprise the following: (a) Chapters 1–3, (b) Chapter 4, (c) a choice from Chapter 5 with the emphasis placed on specification and approximation problem, (d) Chapter 8, (e) a choice from Chapter 9 (digital specification and approximation problem). Combine the text with the MATLAB Signal Processing Toolbox and the *Mathematica* Signals and Systems Pack to illustrate the classic filter design procedures. Proceed lightly through our *Mathematica* Example Notebooks and our MATLAB filter design toolbox.

A one-semester introductory analog filter design course at a sophomore-junior level using this book could comprise the following: (a) Chapters 1–3, (b) Chapters 4, 5 and 7, (c) utilize the MATLAB Signal Processing Toolbox, and the *Mathematica* Signals and Systems Pack, to illustrate the classic analog filter design, (d) proceed through our *Mathematica* Example Notebooks, and our MATLAB analog filter design toolbox.

A one-semester introductory digital filter design course at a sophomore-junior level using this book could comprise the following: (a) Chapters 1–3, (b) Chapters 8, 9 and 11, (c) utilize the MATLAB Signal Processing Toolbox, and the *Mathematica* Signals and Systems Pack, to illustrate the classic digital filter design, (d) proceed through our *Mathematica* Example Notebooks, and our MATLAB digital filter design toolbox.

In addition to these course formats this book can be used as the basic text for a thorough, two-semester sequence on advanced filter design. The portions of the book not used in an introductory course on filter design, together with other sources, can form the basis for a senior elective course. Alternatively, for a two-semester course, we suggest coverage of the first 11 chapters, proceeding lightly through Chapters 12 and 13, and covering thoroughly Chapters 5 and 9 because they introduce the design space concept in filter design.

The book can serve as a text for a sequence of two one-semester courses on analog and digital filters for senior undergraduate or first-year graduate students. Such a course could comprise the following: (a) review of Chapters 1–3, (b) Chapters 4, 5, (c) brief discussion of analog-filter design algorithms (Chapter 6) with the emphasis placed on application rather than derivation, (d) Chapter 7 in full depth, (e) Chapters 8, 9, (f) brief discussion of digital-filter design algorithms (Chapter 10) with the emphasis placed on application rather than derivation, (g) Chapter 11 in full depth, (h) a choice from Chapters 12 and 13, depending on the course orientation desired.

The book's structure allows students who are interested in only analog filters to skip chapters on digital filters, without loss of continuity, and vice versa. It should be pointed out that not all sections in every chapter are covered in class. Also, various topics can be omitted at the discretion of the instructor. Depending upon the background the students can utilize chapters 1, 2, and 3 to review and expand their knowledge of linear system theory for continuous-time and discrete-time systems.

Advanced postgraduate courses (masters's programs and Ph.D. programs) can also be prepared from Chapters 12 and 13.

Selected topics chosen from the book chapters can be used in Electronics and Electric Circuit Theory courses, too.

We have included a collection of more that 70 *Mathematica* notebooks, numerous MATLAB scripts, and many end-of-chapter problems and exercises. This variety and quantity will hopefully provide instructors with considerable flexibility in putting together homework sets that are tailored to the specific needs of their students. Many filter realizations, both analog and digital, presented throughout the book can help lecturers organize versatile homeworks, projects and tests for the students. In addition, the filter design algorithms (Chapters 6 and 10) can be directly programmed in any language or environment such as Visual BASIC, Visual C, Maple, DERIVE, or MathCAD.

We thank Professor Ljiljana Milić for her valuable comments which have improved the book. We would like to thank Professor Marija Hribšek, Professor Antonije Djordjević and Professor Veljko Milutinović, for their encouragement throughout the period in which the book was written. The first author is grateful to general manager Siniša Davitkov for providing him with the opportunity to work on filter design. We would like to thank Professor George S. Moschytz for his encouragement and support while working on the writing this book.

The continuing encouragement, patience, technical support, and enthusiasm provided by Prentice Hall, and in particular by Alice Dworkin have been important in bringing this project to fruition.

We also want to thank the very thoughtful and careful reviewers, Professor Igor Tsukerman, The University of Akron, and Professor Michael J. Werter, The University of California at Los Angeles, for their useful comments.

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