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

自适应滤波器原理

（第四版）

Adaptive Filter Theory

Fourth Edition

英文原版

[美] Simon Haykin 著

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内容简介

自适应滤波器是现代信号处理的一个重要组成部分。本书共17章，系统全面地阐述了自适应滤波器的数学基础、基本结构和基本算法，从维纳滤波、卡尔曼滤波直到现代的盲自适应技术和神经网络方法，充分反映了近年来该领域的新理论、新技术和新应用，集基本理论、应用技术、实现方法于一身，内容丰富、概念清晰、取材新颖、阐述清楚、系统性好、可读性强。书中配有大量富有特色的例题、习题及计算机实验结果，图文并茂、深入浅出。这些特色既有利于读者对相关内容的掌握和理解，又可以启发读者深入思考，培养分析问题、解决问题的创新能力。本书可作为通信和电子信息类高年级本科生和研究生的教材或参考书，对从事自适应信号处理及相近学科的教师和研究人员，也有很好的参考价值。

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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

教材出版委员会

Preface

The subject of adaptive filters constitutes an important part of statistical signal processing. Whenever there is a requirement to process signals that result from operation in an environment of unknown statistics or one that is inherently nonstationary, the use of an adaptive filter offers a highly attractive solution to the problem as it provides a significant improvement in performance over the use of a fixed filter designed by conventional methods. Furthermore, the use of adaptive filters provides new signal-processing capabilities that would not be possible otherwise. We thus find that adaptive filters have been successfully applied in such diverse fields as communications, control, radar, sonar, seismology, and biomedical engineering, among others.

Aims of the Book

The primary aim of this book is to develop the mathematical theory of various realizations of *linear adaptive filters*. Adaptation is accomplished by adjusting the free parameters (coefficients) of a filter in accordance with the input data, which, in reality, makes the adaptive filter nonlinear. When we speak of an adaptive filter being "linear," we mean the following: The input–output map of the filter obeys the principle of superposition whenever, at any particular instant of time, the filter's parameters are all fixed.

There is no unique solution to the linear adaptive filtering problem. Rather, we have a "kit of tools" represented by a variety of recursive algorithms, each of which offers desirable features of its own. This book provides such a kit. It also provides an introduction to neural networks, which are basic to nonlinear adaptive filtering.

In terms of background, it is assumed that the reader has taken introductory undergraduate courses on probability theory and digital signal processing; undergraduate courses on communication and control systems would also be an advantage.

Organization of the Book

The book begins with an introductory chapter, where the operations and different forms of adaptive filters are discussed in general terms. The chapter ends with historical notes, which are included to provide a source of motivation for the interested reader to plough through the rich history of the subject. The concepts and algorithms introduced in this chapter are explained in detail in subsequent parts of the book.

The main chapters of the book, 17 in number, are organized as follows:

- *Stochastic processes and models.* This material, presented in Chapter 1, emphasizes partial characterization (i.e., second-order statistical description) of stationary stochastic processes. As such, it is basic to much of what is presented in the rest of the book.
- *Wiener filter theory and its application to linear prediction.* The Wiener filter, presented in Chapter 2, defines the optimum linear filter for a stationary environment, and therefore provides a framework for the study of linear adaptive filters. Linear prediction theory, encompassing both of its forward and backward forms and variants thereof, is discussed in Chapter 3; the chapter finishes with the application of linear prediction to speech coding.
- *Least-mean-square (LMS) family of adaptive filters.* The LMS filter is built around a transversal (i.e., tapped-delay-line) structure. In its most basic form, it is simple to design, yet highly effective in performance—two practical features that have made it highly popular in various applications. Chapter 4 presents the fundamentals of an old optimization technique known as the method of steepest descent, from which the LMS filter is readily derived. Chapter 5 presents a detailed treatment of the many facets of the LMS filter, its theory and practical applications. The two highlights of the chapter are:
  (i) *Small-step-size statistical theory*, which provides a fairly accurate description of the transient behavior of the LMS filter and its learning curve when the step-size parameter is assigned a small value. This new theory, rooted in the Langevin equation of nonequilibrium thermodynamics, avoids the unrealistic assumptions made in the independence theory traditionally used in the study of LMS filters. Computer simulations are presented, demonstrating close agreement between the findings of the small-step-size theory and experimental results.
  (ii) H^∞ *theory*, which provides the mathematical basis for the deterministic robustness of the LMS filter.

  Chapters 6 and 7 expand on the LMS family of LMS filters by presenting detailed treatments of normalized LMS filters, affine projection adaptive filters, frequency-domain and subband adaptive LMS filters; the affine projection filter is an intermediate adaptive filter between the normalized LMS filter and recursive least-squares filter.
- *Recursive least-squares (RLS) adaptive filters.* The RLS filter overcomes some practical limitations of the LMS filter by providing a faster rate of convergence and an insensitive performance to variations in the eigenvalue spread of the correlation matrix of the input signal; the price paid for these improvements is increased computational complexity. Chapter 8 discusses the method of least squares, which may be viewed as the deterministic counterpart of the Wiener filter rooted in stochastic processes. In the method of least-squares, the input data are processed on a block-by-block basis; block methods, disregarded in the past because of their numerical complexity, are becoming increasingly attractive, thanks to continuing improvements in digital computer technology. Chapter 9 builds on the method of

least squares, and uses the matrix inversion lemma to derive the RLS filter. The highlights of this chapter are:

(i) Statistical theory of RLS filters.

(ii) H^{∞} theory of RLS filters.

In reality, the RLS adaptive filter is a special case of the celebrated Kalman filter that emphasizes the notion of a state. It is therefore important that we have a good understanding of Kalman filter theory, which, in a stationary environment, also includes the Wiener filter as a special case. Derivations of the Kalman filter, its variants and extension, are discussed in Chapter 10. This chapter also establishes the one-to-one correspondences between Kalman filters and RLS filters, thereby providing the framework for a unified treatment of the whole family of RLS adaptive filters. Chapter 11, built on Givens rotations, derives the square-root information and covariance forms of square-root RLS filters, which overcome numerical difficulties encountered in the digital implementation of ordinary RLS filters. Chapter 12, on order-recursive filters, describes latticelike structures for the design of adaptive filters that are of the same order of computational complexity as LMS filters; the improvement in computational complexity is achieved by exploiting the time-shifting property inherent to temporal processing. Chapter 12 presents derivations of the gradient adaptive lattice (GAL) and QR-decomposition-based least-squares lattice (QRD–LSL) algorithms, which are respectively the simplest in computational terms and most powerful in performance terms.

- *Finite-precision effects.* The theory of linear adaptive filters presented in Chapters 5 through 12, is based on continuous mathematics (i.e., infinite precision). When, however, any adaptive filter is implemented in digital form, effects due to the use of finite-precision arithmetic arise. Chapter 13 discusses these effects in the digital implementation of LMS and RLS filters.
- *Tracking of time-varying systems.* Chapter 14 expands on the theory of LMS and RLS filters by evaluating and comparing their performances when they operate in a nonstationary environment, assuming a Markov model. The chapter uses the extended Kalman filter to derive modified forms of RLS filters that are assured of optimality over the LMS filter in a nonstationary environment. The chapter finishes by deriving new forms of LMS and RLS filters with adaptive memory which respectively permit recursive adjustments to the step-size parameter and exponential weighting factor of these filters.
- *Infinite-duration impulse response (IIR) adaptive filters.* The linear adaptive filters discussed in Chapters 5 through 14 are all built around transversal or lattice structures that are characterized by an impulse response of finite duration. Chapter 15 presents a brief treatment of the output-error method and equation-error method for the design of IIR adaptive filters, and discusses practical issues that arise in their use. The chapter also describes Laguerre adaptive filters that combine the desirable properties of FIR and IIR structures.
- *Blind deconvolution.* The linear adaptive filters studied in Chapters 5 through 15 assume the availability of a desired response, which is intended to guide the adap-

tation of free parameters of the filter during training. When there is no desired response available, we have to resort to the use of blind adaptation (i.e., unsupervised adaptive filtering). Chapter 15 discusses two primary blind deconvolution algorithms:

- Subspace decomposition algorithms based on second-order statistics, which exploit the cyclostationary nature of modulated signals in applications involving data transmission over communication channels.
- Bussgang algorithms, which exploit higher order statistics of the received signal at the output of a communication channel.
- The chapter finishes with a discussion of Bussgang fractionally spaced equalizers, where these two major themes of blind deconvolution are tied together.

- *Back-propagation learning.* Neural networks, built around nonlinear processing units, provide powerful tools for solving difficult nonlinear adaptive filtering problems. Multilayer perceptrons, with one or more hidden layers of processing units, constitute an important class of neural networks. Chapter 17 derives the back-propagation algorithm for the supervised training of multilayer perceptrons; the back-propagation algorithm may be viewed as a generalization of the LMS algorithm. The novel feature of the material presented in this chapter is emphasis on the complex form of the back-propagation algorithm, which makes it consistent with the rest of the book.

The book concludes with an Epilogue, where the following five topics are briefly discussed:

- Proportionate adaptation
- Robust statistics
- Blind source separation
- Dynamically driven recurrent neural networks
- Derivative-free state estimation for nonlinear dynamically systems

These discussions are included to provide the reader with a more complete picture of the ever-expanding subject of adaptive filters.

The book also includes appendices on the following topics:

- Complex variable theory
- Differentiation with respect to a vector
- Method of Lagrange multipliers
- Estimation theory
- Eigenanalysis
- Rotations and reflections
- Complex Wishart distribution

In different parts of the book, use is made of the fundamental ideas presented in these chapters.

Ancillary Material

- A Glossary is included, consisting of a list of definitions, notations and conventions, a list of abbreviations, and a list of principal symbols used in the book.
- All publications referred to in the text are compiled in the Bibliography. Each reference is identified in the text by the name(s) of the author(s) and the year of publication. The Bibliography also includes many other references that have been added for completeness.

Examples, Computer Experiments, and Problems

Many examples are included in different chapters of the book to illustrate concepts and theories under discussion.

The book also includes many computer experiments that have been developed to illustrate the underlying theory and applications of the LMS and RLS algorithms. These experiments help the reader to compare the performances of different members of these two families of linear adaptive filtering algorithms.

Each chapter of the book, except for the introductory chapter, ends with problems that are designed to do two things:

- Help the reader to develop a deeper understanding of the material covered in the chapter.
- Challenge the reader to extend some aspects of the theory discussed in the chapter.

Solutions Manual

The book has a companion solutions manual that presents detailed solutions to all the problems at the end of Chapters 1 through 17 of the book. A copy of the manual can be obtained by instructors who have adopted the book for classroom use by writing directly to the publisher.

The MATLAB codes for all the computer experiments can be accessed by going to the web site http://www.prenhall.com/haykin/

Use of the Book

The book is written at a level suitable for use in graduate courses on adaptive signal processing. In this context, it is noteworthy that the organization of the material covered in the book offers a great deal of flexibility in the selection of a suitable list of topics for such a graduate course.

It is hoped that the book will also be useful to researchers and engineers in industry as well as government establishments, working on problems relating to the theory and applications of adaptive filters.

Simon Haykin

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Simon Haykin

目 录 概 览

Contents