国外电子与通信教材系列

西蒙·赫金

信号与系统

（第二版）

Signals and Systems

Second Edition

英文版

[加] Simon Haykin
[美] Barry Van Veen 著

WILEY
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内 容 简 介

本书全面、系统地介绍了信号与系统的基本概念、理论、方法及应用。全书共分10章。第1章介绍了信号与系统的基本概念；第2章讨论了线性非时变系统的时域分析方法；第3章和第4章分别讨论了离散时间周期与非周期信号、连续时间周期与非周期信号，以及线性非时变系统的傅里叶描述以及傅里叶描述在混合信号类型中的应用；第6章和第7章分别讨论了连续时间信号与离散时间信号的复指数描述；第5章、第8章和第9章分别介绍了信号与系统在通信系统、滤波器与均衡器以及线性反馈系统中的应用；第10章为若干关于非稳定信号以及非线性与时变系统的课题提供了简要的说明。

本书在体系和内容上独具特色。第1章包含了有关噪声的新内容，第4章特别介绍了在混合信号应用中如何在4种基本傅里叶表示方法之间建立联系。全书各章都有用MATLAB语言解题的内容、参考资料以及进一步的阅读材料，并配有相当数量的例题。通过书中大量的各类习题以及计算机实验，能够使读者开阔视野，为读者提供了足够的训练空间。

本书可作为电气工程、电子、通信、信号处理、自动控制、计算机等专业信号与系统课程的英文教材或参考书，也可供从事相关领域工作的工程技术人员参考。

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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

Notation

$[\cdot]$ indicates discrete valued independent variable, e.g. $x[n]$
$(\cdot)$ indicates continuous valued independent variable, e.g. $x(t)$

- Complex numbers
  - $|c|$ magnitude of complex quantity c
  - $\arg\{c\}$ phase angle of complex quantity c
  - $\mathrm{Re}\{c\}$ real part of c
  - $\mathrm{Im}\{c\}$ imaginary part of c
  - c^* complex conjugate of c
- Lower case functions denote time-domain quantities, e.g. $x(t)$, $w[n]$
- Upper-case functions denote frequency- or transform-domain quantities
  - $X[k]$ discrete-time Fourier series coefficients for $x[n]$
  - $X[k]$ Fourier series coefficients for $x(t)$
  - $X(e^{j\Omega})$ discrete-time Fourier transform of $x[n]$
  - $X(j\omega)$ Fourier transform of $x(t)$
  - $X(s)$ Laplace transform of $x(t)$
  - $X(z)$ z-transform of $x[n]$
- Boldface lower-case symbols denote vector quantities, e.g., $\mathbf{q}$
- Boldface upper-case symbols denote matrix quantities, e.g., $\mathbf{A}$
- Subscript δ indicates continuous-time representation of a discrete-time signal
  - $x_\delta(t)$ continuous-time representation for $x[n]$
  - $X_\delta(j\omega)$ Fourier transform of $x_\delta(t)$
- Sans serif type indicates MATLAB variables or commands, e.g., `X = fft(x,n)`
- 0^0 is defined as 1 for convenience
- arctan refers to the four quadrant inverse tangent function and produces a value between $-\pi$ and π radians

Principal Symbols

- j square root of -1
- $\mathtt{i}$ square root of -1 used by MATLAB
- T_s sampling interval of T_s in seconds
- T fundamental period for continuous-time signal in seconds

N	fundamental period for discrete-time signal in samples
ω	(angular) frequency for continuous-time signal in radians/second
Ω	(angular) frequency for discrete-time signal in radians
ω_o	fundamental (angular) frequency for continuous-time periodic signal in radians/second
Ω_o	fundamental (angular) frequency for discrete-time periodic signal in radians
$u(t), u[n]$	step function of unit amplitude
$\delta[n], \delta(t)$	unit impulse
$H\{\cdot\}$	representation of a system as an operator H
$S^\tau\{\cdot\}$	time shift of τ units
$H^{\text{inv}}, h^{\text{inv}}$	superscript inv denotes inverse system
$*$	denotes convolution operation
$\circledast$	periodic convolution of two periodic signals
$H(e^{j\Omega})$	discrete-time system frequency response
$H(j\omega)$	continuous-time system frequency response
$h[n]$	discrete-time system impulse response
$h(t)$	continuous-time system impulse response
$y^{(h)}$	superscript (h) denotes homogeneous solution
$y^{(n)}$	superscript (n) denotes natural response
$y^{(f)}$	superscript (f) denotes forced response
$y^{(p)}$	superscript (p) denotes particular solution
$\overset{DTFS;\,\Omega_o}{\longleftrightarrow}$	discrete-time Fourier series pair with fundamental frequency Ω_o
$\overset{FS;\,\omega_o}{\longleftrightarrow}$	Fourier series pair with fundamental frequency ω_o
$\overset{DTFT}{\longleftrightarrow}$	discrete-time Fourier transform pair
$\overset{FT}{\longleftrightarrow}$	Fourier transform pair
$\overset{\mathcal{L}}{\longleftrightarrow}$	Laplace transform pair
$\overset{\mathcal{L}_u}{\longleftrightarrow}$	unilateral Laplace transform pair
$\overset{z}{\longleftrightarrow}$	z-transform pair
$\overset{z_u}{\longleftrightarrow}$	unilateral z-transform pair
$\text{sinc}(u)$	$\dfrac{\sin(\pi u)}{\pi u}$
$\cap$	intersection
$T(s)$	closed-loop transfer function
$F(s)$	return difference
$L(s)$	loop transfer function

Abbreviations

A	amperes (units for electric current)
A/D	analog-to-digital (converter)
AM	amplitude modulation
BIBO	bounded input-bounded output
BPSK	binary phase-shift keying
CD	compact disc
CW	continuous wave
D/A	digital-to-analog (converter)
dB	decibel
DSB-SC	double-sideband suppressed carrier
DTFS	discrete-time Fourier series
DTFT	discrete-time Fourier transform
ECG	electrocardiogram
F	Farads (units for capacitance)
FDM	frequency-division multiplexing
FFT	fast Fourier transform
FIR	finite-duration impulse response
FM	frequency modulation
FS	Fourier series
FT	Fourier transform
H	Henries (units for inductance)
Hz	Hertz
IIR	infinite-duration impulse response
LTI	linear time-invariant (system)
MEMS	microelectricalmechanical system
MSE	mean squared error
PAM	pulse-amplitude modulation
PCM	pulse-code modulation
PM	phase modulation
QAM	quadrature-amplitude modulation
RF	radio frequency
ROC	region of convergence
rad	radian(s)
s	second(s)
SSB	single sideband modulation
STFT	short-time Fourier transform
TDM	time-division multiplexing
V	volts (units for electric potential)
VLSI	very large scale integration
VSB	vestigial sideband modulation
WT	wavelet transform

Preface

The "Signals and Systems" Course in the Electrical Engineering Undergraduate Curriculum

A course on "signals and systems" is fundamental to the study of the many fields that constitute the ever-expanding discipline of electrical engineering. Signals and systems serves as the prerequisite for additional coursework in the study of communications, signal processing, and control. Given the pervasive nature of computing, concepts from signals and systems, such as sampling, are an important component of almost every electrical engineering field. Although the signals and systems that arise across these diverse fields are naturally different in their physical make-up and application, the principles and tools of signals and systems are applicable to all of them. An introductory course on "signals and systems", commonly takes one of two forms:

- A one-semester course that focuses on the analysis of deterministic signals and an important class of systems known as linear time-invariant (LTI) systems, with practical examples drawn from communication and control systems.
- A two-semester course that expands on the one-semester course by including more detailed treatment of signal processing, communication and control systems.

This course is usually offered at the sophomore or junior level and assumes the student has a background in calculus and introductory physics.

How this Book Satisfies the Essential Needs of this Course

Given the introductory nature of the signals and systems course and diversity of applications for the topic, the textbook must be easy to read, accurate, and contain an abundance of insightful examples, problems, and computer experiments to expedite learning the fundamentals of signals and systems in an effective manner. This book has been written with all of these objectives in mind.

The second edition builds on the first edition's success at providing a balanced and integrated treatment of continuous- and discrete-time forms of signals and systems. This approach has the pedagogical advantage of helping the student see the fundamental similarities and differences between continuous- and discrete-time representations and reflects the integrated nature of continuous- and discrete-time concepts in modern engineering practice. One consistent comment from users of the first edition and reviewers of the second is that the compelling nature of our approach becomes very apparent in Chapter 4 with the coverage of sampling continuous-time signals, reconstruction of continuous-time signals from samples, and other applications involving mixtures of different signal classes. The integrated approach is also very efficient in covering the large range of topics that are typically required in a signals and systems course. For example, the properties of all four Fourier representations are covered side-by-side in Chapter 3. Great care has been taken in the presentation of the integrated approach to enhance understanding and avoid confusion. As an example of this, the four Fourier representations are treated in Chapter 3 as similar, yet distinct representations that apply to distinct signal classes. Only after the student has mastered them individually is the possibility of using Fourier representations to cross the boundaries between signal classes introduced in Chapter 4.

Given the mathematical nature of signal representation and system analysis, it is rather easy for the reader to lose sight of their practical application. Chapters 5, 8, and 9 deal with applications drawn from the fields of communication systems, design of filters, and control systems in order to provide motivation for the reader. In addition, considerable effort has been expended in the second edition to provide an application focus throughout the tool-oriented chapters by including an abundance of application-oriented examples. A set of six theme examples, introduced in Chapter 1 and revisited throughout the remaining chapters, is used to show how different signal representation and system analysis tools provide different perspectives on the same underlying problem. The theme examples have been selected to sample the broad range of applications for signals and systems concepts.

The text has been written with the aim of offering maximum teaching flexibility in both coverage and order of presentation, subject to our philosophy of truly integrating continuous- and discrete-time concepts. When continuous- and discrete-time concepts are introduced sequentially, such as with convolution in Chapter 2 and Fourier representations in Chapter 3, the corresponding sections have been written so that the instructor may present either the continuous- or discrete-time viewpoint first. Similarly, the order of Chapters 6 and 7 may be reversed. A two-semester course sequence would likely cover most, if not all, of the topics in the book. A one-semester course can be taught in a variety of ways, depending on the preference of the instructor, by selecting different topics.

Structure Designed to Facilitate and Reinforce Learning

A variety of features have been incorporated into the second edition to facilitate and reinforce the learning process. We have endeavored to write in a clear, easy to follow, yet precise manner. The layout and format has been chosen to emphasize important concepts. For example, key equations and procedures are enclosed in boxes and each example is titled. The choice and layout of figures has been designed to present key signals and systems concepts graphically, reinforcing the words and equations in the text.

A large number of examples are included in each chapter to illustrate application of the corresponding theory. Each concept in the text is demonstrated by examples that em-

phasize the sequence of mathematical steps needed to correctly apply the theory and by examples that illustrate application of the concepts to real-world problems.

An abundance of practice is required to master the tools of signals and systems. To this end, we have provided a large number of problems with answers immediately following introduction of significant concepts, and a large number of problems without answers at the end of each chapter. The problems within the chapters provide the student with immediate practice and allow them to verify their mastery of the concept. The end of the chapter problems offer additional practice and span a wide range of difficulty and nature, from drilling basic concepts to extending the theory in the text to new applications of the material presented. Each chapter also contains a section illustrating how MATLAB, acronym for MATrix LABoratory and product of The Math Works, Inc., may be used to explore concepts and test system designs within the context of a "Software Laboratory". A complementary set of computer-oriented end of chapter problems is also provided.

New to the Second Edition of the Book

In general terms, this new edition of the book follows the organization and philosophy of the first edition. Nevertheless, over and above new examples and additional problems, some important changes have been made to the book. In addition to the layout and format improvements noted above, long sections in the first edition have been broken up into smaller units. The significant changes to each chapter are summarized as follows:

- Chapter 1: Two new sections, one on Theme Examples and the other on electrical noise, have been added. The Theme Examples, six in number, illustrate the broad range of problems to which signals and systems concepts apply and provide a sense of continuity in subsequent chapters of the book by showing different perspectives on the same problem. Two new subsections, one on MicroElectroMechanical Systems (MEMS) and the other on derivatives of the unit-impulse function, have also been added.
- Chapter 2: The treatment of discrete- and continuous-time convolution has been reorganized into separate, yet parallel sections. The material introducing the frequency response of LTI systems has been removed and incorporated into Chapter 3. The treatment of differential and difference equations has been expanded to clarify several subtle issues.
- Chapter 3: The chapter has been written with increased emphasis on applications of Fourier representations for signals through the introduction of new examples, incorporation of filtering concepts contained in Chapter 4 of the first edition, and reordering the presentation of properties. For example, the convolution property is presented much earlier in the second edition because of its practical importance. Derivations of the discrete-time Fourier series, Fourier series, and discrete-time Fourier transform have been removed and incorporated as advanced problems.
- Chapter 4: The focus has been tightened as reflected by the new title. Material on frequency response of LTI systems has been moved to Chapter 3 and advanced material on interpolation, decimation, and fast convolution has been removed and incorporated as advanced problems.
- Chapter 5: A new section on the Costas receiver for demodulation of double sideband-suppressed carrier modulated signals has been added.

- Chapter 6: The definition of the unilateral Laplace transform has been modified to include impulses and discontinuities at $t = 0$ and the material on Bode diagrams in Chapter 9 of the first edition is now incorporated in the discussion of graphical evaluation of frequency response.
- Chapter 9: A new section on the fundamental notion of feedback and "why feedback?" has been introduced. Moreover, the treatment of feedback control systems has been shortened, focusing on the fundamental issue of stability and its different facets.
- Chapter 10: The epilogue has been completely rewritten. In particular, more detailed treatments of wavelets and the stability of nonlinear feedback systems have been introduced.
- Appendix F: This new appendix presents a tutorial introduction to MATLAB.

Supplements

The following supplements are available from the publishers website:

www.wiley.com/college/haykin

PowerPoint Slides: Every illustration from the text is available in PowerPoint format enabling instructors to easily prepare lesson plans.

Solutions Manual: An electronic Solutions Manual is available for download from the website. If a print version is required, it may be obtained by contacting your local Wiley representative. Your representative may be determined by finding your school on Wiley's CONTACT/Find a Rep webpages.

MATLAB resources: M-files for the computer-based examples and experiments are available.

About the Cover of the Book

The cover of the book is an actual photograph of Mount Shasta in California. This picture was chosen for the cover to imprint in the mind of the reader a sense of challenge, exemplified by the effort needed to reach the peak of the Mount, and a sense of the new vistas that result from climbing to the peak. We thus challenge the reader to master the fundamental concepts in the study of signals and systems presented in the book and promise that an unparalleled viewpoint of much of electrical engineering will be obtained by rising to the challenge.

In Chapter 1 we have included an image of Mount Shasta obtained using a synthetic aperture radar (SAR) system. A SAR image is produced using many concepts from the study of signals and systems. Although the SAR image corresponds to a different view of Mount Shasta, it embodies the power of signals and systems concepts for obtaining different perspectives of the same problem. We trust that motivation for the study of signals and systems begins with the cover.

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Simon Haykin
Barry Van Veen

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