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Linear Control System Analysis and Design

Fourth Edition

线性控制系统分析与设计

第 4 版

John J.D'azzo
Constantine H.Houpis

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LINEAR CONTROL SYSTEM ANALYSIS AND DESIGN

Conventional and Modern

Fourth Edition

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出版说明

郑大钟
清华大学信息科学与技术学院

当前，在我国的高等学校中，教学内容和课程体系的改革已经成为教学改革中的一个非常突出的问题，而为数不少的课程教材中普遍存在的“课程体系老化，内容落伍时代，本研层次不清”的现象又是其中的急需改变的一个重要方面。同时，随着科教兴国方针的贯彻落实，要求我们进一步转变观念扩大视野，使教学过程适应以信息技术为先导的技术革命和我国社会主义市场经济体制的需要，加快教学过程的国际化进程。在这方面，系统地研究和借鉴国外知名大学的相关教材，将会对推进我们的课程改革和推进我国大学教学的国际化进程，乃至对我们一些重点大学建设国际一流大学的努力，都将具有重要的借鉴推动作用。正是基于这种背景，我们决定在国内推出信息技术学科和电气工程学科国外知名大学原版系列教材。

本系列教材的组编将遵循如下的几点基本原则。(1)书目的范围限于信息技术学科和电气工程学科所属专业的技术基础课和主要的专业课。(2)教材的范围选自于具有较大影响且为国外知名大学所采用的教材。(3)教材属于在近5年内所出版的新书或新版书。(4)教材适合于作为我国大学相应课程的教材或主要教学参考书。(5)每本列选的教材都须经过国内相应领域的资深专家审看和推荐。(6)教材的形式直接以英文原版形式印刷出版。

本系列教材将按分期分批的方式组织出版。为了便于使用本系列教材的相关教师和学生从学科和教学的角度对其在体系和内容上的特点和特色有所了解，在每本教材中都附有我们所约请的相关领域资深教授撰写的影印版序言。此外，出于多样化的考虑，对于某些基本类型的课程，我们还同时列选了多于一本的不同体系、不同风格和不同层次的教材，以供不同要求和不同学时的同类课程的选用。

本系列教材的读者对象为信息技术学科和电气工程学科所属各专业的本科生，同时兼顾其他工程学科专业的本科生或研究生。本系列教材，既可采用作为相应课程的教材或教学参考书，也可提供作为工作于各个技术领域的工程师和技术人员的自学读物。

组编这套国外知名大学原版系列教材是一个尝试。不管是书目确定的合理性，教材选择的恰当性，还是评论看法的确切性，都有待于通过使用和实践来检验。感谢使用本系列教材的广大教师和学生的支持。期望广大读者提出意见和建议。

Linear Control System Analysis and Design

（第4版）

影印版序

由 John J. D'azzo 和 Constantine H. Houpis 编著的"Linear Control System Analysis and Design"一书，初版本出版于 1975 年，现今的第四版版本出版于 1995 年。本书的定位是要为期望获得控制理论的坚实基础的工程系科本科生提供一本内容适度和可读性好的教材。在安排上覆盖了经典控制理论和现代控制理论的基础部分，在对象上包括了连续控制系统和数字控制系统，在方法上兼顾了频率响应法、根轨迹法和状态空间法，在论述上涉及到控制系统模型的建立、系统特性和性能的分析、以及基于状态反馈和输出反馈的控制器的设计等基本部分。本书问世以来，以其内容的基础性，论述的严谨性，教学的适用性，内容的不断删旧更新，而被美国多所知名大学采用作为控制理论与控制工程专业方向的本科层次的控制理论教材或主要教学参考书。

纵观本书的体系结构和内容取舍，可以看出，作为面向控制工程系科本科生的控制理论教材，本书具有如下四个明显的特点。

(1) 体系结构上突出了层次性，把全书所涉及的章节内容从学科和教学的角度区分为三个层面，为教和学提供了清晰的分界线。一是"模型和求解"层面，由第 2 章到第 4 章构成，着重于介绍对各类物理系统建立模型所必要的数学基础和建立方法，以及求解系统响应的古典方法和拉普拉斯变换方法。二是"基本理论和方法"层面，覆盖第 5 章到第 15 章，包含了自动化专业本科生控制理论教学的必需知识结构，着重于有层次地介绍控制系统的描述方法和基本特性，基于频率响应法、根轨迹法和状态空间法的控制系统分析和设计技术，灵敏度分析和数字控制系统专题等。三是"本科层次高等专题"层面，包括第 16 章到第 18 章，分别介绍了三类特殊的先进控制系统的设计技术，以扩大教学的视野和知识面。

(2) 内容取舍上兼顾了基础性和时代性，把全书的主要内容配置在控制理论中的基本的和现代的理论和方法上，以期向控制工程学科的本科生提供清晰的、数量适度的、与时代相匹配的知识。表现在对象上，主要以单输入单输出(SISO)系统为主，适量讨论多输入多输出(MIMO)系统。表现在系统类型

上，除了连续时间系统分析和设计的基础内容外，新版基于计算机广泛应用的时代特点加强和充实了数字控制系统部分。表现在内容上，除了比较成熟的基本内容外，适量介绍了新发展的内容。表现在计算手段上，除了传统的手算方式外，几乎在每一部分中都介绍和强调了基于 MATLAB 等常用软件的计算方式。

(3) 论述上注重了严谨性和直观性的结合，把对问题的分析和讨论置于直观的背景和严格的演绎上，以符合控制工程本科生的知识基础和认识规律。这既表现在，在对问题提出和模型建立的论述中，列举了各种不同类型的物理系统甚至实型系统；也表现在，在有关结论和公式的导出中，在进行严格演绎的同时，"舍弃"了那种为工程本科生难以接受和理解的大量的数学化推导。同时，为增加对各种控制系统的分析和设计的论述的直观性，书中给出了多个取自于电气、航天、机械等工程实际领域的例子。

(4) 论述深度上有比较合理的把握。相比于研究生控制理论课程，本书所涉及的问题要"基本"一些，论述的程度上要"浅显"一些。而相比于非控制工程学科的本科生控制理论课程，本书的内容要更为"全面"一些，分析论述要更有"深度"一些。

影印本书是为控制工程学科及需要坚实控制理论基础的工程学科专业本科生提供教材或教学参考书，同时也可供相应领域的工程师和技术人员作为自学读物。

郑大钟
清华大学自动化系
2000 年 10 月

PREFACE

The emphasis of this fourth edition is on strengthening its use as a textbook for undergraduates who desire to obtain a solid foundation in control theory. Both analog and sampled-data single-input single-output (SISO) feedback-control systems are covered in detail. This has been accomplished by deleting the optimal control chapters of the prior editions and by strengthening the digital control chapter. The text was further strengthened by improving the latter chapters, which present an introduction to advanced control system design techniques for both SISO and multiple-input and multiple-output (MIMO) control systems. These latter chapters are intended for advanced undergraduate and first-year graduate students majoring in control theory. A major revision has also been made in the problem section. To support this emphasis, revisions were incorporated throughout this new edition to enhance the clarity and to streamline for the student a comprehensive presentation of control theory and design. Extensive use is made of computer-aided-design (CAD) packages to assist and simplify the design process.

The authors have exerted meticulous care with explanations, diagrams, calculations, tables, and symbols. The student is made aware that rigor is necessary for design applications and advanced control work. Also stressed is the importance of clearly understanding the concepts that provide the rigorous foundations of modern control theory. The text provides a strong, comprehensive, and illuminating account of those elements of conventional control theory that have relevance in the analysis and design of control systems. The presentation of a variety of different techniques contributes to the development of the student's working understanding of what A. T. Fuller has called "the enigmatic control system." To provide a coherent development of the subject, an attempt is made to eschew formal proofs and lemmas, with an organization that draws the perceptive student steadily and surely into the demanding theory of multivariable control systems. Design examples are included throughout each chapter in order to enhance and solidify the student's understanding of the text material. It is the opinion of the authors that a student who has reached this point is fully equipped to undertake with confidence the challenges presented by more advanced control theories, as typified by Chapters 16 through 18. The importance and necessity of making extensive use of computers is emphasized by references to comprehensive computer-aided-design (CAD) programs. The book uses the computer programs MATLAB®, by The MathWorks, Inc.; ICECAP-PC; and TOTAL-PC (see App. B). These programs have viable control system computational tools.

After much consideration, it was decided to retain Chapter 2, which sets forth the appropriate differential equations to describe the performance of physical systems, networks, and devices. Some elementary matrix algebra, the block diagram, and the transfer function are also included. The essential concept of modern control theory, the state space, is also introduced. The approach used is the simultaneous derivation of the state-vector differential equation with the single-input single-output (SISO) differential equation for a chosen physical system. The relationship of the transfer function to the state equation of the system is deferred until Chapter 4. The derivation of a mathematical description of a physical system by using Lagrange equations is also given.

Chapter 3 serves as reference material for the reader, presenting the classical method of solving differential equations and the nature of the resulting response. Once the state-variable equation has been introduced, careful account is given of its solution. The central importance of the state transition matrix is brought out, and the state transition equation is derived. The idea of an eigenvalue is next explained, and this theory is used with the Cayley-Hamilton and Sylvester theorems to evaluate the state transition matrix.

The early part of Chapter 4 presents a comprehensive description of Laplace transform methods and pole-zero maps. Some further aspects of matrix algebra are introduced before the solution of the state equation by the use of Laplace transforms is dealt with. Finally, the evaluation of transfer matrices is clearly explained.

Chapter 5 begins with system representation by the conventional block-diagram approach. It is followed by a straightforward account of simulation diagrams and the determination of the state transition equation by the use of signal flow graphs. By deriving parallel state diagrams from system transfer functions, the advantages of having the state equation in uncoupled form are established. This is followed by the methods of diagonalizing the system matrix, a clear treatment of how to transform an **A** matrix that has complex eigenvalues into a suitable alternative block-diagonal form, and the transformation to companion form.

In Chapter 6 the basic feedback system characteristics are introduced. This includes the relationship between system type and the ability of the system to follow or track polynomial inputs.

In Chapter 7 the details of the root-locus method of analysis are thoroughly presented. Then the frequency-response method of analysis is given in Chapters 8 and 9, using both the log and the polar plots. These chapters include the following topics: Nyquist stability criterion; correlation between the s plane, frequency domain, and time domain; and gain setting to achieve a desired output response peak value. Chapters 10 and 11 describe the methods for improving system performance, along with examples of the techniques for applying cascade and feedback compensators. Both the root-locus and frequency-response methods of designing compensators are covered. Use of computer-aided-design (CAD) programs to assist the designer is illustrated throughout the text.

The concept of modeling a desired control ratio that has figures of merit that satisfy the system performance specifications is developed in Chapter 12. The system inputs generally fall into two categories: (1) a desired input, which the system output is to track (a tracking system), and (2) a disturbance input, for which the system output is to be minimal (a disturbance-rejection system). Desired control ratios for both types of systems are synthesized by the proper placement of poles and inclusion of zeros, if required. Chapter 12 also includes the Guillemin-Truxal design procedure for designing a tracking control system and a design procedure emphasizing disturbance rejection.

The technique of achieving desired system characteristics by using complete state-variable feedback is developed thoroughly and carefully in Chapter 13. The very important concepts of modern control theory—controllability and observability—are treated in a simple, straightforward, and correct manner. This provides a useful foundation for the work of Chapters 16 and 17.

Chapter 14 includes a presentation of the sensitivity concepts of Bode for the variation of system parameters. Also included is the method of using feedback transfer functions to form estimates of inaccessible states for use in state feedback. An account of trajectories in the state space and some associated phase-plane techniques are also given. A feature of this approach is that the arguments are extended to nonlinear systems. The treatment of such systems by linearization is presented.

Chapter 15 presents an introduction to the analysis and design of digital control systems. This permits an extension from linear control system design to the rapidly growing area of digital control. The effectiveness of digital compensation is clearly demonstrated. The concept of a pseudo-continuous-time (PCT) model of a digital system permits the use of continuous-time methods for the design of digital control systems.

Chapter 16 provides a thorough presentation of the principles and techniques of entire eigenstructure assignment for MIMO systems by means of state feedback. Eigenvalue assignment is extended to include the simultaneous assignment of the associated eigenvectors and provides the means for shaping the output response to meet design specifications.

There are many worthwhile control system design techniques available in the technical literature, which are based on both modern and conventional control theory. The applicability of each technique may be limited to certain classes of design problems. The control engineer must have a sufficiently broad perspective to be able to apply the right technique to the right design problem. For some techniques the designer is assisted by available computer-aided-design (CAD) packages. Design techniques such as LQR, LQG, or LTR are thoroughly covered in the literature. Two design techniques that have very desirable design characteristics for MIMO systems are covered in detail in this text. Chapter 17 presents an output feedback state-space technique based on singular perturbation theory. This leads to the design principles developed by Professor B. Porter, which incorporate proportional plus integral controllers. Application to a practical aircraft control system is demonstrated. Chapter 18 presents a control system design method based on quantitative feedback theory (QFT). This is a very powerful design method when plant parameters vary over a broad range of operating conditions. Chapter 18 presents an introduction to and lays the foundation for the quantitative feedback theory (QFT) developed by Professor I. M. Horowitz. This technique incorporates the concept of designing a robust control system that maintains the desired system performance over a prescribed region of structured plant parameter uncertainty. The authors feel that these methods have proven their applicability to the design of practical MIMO control systems. These chapters are intended to further strengthen the fundamentals presented earlier in the text and to "whet the appetite" of the budding control engineer. They are very effective in achieving robust output feedback high-gain systems.

This textbook provides students of control engineering with a clear, unambiguous, and relevant account of appropriate, contemporary, and state-of-the-art control theory. It is suitable as an introductory and bridging text for undergraduate and graduate students.

The text is arranged so that it can also be used for self-study by the engineer in practice. Included are many examples of feedback control systems in various areas of practice (electrical, aeronautical, mechanical, etc.). It is a strong basic feedback control text that can be used for study in any of the various branches of engineering. To make the text meaningful and valuable to all engineers, the authors have attempted to unify the treatment of physical control systems through use of mathematical and block-diagram models common to all. The text has been thoroughly class-tested, thus enhancing its value for classroom and self-study use. There are many computer-aided-design (CAD) packages available to assist a control engineer in the analysis, design, and simulation of control systems. Some of these are listed in App. B. The use of these packages, such as MATLAB, ICECAP-PC and TOTAL-PC, are stressed throughout the text. In adapting to the use of these packages, an engineer must become *computer literate*. Throughout the text the authors stress the use of *computer-aided-design accuracy checks* (CADAC), in order to assist the engineer in becoming computer literate. CADAC stresses the use of the appropriate fundamentals in assuring the viability of a computer solution.

The authors express their thanks to the students who have used this book and to the faculty who have reviewed it for their helpful comments and recommendations. Especial appreciation is expressed to Dr. R. E. Fontana, Professor Emeritus of Electrical Engineering, Air Force Institute of Technology, for the encouragement he has provided, and to Dr. T. J. Higgins, Professor Emeritus of Electrical Engineering, University of Wisconsin, for his thorough review of the earlier manuscripts.

Appreciation is expressed to Professor Donald McLean, the University of Southampton, England, formerly a visiting Professor at the Air Force Institute of Technology. Our association with him has been an enlightening and refreshing experience. Important advanced concepts are based on collaborative work with Professor Brian Porter, University of Salford, England, and Isaac M. Horowitz, Professor Emeritus, Weizmann Institute of Science, Rehovot, Israel and University of California, Davis. The personal relationship with them has been a source of inspiration and deep respect.

John J. D'Azzo
Constantine H. Houpis

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CONTENTS