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

PEARSON Prentice Hall

动态系统反馈控制

第4版 影印版

Feedback Control of Dynamic Systems

Fourth Edition

GENE F. FRANKLIN
J. DAVID POWELL
ABBAS EMAMI-NAEINI

高等教育出版社
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图字：01－2003－6735 号

图书在版编目（CIP）数据

动态系统反馈控制＝Feedback Control of Dynamic Systems Fourth Edition：第 4 版／(美) 富兰克林 (Franklin, G.F.), (美) 鲍威尔 (Powell, J.D.), (美) 伊麦米－内艾尼 (Emami－Naeini,A.) 著. —影印本. —北京：高等教育出版社，2003.12
ISBN 7－04－013843－3

Ⅰ.动… Ⅱ.①富…②鲍…③伊… Ⅲ.动态系统—反馈控制—高等学校—教材—英文 Ⅳ.TP13

中国版本图书馆 CIP 数据核字(2003)第 117118 号

出版发行	高等教育出版社	购书热线	010－64054588
社　　址	北京市西城区德外大街 4 号	免费咨询	800 810 0598
邮政编码	100011	网　　址	http://www.hep.edu.cn http://www.hep.com.cn
总　　机	010－82028899		
经　　销	新华书店北京发行所		
印　　刷	北京外文印刷厂		
开　　本	787×1092　1/16	版　　次	2003 年 12 月第 1 版
印　　张	58.5	印　　次	2003 年 12 月第 1 次印刷
字　　数	1 000 000	定　　价	72.00 元

前　言

20世纪末，以计算机和通信技术为代表的信息科学和技术对世界经济、科技、军事、教育和文化等产生了深刻影响。信息科学技术的迅速普及和应用，带动了世界范围信息产业的蓬勃发展，为许多国家带来了丰厚的回报。

进入21世纪，尤其随着我国加入WTO，信息产业的国际竞争将更加激烈。我国信息产业虽然在20世纪末取得了迅猛发展，但与发达国家相比，甚至与印度、爱尔兰等国家相比，还有很大差距。国家信息化的发展速度和信息产业的国际竞争能力，最终都将取决于信息科学技术人才的质量和数量。引进国外信息科学和技术优秀教材，在有条件的学校推动开展英语授课或双语教学，是教育部为加快培养大批高质量的信息技术人才采取的一项重要举措。

为此，教育部要求由高等教育出版社首先开展信息科学和技术教材的引进试点工作。同时提出了两点要求，一是要高水平，二是要低价格。在高等教育出版社和信息科学技术引进教材专家组的努力下，经过比较短的时间，第一批引进的20多种教材已经陆续出版。这套教材出版后受到了广泛的好评，其中有不少是世界信息科学技术领域著名专家、教授的经典之作和反映信息科学技术最新进展的优秀作品，代表了目前世界信息科学技术教育的一流水平，而且价格也是最优惠的，与国内同类自编教材相当。

这项教材引进工作是在教育部高等教育司和高教社的共同组织下，由国内信息科学技术领域的专家、教授广泛参与，在对大量国外教材进行多次遴选的基础上，参考了国内和国外著名大学相关专业的课程设置进行系统引进的。其中，John Wiley公司出版的贝尔实验室信息科学研究中心副总裁 Silberschatz 教授的经典著作《操作系统概念》，是我们经过反复谈判，做了很多努力才得以引进的。William Stallings先生曾编写了在美国深受欢迎的信息科学技术系列教材，其中有多种教材获得过美国教材和学术著作者协会颁发的计算机科学与工程教材奖，这批引进教材中就有他的两本著作。留美中国学者 Jiawei Han 先生的《数据挖掘》是该领域中具有里程碑意义的著作。由达特茅斯学院的 Thomas Cormen 和麻省理工学院、哥伦比亚大学几位学者共同编著的经典著作《算法导论》，在经历了11年的锤炼之后于2001年

出版了第二版。目前任教于美国 Massachusetts 大学的 James Kurose 教授，曾在美国三所高校先后 10 次获得杰出教师或杰出教学奖，由他主编的《计算机网络》出版后，以其体系新颖、内容先进而倍受欢迎。在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作。这套引进的教材体现了权威性、系统性、先进性和经济性等特点。

教育部也希望国内和国外的出版商积极参与此项工作，共同促进中国信息技术教育和信息产业的发展。我们在与外商的谈判工作中，不仅要坚定不移地引进国外最优秀的教材，而且还要千方百计地将版权转让费降下来，要让引进教材的价格与国内自编教材相当，让广大教师和学生负担得起。中国的教育市场巨大，外国出版公司和国内出版社要通过扩大发行数量取得效益。

在引进教材的同时，我们还应做好消化吸收，注意学习国外先进的教学思想和教学方法，提高自编教材的水平，使我们的教学和教材在内容体系上，在理论与实践的结合上，在培养学生的动手能力上能有较大的突破和创新。

目前，教育部正在全国 35 所高校推动示范性软件学院的建设和实施，这也是加快培养信息科学技术人才的重要举措之一。示范性软件学院要立足于培养具有国际竞争力的实用性软件人才，与国外知名高校或著名企业合作办学，以国内外著名 IT 企业为实践教学基地，聘请国内外知名教授和软件专家授课，还要率先使用引进教材开展教学。

我们希望通过这些举措，能在较短的时间，为我国培养一大批高质量的信息技术人才，提高我国软件人才的国际竞争力，促进我国信息产业的快速发展，加快推动国家信息化进程，进而带动整个国民经济的跨越式发展。

教育部高等教育司

二〇〇二年三月

To Gertrude, David, Carole
Valerie, Daisy, Annika, Davenport
Malahat, Sheila, Nima

Preface

In this fourth edition we again had the objectives of retaining the best of the previous editions, to rewrite key sections where we felt it was possible to improve the presentations and enhance the book's pedagogical effectiveness, and to take better advantage of the wide use of computers in control design, especially the toolboxes of MATLAB and Simulink, from The Mathworks, Inc.

The basic structure of the book is unchanged and we continue to combine analysis with design using the three approaches of the root locus, frequency response, and state variable equations. The text continues to include carefully worked out examples, many of them new to this edition, to illustrate the material. As a new feature, to assist the students in verifying that they have learned the material, we provide a set of review questions at the end of each chapter with answers in the back of the book. While modest changes were made throughout the entire book, special attention was given to the introduction of transforms in Chapter 3, to the introduction to feedback in Chapter 4, and to the organization and statements of the problems appearing at the end of each chapter.

In the three central chapters on the design methods, we continue to expect the students to learn how to perform the basic calculations by hand in order to be able to guide a design by understanding (and frequently by a quick sketch) rather than by computer rote. However, more than in previous editions, we de-emphasize the manual work and introduce computer tools early on in recognition of the universal use of these tools in control analysis and design. For example, we no longer mark certain problems as requiring a computer but, rather, expect that the student has access to a computer in every case, as needed.

Furthermore, in recognition of the fact that, increasingly, controllers are implemented in embedded computers, we introduce digital control in Chapter 4 and in a number of cases compare the responses of feedback systems using analog controllers with those having a digital "equivalent" controller. As before, we have prepared a collection of all the MATLAB ".m" files used to produce the figures in the book and these are available at the companion web site for this title:

http://www.prenhall.com/franklin

or at the homepage for SC Solutions, Inc.:

http://scsolutions.com/scsolutions.control.html

As representative applications of control, we again present extensive case studies in Chapter 9. In this edition we have added new studies of the control of the read-write head assembly of a computer hard disk and the temperature control of a silicon wafer in a Rapid Thermal Processor used in the fabrication of integrated circuits.

We feel that this fourth edition presents the material with good pedagogical support, provides strong motivation for the study of control, and represents a solid foundation for meeting the educational challenges of a study of feedback control.

Addressing the Educational Challenges

Some of the educational challenges facing students of feedback control are long-standing; others have emerged in recent years. Some of the challenges remain for students across their entire engineering education; others are unique to this relatively sophisticated course. Whether they are old or new, general or particular, the educational challenges we perceived were critical to the evolution of this text. Here we will state several educational challenges and describe our approaches to each of them.

- CHALLENGE: *Students must master design as well as analysis techniques.*

Design is central to all of engineering and especially to control systems. Students find that design issues, with their corresponding opportunities to tackle practical applications, particularly motivating. But students also find design problems difficult because design problem statements are usually poorly posed and lack unique solutions. Because of both its inherent importance for and its motivational effect on students, design is emphasized throughout this text so that confidence in solving design problems is developed from the start.

The emphasis on design begins in Chapter 4, following the development of modeling and dynamic response. The basic idea of feedback is introduced first, showing its influence on disturbance rejection, tracking accuracy, and robustness to parameter changes. The design orientation continues with uniform treatments of the root locus, frequency response, and state variable feedback techniques. All of the treatments are aimed at providing the knowledge necessary to find a good feedback control design with no more complex mathematical development than is essential to clear understanding.

Throughout the text, examples are used to compare and contrast the design techniques afforded by the different design methods and, in the capstone case studies of Chapter 9, complex real-world design problems are tackled using all of the methods in a unified way.

- CHALLENGE: *New ideas continue to be introduced into control.*

Control is an active field of research and hence there is a steady influx of new concepts, ideas, and techniques. In time, some of these elements develop to the point where they join the list of things every control engineer must know. This text is devoted to supporting students equally in their need to grasp both traditional and more modern topics.

In each of our previous editions we have tried to give equal time to root locus, frequency response, and state variable methods for design. In this edition we have shifted the emphasis from manual design methods augmented with computer tools to an emphasis on computer-aided methods augmented with a solid mastery of the underlying techniques. Included in this re-emphasis is the early introduction of sampling, which enables one to design digital controllers. While this material can be skipped to save time without disruption of the flow of the text, we feel that it is very important for students to recognize that digital control is being used increasingly and that the most basic techniques of digital control are easily mastered.

With regret we acknowledge that we are not able at this time to introduce the important topics of hybrid control or designs based on various optimization methods.

- CHALLENGE: *Students need to manage a great deal of information.*

The vast array of systems to which feedback control is applied and the growing variety of techniques available for the solution of control problems means that today's student of feedback control must learn many new ideas. How do students keep their perspective as they plow through lengthy and complex textual passages? How do they identify highlights and draw conclusions? How do they review for exams? Helping students with these tasks was a criterion for the fourth edition. We outline these features in the accompanying table on page xiv.

- CHALLENGE: *Students of feedback control come from a wide range of disciplines.*

Feedback control is an interdisciplinary field in that control is applied to systems in every conceivable area of engineering. Consequently, some schools have separate introductory courses for control within the standard disciplines and some, such as Stanford University, have a single set of courses taken by students from many disciplines. However, to restrict the examples to one field is to miss much of the range and power of feedback; but to cover the whole range of applications is overwhelming. In this book we develop the interdisciplinary nature of the field and provide review material for several of the most common technologies so that students from many disciplines will be comfortable with the presentation. For electrical engineering students who typically have a good background in transform analysis, we include an introduction to writing equations of motion for mechanical mechanisms in Chapter 2. For mechanical engineers, we include in Chapter 3 a review of the Laplace Transform and dynamic response as needed in control. In addition, we introduce other technologies briefly and, from time to time, we present the equations of motion of a physical system without derivation but with enough physical description to

FEATURE	REFERENCE EXAMPLE
Chapter openers offer perspective and overview. They place the specific chapter topic in the context of the discipline as a whole and they briefly overview the chapter sections.	Chapter 3 opener, pp. 94–95
Margin notes help students scan for chapter highlights. They point to important definitions, equations, and concepts.	pp. 49–50
Boxed highlights identify key concepts within the running text. They also function to summarize important design procedures.	Advantage of feedback, p. 206; compensation design, p. 440
Bulleted chapter summaries help with student review and prioritization. These summaries briefly reiterate the key concepts and conclusions of the chapter.	Chapter 2 summary, pp. 77–78
Synopsis of design aids. Relationships used in design and throughout the book are collected in one place for easy reference.	Inside back cover
The *color blue* is used (1) to highlight useful; pedagogical features; (2) to highlight components under particular scrutiny within block diagrams; (3) to distinguish curves on graphs; and (4) to lend a more realistic look to figures of physical systems.	Fig. 5.43, p. 330 Fig. 2.9, p. 32
Review questions at the end of each chapter with solutions in the back guide the student in self-study.	Chapter 2, p. 78

be understood from a response point of view. Examples of some of the physical systems represented in the text include the read-write head for a computer disk drive, a satellite tracking system, the fuel-air ratio in an automobile engine, and an airplane autopilot system.

Outline of the Book

The contents of the book is organized into nine chapters and seven appendixes. The chapters include some sections of advanced or enrichment material marked with a triangular blue icon that can be omitted without interfering with the flow of the material. Examples and problems based on this material are also marked with these icons. The appendixes include background and reference material such as Laplace transform tables, a review of complex variables, a review of matrix theory, and answers to the end-of-chapter review questions.

In Chapter 1, the essential ideas of feedback and some of the key design issues are introduced. The chapter also contains a brief history of control, from

the ancient beginnings of process control to the contributions of flight control and electronic feedback amplifiers. It is hoped that this brief history will give a context for the field, introduce some of the key figures who contributed to its development, and provide motivation to the student for the studies to come.

Chapter 2 is a short presentation of dynamic modeling and includes mechanical, electrical, electro-mechanical, fluid, and thermodynamic devices. It also discusses the state variable formulation of differential equations. This material can be omitted, used as the basis for review homework to smooth out the usual non-uniform preparation of students, or covered in depth.

Chapter 3 covers dynamic response as used in control. Again, much of this material may have been covered previously, especially by electrical engineering students. For many students, the correlation between pole locations and transient response and the effects of extra zeros and poles on dynamic response is new material, as is the notion of stability of a closed-loop system. This material needs to be covered carefully.

Chapter 4 introduces feedback in the most elementary context, permitting concentration on the essential effects of feedback on tracking accuracy, disturbance rejection, and sensitivity to model errors. The basic equation and transfer functions of feedback are introduced along with the definitions of the sensitivity and complementary sensitivity functions. In the context of a first-order model for speed control, the concepts of proportional, integral, and derivative (PID) control are introduced. In this way, the student gets the idea of what control is all about before the tedious rules of root locus or the Nyquist Stability Criterion are developed. Finally, in this chapter the basic issues of digital control are introduced, along with the idea of a digital equivalent controller. In this approach, the central issues of control design are brought forward and can remain in the foreground during the development of the necessary analysis that goes with construction of sophisticated design tools. The concepts of steady-state tracking error and system type are also treated here.

Following the overview of feedback, the core of the book presents the design methods based on root locus, frequency response, and state variable feedback in Chapters 5, 6, and 7, respectively.

Chapter 8 develops in more detail the tools needed to design feedback control for implementation in a digital computer. However, for a complete treatment of feedback control using digital computers, the reader is referred to the companion text, *Digital Control of Dynamic Systems*, by Franklin, Powell, and Workman (Prentice Hall, 1998).

In Chapter 9, the three primary approaches are integrated in several case studies and a framework for design is described that includes a touch of the real-world context of practical control design.

Course Configurations

The material in this text can be covered flexibly. Most first-course students in controls will have some background in dynamics and Laplace transforms.

Therefore, Chapter 2 and most of Chapter 3 would be a review for those students. In a 10-week quarter, it is possible to review Chapter 3, and cover all of Chapters 1, 4, 5, and 6. Most optional sections noted with a blue triangle should be omitted. In the second quarter, Chapters 7 and 9 can be covered comfortably including these optional sections. Alternatively, some optional sections could be omitted and selected portions of Chapter 8 included. A semester course should comfortably accommodate Chapters 1–7, including the review material of Chapters 2 and 3, if needed. If time remains after this core coverage, selected case studies from Chapter 9 or some introduction of digital control from Chapter 8 may be added.

The entire book can also be used for a three-quarter sequence of courses consisting of modeling and dynamic response (Chapters 2 and 3), classical control (Chapters 4–6), and modern control (Chapters 7–9).

Two basic 10-week courses are offered at Stanford and are taken by seniors and first-year graduate students who have not had a course in control, mostly in the Departments of Aeronautics and Astronautics, Mechanical Engineering, and Electrical Engineering. The first course reviews Chapters 2 and 3 and covers Chapters 4–6. The more advanced course is intended for graduate students and reviews Chapters 4–6 and covers Chapters 7–9. This sequence complements a graduate course in linear systems and is the prerequisite to courses in digital control, optimal control, flight control, and smart product design. Several of the subsequent courses include extensive laboratory experiments. Prerequisites for the course sequence include dynamics or circuit analysis and Laplace transforms.

Prerequisites to this Feedback Control Course

This book is for a first course at the senior level for all engineering majors. For the core topics in Chapters 4–7, prerequisite understanding of modeling and dynamic response is necessary. Many students will come into the course with sufficient background in those concepts from previous courses in physics, circuits, and dynamic response. For those needing review, Chapters 2 and 3 should fill in the gaps.

An elementary understanding of matrix algebra is necessary to understand the state-space material. While all students will have much of this in prerequisite math courses, a review of the basic relations is given in Appendix C and a brief treatment of particular material needed in control is given at the start of Chapter 7. The emphasis is on the relations between linear dynamic systems and linear algebra.

Supplements

An Instructor's Manual with complete solutions to homework problems is available to faculty who adopt the fourth edition. The web sites mentioned above include the .m files used to generate all of the MATLAB figures in the book.

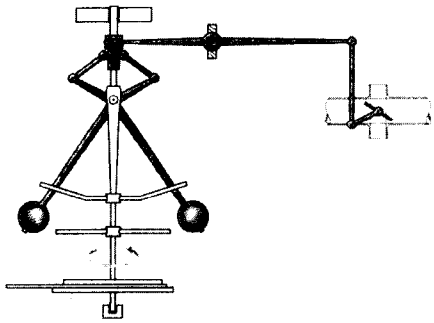
Acknowledgments

Finally, we wish to acknowledge our great debt to all those who have contributed to the development of feedback control into the exciting field it is today and specifically to the considerable help and education we have received from our students and our colleagues. In particular, we have benefited in this effort by many discussions with the following individuals, who have taught introductory control at Stanford: A. E. Bryson, Jr., R. H. Cannon, Jr., D. B. DeBra, S. Rock, C. Tomlin, S. Boyd, and P. Enge. Special thanks go to Prof. Dan DeBra for his careful reading of the manuscript and many useful comments. In addition, our colleagues M. Spong, L. Pao, D. Meyer, K. Pasino, P. Dorato, and M. Saif have provided valuable feedback. We also appreciate the help of D. de Roover, G. van der Linden, J. Ebert, R. Kosut, M. Tao, and A. Rahimi. Furthermore, L. Kobayashi, H-T. Lee, E. Thuriyasena, and M. Matsuoka provided valuable help in proofreading the chapters as well as in the preparation of the solutions manual.

We would also like to thank the following reviewers: Hy D. Tran at the University of New Mexico; Paul I. Ro at North Carolina State University, Lucy Y. Pao at University of Colorado, Arnold Lee Swindlehurst at Brigham Young University, and E. Harry Law at Clemson University.

GENE F. FRANKLIN
J. DAVID POWELL
ABBAS EMAMI-NAEINI
Stanford, California

1 An Overview and Brief History of Feedback Control



Chapter Overview

In this chapter we begin our exploration of feedback control using a simple familiar example: a household furnace controlled by a thermostat. The generic components of a control system are identified within the context of this example. In another example—an automobile cruise control—we develop the elementary static equations and assign numerical values to elements of the system model in order to compare the performance of open-loop control to that of feedback control when dynamics are ignored. In order to provide a context for our studies and to give you a glimpse of how the field has evolved, Section 1.3 provides a brief history of control theory and design. Finally, Section 1.4 provides a brief overview of the contents and organization of the entire book.

郑重声明

Contents