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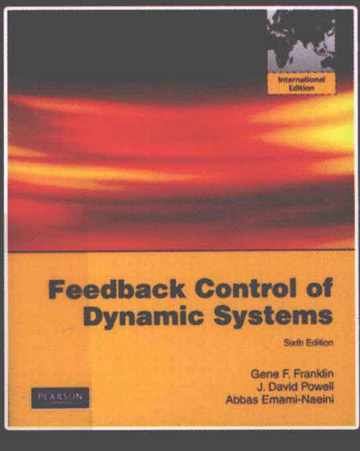
自动控制原理与设计

（第六版）

Feedback Control of Dynamic Systems

Sixth Edition



英文版

[美] Gene F. Franklin
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Abbas Emami-Naeini 著

李中华 改编

電子工業出版社
PUBLISHING HOUSE OF ELECTRONICS INDUSTRY
http://www.phei.com.cn

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北京 · BEIJING

内容简介

本书是自动控制领域的经典著作，以自动控制系统的分析和设计为主线，在回顾自动控制系统动态响应和反馈控制的基本特性基础上，重点介绍了自动控制系统的三种主流设计方法，即根轨迹设计法、频率响应设计法和状态空间设计法。此外，还阐述了非线性系统的分析与设计，给出了一系列经典控制系统设计实例。全书在阐述自动控制原理和设计方法的过程中，适时地穿插 MATLAB 仿真源代码和仿真实验结果。

本书可作为高等院校自动化、电气工程、机电自动化及相关专业的高年级本科生和研究生的教材，还可供从事半导体制造、汽车控制、宇航自动化、运动控制、机器人、化工自动化等相关领域的教师、科研人员、工程技术人员作为参考用书。

图书在版编目（CIP）数据

自动控制原理与设计：第6版 = Feedback Control of Dynamic Systems,Sixth Edition：英文 /（美）富兰克林（Franklin, G. F.）等著；李中华改编. —北京：电子工业出版社，2013.1

国外计算机科学教材系列

ISBN 978-7-121-19102-2

Ⅰ.①自… Ⅱ.①富… ②李… Ⅲ.①自动控制理论－高等学校－教材－英文 Ⅳ.①TP13

中国版本图书馆 CIP 数据核字（2012）第 285234 号

策划编辑：马　岚

责任编辑：马　岚　　文字编辑：陈　磊

印　　刷：三河市鑫金马印装有限公司

装　　订：三河市鑫金马印装有限公司

出版发行：电子工业出版社

北京市海淀区万寿路 173 信箱　邮编：100036

开　　本：787 × 980　1/16　印张：37.75　字数：1100 千字

印　　次：2013 年 1 月第 1 次印刷

定　　价：89.00 元

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前　　言

在今天的社会中，各种自动化装置，如机器人、高速列车、大型飞机、无人值守工厂、办公自动化设备、农业自动化设施、家庭自动化系统等，所形成的社会生产力，把人类社会推进到了一个崭新的自动化时代。伴随着物联网的发展，自动化必将迎来一次变革性的发展机遇。尽管自动化装置种类繁多、应用领域十分广泛、发展演进速度很快，但用于分析和设计自动控制系统的基本概念和基本理论还是不变的。因此，控制工程师们需要了解和掌握控制系统的特性和分析设计方法，并能在实际工程应用中运用自如，切实解决控制需求。此外，控制系统设计中所涉及的许多技术、原理和方法，在其他学科中也有着广泛的应用。

本书在帮助读者掌握实际控制系统分析和设计技术的过程中，融会贯通了由基本概念到具体应用的递进式学习理念。众所周知，要精通控制系统的具体分析和设计，需要有一定的悟性。坚实的理论基础只是确保充分理解控制系统的必要前提，更为重要的是，在实际工作中要能够敏锐地判断控制系统的运行情况，进而思考改进控制系统性能的方法，而且要明白如何改进控制系统的设计，实现期望的控制要求和性能指标。本书的编排和讲解正是沿着这条有效的学习途径进行的，即在对控制问题有一个很好的理解的基础上，再提出行之有效的控制系统设计方案。

本书涵盖了自动控制理论的基础知识和控制系统分析设计的基本方法，重点强调了基本理论分析、方法应用和技术实践，具有以下鲜明的特点。

- 本书整合了自动化专业过去分散的专业课程，将经典自动控制原理、现代控制理论和非线性系统理论中的基础知识全部囊括其中，知识体系清晰、内容丰富饱满、适应当今社会对宽口径自动化专业技术人才的培养需求。
- 每个章节的开篇都提纲挈领地给出了本章的知识背景和控制要求、以及全章的主要内容结构分布。在每个章节的末尾，还对本章的关键知识点进行小结，这有助于读者进一步理解所学知识，形成完整的知识体系。
- 本书在介绍自动控制分析和设计方法的同时，还以丰富的设计实例配以详细的设计步骤，让读者能充分体会到控制系统的每一个设计细节，有利于快速地培养起读者的分析和设计控制系统的能力。
- 本书设有配套的学习网站（http://www.scsolutions.com/public/research/publications/feedback6.html），提供了用来绘制本书中许多图形的计算机仿真程序和学习帮助文件，以及部分附录内容和教材配套的教师资源。书中和配套网站提供的Matlab/Simulink仿真程序为读者提供了验证、分析和设计自动控制系统的范例，让读者能够快速真实地体验到控制效果。

本书内容丰富、概念清晰、特色鲜明、通俗易懂，是自动化专业及其他相关专业不可多得的一部优秀教材和专业指导书。

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_____年_____月_____日

Preface

In this Sixth Edition we again present a text in support of a first course in control and have retained the best features of our earlier editions. For this edition, we have substantially rewritten Chapter 4 on the Basic Properties of Feedback, placing the material in a more logical order and presenting it in a much more effective (bottom up?) manner. We have also updated the text throughout on how computer-aided design is utilized to more fully reflect how design is carried out today. At the same time, we also strive to equip control system engineers with a basic understanding so that computer results can be guided and verified. In support of this updating, MATLAB® referrals have been updated and include some of the latest capabilities in that software. The case studies in Chapter 10 have been retained and a new case study of the emerging Bioengineering field has been added. A Historical Perspective section has been added at the end of each chapter in order to add to the knowledge of how all these concepts came into being. Finally, in order to guide the reader in finding specific topics, we have expanded the Table of Contents to include subsections.

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 many carefully worked out examples to illustrate the material. As before, we provide a set of review questions at the end of each chapter with answers in the back of the book to assist the students in verifying that they have learned the material.

In the three central chapters on design methods we continue to expect the students to learn how to perform the very basic calculations by hand and make a rough sketch of a root locus or Bode plot as a sanity check on the computer results and as an aid to design. However, we introduce the use of MATLAB early on in recognition of the universal use of software tools in control analysis and design. Furthermore, in recognition of the fact that increasingly controllers are implemented in imbedded computers, we again 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 files (both "m" files and SIMULINK® files) used to produce the figures in the book. These are available at the following Web site:

www.FPE6e.com

For the SIMULINK files, there are equivalent LabView files that can be obtained by a link from the same web site.

We have removed some material that was judged to be less useful for the teaching of a first course in controls. However, recognizing that there may still be some instructors who choose to teach the material, or students who want to refer to enrichment and/or review material, we have moved the material to the website above for access by anyone. The Table of Contents provides a guide as to where the various topics are located.

We feel that this Sixth 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. We introduce the study of feedback control, both as a specialty of itself and as support for many other fields.

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 so 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 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 10, complex real-world design problems are attacked using all 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 editions we have tried to give equal importance to root locus, frequency response, and state-variable methods for design. In this edition we continue to emphasize solid mastery of the underlying techniques. coupled with computer based methods for detailed calculation. We also provide an early introduction to data sampling and discrete controllers in recognition of the major role played by digital controllers in our field. While this material can be skipped to save time without harm to the flow of the text, we feel that it is very important for students to understand that computer control is widely used and that the most basic techniques of computer control are easily mastered.

- 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 appropriate conclusions? How do they review for exams? Helping students with these tasks was a criterion for the Fourth and Fifth Editions and continues to be addressed in this Sixth Edition. We outline these features below.

FEATURE

1. *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.
2. *Margin notes* help students scan for chapter highlights. They point to important definitions, equations, and concepts.
3. *Boxed highlights* identify key concepts within the running text. They also function to summarize important design procedures.
4. *Bulleted chapter summaries* help with student review and prioritization. These summaries briefly reiterate the key concepts and conclusions of the chapter.
5. *Synopsis of design aids*. Relationships used in design and throughout the book are collected inside the back cover for easy reference.
6. *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.
7. *Review questions* at the end of each chapter with solutions in the back to guide the student in self-study

- 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, like Stanford, 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 in Chapter 2 an introduction to writing equations of motion for mechanical mechanisms. 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 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 automatic pilot system.

Outline of the Book

The contents of the book are organized into eight chapters and three appendixes. Optional sections of advanced or enrichment material marked with a triangle (△) are included at the end of some chapters. There is additional enrichment material on the website. Examples and problems based on this material are also marked with a triangle (△). The appendices include background and reference material. The appendices in the book include Laplace transform tables, answers to the end-of-chapter review questions, and a list of MATLAB commands. The appendixes on the website include a review of complex variables, a review of matrix theory, some important results related to State-Space design, a tutorial on RLTOOL for MATLAB, and optional material supporting or extending several of the chapters.

In Chapter 1, the essential ideas of feedback and some of the key design issues are introduced. This chapter also contains a brief history of control, from the ancient beginnings of process control to 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 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 represent new material. Stability of dynamic systems is also introduced in this Chapter. This material needs to be covered carefully.

Chapter 3 presents the basic equations and transfer functions of feedback along with the definitions of the sensitivity function. With these tools, open-loop and closed-loop control are compared with respect to disturbance rejection, tracking accuracy, and sensitivity to model errors. Classification of systems according to their ability to track polynomial reference signals or to reject polynomial disturbances is described with the concept of system type. Finally, the classical proportional, integral, and derivative (PID) control structure is introduced and the influence of the controller parameters on a system's characteristic equation is explored along with PID tuning methods. The end-of-chapter optional section treats digital control.

Following the overview of feedback in Chapter 3, the core of the book presents the design methods based on root locus, frequency response, and state-variable feedback in Chapters 4, 5, and 6, respectively.

In Chapter 7 the nonlinear material includes techniques for the linearization of equations of motion, analysis of zero memory nonlinearity as a variable gain, frequency response as a describing function, the phase plane, Lyapunov stability theory, and the circle stability criterion.

In Chapter 8 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 dynamics and Laplace transforms. Therefore, most of Chapter 2 would be a review for those students. In a ten-week quarter, it is possible to review Chapter 2, and all of Chapters 1, 3, 4, and 5. Most boxed sections should be omitted. In the second quarter, Chapters 6, and 7 can be covered comfortably including the boxed sections. A semester course should comfortably accommodate Chapters 1-6, including the review material of Chapters 2, if needed. If time remains after this core coverage, selected nonlinear issues from Chapter 7 and some of the case studies 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), classical control (Chapters 3–5), and modern control (Chapters 6–8).

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 covers Chapters 3–5.
The more advanced course is intended for graduate students and reviews Chapters 3–5 and covers Chapters 6–8. This sequence complements a graduate course in linear systems and is the prerequisite to courses in digital control, nonlinear 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 3–6, 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 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 WE and a brief treatment of particular material needed in control is given at the start of Chapter 6. The emphasis is on the relations between linear dynamic systems and linear algebra.

Supplements

The Web site mentioned above includes the dot-m and dot-mdl files used to generate all the MATLAB figures in the book and these may be copied and distributed to the students as desired. An instructor's manual with complete solutions to all homework problems is available. The Web site also includes advanced material and appendixes.

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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 who taught introductory control at Stanford: A. E. Bryson, Jr., R. H. Cannon, Jr., D. B. DeBra, S. Rock, S. Boyd, C. Tomlin, P. Enge, and C. Gerdes. Other colleagues who have helped us include D. Fraser, N. C. Emami, B. Silver, M. Dorfman, D. Brennan, K. Rudie, L. Pao, F. Khorrami, K. Lorell, and P. D. Mathur.

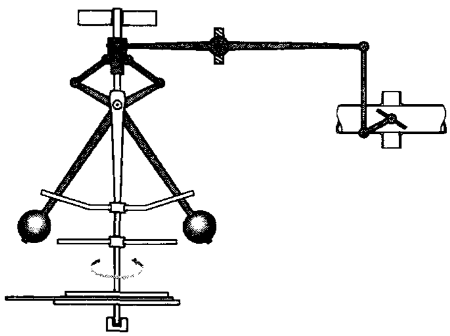
Special thanks go to the many students who have provided almost all the solutions to the problems in the book.

G.F.F.
J.D.P.
A.E.-N.
Stanford, California

Contents

1

An Overview and Brief History of Feedback Control



A Perspective on Feedback Control

Feedback control of dynamic systems is a very old concept with many characteristics that have evolved over time. The central idea is that a system's output can be measured and fed back to a controller of some kind and used to effect the control. It has been shown that signal feedback can be used to control a vast array of dynamic systems including, for example, airplanes and hard-disk data storage devices. To achieve good control there are four basic requirements.

- The system must be stable at all times
- The system output must track the command input signal
- The system output must be prevented from responding too much to disturbance inputs
- These goals must be met even if the model used in the design is not completely accurate or if the dynamics of the physical system change over time or with environmental changes.

The requirement of stability is basic and may have two causes. In the first place, the system may be unstable. This is illustrated by the Segway vehicle, which will simply fall over if the control is turned off. On the other hand, adding feedback may itself drive the system unstable. In ordinary experience such an instability is called a "vicious circle," where the feedback signal that is circled back makes the situation worse rather than better.

There are many examples of the requirement of having the system's output track a command signal. For example, driving a car so that the vehicle stays in its lane is command tracking. Similarly, flying an airplane in the approach to a landing strip requires that a glide path be accurately tracked.

Disturbance rejection is one of the very oldest applications of feedback control. In this case, the "command" is simply a constant set point to which the output is to be held as the environment changes. A very common example of this is the room thermostat whose job it is to hold the room temperature close to the set point as outside temperature and wind change, and as doors and windows are opened and closed.

Finally, to design a controller for a dynamic system, it is necessary to have a mathematical model of the dynamic response of the system in all but the simplest cases. Unfortunately, almost all physical systems are very complex and often nonlinear. As a result, the design will usually be based on a simplified model and must be robust enough that the system meets its performance requirements when applied to the real device. Furthermore, again in almost all cases, as time and the environment change, even the best of models will be in error because the system dynamics have changed. Again, the design must not be too sensitive to these inevitable changes and it must work well enough regardless.

The tools available to control engineers to solve these problems have evolved over time as well. Especially important has been the development of digital computers both as computation aids and as embedded control devices. As computation devices, computers have permitted identification of increasingly complex models and the application of very sophisticated control design methods. Also, as embedded devices, digital devices have permitted the implementation of very complex control laws. Control engineers must not only be skilled in manipulating these design tools but also need to understand the concepts behind these tools to be able to make the best use of them. Also important is that the control engineer understand both the capabilities and the limitations of the controller devices available.

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. In addition, later chapters have brief sections of additional historical notes on the topics