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# Modern Control Engineering (Fourth Edition)

# 现代控制工程

## （第4版）

KATSUHIKO OGATA
（绪方胜彦）



清华大学出版社

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**（第 4 版）**

Katsuhiko Ogata

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# 国际知名大学原版教材
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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。

## Modern Control Engineering, Fourth Edition

# 影印版序

美国明尼苏达大学 Katsuhiko Ogata 著的《现代控制工程》是国际上采用较广和影响较大的一部本科生和一年级研究生自动控制理论课程教材。从 1970 年问世至今，已从第 1 版修订到了第 4 版。除了英文版外，还被翻译成多种其他主要文字，包括中文简体字、中文繁体字、法文、俄文、日文、西班牙文等。

《现代控制工程》第 1 版出版于 1970 年，这是首次将现代控制理论基本内容和经典控制理论内容融为一体的控制理论教材。1976 年翻译成中文简体字版在中国大陆出版，其体系的新颖、内容的丰富、物理概念清晰、例题习题量大、教学适用性好等突出特点，使我国高等院校控制相关学科的众多师生视野为之一新，在相当一段时期里广泛采用作为自动控制理论课程的教材或参考书。本书第 2 版出版于 1990 年，并于 1993 年翻译成中文繁体字版在中国台湾地区出版。这一版在保持原书基本特点基础上，适度地增加了极点配置、状态观测器、控制系统仿真等新内容。本书第 3 版出版于 1997 年，2000 年翻译成中文简体字版在中国大陆出版。第 3 版在内容上作了大量的调整和修改，不再包含非线性控制系统的描述函数分析、相平面分析、离散系统的 Z 变换法等传统内容，增加了 PID 控制器和鲁棒控制器等设计方面的新内容，最为主要的是把 MATLAB 作为基本工具融入到教材论述的各个部分，顺应了国际上新近出版的科技教材和科技著作中将 MATLAB 全面应用于计算、建模、分析、设计、仿真等方面的大趋势。现今推出的是出版于 2002 年的《现代控制工程》第 4 版，这一版从自动控制理论课程的定位出发，更加强调内容基础性和避免过分工程性，对第 3 版中某些过分工程性和超出基础性的内容作了大刀阔斧式的删除。第 3 版中被删除的内容包括，第 5 章“控制系统的基本控制作用和响应”中极大部分内容，第 10 章“PID 控制与鲁棒控制”中鲁棒控制部分，第 13 章“李雅普诺夫稳定性分析和二次型最佳控制”中的极大部分内容即李雅普诺夫稳定性分析和模型参考控制系统分析部分，以及附录“MATLAB 应用的基础知识”中全部内容。可以认为，这体现了作者对自动控制理论教材定位的一种思考，研究对象回归到限于以电气、机械、液动、气动、热力等广泛物理对象为背景的线性时不变系统，研究领域覆盖系统的建模、分析和设计基本内容，研究方法包括基本的经典控制方法和状态空间方法，整个计算、建模、分析、设计、仿真基于 MATLAB 工具。

《现代控制工程》第 4 版共辖 4 个板块和 12 章内容。“引论和准备知识板块”包括第 1

章控制系统引论和第 2 章拉普拉斯变换。"系统建模板块"分成两章论述，以突出建模问题的重要性和强调背景系统的多样性，第 3 章动态系统的数学建模属于基础部分并讨论了机械系统和电系统的建模，第 4 章流体系统和热系统的数学建模属于扩展部分，推进讨论了液动系统、气动系统和热力系统的建模，这种做法有利于适应不同专业学科的教学需要。"系统分析板块"按方法由两个部分所构成，经典方法部分包括第 5 章暂态和稳态响应分析、第 6 章根轨迹分析和第 8 章频率特性分析，状态空间方法部分包括第 11 章状态空间中控制系统的分析。"系统设计板块"则由四章组成，第 7 章基于根轨迹法的控制系统设计和第 9 章基于频率特性的控制系统设计属于经典控制理论设计方法，第 12 章状态空间中控制系统的设计属于现代控制理论设计方法，第 10 章 PID 控制器和两自由度控制系统则属于专题内容。

《现代控制工程》第 4 版体系清晰，论述细腻，内容丰富，行文流畅，例题习题量大类广，并以 MATLAB 贯穿始终，具有很宽的专业适用面和多样化使用方式。本书既适合于作为自动控制理论课程的教材和参考书使用，也适合于科学工作者和技术人员作为学习控制系统的分析和设计的自学读物。特别是，对于现今正在提倡和开展的采用英语直接教学或采用双语教学，本书不失为一本很好的和适用的教材或参考书。

**郑大钟**
**清华大学自动化系**
**2005 年 11 月**

# Preface

This book presents a comprehensive treatment of the analysis and design of control systems. It is written at the level of the senior engineering (mechanical, electrical, aerospace, and chemical) student and is intended to be used as a text for the first course in control systems. The prerequisite on the part of the reader is that he or she has had introductory courses on differential equations, vector-matrix analysis, circuit analysis, and mechanics.

The main revision made in the fourth edition of the text is to present two-degrees-of-freedom control systems to design high performance control systems such that steady-state errors in following step, ramp, and acceleration inputs become zero. Also, newly presented is the computational (MATLAB) approach to determine the pole-zero locations of the controller to obtain the desired transient response characteristics such that the maximum overshoot and settling time in the step response be within the specified values. These subjects are discussed in Chapter 10. Also, Chapter 5 (primarily transient response analysis) and Chapter 12 (primarily pole placement and observer design) are expanded using MATLAB. Many new solved problems are added to these chapters so that the reader will have a good understanding of the MATLAB approach to the analysis and design of control systems. Throughout the book computational problems are solved with MATLAB.

This text is organized into 12 chapters. The outline of the book is as follows. Chapter 1 presents an introduction to control systems. Chapter 2 deals with Laplace transforms of commonly encountered time functions and some of the useful theorems on Laplace transforms. (If the students have an adequate background on Laplace transforms, this chapter may be skipped.) Chapter 3 treats mathematical modeling of dynamic systems (mostly mechanical, electrical, and electronic systems) and develops transfer function models and state-space models. This chapter also introduces signal flow graphs. Discussions of a linearization technique for nonlinear mathematical models are included in this chapter.

Chapter 4 presents mathematical modeling of fluid systems (such as liquid-level systems, pneumatic systems, and hydraulic systems) and thermal systems. Chapter 5 treats transient response analyses of dynamic systems to step, ramp, and impulse inputs. MATLAB is extensively used for transient response analysis. Routh's stability criterion is presented in this chapter for the stability analysis of higher order systems. Steady-state error analysis of unity-feedback control systems is also presented in this chapter.

Chapter 6 treats the root-locus analysis of control systems. Plotting root loci with MATLAB is discussed in detail. In this chapter root-locus analyses of positive-feedback systems, conditionally stable systems, and systems with transport lag are included. Chapter 7 presents the design of lead, lag, and lag–lead compensators with the root-locus method. Both series and parallel compensation techniques are discussed.

Chapter 8 presents basic materials on frequency-response analysis. Bode diagrams, polar plots, the Nyquist stability criterion, and closed-loop frequency response are discussed including the MATLAB approach to obtain frequency response plots. Chapter 9 treats the design and compensation techniques using frequency-response methods. Specifically, the Bode diagram approach to the design of lead, lag, and lag–lead compensators is discussed in detail.

Chapter 10 first deals with the basic and modified PID controls and then presents computational (MATLAB) approach to obtain optimal choices of parameter values of controllers to satisfy requirements on step response characteristics. Next, it presents two-degrees-of-freedom control systems. The chapter concludes with the design of high performance control systems that will follow a step, ramp, or acceleration input without steady-state error. The zero-placement method is used to accomplish such performance.

Chapter 11 presents a basic analysis of control systems in state space. Concepts of controllability and observability are given here. This chapter discusses the transformation of system models (from transfer-function model to state-space model, and vice versa) with MATLAB. Chapter 12 begins with the pole placement design technique, followed by the design of state observers. Both full-order and minimum-order state observers are treated. Then, designs of type 1 servo systems are discussed in detail. Included in this chapter are the design of regulator systems with observers and design of control systems with observers. Finally, this chapter concludes with discussions of quadratic optimal regulator systems.

In this book, the basic concepts involved are emphasized and highly mathematical arguments are carefully avoided in the presentation of the materials. Mathematical proofs are provided when they contribute to the understanding of the subjects presented. All the material has been organized toward a gradual development of control theory.

Throughout the book, carefully chosen examples are presented at strategic points so that the reader will have a clear understanding of the subject matter discussed. In addition, a number of solved problems (A-problems) are provided at the end of each chapter, except Chapter 1. These solved problems constitute an integral part of the text. Therefore, it is suggested that the reader study all these problems carefully to obtain a deeper understanding of the topics discussed. In addition, many problems (without solutions) of various degrees of difficulty are provided (B-problems). These problems may be used as homework or quiz purposes. An instructor using this text can obtain a complete solutions manual (for B-problems) from the publisher.

Most of the materials including solved and unsolved problems presented in this book have been class tested in senior level courses on control systems at the University of Minnesota.

If this book is used as a text for a quarter course (with 40 lecture hours), most of the materials in the first 10 chapters (except perhaps Chapter 4) may be covered. [The first nine chapters cover all basic materials of control systems normally required in a first course on control systems. Many students enjoy studying computational (MATLAB) approach to the design of control systems presented in Chapter 10. It is recommended that Chapter 10 be included in any control courses.] If this book is used as a text for a semester course (with 56 lecture hours), all or a good part of the book may be covered with flexibility in skipping certain subjects. Because of the abundance of solved problems (A-problems) that might answer many possible questions that the reader might have, this book can also serve as a self-study book for practicing engineers who wish to study basic control theory.

I would like to express my sincere appreciation to Professors Athimoottil V. Mathew (Rochester Institute of Technology), Richard Gordon (University of Mississippi), Guy Beale (George Mason University), and Donald T. Ward (Texas A & M University), who made valuable suggestions at the early stage of the revision process, and anonymous reviewers who made many constructive comments. Appreciation is also due to my former students, who solved many of the A-problems and B-problems included in this book.

*Katsuhiko Ogata*

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# 1

# Introduction to Control Systems

## 1-1 INTRODUCTION

Automatic control has played a vital role in the advance of engineering and science. In addition to its extreme importance in space-vehicle systems, missile-guidance systems, robotic systems, and the like, automatic control has become an important and integral part of modern manufacturing and industrial processes. For example, automatic control is essential in the numerical control of machine tools in the manufacturing industries, in the design of autopilot systems in the aerospace industries, and in the design of cars and trucks in the automobile industries. It is also essential in such industrial operations as controlling pressure, temperature, humidity, viscosity, and flow in the process industries.

Since advances in the theory and practice of automatic control provide the means for attaining optimal performance of dynamic systems, improving productivity, relieving the drudgery of many routine repetitive manual operations, and more, most engineers and scientists must now have a good understanding of this field.

**Historical Review.** The first significant work in automatic control was James Watt's centrifugal governor for the speed control of a steam engine in the eighteenth century. Other significant works in the early stages of development of control theory were due to Minorsky, Hazen, and Nyquist, among many others. In 1922, Minorsky worked on automatic controllers for steering ships and showed how stability could be determined from the differential equations describing the system. In 1932, Nyquist developed a relatively simple procedure for determining the stability of closed-loop systems on the basis of open-loop response to steady-state sinusoidal inputs. In 1934, Hazen, who introduced the term servomechanisms for position control systems, discussed the design of relay servomechanisms capable of closely following a changing input.

During the decade of the 1940s, frequency-response methods (especially the Bode diagram methods due to Bode) made it possible for engineers to design linear closed-loop control systems that satisfied performance requirements. From the end of the 1940s to the early 1950s, the root-locus method due to Evans was fully developed.

The frequency-response and root-locus methods, which are the core of classical control theory, lead to systems that are stable and satisfy a set of more or less arbitrary performance requirements. Such systems are, in general, acceptable but not optimal in any meaningful sense. Since the late 1950s, the emphasis in control design problems has been shifted from the design of one of many systems that work to the design of one optimal system in some meaningful sense.

As modern plants with many inputs and outputs become more and more complex, the description of a modern control system requires a large number of equations. Classical control theory, which deals only with single-input–single-output systems, becomes powerless for multiple-input–multiple-output systems. Since about 1960, because the availability of digital computers made possible time-domain analysis of complex systems, modern control theory, based on time-domain analysis and synthesis using state variables, has been developed to cope with the increased complexity of modern plants and the stringent requirements on accuracy, weight, and cost in military, space, and industrial applications.

During the years from 1960 to 1980, optimal control of both deterministic and stochastic systems, as well as adaptive and learning control of complex systems, were fully investigated. From 1980 to the present, developments in modern control theory centered around robust control, $H_\infty$ control, and associated topics.

Now that digital computers have become cheaper and more compact, they are used as integral parts of control systems. Recent applications of modern control theory include such nonengineering systems as biological, biomedical, economic, and socioeconomic systems.

**Definitions.** Before we can discuss control systems, some basic terminologies must be defined.

***Controlled Variable and Manipulated Variable.*** The *controlled* variable is the quantity or condition that is measured and controlled. The *manipulated* variable is the quantity or condition that is varied by the controller so as to affect the value of the controlled variable. Normally, the controlled variable is the output of the system. *Control* means measuring the value of the controlled variable of the system and applying the manipulated variable to the system to correct or limit deviation of the measured value from a desired value.

In studying control engineering, we need to define additional terms that are necessary to describe control systems.

***Plants.*** A plant may be a piece of equipment, perhaps just a set of machine parts functioning together, the purpose of which is to perform a particular operation. In this book, we shall call any physical object to be controlled (such as a mechanical device, a heating furnace, a chemical reactor, or a spacecraft) a plant.

***Processes.*** The *Merriam–Webster Dictionary* defines a process to be a natural, progressively continuing operation or development marked by a series of gradual changes that succeed one another in a relatively fixed way and lead toward a particular result or end; or an artificial or voluntary, progressively continuing operation that consists of a series of controlled actions or movements systematically directed toward a particular result or end. In this book we shall call any operation to be controlled a *process*. Examples are chemical, economic, and biological processes.

***Systems.*** A system is a combination of components that act together and perform a certain objective. A system is not limited to physical ones. The concept of the system can be applied to abstract, dynamic phenomena such as those encountered in economics. The word system should, therefore, be interpreted to imply physical, biological, economic, and the like, systems.

***Disturbances.*** A disturbance is a signal that tends to adversely affect the value of the output of a system. If a disturbance is generated within the system, it is called *internal*, while an *external* disturbance is generated outside the system and is an input.

***Feedback Control.*** Feedback control refers to an operation that, in the presence of disturbances, tends to reduce the difference between the output of a system and some reference input and does so on the basis of this difference. Here only unpredictable disturbances are so specified, since predictable or known disturbances can always be compensated for within the system.

## 1–2 EXAMPLES OF CONTROL SYSTEMS

In this section we shall present several examples of control systems.

**Speed Control System.** The basic principle of a Watt's speed governor for an engine is illustrated in the schematic diagram of Figure 1–1. The amount of fuel admitted

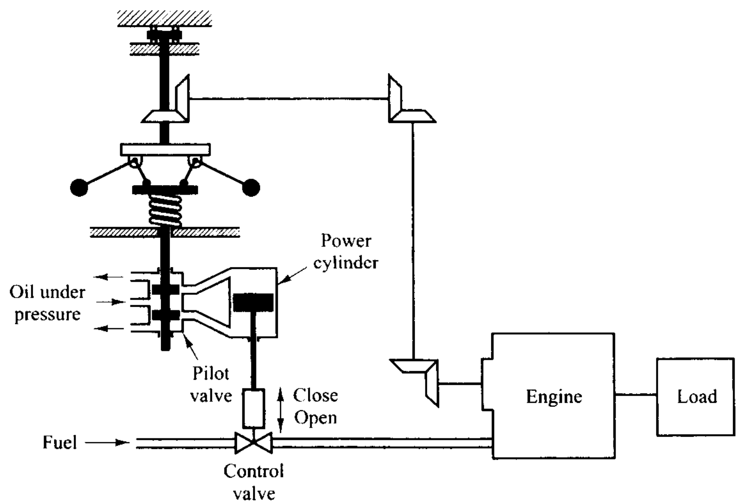


**Figure 1–1**
Speed control system.