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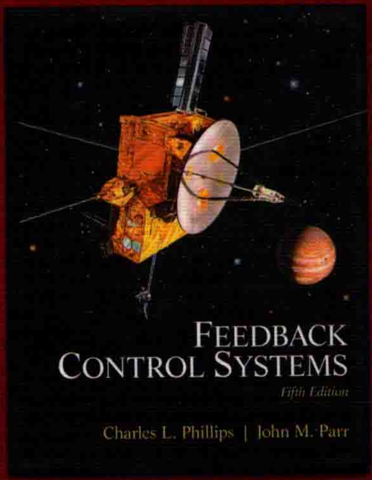

反馈控制系统

（第5版）

Feedback Control Systems

Fifth Edition

[美] Charles L. Phillips
John M. Parr 著
詹俦军 编译

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编译者序

反馈自动控制的技术已经广泛应用于现代社会的各个领域,例如电子、通信、交通和国防。自动控制系统分析和设计的理论应用范围更加广阔。自动控制的概念、方法和理论体系已经应用到了许多科学领域,例如复杂网络,形成了一大批新的交叉学科,例如经济学、复杂网络和系统生物学。本书系统全面地介绍了经典控制理论的基本内容,主要包括自动控制概论(第1章)、控制系统的数学模型(第2章和第3章)、系统响应(第4章)、线性系统的时域分析法(第5章和第6章)、线性系统的根轨迹法(第7章)、线性系统的频域分析法(第8章和第9章)、现代控制(第10章)、离散系统采样分析和控制(第11~13章和第14章)、非线性系统分析(第15章)。同时,介绍了MATLAB软件在自动控制系统仿真中的基本应用。本书每章都选配了一定数量的习题并提供了部分参考答案,以便于读者深入理解控制理论的重要概念和具体应用。

本书涵盖了经典自动控制理论的基础知识,详细介绍了自动控制理论的基本理论分析方法,并且就具体应用设计和技术案例实践给出了翔实而丰富的例子,具有以下鲜明的特点:

(1) 本书内容全面,详细介绍了经典自动控制理论、状态空间控制理论、离散数字系统控制理论技术和非线性系统分析的基本知识。整本书结构清晰明了、内容丰富,融会贯通了由基本概念到实际应用的思想。本书浅显易懂,数学理论分析过程翔实,读者只需要一定的微分方程、线性代数和拉普拉斯变换基础就可以理解其中的知识,可以作为大多数高校的教材。

(2) 每章的结构安排清晰合理。每章的简介(Introduction)部分都提纲挈领地给出了章节的知识背景和控制要求,以及章节的主要内容结构分布。在每章的各个小节,作者首先详细介绍各种理论、技术,紧接着给出翔实的例子,避免了读者局限于抽象的理论。而每章末尾对关键的知识点及时地进行了小结,有助于加深读者对所学知识的了解,形成完整的知识理论体系。

(3) 本书较早地引入了MATLAB的使用,并且在大量的实例中对使用MATLAB进行了分析。关键的例子在书本中提供了具体代码,读者可以轻松地在MATLAB中进行模仿练习。因此建议读者结合MATLAB学习,有利于快速培养起分析和设计控制系统的能力。

原书中被删除的章节:

(1) 3.8小节为模拟仿真,而现代大多数为数字仿真,该节内容已经过时,因此删除。

(2) 7.12小节的实用性不强,因此删除。

(3) 第11、12章中的关于信号流程图(signal-flow chart)部分由于在前述章节有介绍,

因此予以简化。

(4) 第13章中的第5、6、12、13、15小节中很多概念内容在连续系统中均有介绍,因此删除。

(5) 第14章中的第4、5和6小节缺乏实用性,因此删除。

(6) 附录A中介绍的量和单位,在我国离散数学课程中有完整的介绍,因此删除。

本书是在英文原版书基础之上进行了编译和删减而成,书中的电气符号及变量形式均保留了外版书的原文,特此说明。

这是笔者第一次做这种注释工作,再加上本书各方面的应用实例很多,难免有理解不当之处,非常希望听到读者的反馈意见。

编　者

2016年8月

Preface

The structure and philosophy of the previous editions of *Feedback Control Systems* remains unchanged in the fifth edition. However, the focus has been sharpened as a result of the experience using the first four editions and the reactions of colleagues who have taught from the book. Some explanations have been enhanced. Where appropriate, a number of examples have been improved. The majority of the end-of-chapter problems have been either altered or replaced.

The simulation program SIMULINK®, a block-diagram program to be used with MATLAB®, is introduced to illustrate the simulation of both continuous (analog) and discrete systems, and of nonlinear continuous systems. New capabilities of MATLAB have been added and many examples contain short MATLAB programs. In this fifth edition, the MATLAB programs given in the examples may be downloaded from the Companion Website http://www.pearsonhighered.com/phillips

This book is intended to be used primarily as a text for junior- and senior-level students in engineering curricula and for self-study by practicing engineers with little or no experience in control systems. For maximum benefits, the reader should have had some experience in linear system analysis.

The material of this book is organized into three principal areas: analog control systems, digital control systems, and nonlinear analog control systems. Chapter 1 presents a brief introduction and an outline of the text. In addition, some control systems are described to introduce the reader to typical applications. Next, a short history of feedback control systems is given. The mathematical models of some common components that appear in control systems are developed in Chapter 2.

Chapters 3 through 10 cover the analysis and design of linear analog systems; that is, control systems that contain no sampling. Cshapter 2 develops the transfer-function model of linear analog systems, and Chapter 3 develops the state-variable model.

Chapter 4 covers typical responses of linear analog systems, including the concept of frequency response. Since many of the characteristics of closed-loop systems cannot be adequately explained without reference to frequency response, this concept is developed early in the book. The authors believe that the frequency-response concept ranks in importance with the time-response concept.

Important control-system characteristics are developed in Chapter 5. Some of the applications of closed-loop systems are evident from these characteristics. The concept of system stability is developed in Chapter 6 along with the Routh-Hurwitz stability criterion. Chapter 7 presents analysis and design by root-locus procedures, which are basically time-response procedures. The equally important frequency-response analysis and design procedures are presented in Chapters 8 and 9. Chapter 10 is devoted to modern control-system design. Pole-placement design is developed, and the design of state estimators is introduced.

Chapters 3 through 10 applies directly to analog control systems and Chapters 11 through 14 applies to digital control systems. Essentially all the analog analysis and design techniques of Chapters 3 through 9 are developed again for digital control systems. These topics include typical responses, characteristics, stability, root-locus analysis and design, and frequency-response analysis and design.

Nonlinear system analysis is presented in Chapter 15. These methods include the describing-function analysis, linearization, and the state-plane analysis.

Usually, nonlinear controls are not covered in introductory books in control. However, many of the important characteristics of physical systems cannot be explained on the basis of linear systems. For example, stability as a function of signal amplitude is one of the most common phenomena observed in closed-loop physical systems, and the describing function is included in Chapter 15 to offer an analysis procedure that explains this phenomenon. Lyapunov's first stability theorem is also presented to illustrate some of the pitfalls of linear system-stability analysis.

Many examples are given, with an effort to limit each example to illustrating only one concept. It is realized that in using this approach, many obvious and interesting characteristics of the systems of the examples are not mentioned; however, since this is a book for beginning students in feedback control, making the examples more complex would tend to add confusion.

In general, each chapter is organized such that the more advanced material is placed toward the end of the chapter. This placement is to allow the omission of this material by those instructors who wish to present a less intense course.

This book may be covered in its entirety as a three-hour one-semester course in analog control (Chapters 1 through 9), and a three-hour one-semester course in digital control and nonlinear control with an introduction to modern control (Chapters 10 through 15). The material may also be covered in two-quarter course sequence, with approximately five hours for each course. With the omission of appropriate material, the remaining material may be covered in courses with fewer credits. If a course in digital control is taught without the coverage of the first nine chapters, some of the material of the first nine chapters must be introduced; Chapters 11 through 13 rely on some of this material. An asterisk sign is used to mark the problems with answers given in Appendix D. A manual containing the solutions to all problems at the end of the chapters is available for teachers who have adopted the text for use in the classroom.

NEW TO THIS EDITION

The following improvements have been made to the fifth edition:

- More than 70 percent of the end-of-chapter problems are new or revised.
- Additional examples.
- Additional explanation of some concepts and procedures.
- More extensive use of MATLAB in examples and problem sets.
- Companion Website contains M-files.
- A new Appendix that introduces control-system applications of MATLAB.
- A new Appendix with answers for selected end-of-chapter problems.
- The end-of-chapter problems are grouped into sets so that each set corresponds to a section of the chapter. In each set, at least one problem has its answer provided in Appendix E. Other problems in the set are based on the same concepts as the one with its answer given. This can provide immediate feedback to students in cases where the problems do not provide a second method of verification.
- A new chapter 14 on discrete-time pole assignment and state estimation has been added.

ACKNOWLEDGMENTS

We wish to acknowledge the many colleagues, graduate students, and staff members of Auburn University, the University of West Florida, and the University of Evansville who have contributed to the development of this book. We are especially indebted to Professor J. David Irwin, head of the department of Electrical Engineering of Auburn University, and to Professor Dick Blandford, chairman of the Electrical Engineering and Computer Science Department of the University of Evansville, for their aid and encouragement.

Thanks to Royce D. Harbor for his significant contributions to the first edition.

Finally, we express our gratitude and love for our families, without whom this undertaking would not have been possible.

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Contents

CHAPTER 1

Introduction

本书介绍闭环控制系统的分析与设计。在闭环控制系统分析方面，我们希望能够了解系统的特性（稳态和瞬态特性）；在闭环控制系统设计方面，则注重如何配置设计闭环系统以使得系统呈现设计者所需要的系统特性。

This book is concerned with the analysis and design of closed-loop control systems. In the *analysis* of closed-loop systems, we are given the system, and we wish to determine its characteristics or behavior. In the *design* of closed-loop systems, we specify the desired system characteristics or behavior, and we must configure or synthesize the closed-loop system so that it exhibits these desired qualities.

We define a closed-loop system as one in which certain of the system forcing signals (we call these *inputs*) are determined, at least in part, by certain of the responses of the system (we call these *outputs*). Hence, the system inputs are a function of the system outputs, and the system outputs are a function of the system inputs. A diagram representing the functional relationships in a closed-loop system is given in Figure 1.1.

An example of a closed-loop system is the temperature-control system in the home. For this system we wish to maintain, automatically, the temperature of the living space in the home at a desired value. To control any physical variable, which we usually call a *signal,* we must know the value of this variable; that is, we must measure this variable. We call the system for the measurement of a variable a *sensor,* as indicated in Figure 1.2. In a home temperature-control system, the sensor is a thermostat, which indicates a low temperature by closing an electrical switch and an acceptable temperature by opening the same switch. We define the *plant* of a control system as that part of the system to be controlled. It is assumed in this example that the temperature is increased by activating a gas furnace. Hence the plant input is the electrical signal that activates the furnace, and the plant output signal is the actual temperature of the living area. The plant is represented as shown in Figure 1.2. In the home-heating system, the output of

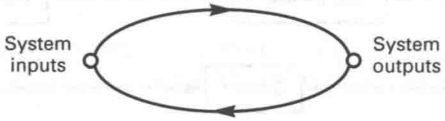


FIGURE 1.1
Closed-loop system.

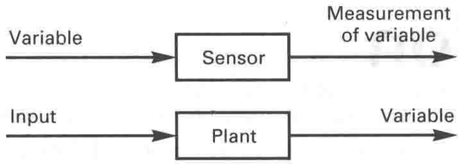


FIGURE 1.2
Control-system components.

each of the systems is connected to the input of the other to form the closed loop. However, in most closed-loop control systems, it is necessary to connect a third system into the loop to obtain satisfactory characteristics for the total system. This additional system is called a *compensator*, a *controller*, or simply a *filter*.

The usual form of a single-loop closed-loop control system is given in Figure 1.3. The system input is a reference signal; usually we want the system output to be equal to this input. In the home temperature-control system, this input is the setting of the thermostat. If we want to change the temperature, we change the system input. The system output is measured by the sensor, and this measured value is compared with (subtracted from) the input. This difference signal is called the *error signal,* or simply the error. If the output is equal to the input, this error signal is zero, and the plant output remains at its current value. If the error is not zero, in a properly designed system the error signal causes a response in the plant such that the magnitude of the error is reduced. The compensator is a filter for the error signal, since usually satisfactory operation does not occur if the error signal is applied directly to the plant.

Control systems are sometimes divided into two classes. If the object of the control system is to maintain a physical variable at some constant value in the presence of disturbances, we call this system a *regulator*. One example of a regulator control system is the speed-control system on the ac power generators of power utility companies. The purpose of this control system is to maintain the speed of the generators at the constant value that results in the generated voltage having a frequency of 60 Hz in the presence of varying electrical power loads. Another example of a regulator control system is the biological system that maintains the temperature of the human body at approximately 98.6°F (37℃) in an environment that usually has a different temperature.

The second class of control systems is the *servomechanism*. Although this term was originally applied to a system that controlled a mechanical position or motion, it is now often used to describe a control system in which a physical variable is required to follow, or track, some desired time function. An example of this type of system is an automatic aircraft landing system, in which the aircraft follows a ramp to the desired touchdown point. A second example is the control systems of a robot, in which the robot hand is made to follow some desired path in space.

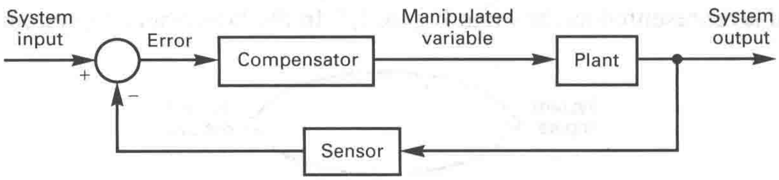


FIGURE 1.3
Closed-loop control system.

The preceding is a very simplified discussion of a closed-loop control system. The remainder of this book improves upon this description. In order to perform either mathematical analysis or design, it is necessary that we have a mathematical relationship between the input and the output for each of the blocks in the control system of Figure 1.3. The purpose of Chapter 2 is to develop these functional relationships for some common physical systems. Chapter 3 presents a different method of expressing these functional relationships.

We examine typical responses that occur in control systems in Chapter 4 and look at control-system specifications in Chapter 5. Chapter 6 presents concepts and some analysis techniques for system stability. The root locus, one of the principal methods of analysis and design, is developed in Chapter 7. Chapters 8 and 9 present a second principal analysis and design method, the frequency response. Chapter 10 presents an introduction to a different method of design of control systems, which is classified as a modern control procedure.

In Chapters 2 through 9, it is assumed that no system signals appear in sampled form and in particular that no digital computers are used in the control of the system. The systems considered in these chapters are called *analog* systems, *continuous-data* systems, or *continuous-time* systems. Chapters 11 through 13 consider systems in which sampling does occur, and these systems are called *sampled-data* systems. If a digital computer is used in the control of these systems, the systems are then called *digital* control systems. The terms *discrete-time* systems or simply *discrete* systems are also used to refer to sampled-data systems and digital control systems.

In Chapters 2 through 13, all systems are assumed to be linear (linearity is defined in Chapter 2). However, physical systems are not linear, and in general, nonlinear systems are difficult to analyze or design. Throughout this book, we discuss the problems of the inaccurate representations in the functional relationships that we use to model physical systems. However, for some physical systems, the linear model is not sufficiently accurate, and nonlinearities must be added to the system model to improve the accuracy of these functional relationships. We consider some common nonlinearities and some properties and analysis methods for nonlinear systems in Chapter 15.

In the analysis of linear systems, we use the Laplace transform for analog systems and the z-transform for discrete systems. Appendix B presents the concepts and procedures of the Laplace transform, and the z-transform is covered in Chapter 11. Next, the control problem is presented, and then some control systems are discussed.

1.1 THE CONTROL PROBLEM

We may state the control problem as follows. A physical system or process is to be accurately controlled through closed-loop, or feedback, operation. An output variable, called the response, is adjusted as required by the error signal. This error signal is the difference between the system response, as measured by a sensor, and the reference signal, which represents the desired system response.

Generally, a controller, or compensator, is required to filter the error signal in order that certain control criteria, or specifications, be satisfied. These criteria may involve, but not be limited to:

1. Disturbance rejection
2. Steady-state errors

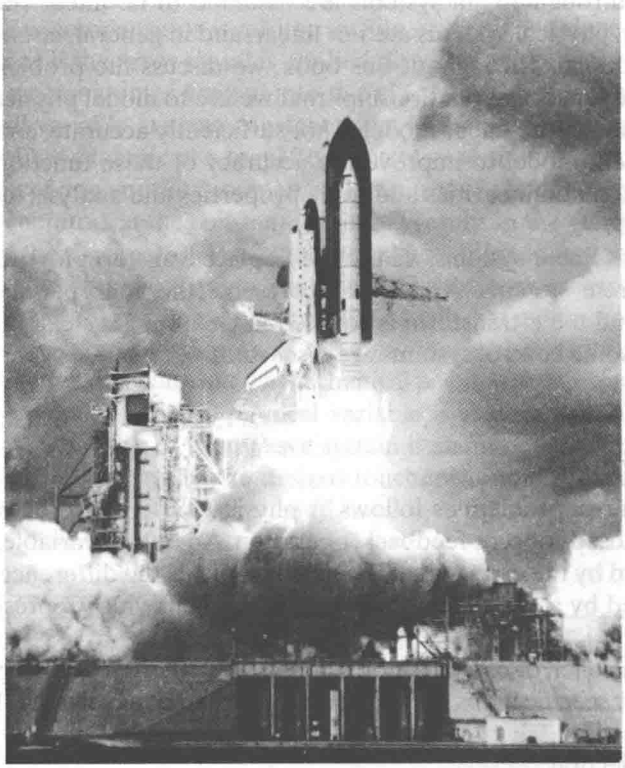
3. Transient response characteristics
4. Sensitivity to parameter changes in the plant

Solving in control problem generally involves

1. Choosing sensors to measure the plant output
2. Choosing actuators to drive the plant
3. Developing the plant, actuator, and sensor equations (models)
4. Designing the controller based on the models developed and the control criteria
5. Evaluating the design analytically, by simulation, and finally, by testing the physical system
6. If the physical tests are unsatisfactory, iterating these steps

Because of inaccuracies in the models, the first tests on the physical control system are usually not satisfactory. The controls engineer must then iterate this design procedure, using all tools available, to improve the system. Generally, intuition, developed while experimenting with the physical system, plays an important part in the design process.

The relationship of mathematical analysis and design to physical-system design procedures is depicted in Figure 1.4 [1]. In this book, all phases shown in the figure are discussed, but



NASA space shuttle launch. (Courtesy of NASA.)