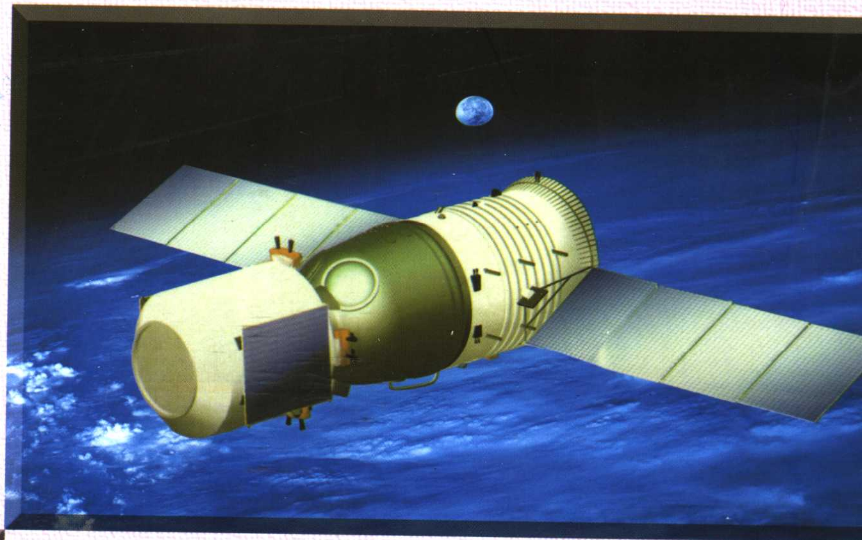
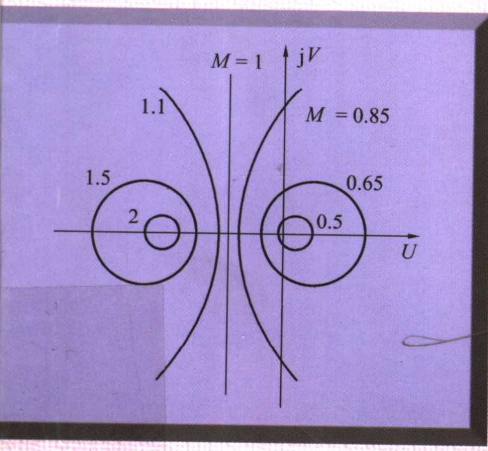
高等学校“十一五”规划教材

AUTOMATIC CONTROL PRINCIPLE





自动控制原理

（中英文对照）

李道根　主编
王建华　主审

哈爾濱工業大學出版社

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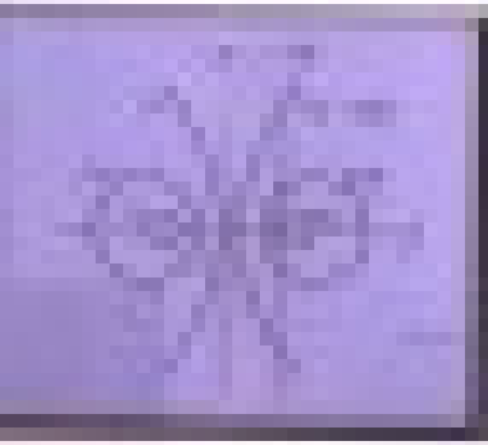

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Brief of contents

This textbook states the basic concepts, principles and various analysis techniques of classical control theory. The textbook consists of seven chapters, among them the former six chapters describe the analysis and synthesis of linear time-invariant systems, and the last chapter describes non-linear systems.

The book is printed in a bilingual form to make convenience for reader's reading and studying. This text book could be used as a professinal teaching material for the speciallies of automation, electrical engineering and automation, and so on, as well as a self-studying material or a reference book for graduated students of other relevaut specialties and teachers.

内 容 提 要

本书阐述了经典控制理论的基本概念、原理和分析方法。全书共七章,前六章介绍线性时不变系统的分析和综合,最后一章介绍非线性系统。

本书以双语形式出版,以方便读者的阅读和学习。本书是工科院校自动控制及自动化类专业教材,也是专业英语教材,同时也可作为其他相关专业研究生和教师的参考书。

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Preface

With the coming of economic globalization and knowledge-based economy, higher demand of the quality of higher education is put forward. In 2001, National Ministry of Education introduced "On the strengthening of Undergraduate Education in improving the quality of teaching some of the views", in which twelve measurements to enhance undergraduate teaching and improve teaching quality were brought forward to answer the new situation of higher education, and "bilingual teaching" was one of them. National Ministry of Education calls for actively promotion to develop bilingual teaching in colleges and universities, and exert much effort to open up 5% ~ 10% of the bilingual courses in three or five years.

Early of 2007, National Ministry of Education and Ministry of Finance jointly introduced the "Opinion on the implementation of quality of undergraduate education and teaching reform", encouraging colleges and universities to build 500 bilingual teaching model curriculums within five years. The complier of this book conforms to the trend of the development of higher education, carried through bilingual teaching of "Automatic control principle" in automation and electrician engineering and automation specialties, actively explored for the bilingual teaching models and methodologies adapting to ordinary colleges. This book is one of the fruits of their bilingual teaching practice.

The compliers take two years to accomplish this bilingual teaching material based on the long-term accumulation of teaching, bilingual teaching experience and the reference to the large number of original material. Two academic years' bilingual teaching practice indicates that this book is satisfactory for teaching demand of automation and relevant speciality.

The whole book is well-structured with concise content which not only considers the integrity of the classical control theory, but also strives to give prominence to key concepts and connects theory with practice. This book is guidebook-structured, explains the profound things in a simple way, and concisely expatiates basic concepts avoiding complicated mathematic derivation, that provides strong readability.

This book can be used as professional teaching materials for the specialties of automation, electrical engineering and automation and so on, as well as reference books for relevant technical staff.

Li Wenxiu
July, 2007

序

经济全球化进程的加快和知识经济时代的到来,对高等教育质量提出了更高的要求。教育部2001年出台了《关于加强高等学校本科教学工作提高教学质量的若干意见》,针对我国高等教育面对的新形势提出了十二条加强本科教学工作、提高教学质量的措施和意见,其中之一就是"开展双语教学"。教育部要求各高校积极推动使用英语等外语进行公共课和专业课的教学,力争在三年内,开出5%~10%的双语课程。

2007年初,教育部、财政部又联合出台了《关于实施高等学校本科教学质量与教学改革工程的意见》,提出在五年内要建设500门双语教学示范课程。编者顺应高等教育的发展潮流,对所在学校的自动化和电气工程及其自动化专业的"自动控制原理"课程进行了双语教学,积极探索适合普通高等院校(理工类专业)的双语教学模式和方法,本书正是编者开展双语教学研究的成果之一。

编者基于长期的教学积累和开展双语教学的心得体会,在参考了大量原版教材的基础上,编写了这本《自动控制原理》双语教材,并经过了两个学年的双语教学实践,教学效果表明该教材基本能够满足自动化及相关专业双语教学的需要。

全书内容精练,结构严谨,既考虑了经典控制理论体系的系统性和完整性,又力求做到重点突出,理论联系实际。全书层次分明、深入浅出,对基本概念的阐述简明扼要,避免了繁杂的数学推导,可读性较强,便于学生掌握经典控制理论的基本知识。

本书适用于工程与应用类自动化专业、电气工程及其自动化专业或相近专业的教学,也可作为相关专业工程技术人员的参考书。

李文秀

2007年7月

Foreword

Automatic control theory is widely applied in so many fields, such as industry, agriculture, shipbuilding and aviation, that greatly contributes to social development and economic construction. In recent years the compliers carried through bilingual teaching of "Automatic control principle" in the specialties of automation and electrical engineering and automation. This book is a product of our bilingual teaching practice and experience. The book is printed in a bilingual form to provide convenience for reader.

This book tries our best to explain the profound things in a simple way, apply rigorous theory and give prominence to system organization and give balance to engineering. We expect this book would play an active role in improving english application ability of reader, cultivating correction ideation and the ability to connect theory with practice of students.

This book can be used as a professional teaching material for the speciallies of automation, electricial engineering and automation and so on, as well as a reference book for graduated students of other relevant speciaties and teachers.

This book is edited by Li Daogen. The chief revisor is Li Wenxiu. Dr. Zhu Zhiyu compiles Chapter two, three, Dr. Liu Weiting compiles Chapter four, and Li Daogen writes the rest. We would especially like to thank Hao Peng, Wang Fang and Zong Yang for drawing the figures and tables in this book. And we would like to thank all the teachers and students for their help in the production and editing of this book.

It is inevitable there are some mistakes in this book because of our limited level, any criticism and correction will be appreciated.

Compiler Li Daogen
June, 2007

前　言

“自动控制理论”广泛应用于工业、农业、船舶、航空航天等诸多领域，在促进社会发展和经济建设中做出了重要贡献。近几年来，编者对自动化和电气工程及其自动化等专业的“自动控制原理”课程进行了双语教学尝试，本书就是编者在开展“双语”教学实践的基础上，结合多年讲授“自动控制原理”课程的心得和体会编写而成的。全书采用中英文对照的形式出版，以方便读者阅读和学习。

全书力求做到深入浅出，理论严谨，突出系统性，并兼顾工程性。本书对提高读者的英语应用能力，培养学生的辨正思维能力和理论联系实践的能力，都具有一定的作用。

本书可作为工科自动化、电气工程及其自动化专业教材，也可作为相关专业研究生和教师的参考书目。

本书由李道根主编，王建华主审。本书第1章、第5~7章由李道根编写，第2、3章由朱志宇编写，第4章由刘维亭编写。郝鹏、王芳、宗阳等绘制了书中的图表。在此，仅向参与和关心本书编写工作的各位教师和同学表示感谢。

由于作者水平有限，书中存在的错误和不妥之处，敬请读者批评指正。

编　者
2007年6月

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Chapter 1 Introduction to Control System

1.1 Introduction

1.1.1 Control Engineering and Automation

As an application of scientific and mathematical principles to the design, manufacture, and operation of systems, such as machines, plants, processes, and etc., control engineering is concerned with understanding and controlling the material and forces of nature for the benefit of humankind. Control system engineers are concerned with understanding and controlling systems to provide useful economic products for society. Control engineering is based on the foundations of feedback theory and linear system analysis, and it integrates the concepts of network theory and communication theory. Therefore, control engineering is not limited to any engineering discipline but is equally applicable to aeronautical, chemical, mechanical, environmental, and electrical engineering. For example, quite often, a control system includes electrical, mechanical, and chemical components. Furthermore, as the understanding of the dynamics of business, social, and political systems increases, the ability to control these systems will increase also.

The control of a plant or process by automatic rather than manual means is called automation; or we can say that automation is an automatic technology of machines, plants, processes, and etc. Automation is used to improve productivity and obtain high-quality products.

1.1.2 History of Automatic Control

The simplest way to automate the control of a plant or process is through conventional feedback control. The use of feedback to control a system has had a long history. Historically, a key step forward in the development of control occurred during the industrial revolution. At that time, machines were developed that greatly enhanced the capacity to turn raw materials into products of benefit to society. The associated machines, especially steam engines, involved large amounts of power, and it was soon realized that this power needed to be controlled in an organized fashion if the systems were to operate safely and efficiently. A major development at that time was Watt's fly-ball governor. This device regulates the speed of a steam engine by throttling the flow of steam.

The World Wars also led to many developments in control engineering. Some of these were associated with guidance systems and anti-aircraft systems while others were connected with the enhanced manufacturing requirements necessitated by the war effort.

The push into space in the 1960's and 1970's also depended on control development. These developments then flowed back into consumer goods, as well as into commercial, environmental, and medical applications.

By the end of the twentieth century, control has become a ubiquitous (but largely unseen) element of modern society. Virtually every system we come in contact with is underpinned by sophisticated control systems. Examples range from simple household products (temperature regulation in air-conditioners, thermostats in hot-water heaters, etc.), to large-scale systems (such as chemical plants, aircraft, and manufacturing processes).

Beyond these industrial examples, feedback regulatory mechanisms are central to the operation of biological systems, communication networks, national economies, and even human interactions. Indeed, if one thinks carefully, control in one form or another can be found in every aspect of life.

Thus, control engineering is an exciting multidisciplinary subject with an enormously large range of practical applications. Moreover, interest in control is unlikely to diminish in the foreseeable future. On the contrary, it is likely to become ever more important, because of the increasing globalization of markets and environmental concerns.

Market globalization is increasingly occurring, and this situation means that manufacturing industries are necessarily placing increasing emphasis on issues of quality and efficiency. This focuses attention on the development of improved control systems, so that the plants and processes operate in the best possible way. In particular, improved control is a key enabling technology underpinning.

Again, control engineering is a core enabling technology in reaching the goals of respecting finite natural resources and preserving our fragile environment.

1.1.3 Historical Periods of Control Theory

We have seen above that control engineering has taken several major steps forward at crucial events in history. Each of these steps has been marched by a corresponding burst of development in the underlying theory of control.

Early on, when the concept of feedback was applied, engineers sometimes encountered unexpected results. These then became catalysts for rigorous analysis.

The developments around the period of the Second World War were also marched by significant developments in control theory. This resulted in simple graphical means for analyzing single-variable feedback control problems. These methods are now generally known by the generic term classical control theory.

The 1960's saw the development of an alternative state-space approach to control. This followed the publication of work by Wiener, Kalman (and others) on optimal estimation and control. This work allowed multivariable problem to be treated in a unified fashion. This had been difficult, if not impossible, in the classical framework. This set of developments is termed modern control theory.

The theory of automatic control is a large, exciting, and extremely useful engineering discipline. One can readily understand the motivation for the study of automatic control theory.

1.1.4 Future Evolution of Control Systems

The continuing goal of control systems is to provide extensive flexibility and high level of autonomy. Today's industrial robot is perceived as quite autonomous: once it is programmed, further intervention is not normally required. Because of sensory limitations, these robotic systems have limited flexibility in adapting to work environment changes, which is the motivation of computer vision research. The control system is very adaptable, but it relies on human supervision. Advanced robotic systems are striving for task adaptability through enhanced sensory feedback. Research areas concentrating on artificial intelligence, sensor integration, computer vision, and off-line CAD/CAM programming will make systems more universal and economical. Control systems are moving toward autonomous operation as an enhancement to human control. Research in supervisory control, human-machine interface methods to reduce operator burden, and computer database management is intended to improve operator efficiency. Many research activities are common to robotics and control systems and are aimed toward to reducing implementation cost and expanding the realm of application. These include improved communications methods and advanced programming languages.

1.1.5 Control System

A control system is an organized collection of interacting units designed to achieve some specified objectives by manipulation and control of materials, energy, and information. In studying automatic control theory we are concerned with the signal flow within a system rather than the material flow and energy flow.

A control system is dynamic in nature and there exists cause-and-effect relationship among the components of a system. Hence, a system and its components can be represented graphically with a so-called block diagram, as shown in Fig. 1.1. Within the block there is the name, function, or mathematic model of the corresponding system or its component; the lines with arrow indicate the direction of signal flow. In a control system, the plant or process to be controlled is called the controlled object, and the quantity to be chosen to characterize the system behavior is called the controlled variable, or output for short. Corresponding to the controlled variable, a desired value or command input is established. The input-output relationship represents a cause-and-effect relationship of the system. A disturbance is an external action (other than the command input) that tends to drive the controlled variable away from its desired value. The disturbance-output relationship is another cause-and-effect relationship of the system.

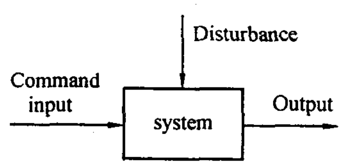

Figure 1.1 Block representing a system

1.2 Open-and Closed-Loop Control

Usually, an automatic control system consists of the controlled object and its controller. Based on how the control action is generated, i.e., whether the generation of control action is depended on the actual output, the control systems may be classified as open-loop control systems and closed-loop control systems.

1.2.1 Open-Loop Control

An open-loop control system is a system without feedback, and in which the signal flow from input to the output is unidirectional. In the case of open-loop control, the generation of control action is independent of the actual output, i.e., the control action is depended only on the command input and/or disturbance.

1. Manipulation according to command input

One mode of open-loop control is the manipulation according to command input, as shown in Fig.1.2. The controller accepts the command input and manipulates the plant to obtain a desired output. The desired value of the output may be changed and then the input will need to be changed to adjust the plant operation.

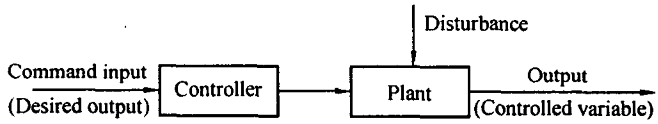

Figure 1.2 Functional block diagram of manipulation according to input

An example is a turntable used to rotate a disk at a constant speed, as shown in Fig.1.3. This system uses a battery source to provide a reference voltage that is proportional to the desired speed. This voltage is amplified and applied to the dc motor, which provides a speed proportional to the applied voltage. In this system, a variation of the speed from the desired value, due to some reason, can in no way cause a change of voltage applied on the dc motor to maintain the desired speed. In this case, it can also be said that the output has no influence on the input.

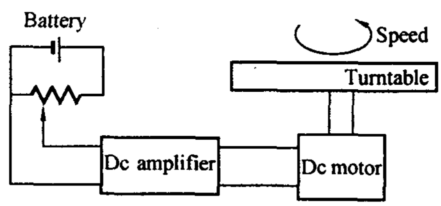

Figure 1.3 Open-loop control of turntable speed

Another example of manipulation according to command input is a generator-load system, as shown in Fig.1.4. The voltage provided by the generator is proportional to the exciting voltage of exciter, which can be adjusted with a potentiometer.

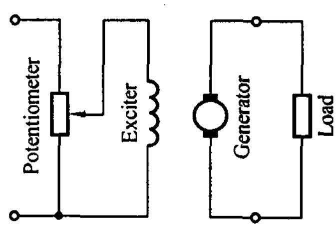

Figure 1.4 Open-loop control of a generator-load system

Obviously, the voltage across the load will be affected by the disturbance, for example the fluctuation of load or the parameter variation of certain components, the actual output will be away from the desired value and cannot return to the original condition by itself.

2. Compensation according to disturbance

Another mode of open-loop control is the compensation according to disturbance, as shown in Fig. 1.5. In this case, the controller accepts the disturbance signal, if it is measurable, and generates an additional control action to compensate the effect of disturbance on the system.

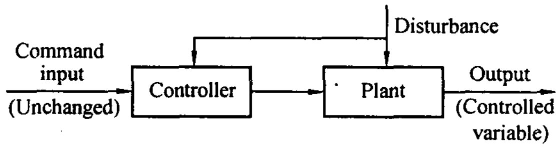

Figure 1.5 Compensation according to disturbance

An example of this open-loop control fashion is the generator-load system, as shown in Fig. 1.6, but a part of the exciter winding is connected in the generator-load loop. Now, if the load voltage is decreased due to a increment of load, the current flowing through the load and exciting winding will be increased, which will result in increasing the terminal voltage of generator.

Although an open-loop system is simpler and less expensive to construct, it requires detailed knowledge of each component in order to determine the input value for a required output. Moreover, the variation of system parameters and/or the external disturbance may have bad influences on the control accuracy.

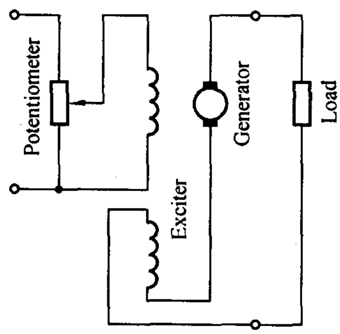

Figure 1.6 A generator-load system with compensation in terms of disturbance

1.2.2 Closed-Loop Control

In contrast to an open-loop control system, a closed-loop control system utilizes an additional measure of the actual output to compare with the desired value of output, as shown in Fig. 1.7. The measure of the actual output is called feedback signal. A feedback control system is a control system that tends to maintain a prescribed relationship of one system variable to another by comparing functions of these variables and using the difference as a means of control.

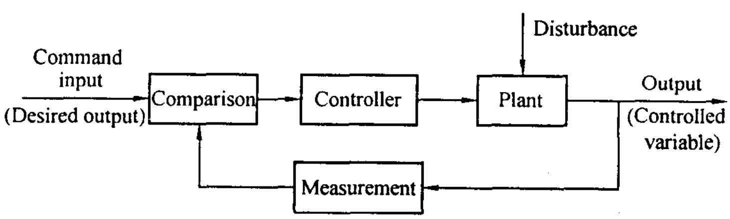

Figure 1.7 Function block diagram of a closed-loop control system

Fig. 1.8 shows a closed-loop control of the speed of a turntable, where a tachometer is used to measure the actual speed and output a voltage proportional to the speed. This system uses a function of the output and input to control the plant. The difference between the input and feedback signal is used to control the system so that the difference is continuously reduced. The feedback concept has