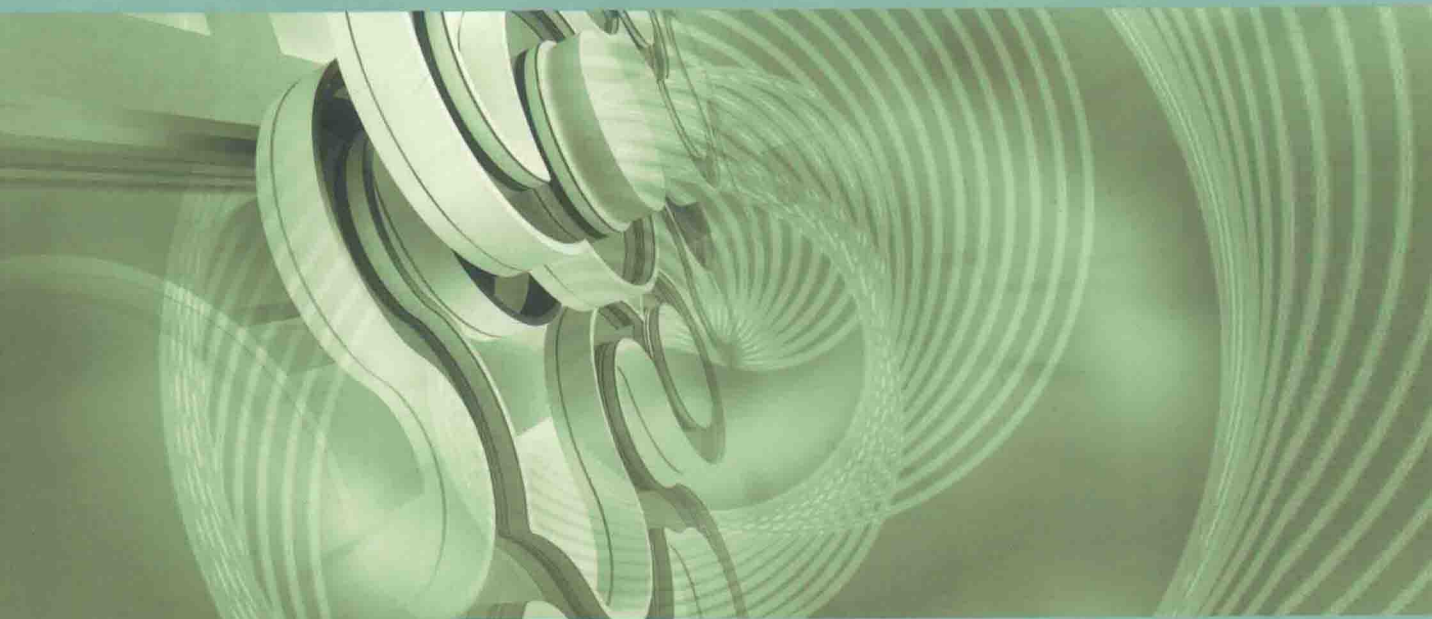




普通高等教育“十二五”规划教材



自动控制理论与应用

Automatic Control Theory and Application

戴亚平 编著



中国电力出版社
CHINA ELECTRIC POWER PRESS



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Automatic Control Theory and Application

编著 戴亚平
主审 李少远



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内 容 提 要

本书为普通高等教育“十二五”规划教材。

本书比较全面地介绍了自动控制系统分析与设计的基本理论和应用技术。主要内容包括控制系统概述、系统的数学模型、反馈控制系统的特征、线性反馈系统的稳定性、根轨迹法、频率响应法、频域中的稳定性分析、频域法校正、状态空间与状态方程和状态变量反馈系统设计。本书知识分布较宽,难度适中,突出了控制系统特性分析方法和控制器初步设计理念,强调了建立基本概念和掌握基本分析技能,所举案例多来源于工业过程控制领域,同时还给出了可以应用 MATLAB 工具进行仿真的提示。

本书可作为普通高等院校自动化、电气工程及其自动化等专业自动控制理论的双语教学教材,也可供相关工程技术人员学习参考。

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Preface

《Automatic Control Theory and Application》is an important basement course for the subject of Control Science and Engineering. By means of the tools of Mathematics and Computer technology, several of control strategies, mathematical modeling, system analysis and design will be studied. The course will make students not only to understand the theory of automation, but also to grasp how to deal with the question in real control systems. Even more, the automatic theory is the basement of other relative courses.

The course of Automatic Control Theory with bilingual was first given out for the students in Beijing Institute of Technology in 1999. After more than 10 years, a lot of teacher's lesson plan and class notes had been accumulated, students need only to copy teacher's PPT after the class, and then review the knowledge according to the outline of teacher's Lecture Notes. So we think to collect the Lecture Notes, and make them for a book maybe a good idea for our students, they need not to copy the PPT after the class at least. Also to read a book is more easy and convenient than to read the PPT on screen.

Even we had built a Web Station for the students in Beijing Institute of Technology, students can log in the Web of Remote Control Laboratory, download the PPT of texts and meanwhile they can do some experiments to practice how to control a plant by some control algorithm. In 2008, the course of Automatic Control Theory (A) got award of "Beijing Excellent Course" from Beijing Municipal Education Commission.

前言

《自动控制理论与应用》是控制科学与工程学科的重要基础和核心内容之一,它以工程领域内的控制系统为主要对象,以数学方法和计算机技术为主要工具,研究各种控制策略及控制系统的建模、分析、综合、设计和实现的理论、技术和方法。通过本课程的学习,学生可以了解和掌握自动控制理论的精髓,提高运用所学理论分析问题和解决实际问题的能力,为后续专业课程的学习打下坚实的理论基础。

双语教学的《自动控制理论与应用》从1999年开始在北京理工大学正式开课。经过了10多年的时间,老师们积累了大量的笔记和教案,北京理工大学的学生可以在课后拷贝任课教师的课件,并且根据课件的大纲进行课程的复习。我们把这些课堂笔记与教案汇集起来变成一本教科书,这样可以免去学生们在课后拷贝教师的课件的辛苦。毕竟手持一本教科书听课比在课后从电脑上查看课件要容易也方便许多。

我们还专门为这门课程在北京理工大学的校园网内建立了一个网站,教师的课件都公布在这个网站上,学生们通过登录我们提供的网址可以进入这个远程控制实验室,下载相关的课件,同时学生们可以做一些针对实际被控对象的一些简单控制方法的实验。在2008年,这门课程被北京市教育委员会评为北京市精品课程。

The Main purpose of writing this book is to help students who studying the automatic control theory bilingually, to help them to absorb the knowledge as much as they can in the shorter and shorter study period. There will be "three domain" introduced to readers of this book: time domain, s-domain and f-domain. And there will be "one space" method introduced in this book —state space method. According to the "three domain" and "one space", students will get the knowledge of classical control theory and simple modern control theory.

Author at Dec.10, 2014

写本书的主要目的是帮助那些正在学习自动控制理论双语课程的学生，能够在越来越少的授课时间内学到尽可能多的知识。在本书中，将根据“三域”和“一空间”讲述自动控制理论的基本原理。“三域”分别指“时间域”、“复数域”和“频率域”，而一空间则指的是“状态空间”。通过对这“三域”和“一空间”的深入学习，学生便会获得经典控制理论与简单的现代控制理论的相关知识。

作者于 2014 年 12 月 10 日

Contents

Preface

Chapter 1 Introduction to Control Systems 1

- 1.1 History of Automatic Control 3
- 1.2 The Concepts of Control Systems 4
- 1.3 Example of Automatic Control System 6
- 1.4 The Main Content of This Book 7

Chapter 2 Mathematical Model of Systems 11

- 2.1 Introduction 13
- 2.2 Differential Equations of Physical Systems 13
- 2.3 Linear Approximations of Nonlinear Systems 19
- 2.4 The Laplace Transform 21
- 2.5 The Transfer Function of Linear Systems 25
- 2.6 Block Diagram Models 28
- 2.7 Signal-Flow Graph Models 31
- 2.8 Summary 35

Chapter 3 Feedback Control System

Characteristic 39

- 3.1 Introduction 41
- 3.2 Test Input Signal 41
- 3.3 The Transient Response of Control System with Step Input 41
- 3.4 Performance of a Second-order System 48
- 3.5 Summary 52

Chapter 4 The Stability of Linear Feedback

System 55

- 4.1 Introduction 57
- 4.2 Stability of Dynamic System 57
- 4.3 Routh-Hurwitz Criterion 58
- 4.4 The Steady State Error of Feedback Control System 63
- 4.5 Higher-order System Motion 66
- 4.6 Effects of Parameters on Stability 69
- 4.7 Summary 69

目 录

前言

第 1 章 控制系统概述 1

- 1.1 自动控制理论与实践的发展简史 3
- 1.2 控制系统的一些基本概念 4
- 1.3 自动控制系统的举例 6
- 1.4 本书的主要内容简介 7

第 2 章 系统的数学模型 11

- 2.1 概述 13
- 2.2 物理系统的微分方程 13
- 2.3 非线性系统的线性逼近 19
- 2.4 拉普拉斯变换 21
- 2.5 线性系统的传递函数 25
- 2.6 框图模型 28
- 2.7 信号流图模型 31
- 2.8 小结 35

第 3 章 反馈控制系统的特征

..... 39

- 3.1 概述 41
- 3.2 测试输入信号 41
- 3.3 阶跃输入的瞬态响应 41
- 3.4 二阶系统的性能指标 48
- 3.5 小结 52

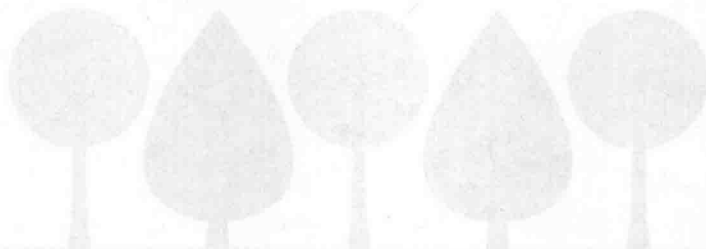
第 4 章 线性反馈系统的稳定性

..... 55

- 4.1 概述 57
- 4.2 动态系统的稳定性 57
- 4.3 劳斯-赫尔维兹判据 58
- 4.4 反馈控制系统的稳态误差 63
- 4.5 高阶系统的时域分析 66
- 4.6 参数对稳定性的影响 69
- 4.7 小结 69

Chapter 5 The Root Locus Method	75	第5章 根轨迹法	75
5.1 Introduction	77	5.1 概述	77
5.2 The Root Locus Concept and Examples	77	5.2 根轨迹的基本概念与举例	77
5.3 The Root Locus Plot Procedure.....	79	5.3 绘制根轨迹的步骤.....	79
5.4 Examples for Drawing Root Locus	89	5.4 绘制根轨迹的几个实例	89
5.5 Zero-degree Root Locus and Parameter Root Locus	91	5.5 零度根轨迹和参数根轨迹	91
5.6 Compensation by Using Root Locus Method	93	5.6 利用根轨迹法进行校正	93
5.7 Summary	98	5.7 小结	98
Chapter 6 Frequency Response Methods	105	第6章 频率响应法	105
6.1 Introduction	107	6.1 概述	107
6.2 Fourier Transfer.....	107	6.2 傅里叶变换.....	107
6.3 Frequency Response Function.....	108	6.3 频率响应函数.....	108
6.4 Diagram of Frequency Response Function	110	6.4 频率响应函数图	110
6.5 Frequency Response Function of Elementary Unit.....	115	6.5 典型环节的频率特性	115
6.6 Diagram of Complex Frequency Response Function.....	121	6.6 复合传递函数频率响应曲线的绘制	121
6.7 Summary	123	6.7 小结	123
Chapter 7 Stability in the Frequency Domain	131	第7章 频域中的稳定性分析	131
7.1 Introduction	133	7.1 引言	133
7.2 Nyquist Stability Criterion	134	7.2 Nyquist 稳定性判据	134
7.3 Stability Margin of System	143	7.3 系统稳定裕度	143
7.4 Dynamics Performance of Closed-loop from Open-loop Frequency Characteristic	144	7.4 根据开环系统频率特性获得闭环系统的动态特性.....	144
7.5 Summary	148	7.5 小结	148
Chapter 8 Compensator Design in Frequency Domain	153	第8章 频域法校正	153
8.1 Introduction	155	8.1 引言	155
8.2 Cascade Compensation	155	8.2 串联校正	155
8.3 System Design Using Integration Networks	166	8.3 加PI环节的系统设计	166
8.4 Summary	167	8.4 小结	167
Chapter 9 State Space and State Equation	173	第9章 状态空间与状态方程	173
9.1 Introduction	175	9.1 概述	175
9.2 State Vector and State Space	175	9.2 状态矢量与状态空间.....	175
9.3 State Equation and Output Equation.....	177	9.3 状态方程与输出方程.....	177

9.4 State Space Model from Differential Equation.....	179	9.4 由微分方程获得状态空间模型.....	179
9.5 The Transfer Function and the State Equation.....	181	9.5 传递函数与状态方程.....	181
9.6 The State Transition Matrix.....	182	9.6 状态转移阵.....	182
9.7 Summery.....	185	9.7 小结.....	185
Chapter 10 Design of State Variable Feedback System.....	189	第 10 章 状态变量反馈系统设计.....	189
10.1 Introduction.....	191	10.1 概述.....	191
10.2 State Controllability and Observability.....	191	10.2 状态的可控性与可观测性.....	191
10.3 System Structure Decompose.....	197	10.3 系统的结构分解.....	197
10.4 Canonical Form of Single Input System.....	200	10.4 单输入系统的规范形式.....	200
10.5 The Relation of Transfer Function and State Variable Coefficients.....	205	10.5 传递函数与状态变量参数之间的关系.....	205
10.6 Pole Placement Using State Feedback.....	207	10.6 运用状态反馈进行极点配置.....	207
10.7 Ackerman's Formula.....	209	10.7 奥克曼公式.....	209
10.8 Stabilization.....	210	10.8 可镇定性.....	210
10.9 State Observer.....	211	10.9 状态观测器.....	211
10.10 Summery.....	215	10.10 小结.....	215
Appendix Table of Laplace Transform Pairs.....	218	附录 常用函数拉普拉斯变换对照表.....	218
1.1 History of Automatic Control Systems.....	1	1.1 自动控制理论与发展简史.....	1
1.2 Control Systems and Some Basic Concepts.....	12	1.2 控制系统的一些基本概念.....	12
1.3 Example of Automatic Control Systems.....	13	1.3 自动控制系统的举例.....	13
1.4 The Main Content of This Book.....	14	1.4 本书的主要内容简介.....	14



1.1 History of Automatic Control

1.1 自动控制理论与实践的发展简史

(1) The first reaction rate feedback controller used in an industrial process is generally agreed to be James Watt's flyball governor, developed in 1769 for controlling the speed of a steam engine.

(1) 最早应用于工业过程的反馈控制器，被公认为是瓦特的飞球调速器，它是在1769年用于控制蒸汽机的速度。

The self-mechanical device, shown as Figure 1.1.1, measures the speed of the output shaft and utilized the mechanism of the flyball with speed to control the valve and then the engine. When the speed increases, the ball weights raise and move away from the shaft axis, thus closing the valve. The engine uses its power from the steam to turn the shaft, but the speed measurement is less accurate.

瓦特蒸汽机的调速器装置如图 1.1.1 所示。通过测量输出轴的转速，并利用飞球调速器的速度来控制阀门，从而控制蒸汽机的转速。当速度增大时，球重抬起并远离轴心，从而关闭阀门。蒸汽机利用其从蒸汽中获得的功率来驱动轴，但速度测量精度较低。

Chapter 1

Introduction to Control Systems

控制系统概述

1.1 History of Automatic Control

1.1 自动控制理论与实践的发展简史

1.2 The Concepts of Control Systems

1.2 控制系统的一些基本概念

1.3 Example of Automatic Control System

1.3 自动控制系统的举例

1.4 The Main Content of This Book

1.4 本书的主要内容简介

(2) In 1868, L. C. Maillart developed a mechanical theory related to control systems based on differential equation model of a governor.

(2) 1868年，L. C. Maillart 发展了与控制系统相关的机械理论，基于调速器的微分方程模型。

(3) Conventional control theory, especially to Single input Single output (SISO) systems, its mathematical foundation is the Laplace transform.

(3) 经典控制理论，特别是单输入单输出 (SISO) 系统，其数学基础是拉普拉斯变换。

(4) Routh in 1881 and Hurwitz in 1895, algebraic stability criterion.

(4) 劳斯于1881年，Hurwitz于1895年，建立了代数稳定性判据。

(5) A. M. Lyapunov set up the stability theory in 1892.

(5) 李雅普诺夫于1892年建立了稳定性理论。

(6) Bode and Nichols presented frequency response analysis in 1927.

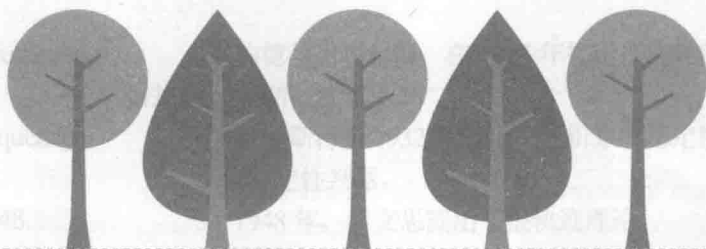
(6) 伯德和尼科尔斯于1927年提出了频率响应分析。

(7) Nyquist presented the steady-state frequency response techniques in 1932.

(7) 奈奎斯特于1932年提出了稳态频率响应技术。

(8) Evans setup the root-locus theory in 1948.

(8) 埃文斯于1948年建立了根轨迹理论。





1.1 History of Automatic Control

(1) The first automatic feedback controller used in an industrial process is generally agreed to be James Watt's flyball governor, developed in 1769 for controlling the speed of a steam engine.

The all-mechanical devices, shown as Figure.1.1, measure the speed of the output shaft and utilized the movement of the fly ball with speed to control the valve and therefore the amount of steam entering the engine. As the speed increases, the ball weights raise and move away from the shaft axis, thus closing the valve. The flyweights require power from the engine to turn and therefore cause the speed measurement to be less accurate.

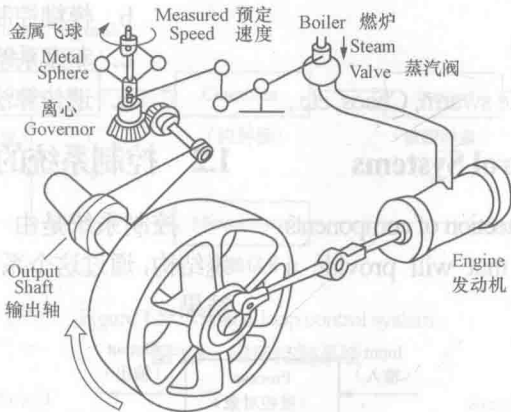


Figure 1.1 James Watt's Flyball Governor (1769)

图 1.1 瓦特蒸汽机调速机械装置

(2) In 1868, J. C. Maxwell formulated a mathematical theory related to control theory using a differential equation model of a governor.

(3) Conventional control theory is effectively applied to many control design problems, especially to Single-input Single-output (SISO) systems. Its mathematical foundation is the Laplace transform.

1) Routh in 1884 and Hurwitz in 1895, algebra stability criterion.

2) A. M. Lyapunov, set up the stability theory in 1892.

3) Bode and Nichols presented frequency-response analysis in 1927.

4) Nyquist presented the steady-state frequency-response techniques in 1932.

5) Evans set up the root-locus theory in 1948.

(4) Modern control theory(1960) is based on state

1.1 自动控制理论与实践的发展简史

(1) 最早的应用于工业过程的反馈控制器，被认为是瓦特的飞球控制器，出现在 1769 年用于控制蒸汽机的速度。

瓦特蒸汽机的调速机械装置如图 1.1 所示，通过测量输出轴的速度，并且利用金属飞球的随之转动来控制阀门来调节进入发动机的蒸汽量。当速度增大时，球的重力增大，带动金属飞球外胀，飞球胀开以后，就会关闭蒸汽阀门。飞行重力所需要的动力来源于引擎，并且能够影响速度测量的精度。

(2) 1868 年，麦克斯韦将蒸汽机的调速过程变成了一个线性微分方程的问题。

(3) 经典控制理论的发展有效地解决了当时很多的控制系统设计问题，特别是单输入单输出系统，这部分经典控制论的数学基础是拉普拉斯变换。

1) 劳斯于 1884 年，霍尔维兹于 1895 年，建立了稳定性判据的代数式。

2) 李亚普诺夫于 1892 年建立了稳定性理论。

3) 伯德与尼科尔斯，在 1927 年提出了用频率方法进行系统的分析。

4) 奈奎斯特于 1932 年提出了分析系统稳定性的奈奎斯特稳定性判据。

5) 1948 年，伊文思提出了根轨迹理论。

(4) 现代控制理论是 1960 年以后发展起来的，其

variable methods, for the design of multiple-input multiple-output(MIMO) systems.

- 1) Wiener(1948), Cybernetics.
- 2) Bellman(1957), Dynamic programming.
- 3) Pontryagin(1962), Maximum principle.
- 4) Kalman(1960), Controllability and observability.
- 5) Kalman and Bucy(1961), Combination of optimal filter and optimal controller, Linear quadratic Gaussian (LQG) control.

(5) Advanced control theory:

- 1) Robust theory (1980s).
- 2) Adaptive control theory (1970s).
- 3) Intelligent control theory (1980s):
 - a. Artificial Neural Networks(ANNS);
 - b. Fuzzy Control (FC);
 - c. Expert System (ES).
 - d. Genetic Algorithm, Particle swarm, Chaos, etc..

1.2 The Concepts of Control Systems

A control system is an interconnection of components forming a system configuration that will provide a desired system response.

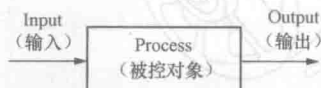


Figure 1.2 Process to be controlled

图 1.2 控制系统框图

1.2.1 Open-loop Control system

An open-loop control system utilizes an actuating device to control the process directly without using feedback. It is shown at Figure 1.3.

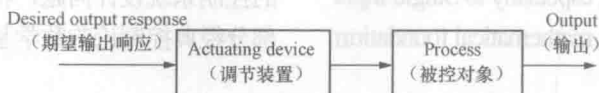


Figure 1.3 Open-loop control system (without feedback)

图 1.3 开环控制系统 (未施加反馈)

The automatic toast in Figure 1.4 is an example of open-loop control system.

Therefore, concerning a known number of input amounts and output quantity, and the inside and outside disturbance do not existing, adopt an open-loop control system to be proper. While, the component parameter may have no way to anticipate changes in there being existing the disturbance, closed-loop control system

数学基础是状态变量法, 此方法更有利于分析和设计多输入多输出的控制系统。

- 1) 维纳 (1948), 出版著名的《控制论》。
- 2) 贝尔曼 (1957), 提出了动态规划。
- 3) 庞特利亚金 (1962), 提出了极大值原理。
- 4) 卡尔曼 (1960), 建立了状态可控与可观测理论。
- 5) 卡尔曼与布什 (1961), 提出了基于线性二次型性能指标的最优控制问题, 并提出 Kalman 滤波理论。

(5) 先进的控制理论:

- 1) 鲁棒控制理论 (20 世纪 80 年代)。
- 2) 自适应控制 (20 世纪 70 年代)。
- 3) 智能控制理论 (20 世纪 80 年代):
 - a. 人工神经网络;
 - b. 模糊控制;
 - c. 专家系统;
 - d. 遗传算法, 粒子群算法、混沌等。

1.2 控制系统的一些基本概念

控制系统是由一些部件组装连接而成的一种系统结构, 通过这个系统的工作能够产生所期望的输出结果。

1.2.1 开环控制系统

开环控制系统: 由调节装置直接去控制被控对象, 并且没有构成反馈回路的系统, 如图 1.3 所示。

图 1.4 所示的自动面包片烘烤机就是一个开环控制的实例。

如果输入量和输出量的关系已知, 并且不存在内部和外部扰动时, 采用开环控制是适宜的。当系统存在着无法预料的扰动和 (或) 系统中元件参数可能有无法预料的变化时, 闭环系统似乎显得更为优越。



looks like being more advantageous right away.



Input: electricity 输入: 电信号
Output: thermal 输出: 热能
Merit: simple and inexpensive.
优点: 装置简单且价格低廉
Shortcoming: Can't control the degree of bake automatically.
不足: 无法根据烘烤的程度自动调节

Figure 1.4 Automatic toast
图 1.4 自动面包片烘烤机

1.2.2 Closed-loop Control system

A closed-loop control system uses a measurement of the output and feedback of this signal to compare it with the desired output (reference or command).

1.2.2 闭环控制系统

闭环控制系统为运用检测装置测量输出信号，并将此信号反馈到输入端与期望的输出信号（参考输入或命令）进行比较得到一个差值，（用此差值作为控制信号来进行系统的自动调节）。

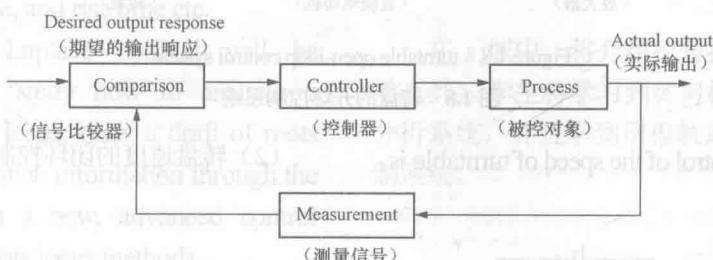


Figure 1.5 Closed-loop control system
图 1.5 闭环控制系统

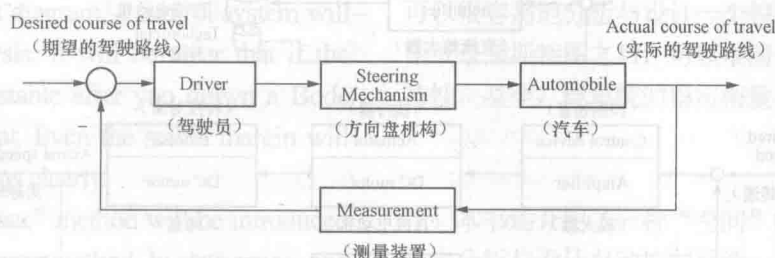


Figure 1.6 Driving control system
图 1.6 汽车驾驶控制系统

The Driver comes to adjust a steering wheel according to difference between reality running direction and expected running direction.

驾驶员根据期望的驾驶路线与实际的驾驶路线的差异来调节方向盘。



Figure 1.7 Closed-loop control of the speed of turntable
图 1.7 转盘转速的闭环控制

1.3 Example of Automatic Control System

For a servo control system--Turntable Speed Control. [2]

(1) A open-loop control of the speed of turntable is show as Figure1.8.

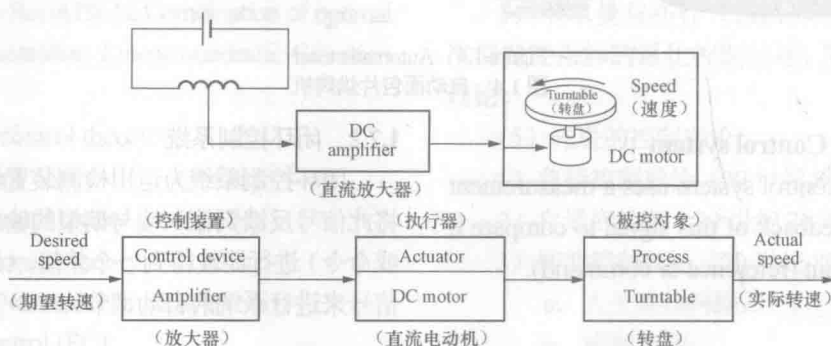


Figure 1.8 turntable open-loop control system

图 1.8 转盘的开环控制系统

(2) A closed-loop control of the speed of turntable is shown as Figure 1.9.

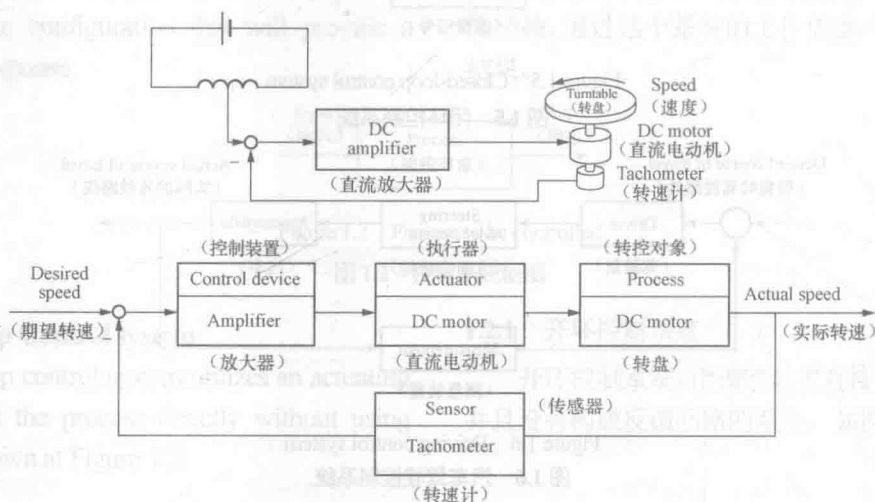


Figure 1.9 Closed-loop control of the speed of turntable

图 1.9 转盘的闭环控制系统

Consideration:

(1) What is the function of Tachometer?

Answer: The Tachometer is a sensor, it measures the speed of Turntable, and gives feedback of the speed to the input, and then compare with the desired speed of Turntable, the Actuator will adjust the DC motor according to the error of desired speed with Tachometer.

(2) what is the advantage with closed-loop feed

1.3 自动控制系统的举例

对于一个伺服控制系统的转盘速度控制问题[2]。

(1) 转盘速度的开环控制如图 1.8 所示。

(2) 转盘速度的闭环控制如图 1.9 所示。

思考:

(1) 转速计起的作用是什么?

答案: 转速计是一台传感器, 用来测量转盘的速度, 并把速度反馈 (将速度信号转换成电信号) 回输入端, 与转盘的期望转速 (电信号) 相比较 (得到一个误差值), 执行机构根据转盘的期望速度的误差调节直流电动机 (控制器) (实现对转盘转速的自动控制)。

(2) 负反馈闭环控制比开环控制的优越性在哪?



back control compare with open-loop control?

Answer: Open loop control system can not adjust the DC motor automatically, but closed loop control system can do.

1.4 The Main Content of This Book

There are “three domain” will be introduced to reader in this book: time domain, s -domain and f -domain. In time domain, how to set up a mathematic model according to differential equations will be introduced, and find the solution of the system's output through to find the solution of differential equation. Even more, students will get the knowledge about system performance index such as steady state error, the overshoot, the settle time, and rise time etc.

In s -domain, the Laplace method will be introduced. Student will study how to analysis a system according to root locus, draw a draft of roots locus. And get the steady state information through the roots locus, even design a new, advanced control system according to the roots locus methods.

In f -domain, Forier method will be used to analysis and design the control system. By means of Bode diagram, Nyquist diagram, a control system will be designed and analysis. It will be clear that if the system is stable or unstable after you drawn a Bode diagram or Nyquist plot. Even the stable margin will be shown in the diagrams clearly.

There are “one space” method will be introduced in this book — state space method. In state space, one can analysis and design the control system by means of another mathematical tool — linear algebra. The state space method is used widely now, because it will deal with some difficult problem that the classical methods can't do, such as multi-input multi-output (MIMO) system, Nonlinear system, time vary system etc.

Homework

1. Review:

- (1) The solution of differential equations
- (2) Laplace Transform
- (3) Matrix Linear Algebra

2. A precise optical signal source can control the output power level to within 1%. A laser is controlled

答案: 开环控制系统无法自动调节直流电机, (对转盘的转速实行自动调节), 而闭环系统可以。

1.4 本书的主要内容简介

本书将介绍三个“域”: 时间域、 s 域、 f 域。(将在这三个域中介绍如何应用经典的控制理论方法分析和设计一个自动控制系统)。在时间域里, 介绍如何用微分方程建立系统的数学模型, 通过求解微分方程得到系统的输出。而且, 在时间域里, 学生可以学习到关于稳态误差、超调量、过渡时间、上升时间等系统的性能指标。

在 s 域中, 将介绍拉普拉斯变换 (一种新的数学工具)。学生将学习到如何根据画出的根轨迹草图分析系统, 并且学到用根轨迹来分析与设计一个控制系统。

在 f 域中, 本书介绍了傅里叶变换 (作为数学工具) 进行系统分析与设计。通过伯德图、奈奎斯特图, 可以很容易地分析与设计一个控制系统。在画出伯德图或奈奎斯特图之后, 可以很清楚地看出系统的稳定特性, 甚至, 连系统的稳定裕量都能看得清清楚楚。

本书还介绍了一种“空间”的方法——状态空间法来分析与设计自动控制系统。这种方法借助于线性代数理论, 状态空间变量的概念, 实现对系统的分析与设计。这种方法更加适应应用多输入——多输出系统, 非线性系统以及时变系统的分析与设计, 因此得到了广泛的应用。

作 业

1. 复习:

- (1) 微分方程的解—特解、通解
- (2) 拉氏变换—性质、正反变换、初始条件
- (3) 矩阵线性代数—状态空间, 状态方程, 状态

方程的解

2. 精确的光信号源可以将功率输出精度控制在



by an input current to yield the power output. A microprocessor controls the input current to the laser. The microprocessor compares the desired power level with a measured signal proportional to the laser power output obtained from a sensor. Complete the block diagram representing this closed-loop control system shown in Figure H1.1, identifying the output, input, and measured variables and the control device.^[2]

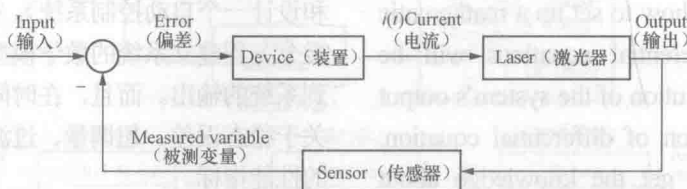


Figure H1.1 Partial block diagram of an optical source.

图 H1.1 光源方框图

3. An autofocus camera will adjust the distance of the lens from the film by using a beam of infrared or ultrasound to determine the distance to the subject. Sketch a block diagram of this open-loop control system, and briefly explain its operation.^[2]

4. Because a sailboat can't sail directly into the wind, and traveling straight downwind is usually slow, the shortest sailing distance is rarely a straight line. Thus sailboats tack upwind — the familiar zigzag course — and jibe downwind. A tactician's decision of when to tack and where to go, can determine the outcome of a race. Describe the process of tacking a sailboat as the wind shifts direction. Sketch a block diagram depicting this process.^[2]

5. Automated highways may be prevalent in the next decade. Consider two automated highway lanes merging into a single lane, and describe a control system that ensures the vehicles merge with a prescribed gap between two vehicles.^[2]

1%以内。激光器由输入电流控制并产生功率，作用在激光器上的输入电流由一个微处理器控制，微处理器将期望的功率值与由传感器测得的激光器的输出功率值作比较。这个闭环控制系统的框图如图 H1.1 所示。辨别其输出变量、输入变量、被测变量和控制装置^[2]。

3. 测相机到物体的距离，并据此来调整镜头到胶片的距离。请画出该开环控制系统的框图，并简要说明它的操作过程^[2]。

4. 因为帆船不能正面迎风行驶，而且完全顺风行驶的速度较慢，因此帆船的最短行驶路径很少是直线。因此帆船往往是在逆风转舵——我们熟悉的之字形路线——或顺风转舵。一个舵手何时转舵以及如何转舵，可能会决定一次比赛的成绩。请描述当风向改变时调整帆船航向的过程，并画出描述该过程的框图^[2]。

5. 未来十年，自动化的高速公路可能会风靡全球。在两条自动化的高速公路汇合成一条高速公路的情况下，应有一个交通控制系统来确保车辆以规定的车距汇入高速公路。请描述所需要的交通控制系统^[2]。



常用的控制类词汇中英文对照

中文关键词	Key Words
控制装置	control device
输入变量	input variable
输出变量	output variable
被测变量	measured variable
控制对象	process
传感器	sensor
放大器	amplifier
开环控制	open-loop control
闭环控制	closed-loop control
调节器	actuator
手动控制	manual control
比较器	comparison
反馈控制	feedback control
部件, 器件	components
期望的系统响应	desired system response
性能	performance
指标	specification
拉普拉斯变换	Laplace Transform

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