

Exhibit 2009

Automatic Control Systems

fifth edition

Benjamin C. Kuo

Professor of Electrical and Computer
Engineering
University of Illinois at Urbana-Champaign

PRENTICE-HALL, INC., Englewood Cliffs, N.J.

Library of Congress Cataloging-in-Publication Data

KUO, BENJAMIN C., (date)

Automatic control systems.

Includes bibliographical references and index.

1. Automatic control. 2. Control theory. I. Title.

TJ213.K8354 1987 629.8'3 86-17047

ISBN 0-13-054842-1

Editorial/production supervision

and interior design: Elena Le Pera

Cover: Original design by Benjamin C. Kuo, adapted by Karen Stephens

Manufacturing buyer: Rhett Conklin

©1987 by Prentice-Hall, Inc.

A Division of Simon & Schuster

Englewood Cliffs, New Jersey 07632

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

Printed in the United States of America

10 9 8 7 6 5 4

ISBN 0-13-054842-1 025

Prentice-Hall International (UK) Limited, London

Prentice-Hall of Australia Pty. Limited, Sydney

Prentice-Hall Canada Inc., Toronto

Prentice-Hall Hispanoamericana, S. A., Mexico

Prentice-Hall of India Private Limited, New Delhi

Prentice-Hall of Japan, Inc., Tokyo

Prentice-Hall of Southeast Asia Pte. Ltd., Singapore

Editora Prentice-Hall do Brasil, Ltda., Rio de Janeiro

Contents

PREFACE x

1 INTRODUCTION 1

- 1.1 Control Systems 1
- 1.2 What Is Feedback and What Are Its Effects 1
- 1.3 Types of Feedback Control Systems 1

2 MATHEMATICAL FOUNDATION 16

- 2.1 Introduction 16
- 2.2 Complex-Variable Concept 16
- 2.3 Differential Equations 19
- 2.4 Laplace Transform 22
- 2.5 Inverse Laplace Transform by Partial-Fraction Expansion 22
- 2.6 Application of Laplace Transform to Ordinary Differential Equations 32
- 2.7 Elementary Matrix Theory 34
- 2.8 Matrix Algebra 40
- 2.9 Vector-Matrix Form of State Equations 47
- 2.10 Difference Equations 47
- 2.11 The z-Transform 49
- 2.12 Application of the z-Transform to the Difference Equations 58

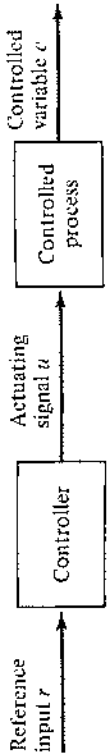


Figure 1-3 Elements of an open-loop control system.

The elements of an open-loop control system can usually be divided into two parts: the controller and the controlled process, as shown by the block diagram in Fig. 1-3. An input signal or command r is applied to the controller, whose output acts as the actuating signal u ; the actuating signal then controls the controlled process so that the controlled variable c will perform according to some prescribed standards.

In simple cases, the controller can be an amplifier, mechanical linkages, or other control means, depending on the nature of the system. In more sophisticated electronics control, the controller can be an electronic computer, such as a microprocessor.

Closed-Loop Control Systems (Feedback Control Systems)

What is missing in the open-loop control system for more accurate and more adaptive control is a link or feedback from the output to the input of the system. To obtain more accurate control, the controlled signal $c(t)$ should be fed back and compared with the reference input, and an actuating signal proportional to the difference of the input and the output must be sent through the system to correct the error. A system with one or more feedback paths such as that just described is called a *closed-loop system*.

The block diagram of a closed-loop idle-speed control system is shown in Fig. 1-4. The reference input ω_r sets the desired idling speed. Ordinarily, when the load torque is zero, the engine speed at idle should agree with the reference value ω_r , and any difference between the actual speed and the desired speed caused by any disturbance such as the load torque T_L is sensed by the speed transducer and the

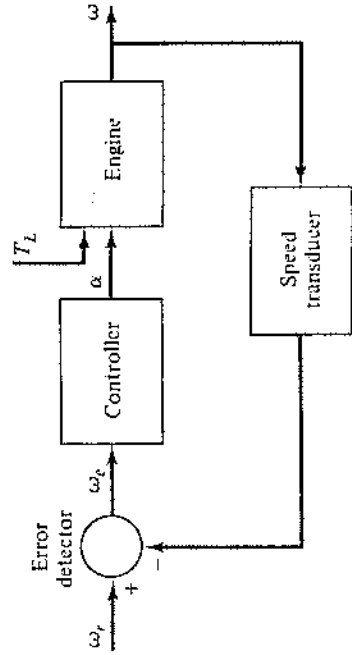


Figure 1-4 Closed-loop idle-speed control system.

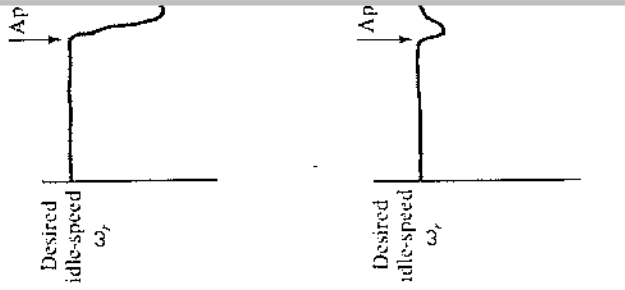


Figure 1-5 (a) Typical idle-speed response of an open-loop system. (b) Typical idle-speed response of a closed-loop system.

error detector, and the controller will operate on the difference to adjust the throttle angle α to correct the error.

Figure 1-5 illustrates a comparison of the typical open-loop and closed-loop idle-speed control systems. In Fig. 1-5(a) the open-loop system will drop and settle at a lower value than the desired speed. In Fig. 1-5(b) the closed-loop system will drop and settle at the preset value after the application of T_L .

The idle-speed control system illustrated above is a system whose objective is to maintain the system output at a desired value. As another illustrative example of a closed-loop control system, consider the block diagram of the printwheel control system of a typewriter. The printwheel, which typically has 96 or 100 positions, is used to position the desired character in front of the hammer. When a key on the keyboard is depressed, a command for the printwheel position to the next position is initiated. The microprocessor

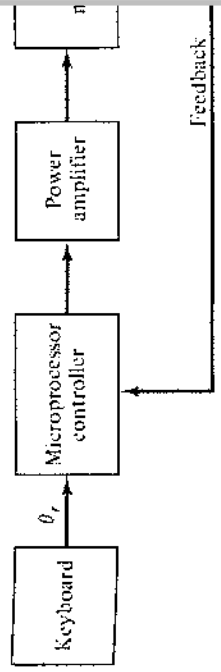


Figure 1-6 Printwheel control system.