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Control System Design Guide

USING YOUR COMPUTER TO DEVELOP AND DIAGNOSE FEEDBACK CONTROLLERS

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Preface

The need for practical control techniques was demonstrated on my first day as a design engineer. A schematic for a motor controller showed nearly a dozen components with values that depended on the application. Tuning, the process of determining those values, was done by trial and error because people in my company thought the values could not be calculated. When I attempted to use what I had learned in school to explain the circuit, the most senior engineer remarked, "I don't know anything about poles or zeros, but I do know how to tune a system."

There was a wide gap between what I had learned from college and what he had learned from experience, but neither of us had any idea how to tune a system by calculation. While an academic engineering program provides the necessary foundation for control system design, the techniques taught in controls classes are often fundamentally impractical. This book focuses on practical techniques—techniques that can be used to find solutions to real problems. For example, at my company we have applied some of these techniques to tune systems by calculation. The process takes less time and is more consistent than trial and error, while maintaining the same performance.

This book is written for engineers. You need to be familiar with the frequency domain, basic op-amp circuits, and networks—material required in a BSEE program. Also, you need to be familiar with BASIC programming language. You do not have to know control theory, though prior knowledge of controls, either through classes or experience, is certainly an advantage.

The goal of this book is to teach you how to use your computer to design and troubleshoot a basic control system. Design guidelines, practical examples, and simple computer programs are included throughout for hands-on training. Spice, a popular circuit simulation program, is applied to control systems. Since this is not a textbook, background material and mathematical development are kept to a minimum.

Following an introductory chapter, Chapters 2 and 3 present background material on the *s* domain for analog controllers and the *z* domain for digital controllers. Chapter 4 introduces tuning, and Chapter 5 presents five commonly used controllers. Chapter 6 discusses filters from the control system designer's point of view. Finally, Chapters 7 and 8 present techniques to model the control system in the frequency and time domains.

Chapters 4, 5, and 6 use Spice, which is a powerful tool for control system designers. If you do not have access to Spice, you can obtain an evaluation version of PSpice from MicroSim. You are encouraged to order PSpice as you begin reading the book so that it will arrive before you need it. You can obtain information by writing to

MicroSim Corporation
20 Fairbanks
Irvine, CA 92718-9905

The software is free, although there is a nominal fee for copying, shipping, and handling. All of the examples in this book will work with the evaluation version. There is a brief PSpice tutorial in Appendix H which explains how PSpice is used in this book.

There are a total of about 50 programs and models in this book. You can type these programs into your computer from the text. For convenience, you can obtain them from the author on a diskette for the IBM-PC and compatibles by writing to

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305 West Eakin Street
Blacksburg, VA 24060

Again, the software is free, although there is a $10.00 fee for copying, shipping, and handling. Specify diskette size (3.5 or 5.25 in.). Add $2.50 for shipment outside of the United States.

I must express the gratitude I feel toward my wife LeeAnn, who labored many hours correcting errors, strengthening weaknesses, and discovering incongruities. Her efforts will serve every reader. I am indebted to Ed Cusson for the education he provided and to Calvin Shuler and Martin Piedl for their frequent guidance and support. Also, I am grateful for the advice of all my co-workers at Industrial Drives and for the encouragement from my supervisors to take on the task of writing this book.

George Ellis

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CHAPTER 1

Introduction

Control theory describes the operation of feedback systems. It applies to devices as simple as temperature regulators and as complex as multivariable observer systems. It can help you anticipate problems, suggest solutions, and predict performance. Skillfully used, control techniques can guide engineers in every phase of product and process design cycles.

The wide availability of personal computers and work stations is an important advance for control system designers. Many of the classical control methods are graphical rather than analytical, because their creators sought to avoid what was then an overwhelming number of calculations. Fortunately, these calculations no longer present a barrier. Virtually every personal computer can execute the algorithms required by analytical methods. With this in mind, the principles and methods presented herein are essentially analytical, and the arithmetic is meant to be carried out by a computer.

Colleges teach controls with little emphasis on day-to-day problems. The academic community focuses on mathematical derivations and advanced control schemes, neglecting methods that can be applied to common problems. Students frequently complete engineering programs having taken several courses on controls and still having no idea how to design, model, build, or tune a basic control system. Without practical control techniques, engineers must depend on company history, intuition, and trial-and-error methods.

Most engineers understand the foundations of control theory. Concepts such as transfer functions, block diagrams, the *s*-domain, and Bode plots are familiar to almost all of us. But how should the working engineer apply these concepts? As in most disciplines, he or she must be fluent in the basics.

Any presentation of control techniques should concentrate on helping the reader to understand, apply, and extend the basics of control theory to real-world systems.

In order to be fluent, you must practice. You are encouraged to work every example, to enter and execute every program, to run every experiment, and to tune every system contained in the following chapters. Without doubt, thorough understanding of simple problems is the key to applying controls.

This book avoids the material and organization of control theory textbooks. For example, design guidelines are presented throughout; these guidelines are a combination of industry-accepted practices and warnings against common pitfalls. Nontraditional subjects, such as filters and modeling, are presented here because they are essential to understanding and implementing control systems in the workplace. The focus of each chapter of this book is to teach you how to use control theory on the job.

CHAPTER 2

The s Domain

This chapter will concentrate on background material such as Laplace transforms and Bode plots. Since the topics are basic to electrical engineering, the material will be presented as a brief review. This chapter will focus on analog controllers; the next chapter will focus on digital controllers.

The sample programs presented here are written in BASIC and are geared toward readers with little programming experience. As you come to them, take a few minutes to enter and execute each program on your computer. They will run on almost any computer that supports BASIC, including IBM compatible personal computers. As an alternative for C programmers, the sample programs are written in C and listed in Appendix I.

Analog circuits are provided for system simulation, even if you plan to use digital controllers. Again, take the time to build (or simulate) the circuits and verify the operation. These circuits require only an op-amp, standard resistors and capacitors, a signal generator, and a two-channel oscilloscope. Most of the examples in this book are run on PSpice, a circuit simulator that is discussed in Appendix H. The Preface discusses how you can obtain an evaluation module of PSpice and a copy of all the programs in this book on diskette.

Transfer Functions

Transfer functions describe the relationship between the input and the output. For example, consider an integrator:

$$V_o(s) = \frac{V_i(s)}{s} \tag{2.1}$$

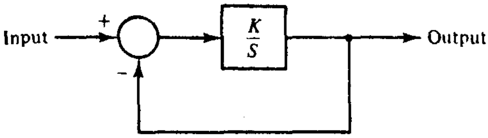

Figure 2-1 Low-pass filter.

The transfer function in this case is $1/s$ because

$$\frac{V_o(s)}{V_i(s)} = \frac{1}{s} \tag{2.2}$$

Block Diagrams

Block diagrams are graphical representations of systems. The diagram can be made of many blocks where each block is a transfer function. Blocks can be combined to form larger transfer functions. This is useful because simple blocks, such as integration, can be combined to form complex control functions.

Figure 2-1 shows a block diagram of a low-pass filter that is constructed from an integrator. The low-pass filter has a break frequency of K radians per second or $K/2\pi$ Hz and a direct-current (DC) gain of 1.

Combining Blocks

You can often simplify a block diagram by combining some of the blocks. If two blocks are in parallel, then they can be combined as the sum of the individual blocks. If two blocks are cascaded (i.e., in series), they can be represented as the product of the two blocks. For example, Figure 2-2 can be combined to form one block:

$$(G_1 + G_2)G_3 \tag{2.3}$$

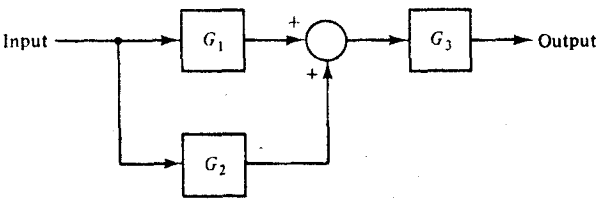

Figure 2-2 Cascade and parallel blocks.

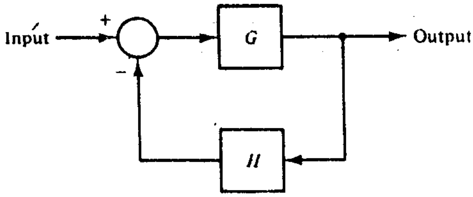

Figure 2-3 Simple feedback system.

Parallel and cascade blocks are simple to combine. However, reducing diagrams with feedback loops is more complicated. There are two methods for doing this:

1. $G/(1 + GH)$ rule
2. Mason's rule

$G/(1 + GH)$ Rule

The $G/(1 + GH)$ rule is the simplest way to combine blocks. To use this rule, you must configure the system as having one forward gain (G) and one feedback gain (H) as shown in Figure 2-3. The system can then be combined into one block with a gain of $G/(1 + GH)$ as shown in Figure 2-4. For example, return to Figure 2-1:

$$G = \frac{K}{S} \qquad H = 1$$

Using the $G/(1 + GH)$ rule, you can represent the low-pass filter as

$$T(s) = \frac{K/s}{1 + K/s \cdot 1} = \frac{K}{K + s} \tag{2.4}$$

This is the familiar transfer function of a low-pass filter.

Multiloop Systems

$G/(1 + GH)$ can be applied repeatedly to reduce multiloop systems. For example, it can simplify Figure 2-5, but it requires several steps:

1. Combine G_1 and H_1 to form $G_1/(1 + G_1H_1)$.
2. Combine G_2 and H_2 to form $G_2/(1 + G_2H_2)$.

Figure 2-4 Reduced simple feedback system.