Process Control Systems

Third Edition

Application, Design, and Tuning

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Application, Design, and Adjustment

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McGraw-Hill Book Company
New York St. Louis San Francisco Auckland
Bogotá Düsseldorf London Madrid Mexico
Milan Montreal New Delhi Panama
Paris São Paulo Singapore
Sydney Tokyo Toronto

Library of Congress Cataloging-in-Publication Data

Shinskey, F. Greg.
Process control systems.

Bibliography: p.
Includes index.
1. Process control. I. Title.
TP155.75.S5 1988 660.2′81 88-12868
ISBN 0-07-056903-7

1234567890 DOC/DOC 89321098

ISBN 0-07-056903-7

The editors for this book were Betty Sun and Martha Gleason, the designer was Naomi Auerbach, and the production supervisor was Richard A. Ausburn. It was set in Century Schoolbook by Bi-Comp Incorporated.

Printed and bound by R. R. Donnelley & Sons Company.

Process Control Systems

To all who have sought my help

Preface

My formal education in control theory began in 1957 under the direction of Les Zoss, then at Taylor Instrument Co. (later at Valparaiso University). The course followed the text he coauthored, *Frequency Response for Process Control* (W. I. Caldwell, G. H. Coon, and L. M. Zoss, McGraw-Hill, New York, 1959), which was in its final manuscript form at the time. That technology was based on operational calculus and required testing an unknown process with sine waves of various frequencies.

While I learned much from that course, and occasionally draw upon that knowledge, I soon discovered the limitations of frequency response. One of my early projects was the stabilization of a pH-control loop, where the limitations of linear algebra became obvious. And not surprisingly, operators were also reluctant to let anyone cycle their process with sine waves just to gather information.

The tools of frequency-response analysis are logarithmic plots where dead time appears as an exponential function, as it does in its Laplace transformation. But the performances we observe on recorders and screens are linear functions of time. We can measure dead time and period of oscillation directly, whereas we must calculate frequency.

Another difficulty I have had with classical control theory is trying to teach it to novices. If all relationships are expressed in transforms, it becomes necessary to introduce the course with a session on operational calculus. This delays and frustrates learning.

But I found that by remaining in the time domain, I could describe the essential properties of a control loop in one lesson, using dead time as a vehicle. In this way, students begin to appreciate the essence of process control at once with a foundation easily built upon. This method was followed in writing the first edition of *Process-Control Systems* and continues here.

There are some theoreticians who insist that transforms are essential to understanding control, especially z transforms, now that sampled-data control is in wide use. But I cannot agree. The preparation of this third edition began with the opportunity to simulate process-control loops using a personal computer. The computer has enabled me to prove many of my ideas, scrap or change other ones, and illustrate concepts with rigor and precision. There is no longer a need to follow a particular mathematical method to solve a control problem; it is simpler to simulate the process and controllers, and evaluate the results, in the familiar time domain. This procedure has been followed in preparing the response curves and tabular results included in this edition.

The computer has not only improved the accuracy of performance estimates, but it has also allowed them to be evaluated in absolute units. For example, we now know not only that one controller or combination of controller settings is better than another, but also how it compares to the best possible control.

One of the outcomes of using simulations is reporting performance in terms of integrated absolute error (IAE), a factor which cannot be calculated analytically but must be integrated during each experiment. Having the advantage of assuring damping, which integrated error (IE) does not, IAE replaces IE as the performance measure used in earlier editions of this text.

Chapters 1 and 2 have changed less than the others, owing to their emphasis on fundamentals. However, simulation has yielded an important relationship between damping and period which was not included in earlier editions, along with analytical estimates of minimum IAE.

In Chap. 3, the treatment of hydraulic resonance has been expanded to include variable damping, and a new level controller was discovered to suit that situation. The typical temperature loop has been analyzed more completely for nonlinear characteristics. Included is a method for estimating flowmeter accuracy.

Chapter 4 introduces some new control functions and evaluates familiar ones more precisely, giving very clear performance comparisons. Both the potential and the risk of model-based controllers are quantified. New tuning rules are developed and extended to include secondary lags along with dead time. Simulation has also given a better insight into the nonlinear processes and controllers described in Chap. 5. Negative resistance was found to be controllable within well-defined limits, much as an exothermic reactor.

Chapter 6 now has tuning rules for cascade control systems and an evaluation of several types of self-tuning controllers. Chapter 7 has a new section on averaging level control by feedforward, and a comprehensive procedure for tuning dynamic compensators in the presence of imbalances in both process dead time and capacity.

Much has been discovered by many researchers about control-loop interaction since the second edition was printed, as reported in Chap. 8. The chapter has been largely rewritten, incorporating extensive tuning rules for controllers in interacting processes that could only have been developed through simulation.

In Chap. 9, the arithmetic averaging procedure used to model heat transfer has been replaced with the more accurate logarithmic mean; most of the figures are new. A new boiler drum-level control system is presented, along with asymmetric control of compressor surge.

Chapter 10 explores the margins of stability of exothermic reactors, as discovered through simulation. Discussions on conversion control and maximization of production have replaced batch-reactor control, which has been moved to Chap. 12.

Chapter 11 has been completely rewritten, based on recent experiences in distillation control and interaction analysis. A method that has been developed for control of side-stream columns is described here. Control of evaporators and continuous dryers has been added, so that all mass-transfer operations are covered in a single chapter. Less common and less demanding applications have been dropped.

Chapter 12 is all new, devoted exclusively to control of batch processes. It begins with a treatment of their general characteristics, such as zero-load and variable-volume operations. Various controllers are compared for their response to startup and ramp set-point changes. This knowledge is then applied to batch-reactor control. The chapter concludes with a coverage of batch distillation and drying.

As with the previous edition, there are worked examples throughout the book and problems at the end of each chapter, with their solutions in Appendix B.

For the reader who wants more depth and breadth of learning in the subject, the simulations which produced the response curves and tabular data in this book are all available on diskettes. This software supplement runs in BASIC and GW-BASIC on the IBM PC and compatibles equipped with CGA color and graphic capability. The programs are not compiled, but they are listed in source code as exemplary lessons in simulation. This allows the user to modify them to suit particular needs.

In closing, I gratefully acknowledge the help of Judy Pelletier, who typed the manuscript with its many equations for this edition.

Greg Shinskey

Contents

Part

1

Understanding Feedback Control

Chapter

1

Dynamic Elements in the Control Loop

The economic performance of most processes—and certainly their safety and operability—depend to a large extent on how well they are controlled. Therefore considerable incentive exists to apply controls to processes lacking them, and to improve the control of those already being regulated.

Yet this is easier said than done. A few processes will be found that respond especially well to control action, but many others do not. A wide range of possibilities exists in this regard, yet most processes can be decomposed into relatively elementary blocks, each of which yields to analysis and characterization. Once these elements are understood, the process may be reconstructed and its behavior predicted from that knowledge.

This chapter attempts to describe how the elements themselves behave in a feedback control loop. While feedback is not the only control method, nor always the most effective, it is the simplest and most robust, i.e., most useful over a wide range of process parameters and operating conditions. It also demands less process knowledge—or less-precise process knowledge—on the part of the control engineer and is therefore more widely applicable than other methods.

Yet this chapter will demonstrate that some process knowledge is still necessary if the process is to be controlled effectively by feedback.

Its characteristics determine how well it can be controlled, and also what controller settings are required to produce the best results.

Negative Feedback

There are two kinds of feedback possible in a closed loop, positive and negative. Positive feedback is an operation which augments an imbalance, thereby precluding stability. If a temperature controller with positive feedback were used to heat a room, it would increase the heat when the temperature was above the set point and turn it off when it was below. Loops with positive feedback lock at one extreme or the other. Obviously this property is not conducive to regulation and therefore will be of no further concern at this time.

Negative feedback, on the other hand, works toward restoring balance. If the temperature is too high, the heat is reduced. The action taken—heating—is manipulated negatively, in effect, to the direction of the controlled variable—temperature. Figure 1.1 shows the flow of information in a feedback loop.

At this point in the development of the subject, consider a control loop to be divided into only two parts, the process and the controller. They are distinguished on the basis that the controller is adjustable whereas the process generally is not. In actual practice, the process comprises many elements: valve, piping, pump, vessel, measuring device, transmitter, etc. Yet for the purposes of this discussion all these are assumed to have fixed parameters. In later chapters, the characteristics of these elements are examined in detail; for the moment, they are simply lumped into a process whose characteristics are given.

The process gain is determined as the ratio of a change in its output dc to the change in the input dm which caused it

$$K_p \mathbf{g}_p = \frac{dc}{dm} \tag{1.1}$$

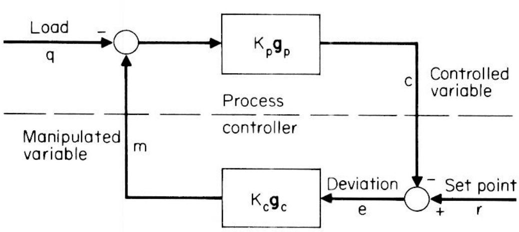

Figure 1.1 The controller manipulates m to counteract the load q and restore deviation e to zero.

where m is manipulated to control c. The gain is shown as consisting of two separate components. The steady-state component K_p does not vary with the period of the exciting signal. The dynamic gain $\mathbf{g}_p$ does, however; it appears as a vector having a scalar component G_p and a phase angle ϕ_p.

The gain of the controller represents the change in its output dm in response to a change in deviation de

$$K_c\mathbf{g}_c = \frac{dm}{de} \tag{1.2}$$

The controller gain is similarly divided into steady-state component K_c, which does not change with period, and a dynamic-gain vector $\mathbf{g}_c$, which does. The vector is ordinarily expressed in terms of its scalar gain G_c and its phase angle ϕ_c.

The negative sign applied to the controlled variable at the summing junction in Fig. 1.1 indicates that the controller has *increase-decrease action;* i.e., the output increases on a decrease in measured input. This action is necessary for negative feedback, with the process shown, because the sign applied to the manipulated variable entering the process is positive. Figure 1.1 might be representative of a heating system, where temperature c increases on an increase in steam-valve position m and decreases on an increase in heat loss q. Some valves close on an increasing signal; these are typically used for cooling. A temperature controller used for cooling will then have increase-decrease action also. When the signs of m and q are reversed, the signs applied to c and r also must be reversed; i.e., *increase-increase control action* is required. Most controllers operating in industry will have increase-decrease action.

The principal function of a controller is to provide regulation against changes in load. This is accomplished by making the gain $K_c\mathbf{g}_c$ of the controller as high as possible. As $K_c\mathbf{g}_c$ increases, the deviation e required to drive m to match a changing load becomes smaller. If $K_c\mathbf{g}_c$ could be set at a very high number, say 100 or more, very little deviation would appear on a change in load. Unfortunately, there is an upper limit which $K_c\mathbf{g}_c$ cannot exceed without leading to undamped oscillations. That limit of stability must be explored in order to determine how effective a feedback controller will be when it is applied to a given process.

Oscillation in a closed loop

Oscillation in a closed loop is sustained much in the same way that a ball is bounced, by the periodic application of force at phase intervals of 360°. A ball struck repeatedly with the same force at its highest position will continue to cycle at a constant amplitude and period. But if the force is applied earlier in the cycle, i.e., less than 360° since the last impulse, the period will be shortened. Then a uniform oscillation requires a uniform force applied at exactly every 360° of phase.

Most controllers actually apply a force continuously rather than in pulses, with the magnitude of the force generally varying sinusoidally as the controlled variable changes sinusoidally. (The presence of nonlinear elements may alter the waveform as described in Chap. 5; for the moment, sinusoidal oscillation is assumed.)

Consider the controlled variable oscillating uniformly as depicted in Fig. 1.2. If the controller has increase-decrease action, as for a heating system, the deviation from the set point will cycle 180° out of phase with the controlled variable, as shown. This 180° shift in phase is the "negative" in negative feedback. If the control vector $\mathbf{g}_c$ has no phase shift, the manipulated variable will cycle in phase with the deviation; its different amplitude reveals the gain of the controller at the period of oscillation.

The controller has converted a rising controlled variable, e.g., temperature, into a falling manipulated variable, e.g., steam-valve position. Because there is assumed to be no phase shift in the controller (other than the 180° attributed to the negative sign), these events occur simultaneously. If there were also no phase shift in the process, a falling steam-valve position would cause temperature to fall *at the same time*. However, the figure shows temperature to be rising as the steam valve closes. Therefore the effect of the steam-valve closing does not appear as a falling temperature until the *next* half-cycle; in effect, the process has delayed the response of temperature to valve position by one half-cycle. This delay contributes the remaining 180° shift in phase necessary for oscillations to persist.

It is possible to introduce some phase shift into the controller by

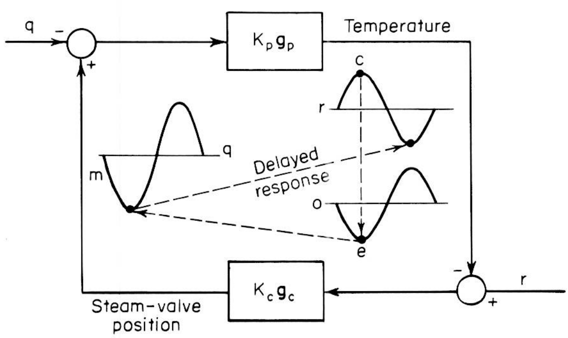

Figure 1.2 The minimum position of the steam valve causes a minimum temperature one half-cycle later.