An Introduction to Process Dynamics and Control

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AN INTRODUCTION TO PROCESS DYNAMICS AND CONTROL

To

My Parents
My Family
and
My Teachers

Preface

This book presents a balanced picture of control from the standpoints of theory and practical application. About equal emphasis is given to control theory and process dynamics. Thus, about half of the material deals with the behavior of control systems, first qualitatively, and finally quantitatively; the other half considers the modeling and dynamic behavior of processes themselves.

The content and style were developed with undergraduates in mind. I have tried to relate the material to that covered in other undergraduate courses in thermodynamics, unit operations, and transport phenomena. My goal was to present sufficient control theory so that the student will gain a general understanding of the unsteady-state behavior of simple control systems and some of the background behind the common methods for tuning controllers.

The pedagogical method of the book is mainly a series of examples although, in most cases, they are not labeled as such. It has been my experience that average undergraduates grasp the material more rapidly this way than if it were presented more abstractly. The problems at the end of each chapter are designed to extend the concepts to other examples.

The book begins with a few introductory chapters to provide a broad, qualitative overview of some control methods such as feedback and feedforward. Gradually some quantitative illustrations are introduced. After a discussion of the Laplace transform, the process dynamics of a variety of simple processes are developed, beginning with first-order processes and advancing through second-order processes to some distributed ones. Finally, a quantitative overview is presented from the standpoints of transient response and frequency response.

Thus the structure of the book is somewhat in the shape of an hourglass. The top and bottom view control systems as a whole, and the middle is devoted to a study of some of the details. The overview at the beginning provides a preview of the subject and points toward the areas that must be studied in order to predict the dynamic behavior of control systems in a quantitative way.

Because of the hourglass structure, the text has been divided into three parts. Part I begins with an introductory chapter that presents some historical background and a series of familiar examples. Chapter 2 discusses the four most common methods of control—open loop, environmental, feedback, and feedforward. Chapter 3 focuses on the two major reasons for control: servo operation and regulator operation.

The quantitative treatment of control commences with Chapter 4 in which the steady-state advantages of feedback and feedforward control are examined. Chapter 5 extends the feedback example of Chapter 4 to a study of its unsteady-state behavior. The standard controller actions are taken up in Chapter 6 and the effects of some of them in simple systems are illustrated. Chapter 7 deals with the Laplace transformation and introduces the concept of a transfer function.

Having developed a broad picture of control systems and controller actions, Part II examines the modeling and dynamics of the processes themselves. It begins with two chapters, which discuss processes that can be characterized by first-order behavior; then it includes a chapter dealing with second-order processes; and, finally, it concludes with a chapter on distributed processes. A unique feature of these chapters is the extensive development of the electrical analogies for nearly all of the processes that are examined. These are very helpful in visualizing the topography of processes and in elucidating the similarities between seemingly unrelated physical examples. Furthermore, they provide another way of looking at a process.

Part III returns to an examination of control system behavior but from a quantitative viewpoint. Chapter 12 provides an introduction to this area by means of an example drawn, to a considerable extent, from some experimental studies that I made. This development relies heavily on material in the previous four chapters and points the way toward the quantitative treatments of system behavior in the last two chapters. Chapter 13 considers the transient response of feedback systems to changes in set point and in load disturbances. The development of the chapter leads quite naturally into a discussion of the reaction curve method for tuning controllers. The book concludes with Chapter 14 which deals with frequency response analysis. The emphasis is on the Bode stability criterion, the use of frequency response as a design tool, and a discussion of the continuous cycling method for tuning controllers.

As mentioned earlier, this book was written mainly for an undergraduate course in process control. I have usually covered most of the material in a one-term course. Sometimes I have omitted a detailed study of Chapter 11 concerning distributed processes. Some readers may find the mastering of the electrical analogies in Part II to be "more work than they are worth." The various sections concerning these analogies could be de-emphasized or even skipped over, since they are not an essential part of the development.

I used the book for a graduate course composed of students who had never had a course in control before. The material in the book was augmented by drawing upon the references cited throughout the text. I also used portions of the first six chapters as a basis for a credit-free evening course in process control for practicing engineers.

Although some readers may feel that the subject of frequency response should be introduced earlier in a course than it is in this book, I feel that that topic and transient response can be more fully appreciated if they are not considered until the completion of Part II. However, both chapters relating to these topics could be taken up at any time after the completion of Chapter 8.

I hardly know where to begin a list of acknowledgments for this book. My interest in writing was cultivated by Professors Fred H. Rhodes and Julian C. Smith of Cornell University in their course in unit operations laboratory, which at times seemed to place more emphasis on the written form of the reports than on the technical aspects of the laboratory! They were devoted to the principle of writing "simply and clearly" and they carried through this crusade by a strict policy of "revise and return." I am also greatly indebted to Professor Peter Harriott of Cornell who whetted my thirst for the subject of process control.

This book evolved through a series of interchanges with my students, who raised many questions and made many suggestions. Thus the chapters were "revised and returned" to the students a number of times. This procedure was made possible by the very considerable efforts of nine secretaries, some of whom have left the department, perhaps out of desperation.

I am particularly grateful for the advice and help of my graduate student, Mohanlal A. Bhalodia. In addition to his technical advice and his preparation of the majority of the drawings for this book, I greatly appreciated his frankness and honesty.

Finally, I am indebted to my family who endured me during the final stages of the manuscript preparation.

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Part I Introductory Concepts of Control

Part II Analysis of Simple Processes

PART I

Introductory Concepts of Control

This book is written in the shape of an hourglass. Part I is designed to convey an understanding of control systems without becoming overly mathematical. This is achieved by using simple models for processes and simple controller actions. Part II focuses on the various types of processes that are controlled. The section commences with relatively simple "lumped parameter" models and ends with an examination of some "distributed parameter" processes. Part III broadens the perspective again to see how the models of the middle section are combined to form a complete control system. The effects of various controller actions on system behavior are studied and some conventional methods for tuning controllers are discussed and compared.

The first three chapters of Part I constitute a qualitative introduction to control methods and systems. The development is based upon intuitive notions and past experience. The main objectives of control systems are discussed.

The quantitative treatment begins in Chapter 4. An understanding of the steady-state behavior of a system under proportional control can be obtained by just using algebra. The development of Chapter 4 is extended to unsteady-state behavior in Chapter 5. System complexity is minimized so that a first-order differential equation describes its behavior.

Chapter 6 examines the most common controller actions and their effects in controlling simple processes. The section concludes with an introduction to the Laplace transformation in Chapter 7. This tool is needed not only for the development of process models in the middle part, but also for the synthesis of complex systems in the last part.

CHAPTER I

Introduction

I. HOW OLD IS THE CONCEPT OF CONTROL?

Process control, of interest to chemical engineers, is a relatively new and specialized topic. However, the need for some background in process control is attested to by the very wide application of instruments and controllers in all types of chemical plants. Hundreds of controllers are used in a modern oil refinery, for example.

Within the past several decades there has been an enormous growth in the application of controllers, not only in chemical plants, but generally throughout technology. This has largely resulted from the increased research in this area. At the same time, there has been a gradual evolution from "classical control theory" to "modern control theory."

However, the concept of control and the use of control devices surely dates far back in history. Man himself was undoubtedly the first control "instrument." From his first appearance on earth, he has found it necessary to exercise disciplinary control over his offspring. For that matter, the idea of parental authority is readily observable in countless members of the animal kingdom. In recorded history, we find that the Romans invented a water-level control device similar to that used in many toilets.

Of course, some dividing lines can be drawn. There is a clear distinction between manual control and automatic control. Manual control implies that there is a man involved in the control system. Parental discipline of children is an example of this. In automatic control, man is essentially removed from the control system, and it controls by itself. The water-level device of the Romans falls into this category.

When people speak of control, they usually have automatic control in mind. From this standpoint, control had its beginnings with the Romans over 2000 years ago. A notable control invention was the flyball governor by James Watt in 1788. This was the crucial contribution made by Watt to the development of the steam engine. By the beginning of the twentieth century, the mathematical foundations for control theory had been laid by such people as Laplace and Fourier. Routh carried out work in analytical dynamics, Kirchhoff in circuit analysis, and Lord Kelvin and Heaviside in physics.

But the development of control theory, per se, and application of it began in the early 1920s. Minorsky's name frequently heads a list of names in the history of control. He was concerned with the automatic steering of ships (1). World War II brought a tremendous impetus for the advancement of control. Engineers and scientists were brought together from many disciplines. Such problems as the automatic bomb sight and control systems for antiaircraft guns required relatively sophisticated theory and equipment. Hence, if the beginnings of control theory mark the beginning of process control, then control dates back only about 40 years.

II. WHAT ARE THE INCENTIVES FOR PROCESS CONTROL?

Although automatic controls will frequently reduce manpower requirements in a plant, this economy factor is usually not the main justification for their installation. The fact is, controls are often a necessity. Standards of quality control for a product may require a degree of control not achievable manually. Sometimes a process may occur so rapidly that it eludes human capabilities. An example of this will be discussed at the end of this chapter concerning the possibility of a midair collision between two airplanes.

The economy factor of controllers has played an important role in some cases. Control has reduced costs by yielding a higher rate of production per dollar of equipment cost when the plant is running, and by reducing shut-down time. Ayres (2) points out that fixed charges continue whether a plant is running or not; hence, downtime can be very expensive. In particular, he cites the case of cracking units in oil refineries. At first, these units could be counted on to run about 87% of the time. In a period of 10 years, average running times rose to 93%. About half of this 6% increase was attributable to improvements in the control systems themselves through new devices and more intelligent use of older ones. The remaining half resulted from changes in operation and design made possible by improvements in automatic control.

If installation of control equipment can result in an improved operating factor, then the payout time for the controls is likely to be quite rapid, possibly in less than a year. This is a faster payout than is normally achieved with processing equipment itself.

Although improvement of the operating factor has been very significant, the biggest dividends from control have been achieved in the area of production capacity per dollar of plant investment. The impact in this area is vividly pointed out by Ayres: "Excluding taxes, the price of motor fuel today is little higher than in 1920, in spite of the shrinking dollar and rising costs, and almost the sole reason is improvement in process equipment made possible by automatic control."

In some cases, a strong argument for automatic control stems from the need for safety. Many simple processes are adequately operated manually, but they might be safer under automatic control.

III. SOME COMMON EXAMPLES OF CONTROL

Many examples of control are found in nature. The leaves of plants tend to turn in the direction of the sun, their motion being controlled by some extremely complex guidance-control system. Another example is the temperature control system of the human body. This system is designed to maintain the temperature at the normal value of 98.6°F. Although there is some variation in temperature with time as well as with position in the body, it is relatively small, especially in some regions, as for example in the brain. An interesting mathematical model of the human thermal system has been developed by Wissler (3). When the body is subjected to a sudden drop in the temperature of its surroundings, the control system senses that it must conserve heat. This is accomplished by reducing the flow rate of blood to the capillaries in the skin. The skin surface then becomes colder, but the internals of the body remain at 98.6°F. This action is reversed when the body is suddenly exposed to warmer surroundings. Blood flow to the capillaries is increased, thus increasing the body surface temperature and increasing the heat removal rate. The ratio of the maximum blood flow rate to the minimum may vary over a hundredfold range in highly vascular regions.

As an introduction to some of the terminology and concepts of control, we shall examine in detail several control systems with which the reader has some experience. One concerns a home-heating system and the other deals with the adjustment of the flow rates of hot and cold water in a shower.

In a home-heating system, the temperature of a room is sensed by the thermostat. When the temperature falls below the desired value, commonly referred to as the "set point" in control terminology, the furnace is turned on. The temperature then rises and when it reaches the set point, the furnace is turned off.

At first glance, it might seem as though perfect control could be achieved. If the temperature were very slightly below the set point, the furnace would be turned on and the temperature of the room would begin to rise. However, as soon as the temperature was very slightly above the set point, the furnace would be turned off and the temperature would begin to fall. This could lead to the conclusion that the temperature oscillates almost imperceptibly about the set point. As it turns out, satisfactory control is achieved, but the temperature may vary a degree or so above and below the set point.

To understand the reason for this, let us suppose that a door is opened, permitting some cold air to enter the room. The temperature may fall a degree or two. The furnace immediately is turned on, but it will take several minutes for the heat to reach the room. In particular, if the system is of the hot-water type, the hot water must be carried to the radiators or heating fins. Then this heat must be transferred to the air. There is a resistance to this heat transfer and the heat capacitance of the mass of air in the room is sizable. Finally, after the room has reached the set-point temperature, the furnace is turned off, but the radiators still contain some warm water, which causes the temperature of the room to continue to rise beyond the set point.

These factors result in some "overshoot" and "undershoot" of the temperature about the set-point temperature. In addition, a "gap" may be incorporated in the thermostat mechanism to insure that the furnace is not being continuously switched on and off. Therefore, the furnace may be on for 10 min, then off for 20, followed by a series of similar cycles.

Although the disturbance to the previously mentioned system was the opening of a door, many others are possible. There could be a sudden drop in the outside temperature, or even a change in the wind velocity. It is important to note that in this temperature control system, the source or cause of the disturbance is really not important. The thermostat cannot distinguish one cause from another, and it would not make any difference if it could.

In the analysis of a control system, it is helpful to draw a diagram indicating the components of the system and their interrelationships. One possible diagram is shown in Figure 1. A box has been used for each component and the boxes are connected by lines that represent signals between