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Readers will find it to be a clear and understandable textbook for control system courses at colleges and universities. It is written for senior electrical, mechanical, aerospace, or chemical engineering students. The reader is expected to have fulfilled the following prerequisites: introductory courses on differential equations, Laplace transforms, vector- matrix analysis, circuit analysis, mechanics, and introductory thermodynamics. The main revisions made in this edition are as follows: • The use of MATLAB for obtaining responses of control systems to various inputs has been increased. • The usefulness of the computational optimization approach with MATLAB has been demonstrated. • New example problems have been added throughout the book. • Materials in the previous edition that are of secondary importance have been deleted in order to provide space for more important subjects. Signal flow graphs were dropped from the book. A chapter on Laplace transform was deleted. Instead, Laplace transform tables, and partial-fraction expansion with MATLAB are pre- sented in Appendix A and Appendix B, respectively. • A short summary of vector-matrix analysis is presented in Appendix C; this will help the reader to find the inverses of n x n matrices that may be involved in the analy- sis and design of control systems. This edition of Modern Control Engineering is organized into ten chapters.The outline of this book is as follows: Chapter 1 presents an introduction to control systems. Chapter 2 deals with mathematical modeling of control systems.A linearization technique for non- linear mathematical models is presented in this chapter. Chapter 3 derives mathematical models of mechanical systems and electrical systems. Chapter 4 discusses mathematical modeling of fluid systems (such as liquid-level systems, pneumatic systems, and hydraulic systems) and thermal systems. Chapter 5 treats transient response and steady-state analyses of control systems. MATLAB is used extensively for obtaining transient response curves. Routh's stability criterion is presented for stability analysis of control systems. Hurwitz stability criterion is also presented. Chapter 6 discusses the root-locus analysis and design of control systems, including positive feedback systems and conditionally stable systems Plotting root loci with MAT- LAB is discussed in detail. Design of lead, lag, and lag-lead compensators with the root- locus method is included. Chapter 7 treats the frequency-response analysis and design of control systems.The Nyquist stability criterion is presented in an easily understandable manner.The Bode di- agram approach to the design of lead, lag, and lag-lead compensators is discussed. Chapter 8 deals with basic and modified PID controllers. Computational approaches for obtaining optimal parameter values for PID controllers are discussed in detail, par- ticularly with respect to satisfying requirements for step-response characteristics. Chapter 9 treats basic analyses of control systems in state space. Concepts of con- trollability and observability are discussed in detail. Chapter 10 deals with control systems design in state space.The discussions include pole placement, state observers, and quadratic optimal control. An introductory dis- cussion of robust control systems is presented at the end of Chapter 10. The book has been arranged toward facilitating the student's gradual understanding of control theory. Highly mathematical arguments are carefully avoided in the presen- tation of the materials. Statement proofs are provided whenever they contribute to the understanding of the subject matter presented. Special effort has been made to provide example problems at strategic points so that the reader will have a clear understanding of the subject matter discussed. In addition, a number of solved problems (A-problems) are provided at the end of each chapter, except Chapter 1. The reader is encouraged to study all such solved problems carefully; this will allow the reader to obtain a deeper understanding of the topics discussed. In addition, many problems (without solutions) are provided at the end of each chapter, except Chapter 1. The unsolved problems (B-problems) may be used as homework or quiz problems. If this book is used as a text for a semester course (with 56 or so lecture hours), a good portion of the material may be covered by skipping certain subjects. Because of the abundance of example problems and solved problems (A-problems) that might answer many possible questions that the reader might have, this book can also serve as a self- study book for practicing engineers who wish to study basic control theories. I would like to thank the following reviewers for this edition of the book: Mark Camp- bell, Cornell University; Henry Sodano, Arizona State University; and Atul G. Kelkar, Iowa State University. Finally, I wish to offer my deep appreciation to Ms.Alice Dworkin, Associate Editor, Mr. Scott Disanno, Senior Managing Editor, and all the people in- volved in this publishing project, for the speedy yet superb production of this book. Katsuhiko Ogata x Preface 1 Introduction to Control Systems 1–1 INTRODUCTION Control theories commonly used today are classical control theory (also called con- ventional control theory), modern control theory, and robust control theory. This book presents comprehensive treatments of the analysis and design of control systems based on the classical control theory and modern control theory.A brief introduction of robust control theory is included in Chapter 10. Automatic control is essential in any field of engineering and science. Automatic control is an important and integral part of space-vehicle systems, robotic systems, mod- ern manufacturing systems, and any industrial operations involving control of temper- ature, pressure, humidity, flow, etc. It is desirable that most engineers and scientists are familiar with theory and practice of automatic control. This book is intended to be a text book on control systems at the senior level at a col- lege or university. All necessary background materials are included in the book. Math- ematical background materials related to Laplace transforms and vector-matrix analysis are presented separately in appendixes. Brief Review of Historical Developments of Control Theories and Practices. The first significant work in automatic control was James Watt's centrifugal gover- nor for the speed control of a steam engine in the eighteenth century. Other significant works in the early stages of development of control theory were due to 1 4 Chapter 1 / Introduction to Control Systems 1–2 EXAMPLES OF CONTROL SYSTEMS In this section we shall present a few examples of control systems. Speed Control System. The basic principle of a Watt's speed governor for an en- gine is illustrated in the schematic diagram of Figure 1–1. The amount of fuel admitted to the engine is adjusted according to the difference between the desired and the actual engine speeds. The sequence of actions may be stated as follows: The speed governor is ad- justed such that, at the desired speed, no pressured oil will flow into either side of the power cylinder. If the actual speed drops below the desired value due to disturbance, then the decrease in the centrifugal force of the speed governor causes the control valve to move downward, supplying more fuel, and the speed of the engine increases until the desired value is reached. On the other hand, if the speed of the engine increases above the desired value, then the increase in the centrifu- gal force of the governor causes the control valve to move upward. This decreases the supply of fuel, and the speed of the engine decreases until the desired value is reached. In this speed control system, the plant (controlled system) is the engine and the controlled variable is the speed of the engine. The difference between the desired speed and the actual speed is the error signal. The control signal (the amount of fuel) to be applied to the plant (engine) is the actuating signal. The external input to dis- turb the controlled variable is the disturbance. An unexpected change in the load is a disturbance. Temperature Control System. Figure 1–2 shows a schematic diagram of tem- perature control of an electric furnace.The temperature in the electric furnace is meas- ured by a thermometer, which is an analog device.The analog temperature is converted Oil under pressure Power cylinder Close Open Pilot valve Control valve Fuel Engine Load Figure 1–1 Speed control system. Section 1–2 / Examples of Control Systems 5 Thermometer Heater Interface Controller InterfaceAmplifier A/D converter Programmed input Electric furnace Relay Figure 1–2 Temperature control system. to a digital temperature by an A/D converter. The digital temperature is fed to a con- troller through an interface.This digital temperature is compared with the programmed input temperature, and if there is any discrepancy (error), the controller sends out a sig- nal to the heater, through an interface, amplifier, and relay, to bring the furnace tem- perature to a desired value. Business Systems. A business system may consist of many groups. Each task assigned to a group will represent a dynamic element of the system. Feedback methods of reporting the accomplishments of each group must be established in such a system for proper operation. The cross-coupling between functional groups must be made a mini- mum in order to reduce undesirable delay times in the system. The smaller this cross- coupling, the smoother the flow of work signals and materials will be. A business system is a closed-loop system.A good design will reduce the managerl- al control required. Note that disturbances in this system are the lack of personnel or ma- terials, interruption of communication, human errors, and the like. The establishment of a well-founded estimating system based on statistics is manda- tory to proper management. It is a well-known fact that the performance of such a system can be improved by the use of lead time, or anticipation. To apply control theory to improve the performance of such a system, we must rep- resent the dynamic characteristic of the component groups of the system by a relative- ly simple set of equations. Although it is certainly a difficult problem to derive mathematical representations of the component groups, the application of optimization techniques to business sys- tems significantly improves the performance of the business system. Consider, as an example, an engineering organizational system that is composed of major groups such as management, research and development, preliminary design, ex- periments, product design and drafting, fabrication and assembling, and tesing. These groups are interconnected to make up the whole operation. Such a system may be analyzed by reducing it to the most elementary set of com- ponents necessary that can provide the analytical detail required and by representing the dynamic characteristics of each component by a set of simple equations. (The dynamic performance of such a system may be determined from the relation between progres- sive accomplishment and time.) 6 Chapter 1 / Introduction to Control Systems Required product Management Research and development Preliminary design Experiments Product design and drafting Fabrication and assembling Testing Product Figure 1–3 Block diagram of an engineering organizational system. A functional block diagram may be drawn by using blocks to represent the func- tional activities and interconnecting signal lines to represent the information or product output of the system operation. Figure 1–3 is a possible block diagram for this system. Robust Control System. The first step in the design of a control system is to obtain a mathematical model of the plant or control object. In reality, any model of a plant we want to control will include an error in the modeling process.That is, the actual plant differs from the model to be used in the design of the control system. To ensure the controller designed based on a model will work satisfactorily when this controller is used with the actual plant, one reasonable approach is to assume from the start that there is an uncertainty or error between the actual plant and its mathematical model and include such uncertainty or error in the design process of the control system. The control system designed based on this approach is called a robust control system. Suppose that the actual plant we want to control is (s) and the mathematical model of the actual plant is G(s), that is, (s)=actual plant model that has uncertainty ¢(s) G(s)=nominal plant model to be used for designing the control system (s) and G(s) may be related by a multiplicative factor such as or an additive factor or in other forms. Since the exact description of the uncertainty or error ¢(s) is unknown, we use an estimate of ¢(s) and use this estimate, W(s), in the design of the controller. W(s) is a scalar transfer function such that where is the maximum value of for and is called the H infinity norm of W(s). 0 ! v ! q!W(jv)!!!W(s)!!q !!¢(s)!!q 6 !!W(s)!!q = max 0!v!q !W(jv)! G ! (s) = G(s) + ¢(s) G ! (s) = G(s)[1 + ¢(s)] G ! G ! G ! desired. Therefore, it is worthwhile to summarize the advantages and disadvantages of using open-loop control systems. The major advantages of open-loop control systems are as follows: 1. Simple construction and ease of maintenance. 2. Less expensive than a corresponding closed-loop system. 3. There is no stability problem. 4. Convenient when output is hard to measure or measuring the output precisely is economically not feasible. (For example, in the washer system, it would be quite ex- pensive to provide a device to measure the quality of the washer's output, clean- liness of the clothes.) The major disadvantages of open-loop control systems are as follows: 1. Disturbances and changes in calibration cause errors, and the output may be different from what is desired. 2. To maintain the required quality in the output, recalibration is necessary from time to time. 1–4 DESIGN AND COMPENSATION OF CONTROL SYSTEMS This book discusses basic aspects of the design and compensation of control systems. Compensation is the modification of the system dynamics to satisfy the given specifi- cations. The approaches to control system design and compensation used in this book are the root-locus approach, frequency-response approach, and the state-space ap- proach. Such control systems design and compensation will be presented in Chapters 6, 7, 9 and 10. The PID-based compensational approach to control systems design is given in Chapter 8. In the actual design of a control system, whether to use an electronic, pneumatic, or hydraulic compensator is a matter that must be decided partially based on the nature of the controlled plant. For example, if the controlled plant involves flammable fluid, then we have to choose pneumatic components (both a compensator and an actuator) to avoid the possibility of sparks. If, however, no fire hazard exists, then electronic com- pensators are most commonly used. (In fact, we often transform nonelectrical signals into electrical signals because of the simplicity of transmission, increased accuracy, increased reliability, ease of compensation, and the like.) Performance Specifications. Control systems are designed to perform specific tasks. The requirements imposed on the control system are usually spelled out as per- formance specifications. The specifications may be given in terms of transient response requirements (such as the maximum overshoot and settling time in step response) and of steady-state requirements (such as steady-state error in following ramp input) or may be given in frequency-response terms. The specifications of a control system must be given before the design process begins. For routine design problems, the performance specifications (which relate to accura- cy, relative stability, and speed of response) may be given in terms of precise numerical values. In other cases they may be given partially in terms of precise numerical values and Section 1–4 / Design and Compensation of Control Systems 9 partially in terms of qualitative statements. In the latter case the specifications may have to be modified during the course of design, since the given specifications may never be satisfied (because of conflicting requirements) or may lead to a very expensive system. Generally, the performance specifications should not be more stringent than neces- sary to perform the given task. If the accuracy at steady-state operation is of prime im- portance in a given control system, then we should not require unnecessarily rigid performance specifications on the transient response, since such specifications will require expensive components. Remember that the most important part of control system design is to state the performance specifications precisely so that they will yield an optimal control system for the given purpose. System Compensation. Setting the gain is the first step in adjusting the system for satisfactory performance. In many practical cases, however, the adjustment of the gain alone may not provide sufficient alteration of the system behavior to meet the given specifications. As is frequently the case, increasing the gain value will improve the steady-state behavior but will result in poor stability or even instability. It is then nec- essary to redesign the system (by modifying the structure or by incorporating addi- tional devices or components) to alter the overall behavior so that the system will behave as desired. Such a redesign or addition of a suitable device is called compensa- tion. A device inserted into the system for the purpose of satisfying the specifications is called a compensator. The compensator compensates for deficient performance of the original system. Design Procedures. In the process of designing a control system, we set up a mathematical model of the control system and adjust the parameters of a compensator. The most time-consuming part of the work is the checking of the system performance by analysis with each adjustment of the parameters.The designer should use MATLAB or other available computer package to avoid much of the numerical drudgery neces- sary for this checking. Once a satisfactory mathematical model has been obtained, the designer must con- struct a prototype and test the open-loop system. If absolute stability of the closed loop is assured, the designer closes the loop and tests the performance of the resulting closed- loop system. Because of the neglected loading effects among the components, nonlin- earities, distributed parameters, and so on, which were not taken into consideration in the original design work, the actual performance of the prototype system will probably differ from the theoretical predictions. Thus the first design may not satisfy all the re- quirements on performance. The designer must adjust system parameters and make changes in the prototype until the system meets the specificications. In doing this, he or she must analyze each trial, and the results of the analysis must be incorporated into the next trial. The designer must see that the final system meets the performance apec- ifications and, at the same time, is reliable and economical. 1–5 OUTLINE OF THE BOOK This text is organized into 10 chapters.The outline of each chapter may be summarized as follows: Chapter 1 presents an introduction to this book. 10 Chapter 1 / Introduction to Control Systems Chapter 2 deals with mathematical modeling of control systems that are described by linear differential equations. Specifically, transfer function expressions of differential equation systems are derived.Also, state-space expressions of differential equation sys- tems are derived. MATLAB is used to transform mathematical models from transfer functions to state-space equations and vice versa.This book treats linear systems in de- tail. If the mathematical model of any system is nonlinear, it needs to be linearized be- fore applying theories presented in this book. A technique to linearize nonlinear mathematical models is presented in this chapter. Chapter 3 derives mathematical models of various mechanical and electrical sys- tems that appear frequently in control systems. Chapter 4 discusses various fluid systems and thermal systems, that appear in control systems. Fluid systems here include liquid-level systems, pneumatic systems, and hydraulic systems. Thermal systems such as temperature control systems are also discussed here. Control engineers must be familiar with all of these systems discussed in this chapter. Chapter 5 presents transient and steady-state response analyses of control systems defined in terms of transfer functions. MATLAB approach to obtain transient and steady-state response analyses is presented in detail. MATLAB approach to obtain three-dimensional plots is also presented. Stability analysis based on Routh's stability criterion is included in this chapter and the Hurwitz stability criterion is briefly discussed. Chapter 6 treats the root-locus method of analysis and design of control systems. It is a graphical method for determining the locations of all closed-loop poles from the knowledge of the locations of the open-loop poles and zeros of a closed-loop system as a parameter (usually the gain) is varied from zero to infinity. This method was de- veloped by W. R. Evans around 1950. These days MATLAB can produce root-locus plots easily and quickly.This chapter presents both a manual approach and a MATLAB approach to generate root-locus plots. Details of the design of control systems using lead compensators, lag compensators, are lag–lead compensators are presented in this chapter. Chapter 7 presents the frequency-response method of analysis and design of control systems. This is the oldest method of control systems analysis and design and was de- veloped during 1940–1950 by Nyquist, Bode, Nichols, Hazen, among others. This chap- ter presents details of the frequency-response approach to control systems design using lead compensation technique, lag compensation technique, and lag–lead compensation technique. The frequency-response method was the most frequently used analysis and design method until the state-space method became popular. However, since H-infini- ty control for designing robust control systems has become popular, frequency response is gaining popularity again. Chapter 8 discusses PID controllers and modified ones such as multidegrees-of- freedom PID controllers. The PID controller has three parameters; proportional gain, integral gain, and derivative gain. In industrial control systems more than half of the con- trollers used have been PID controllers. The performance of PID controllers depends on the relative magnitudes of those three parameters. Determination of the relative magnitudes of the three parameters is called tuning of PID controllers. Ziegler and Nichols proposed so-called "Ziegler–Nichols tuning rules" as early as 1942. Since then numerous tuning rules have been proposed.These days manufacturers of PID controllers have their own tuning rules. In this chapter we present a computer optimization approach using MATLAB to determine the three parameters to satisfy Section 1–5 / Outline of the Book 11 14 Chapter 2 / Mathematical Modeling of Control Systems transient-response or frequency-response analysis of single-input, single-output, linear, time-invariant systems, the transfer-function representation may be more convenient than any other. Once a mathematical model of a system is obtained, various analytical and computer tools can be used for analysis and synthesis purposes. Simplicity Versus Accuracy. In obtaining a mathematical model, we must make a compromise between the simplicity of the model and the accuracy of the results of the analysis. In deriving a reasonably simplified mathematical model, we frequently find it necessary to ignore certain inherent physical properties of the system. In particular, if a linear lumped-parameter mathematical model (that is, one employing ordinary dif- ferential equations) is desired, it is always necessary to ignore certain nonlinearities and distributed parameters that may be present in the physical system. If the effects that these ignored properties have on the response are small, good agreement will be obtained between the results of the analysis of a mathematical model and the results of the experimental study of the physical system. In general, in solving a new problem, it is desirable to build a simplified model so that we can get a general feeling for the solution.A more complete mathematical model may then be built and used for a more accurate analysis. We must be well aware that a linear lumped-parameter model, which may be valid in low-frequency operations, may not be valid at sufficiently high frequencies, since the neg- lected property of distributed parameters may become an important factor in the dynamic behavior of the system. For example, the mass of a spring may be neglected in low- frequency operations, but it becomes an important property of the system at high fre- quencies. (For the case where a mathematical model involves considerable errors, robust control theory may be applied. Robust control theory is presented in Chapter 10.) Linear Systems. A system is called linear if the principle of superposition applies. The principle of superposition states that the response produced by the simultaneous application of two different forcing functions is the sum of the two individual responses. Hence, for the linear system, the response to several inputs can be calculated by treating one input at a time and adding the results. It is this principle that allows one to build up complicated solutions to the linear differential equation from simple solutions. In an experimental investigation of a dynamic system, if cause and effect are pro- portional, thus implying that the principle of superposition holds, then the system can be considered linear. Linear Time-Invariant Systems and Linear Time-Varying Systems. A differ- ential equation is linear if the coefficients are constants or functions only of the in- dependent variable. Dynamic systems that are composed of linear time-invariant lumped-parameter components may be described by linear time-invariant differen- tial equations—that is, constant-coefficient differential equations. Such systems are called linear time-invariant (or linear constant-coefficient) systems. Systems that are represented by differential equations whose coefficients are functions of time are called linear time-varying systems. An example of a time-varying control sys- tem is a spacecraft control system. (The mass of a spacecraft changes due to fuel consumption.) Section 2–2 / Transfer Function and Impulse-Response Function 15 Outline of the Chapter. Section 2–1 has presented an introduction to the math- ematical modeling of dynamic systems. Section 2–2 presents the transfer function and impulse-response function. Section 2–3 introduces automatic control systems and Sec- tion 2–4 discusses concepts of modeling in state space. Section 2–5 presents state-space representation of dynamic systems. Section 2–6 discusses transformation of mathemat- ical models with MATLAB. Finally, Section 2–7 discusses linearization of nonlinear mathematical models. 2–2 TRANSFER FUNCTION AND IMPULSE- RESPONSE FUNCTION In control theory, functions called transfer functions are commonly used to character- ize the input-output relationships of components or systems that can be described by lin- ear, time-invariant, differential equations. We begin by defining the transfer function and follow with a derivation of the transfer function of a differential equation system. Then we discuss the impulse-response function. Transfer Function. The transfer function of a linear, time-invariant, differential equation system is defined as the ratio of the Laplace transform of the output (response function) to the Laplace transform of the input (driving function) under the assumption that all initial conditions are zero. Consider the linear time-invariant system defined by the following differential equation: where y is the output of the system and x is the input. The transfer function of this sys- tem is the ratio of the Laplace transformed output to the Laplace transformed input when all initial conditions are zero, or By using the concept of transfer function, it is possible to represent system dynam- ics by algebraic equations in s. If the highest power of s in the denominator of the trans- fer function is equal to n, the system is called an nth-order system. Comments on Transfer Function. The applicability of the concept of the trans- fer function is limited to linear, time-invariant, differential equation systems.The trans- fer function approach, however, is extensively used in the analysis and design of such systems. In what follows, we shall list important comments concerning the transfer func- tion. (Note that a system referred to in the list is one described by a linear, time-invariant, differential equation.) = Y(s) X(s) = b0 sm + b1 sm - 1 + p + bm - 1 s + bm a0 sn + a1 sn - 1 + p + an - 1 s + an Transfer function = G(s) = l[output] l[input] 2 zero initial conditions = b0 x (m) + b1x (m - 1) + p + bm - 1 x # + bm x (n ! m) a0 y (n) + a1y (n - 1) + p + an - 1 y # + an y 16 Chapter 2 / Mathematical Modeling of Control Systems 1. The transfer function of a system is a mathematical model in that it is an opera- tional method of expressing the differential equation that relates the output vari- able to the input variable. 2. The transfer function is a property of a system itself, independent of the magnitude and nature of the input or driving function. 3. The transfer function includes the units necessary to relate the input to the output; however, it does not provide any information concerning the physical structure of the system. (The transfer functions of many physically different systems can be identical.) 4. If the transfer function of a system is known, the output or response can be stud- ied for various forms of inputs with a view toward understanding the nature of the system. 5. If the transfer function of a system is unknown, it may be established experimen- tally by introducing known inputs and studying the output of the system. Once established, a transfer function gives a full description of the dynamic character- istics of the system, as distinct from its physical description. Convolution Integral. For a linear, time-invariant system the transfer function G(s) is where X(s) is the Laplace transform of the input to the system and Y(s) is the Laplace transform of the output of the system, where we assume that all initial conditions in- volved are zero. It follows that the output Y(s) can be written as the product of G(s) and X(s), or (2–1) Note that multiplication in the complex domain is equivalent to convolution in the time domain (see Appendix A), so the inverse Laplace transform of Equation (2–1) is given by the following convolution integral: where both g(t) and x(t) are 0 for t

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