1

INTRODUCTION

This book is concerned with the development of an understanding of the dynamic physical systems that engineers are called upon to design. The type of systems to be studied can be described by the term *mechatronic*, which implies that while the elements of the system are mechanical in a general sense, electronic control will also be involved. For the design of a computer-controlled system, it is crucial that the dynamics of systems that exchange power and energy in various forms be thoroughly understood. Methods for modeling real systems will be presented, ways of analyzing systems in order to shed light on system behavior will be shown, and techniques for using computers to simulate the dynamic response of systems to external stimuli will be developed. Before beginning the study of physical systems, it is worthwhile to reflect a moment on the nature of the discipline that is usually called *system dynamics* in engineering.

The word *system* is used so often and so loosely to describe a variety of concepts that it is hard to give a meaningful definition of the word or even to see the basic concept that unites its diverse meanings. When the word *system* is used in this book, two basic assumptions are being made:

1. A system is assumed to be an entity separable from the rest of the universe (the environment of the system) by means of a physical or conceptual boundary. An animal, for example, can be thought of as a system that reacts to its environment (the temperature of the air, for example) and that interchanges energy and information with its environment. In this case the boundary is physical or spatial. An air traffic control system, however, is a complex, man-made system, the environment of which is not only the physical surroundings but also the fluctuating demands for air traffic, which ultimately come from human decisions about travel and the shipping of goods. The unifying element in these

two disparate systems is the ability to decide what belongs in the system and what represents an external disturbance or command originating from outside the system.

2. A system is composed of interacting parts. In an animal we recognize organs with specific functions, nerves that transmit information, and so on. The air traffic control system is composed of people and machines with communication links between them. Clearly, the *reticulation* of a system into its component parts is something that requires skill and art, since most systems could be broken up into so many parts that any analysis would be swamped with largely irrelevant detail.

These two aspects of systems can be recognized in everyday situations as well as in the more specific and technical applications that form the subject matter of most of this book. For example, when one hears a complaint that the transportation system in this country does not work well, one may see that there is some logic in using the word *system*. First of all, the transportation system is roughly identifiable as an entity. It consists of air, land, and sea vehicles and the human beings, machines, and decision rules by which they are operated. In addition, many parts of the system can be identified—cars, planes, ships, baggage handling equipment, computers, and the like. Each part of the transportation system could be further reticulated into parts (i.e., each component part is itself a system), but for obvious reasons we must exercise restraint in this division process.

The essence of what may be called the "systems viewpoint" is to concern oneself with the operation of a complete system rather than with just the operation of the component parts. Complaints about the transportation system are often real "system" complaints. It is possible to start a trip in a private car that functions just as its designers had hoped it would, transfer to an airplane that can fly at its design speed with no failures, and end in a taxi that does what a taxi is supposed to do, and yet have a terrible trip because of traffic jams, air traffic delays, and the like. Perfectly good components can be assembled into an unsatisfactory system.

In engineering, as indeed in virtually all other types of human endeavor, tasks associated with the design or operation of a system are broken up into parts that can be worked on in isolation to some extent. In a power plant, for example, the generator, turbine, boiler, and feed water pumps typically will be designed by separate groups. Furthermore, heat transfer, stress analysis, fluid dynamics, and electrical studies will be undertaken by subsets of these groups. In the same way, the bureaucracy of the federal government represents a splitting up of the various functions of government. All the separate groups working on an overall task must interact in some manner to make sure that not only will the parts of the system work, but also the system as a whole will perform its intended function. Many times, however, oversimplified assumptions about how a system will operate are made by those working on a small part of the system. When this happens, the results can be disappointing. The power plant may undergo damage during a full load rejection, or the economy of a country may collapse because of the unfavorable interaction of segments of government, each of which assiduously pursues seemingly reasonable policies.

In this book, the main emphasis will be on studying system aspects of behavior as distinct from component aspects. This requires a knowledge of the component parts of the systems of interest and hence some knowledge in certain areas of engineering that are taught and sometimes even practiced in splendid isolation from other areas. In the engineering systems of primary interest in this book, topics from vibrations, strength of materials, dynamics, fluid mechanics, thermodynamics, automatic control, and electrical circuits will be used. It is possible, and perhaps even common, for an engineer to spend a major part of his or her professional career in just one of these disciplines, despite the fact that few significant engineering projects concern a single discipline. Systems engineers, however, must have a reasonable command of several of the engineering sciences as well as knowledge pertinent to the study of systems per se.

Although many systems may be successfully designed by careful attention to static or steady-state operation in which the system variables are assumed to remain constant in time, in this book the main concern will be with *dynamic* systems, that is, those systems whose behavior as a function of time is important. For a transport aircraft that will spend most of its flight time at a nearly steady speed, the fuel economy at constant speed is important. For the same plane, the stress in the wing spars during steady flight is probably less important than the time-varying stress during flight through turbulent air, during emergency maneuvers, or during hard landings. In studying the fuel economy of the aircraft, a static system analysis might suffice. For stress prediction, a dynamic system analysis would be required.

Generally, of course, no system can operate in a truly static or steady state, and both slow evolutionary changes in the system and shorter time transient effects associated, for example, with startup and shutdown are important. In this book, despite the importance of steady-state analysis in design studies, the emphasis will be on dynamic systems. Dynamic system analysis is more complex than static analysis but is extremely important, since decisions based on static analyses can be misleading. Systems may never actually achieve a possible steady state due to external disturbances or instabilities that appear when the system dynamics are taken into account. Moreover, systems of all kinds can exhibit counterintuitive behavior when considered statically. A change in a system or a control policy may appear beneficial in the short run from static considerations but may have long-run repercussions opposite to the initial effect. The history of social systems abounds with sometimes tragic examples, and there is hope that dynamic system analysis can help avoid some of the errors in “static thinking” [1]. Even in engineering with rather simple systems, one must have some understanding of the dynamic response of a system before one can reasonably study the system on a static basis.

A simple example of a counterintuitive system in engineering is the case of a hydraulic power generating plant. In order to reduce power, wicket gates just before the turbine are moved toward the closed position. Temporarily, however, the power actually increases as the inertia of the water in the penstock forces the flow through the gates to remain almost constant, resulting in a higher velocity of flow through the smaller gate area. Ultimately, the water in the penstock slows down and power is reduced. Without an understanding of the dynamics of this system, one would be led to open the gates to *reduce* power. If this were done, the immediate result would be a gratifying decrease of power followed by a surprising and inevitable increase. Clearly, a good understanding of dynamic response is crucial to the design of a controller for mechatronic systems.

1.1 MODELS OF SYSTEMS

A central idea involved in the study of the dynamics of real systems is the idea of a *model* of a system. Models of systems are simplified, abstracted constructs used to predict their behavior. Scaled physical models are well known in engineering. In this category fall the wind tunnel models of aircraft, ship hull models used in towing tanks, structural models used in civil engineering, plastic models of metal parts used in photoelastic stress analysis, and the "breadboard" models used in the design of electric circuits.

The characteristic feature of these models is that some, but not all, of the features of the real system are reflected in the model. In a wind tunnel aircraft model, for example, no attempt is made to reproduce the color or interior seating arrangement of the real aircraft. Aeronautical engineers assume that some aspects of a real craft are unimportant in determining the aerodynamic forces on it, and thus the model contains only those aspects of the real system that are supposed to be important to the characteristics under study.

In this book, another type of model, often called a *mathematical model*, is considered. Although this type of model may seem much more abstract than the physical model, there are strong similarities between physical and mathematical models. The mathematical model also is used to predict only certain aspects of the system response to inputs. For example, a mathematical model might be used to predict how a proposed aircraft would respond to pilot input command signals during test maneuvers. But such a model would not have the capability of predicting every aspect of the real aircraft response. The model might not contain any information on changes in aerodynamic heating during maneuvers or about high-frequency vibrations of the aircraft structure, for example.

Because a model must be a simplification of reality, there is a great deal of art in the construction of models. An unduly complex and detailed model may contain parameters virtually impossible to estimate, may be practically impossible to analyze, and may cloud important results in a welter of irrelevant detail if it can be analyzed. An oversimplified model will not be capable of exhibiting important effects. It is important, then, to realize that *no system can be modeled exactly* and that any competent system designer needs to have a procedure for constructing a variety of system models of varying complexity so as to find the simplest model capable of answering the questions about the system under study.

The rest of this book deals with models of systems and with the procedures for constructing models and for extracting system characteristics from models. The models will be mathematical models in the usual meaning of the term even though they may be represented by stylized graphs and computer printouts rather than the more conventional sets of differential equations.

System models will be constructed using a uniform notation for all types of physical systems. It is a remarkable fact that models based on apparently diverse branches of engineering science can all be expressed using the notation of *bond graphs* based on energy and information flow. This allows one to study the *structure* of the system model. The nature of the parts of the model and the manner in which the parts interact can be made evident in a graphical format. In this way, analogies between various types of systems are made evident, and experience in one field can be extended to other fields.

Using the language of bond graphs, one may construct models of electrical, magnetic, mechanical, hydraulic, pneumatic, thermal, and other systems using only a rather small set of ideal elements. Standard techniques allow the models to be translated into differential equations or computer simulation schemes. Historically, diagrams for representing dynamic system models developed separately for each type of system. For example, parts a, b, and c of Figure 1.1 each represent a diagram of a typical model. Note that in each case the elements in the diagram seem to have evolved from sketches of devices, but in fact a photograph of the real system would not resemble the diagram at all. Figure 1.1a might well represent the dynamics of the heave motion of an automobile, but the masses, springs, and dampers of the model are not directly related to the parts of an automobile visible in a photograph. Similarly, symbols for resistors and inductors in diagrams such as Figure 1.1b may not correspond to separate physical elements called resistors and chokes but instead may correspond to the resistance and inductance effects present in a single physical device. Thus, even semipictorial diagrams are often a good deal more abstract than they might at first appear.

When mixed systems such as that shown in Figure 1.1d are to be studied, the conventional means of displaying the system model are less well developed. Indeed, few such diagrams are very explicit about just what effects are to be included in the model. The basic structure of the model may not be evident from the diagram. A bond graph is more abstract than the type of diagrams shown in Figure 1.1, but it is explicit and has the great advantage that all the models shown in Figure 1.1 would be represented using exactly the same set of symbols. For mixed systems such as that shown in Figure 1.1d, a universal language such as bond graphs provide is required in order to display the essential structure of the system model.

1.2 SYSTEMS, SUBSYSTEMS, AND COMPONENTS

In order to model a system, it is usually necessary first to break it up into smaller parts that can be modeled and perhaps studied experimentally and then to assemble the system model from the parts. Often, the breaking up of the system is conveniently accomplished in several stages. In this book major parts of a system will be called *subsystems* and primitive parts of subsystems will be called *components*. Of course, the hierarchy of components, subsystems, and systems can never be absolute, since

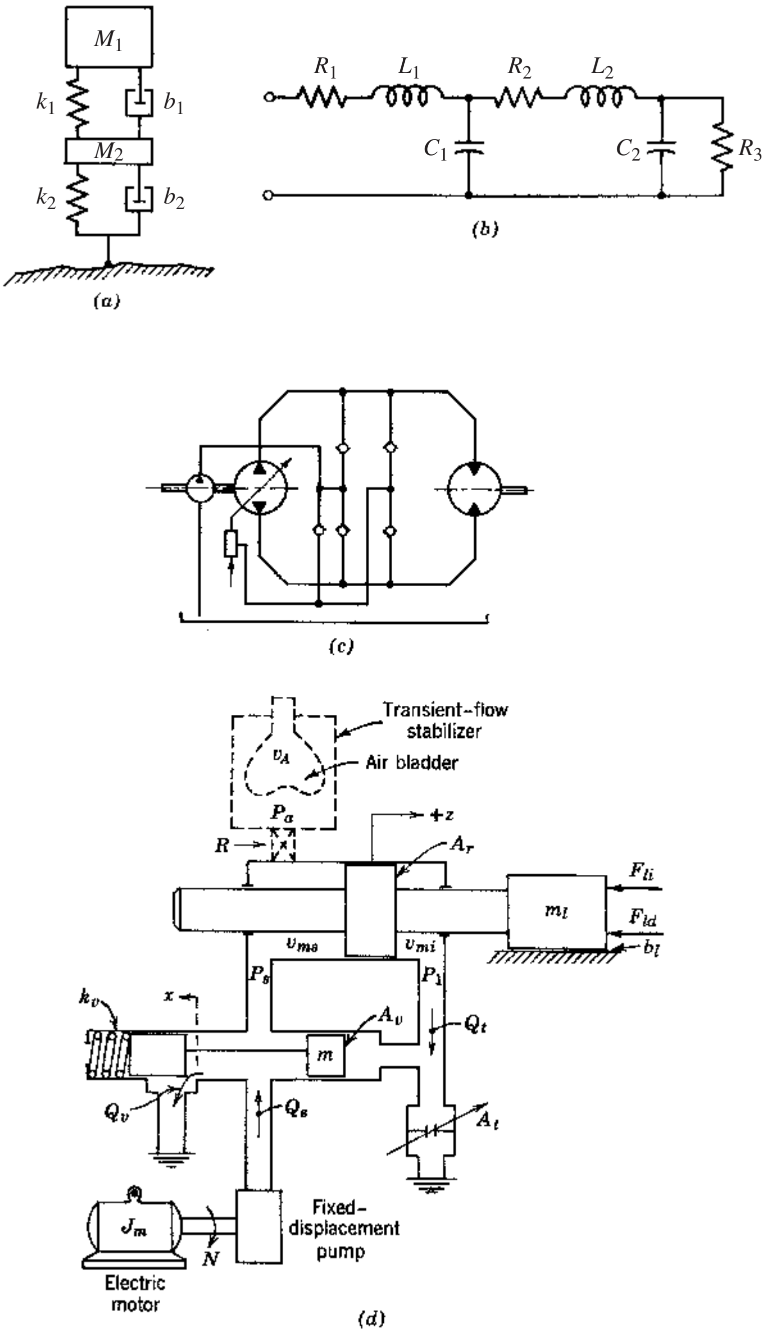

FIGURE 1.1. (*a*) Typical schematic diagram; (*b*) typical electric circuit diagram; (*c*) typical hydraulic diagram; (*d*) schematic diagram of system containing mechanical, electrical, and hydraulic components.

even the most primitive part of a system could be modeled in such detail that it would be a complex subsystem. Yet in many engineering applications, the subsystem and component categories are fairly obvious.

Basically, a subsystem is a part of a system that will be modeled as a system itself; that is, the subsystem will be broken into interacting component parts. A component, however, is modeled as a unit and is not thought of as composed of simpler parts. One needs to know how the component interacts with other components and one must have a characterization of the component, but otherwise a component is treated as a "black box" without any need to know what causes it to act as it does.

To illustrate these ideas, consider the vibration test system shown in Figure 1.2. The system is intended to subject a test structure to a vibration environment specified by a signal generator. For example, if the signal generator delivers a random-noise signal, it may be desired that the acceleration of the shaker table be a faithful reproduction of the electrical noise signal waveform. In a system that is assembled from physically separate pieces, it is natural to consider the parts that are assembled by connecting wires and hydraulic lines or by mechanical fasteners as subsystems. Certainly, the electronic boxes labeled signal generator, controller, and electrical amplifier are subsystems, as are the electrohydraulic valve, the hydraulic shaker, and the test structure. It may be possible to treat some of these subsystems as components if their interactions with the rest of the system can be specified without knowledge of the internal construction of the subsystem. The electrical amplifier is obviously composed of many components, such as resistors, capacitors, transistors, and the like, but if the amplifier is sized correctly so that it is not overloaded, then it may be possible to treat the amplifier as a component specified by the manufacturer's input–output data. Other subsystems may require a subsystem analysis in order to achieve a dynamic description suitable for the overall system study.

Consider, for example, the electrohydraulic valve. A typical servo valve is shown in Figure 1.3. Clearly, the valve is composed of a variety of electrical, mechanical, and hydraulic parts that work together to produce the dynamic response of the valve. For this subsystem the components might be the torque motor, the hydraulic

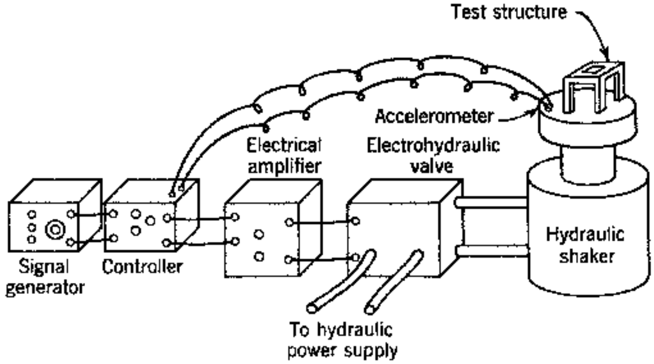

FIGURE 1.2. Vibration test system.

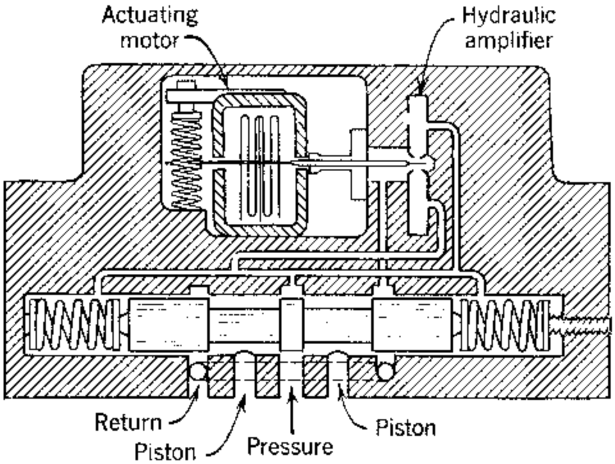

FIGURE 1.3. Electrohydraulic valve.

amplifier, mechanical springs, hydraulic passages, and the spool valve. A subsystem dynamic analysis can reveal weaknesses in the subsystem design that may necessitate the substitution of another subsystem or a reconfiguration of the overall system. Yet such an analysis may indicate that, from the point of view of the overall system, the subsystem may be adequately characterized as a simple component. A skilled and experienced system designer often makes a judgment on the appropriate level of detail for the modeling of a subsystem on an intuitive basis. A major purpose of the methods presented in this book is to show how system models can be assembled conveniently from component models. It is then possible to experiment with subsystem models of varying degrees of sophistication in order to verify or disprove initial modeling decisions.

1.3 STATE-DETERMINED SYSTEMS

The goal of this book is to describe means for setting up mathematical models for systems. The type of model that will be found is often described as a "state-determined system." In mathematical notation, such a system model is often described by a set of ordinary differential equations in terms of so-called *state variables* and a set of algebraic equations that relate other system variables of interest to the state variables. In succeeding chapters an orderly procedure, beginning with physical effects to be modeled and ending with state equations, will be demonstrated. Even though some techniques of analysis and computer simulation do not require that the state equations be written, from a mathematical point of view all the system models are state-determined systems.

The future of all the variables associated with a state-determined system can be predicted if (1) the state variables are known at some initial time and (2) the future time history of the input quantities from the environment is known.

Such models, which are virtually the only ones used in engineering, have some built-in philosophical implications. For example, events in the future do not affect the present state of the system. This implication is correlated with the assumption that time runs only in one direction—from past to future. That models should have these properties probably seems plausible, if not obvious, yet it is remarkably difficult to conceive of a demonstration that real systems always have these properties.

Clearly, past history can have an effect on a system; yet the influence of the past is exhibited in a special way in state-determined systems. All the past history of a state-determined system is summed up in the present values of its state variables. This means that many past histories could have resulted in the same present value of state variables and hence the same future behavior of the system. It also means that if one can condition the system to bring the state variables to some particular values, then the future system response is determined by the future inputs and nothing is important about the past except that the state variables were brought to those values.

Scientific experiments are run as if the systems to be studied were state determined. The system is always started from controlled conditions that are expressed in terms of carefully monitored variables. If the experiment is repeatable, then the assumption is that the state variables are properly initialized by the operations used to set up the experiment. If the experiment is not repeatable, then the assumption is that some important influence has not been controlled. This influence can be either a state variable that was not monitored and initialized properly or an unrecognized input quantity through which the environment influences the system.

State-determined system models have proved useful over centuries of scientific and technical work. For the usual macroscopic systems encountered in engineering, state-determined system models are nearly universal, and there is continuing interest in developing such models for social and economic systems. This book can be regarded as a textbook devoted to the establishment and study of state-determined system models using well-defined physical systems of interest to engineers as examples.

1.4 USES OF DYNAMIC MODELS

In Figure 1.4 a general dynamic system model is shown schematically. The system, S, is characterized by a set of state variables, indicated by X, that are influenced by a set of input variables, U, that represent the action of the system's environment on the system. The set of output variables, Y, are observable aspects of the system's

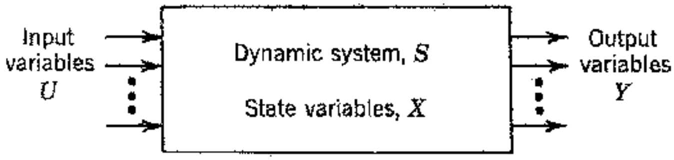

FIGURE 1.4. General dynamic system model.

response or back effects from the system onto the environment. This type of dynamic system model may be used in three quite distinct ways:

1. *Analysis*. Given U for the future, X at the present, and the model S, predict the future of Y. Assuming that the system model is an accurate representation of the real system, analysis techniques allow one to predict system behavior.
2. *Identification*. Given time histories of U and Y, usually by experimentation on real systems, find a model S and state variables X which are consistent with U and Y. This is the essence of scientific experimentation. Clearly, a "good" model is one that is consistent with a great variety of sets U and Y.
3. *Synthesis*. Given U and some desired Y, find S such that U acting on S will produce Y. Most of engineering deals with synthesis, but only in limited contexts are there direct synthesis methods. Often we must be content to accomplish synthesis of systems via a trial-and-error process of repetitive analysis of a series of candidate systems. In this regard, dynamic models pay a vital role, since progress would be slow indeed if one had to construct each candidate system "in the metal" in order to discover its properties.

In this book we will concentrate on setting up system models and predicting the behavior of the systems using analytical or computational techniques. Thus, we will concentrate on analysis, but it is important to remember that the techniques are useful for identification problems and that the major challenge to a systems engineer is to synthesize desirable systems. It may not be too much to say that analysis, except in the service of synthesis, is a rather sterile pursuit for an engineer.

1.5 LINEAR AND NONLINEAR SYSTEMS

An overall system model, consisting of subsystems and their components, requires modeling decisions as to what dynamic effects must be included in order to use the model for its intended purpose. The result of these modeling decisions is typically a system schematic that indicates the important dynamic effects. Figures 1.1 and 1.2 are examples of system schematics where modeling decisions have been made. In Figure 1.1*d*, the important dynamic effects at the component level are indicated by labeling inertial, compliance, and resistance effects. In Figure 1.2, modeling decisions are indicated at the subsystem level, while the detail modeling of each subsystem remains to be done. A very important aspect of the modeling process is whether components of subsystems behave linearly or nonlinearly. As we progress through the chapters, it will become very clear as to what is meant by linear or nonlinear behavior. For now it is simply stated that linear systems are represented by sets of linear, first-order differential equations, and nonlinear systems, while still state determined, are represented by sets of nonlinear, first-order differential equations.

If it is justified to assume that an overall system can be represented as linear, then there exist an abundance of analytical tools for obtaining exact analytical solutions to the linear equations and for extracting incredibly detailed information about the response of the system. Some of the analytical information that is covered in later chapters includes eigenvalues, transfer functions, and frequency response. If the systems have large numbers of state variables, then pencil and paper analysis may not be possible, and one must resort to computation to obtain the linear properties of the system.

If a single component in a system model is represented as a nonlinear element, then the system is nonlinear, and linear analysis tools will not work. Sliding friction is an example of a nonlinear component. There will not exist analytical eigenvalues, transfer functions, or frequency response. In order to extract information about the response of nonlinear systems, one must resort to time step simulation. Fortunately, there is an abundance of commercial programs to simulate nonlinear systems.

The fact is that there are virtually no physical systems that are linear. However, in order to introduce the concepts of constructing overall system models of interacting electrical, mechanical, hydraulic, and thermal components, it is easier to start with linear systems and then extend the procedures to nonlinear systems. In the following five chapters, the emphasis is on linear system models, but whenever possible, the reader is reminded that real physical systems are nonlinear and simulation tools must be used to obtain system responses.

1.6 AUTOMATED SIMULATION

Mathematical models of dynamic physical systems have been made ever since the invention of differential equations. But until the development of powerful computers, there were severe limitations on the analysis of these models. Practically speaking, the dynamic behavior could generally be predicted only for low-order linear models that often were not very accurate representatives of real systems.

There is a lot to be said for the study of low-order linear models in order to gain an appreciation of system dynamics, and the first six chapters of this book deal primarily with just such system models. However, computer simulation can now be used to gain experience with system dynamics even when the system models become large and when they contain nonlinear elements. Chapter 13 discusses some of the issues that arise when dealing with complex but realistic models.

The next Chapters, 2, 3, and 4, present techniques for representing elements of mechanical, electrical, and fluid systems (and combination systems) in the abstract form of bond graphs instead of the schematic diagrams usually used to show vibratory systems, electric circuits, or hydraulic systems. For some, this may seem to be an unnecessary step away from physical reality, but it has useful consequences.

First of all, a bond graph is a precise way to represent a mathematical model. Often schematic diagrams are not entirely clear about whether certain effects are to be included or neglected in the model. Second, for many systems involving two or more forms of energy, such as mechanical, electrical and hydraulic, there are no standard schematic diagrams that clearly indicate assumptions made in the modeling process. Finally, it is much easier to communicate a bond graph model unambiguously to a computer than a schematic diagram.

The bond graph uses only a few standard symbols, whereas typical schematic diagrams for the same system model drawn by different people are almost never identical. Just as computers more easily read bar codes than handwriting, they more easily interpret bond graphs than schematic diagrams.

Computer programs have been developed that recognize bond graphs and can process them in the same manner that a human would in order to extract differential equations for analysis or simulation. In the process, useful facts about the mathematics of the model are discovered even before any numerical parameters or laws have been supplied. Furthermore, when the parameters of the elements and the forcing functions for the system have been specified, the programs can then simulate the response of the system. In this process, only a minimum of human intervention is required.

Although it is important for a system engineer to understand the entire process of modeling and simulation, the use of bond graphs and bond graph simulation programs allows a beginner to start developing the skills associated with computer simulation even before all the bond graph modeling techniques have been learned. This has proved to be very effective in teaching. From the first day, the student can see that, given a bond graph model and a bond graph simulation program, it is possible to see how the model reacts to various input forcing functions and to variations in system parameters. Simple design studies on dynamic systems can be assigned without waiting until the student has learned to make models, derive equations, and use an equation solver. This provides motivation to learn about bond graph dynamic system modeling and numerical simulation techniques.

The fact that the simulation programs are effective for nonlinear as well as linear models, and for large models as well as small ones, may not be fully appreciated by a beginning student. However, in the course of time the significance of this fact should become apparent.

References [2–4] give the names of some of the more well known commercial bond graph processors, some of which are used in conjunction with simulation programs to solve the differential equations. A web search will reveal that there are a number of other bond graph processor programs.

Another category of program is based on a stored library of predetermined bond graph submodels, but in use, replaces bond graph submodels with icons. See Reference [5], for example. Such programs are useful for studying large engineering models but they are less useful for learning about bond graph modeling.

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PROBLEMS

1-1 Suppose you were a heating engineer and you wished to consider a house as a dynamic system. Without a heater, the average temperature in the house would clearly vary over a 24-h period. What might you consider for inputs, outputs, and state variables for a simple dynamic model? How would you expand your model so that it would predict temperatures in several rooms of the house? How does the installation of a thermostatically controlled heater change your model?

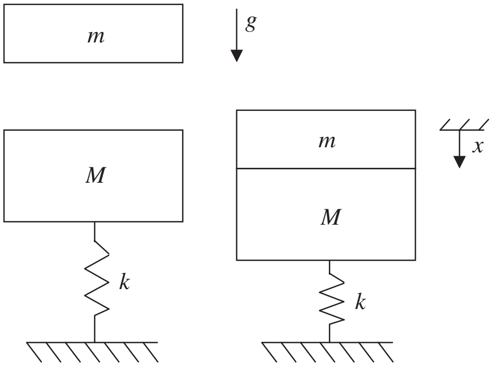
1-2 For a particular car operated on a level road at steady conditions there is a relation between throttle position and speed. Sketch the general shape you would expect for this curve. If recordings were made of instantaneous speed and throttle position while the car was driven normally for several miles on ordinary roads, do you think that the instantaneous values of speed and throttle position would fall on the steady-state curve? What inputs, outputs, and state variable might prove useful in trying to find a dynamic model useful in predicting dynamic speed variations?

1-3 A car is driven over a curb twice—once very slowly and once quite rapidly. What would you need to know about the car in the second case that you did not need to know in the first case if you were required to find the tire force that resulted from going over the curb?

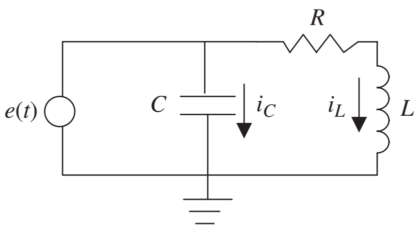
1-4 In the steady state a good weather vane points into the wind, but when the wind shifts, the vane cannot always be trusted to be pointing into the wind. Identify inputs, outputs, and the parameters of the weather vane system that affect its response to the wind. Sketch your idea of how the position of the vane would change in time if the wind suddenly shifted 10°.

1-5 The height of water in a reservoir fluctuates over time. If you had to construct a dynamic system model to help water resource planners predict variations in the height, what input quantities would you consider? How many state variables do you think you would need for your model?

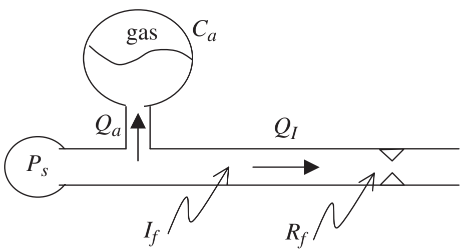
1-6 A mass, M, and spring, k, are at rest in a gravity field, about to be struck by a mass, m, falling from a height, h. The mass, m, sticks to M, and the two move downward. The variable, x, keeps track of the displacement after impact. Sketch the general motion of x for some period of time after impact. How many equations do you think are needed to describe this system mathematically? If the system ever came to rest, what would be the deflection of the spring?



1-7 The system is an electric circuit consisting of an input voltage, $e(t)$, and a capacitor, resistor, and inductor, C, R, L. As will be seen in later chapters, if a voltage is applied to a capacitor, current flows easily at first and then slows as the capacitor becomes charged. Inductors behave just the opposite, in that they reluctantly pass current when a voltage is first applied, and then the current passes easily as time passes. If the input voltage is suddenly raised from zero to some constant value, sketch the current in the capacitor, i_C, and the inductor, i_L, as a function of time. What is the steady-state current in the capacitor and inductor?



1-8 A hydraulic system consists of a supply pressure, P_s, and a long fluid-filled tube. Branching from the tube is an accumulator, C_a, consisting of a compliant gas separated from the fluid by a diaphragm. The long tube has inertia and resistance, I_f and R_f. It may be hard to believe at this point, but this hydraulic



system exhibits identical behavior to that of the electric circuit of Problem 1-7. Armed with this information, sketch the volume flow rate of the fluid into the accumulator, Q_a, and in the tube, Q_I, as a function of time. Also construct a word bond graph of this hydraulic system.

1-9 Shown here is the hydraulic system in Problem 1-8 connected to a hydraulic cylinder of piston area A_p. The piston is connected to a mass, m, attached to the ground through the spring and damper, k and b. This is a "system" consisting of interacting hydraulic and mechanical components. How many variables do you think are needed to fully describe the motion of the system? Sketch how you think the volume flow rate in the accumulator and in the tube will respond to a sudden elevation of the supply pressure. Sketch the motion, x, of the mass. Construct a word bond graph for this system.