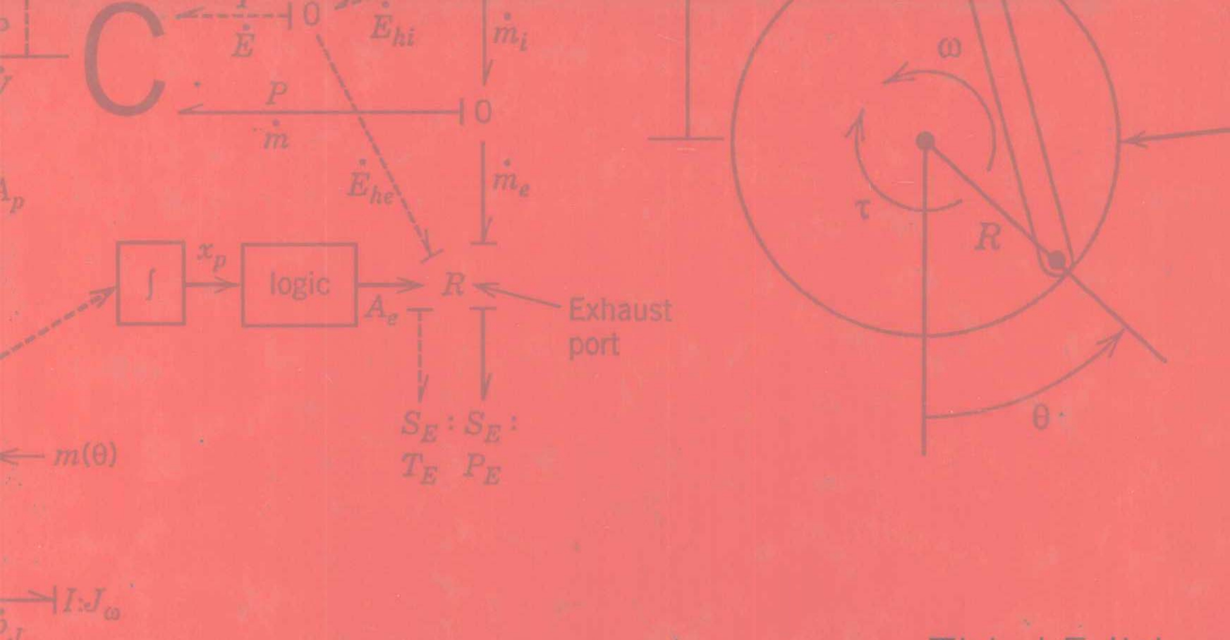

Third Edition

SYSTEM DYNAMICS

Modeling and Simulation of Mechatronic Systems

DEAN C. KARNOPP

DONALD L. MARGOLIS

RONALD C. ROSENBERG

SYSTEM DYNAMICS

Modeling and Simulation of Mechatronic Systems

Third Edition

DEAN C. KARNOPP
Department of Mechanical and Aeronautical Engineering
University of California
Davis, CA

DONALD L. MARGOLIS
Department of Mechanical and Aeronautical Engineering
University of California
Davis, CA

RONALD C. ROSENBERG
Department of Mechanical Engineering
Michigan State University
East Lansing, MI

A Wiley-Interscience Publication
JOHN WILEY & SONS, INC.
New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

This book is printed on acid-free paper. ♾

Library of Congress Cataloging-in-Publication Data:

Karnopp, Dean.
System dynamics : modeling and simulation of mechatronic systems / by Dean Karnopp, Donald L. Margolis, Ronald C. Rosenberg. — 3rd ed.
p. cm.
"A Wiley-Interscience publication."
ISBN 0-471-33301-8 (alk. paper)
1. System engineering. 2. System analysis. 3. Bond graphs.
I. Margolis, Donald L. II. Rosenberg, Ronald C. III. Title.
TA168.K362 2000
620'.001'1—DC21 99-16022

Printed in the United States of America

10 9 8 7 6 5

PREFACE TO THE THIRD EDITION

We are pleased to have been asked to write the third edition of this book. We are true believers in the importance for engineers of understanding the dynamics of systems they design, and we have been promoting these beliefs for many years. The growth in use of our book as well as the increasing availability of other texts in the area of physical system modeling supports our contention. It is well understood that in the design of real systems, the engineer must consider many things that affect system performance. These often include thermal, fluid, electrical, pneumatic, vibrational, magnetic, and other effects. It has become increasingly apparent in engineering schools worldwide that realistic systems have to be modeled, analyzed, and studied, typically with the aid of computers, if good system designs are to result. And we believe that bond graphs are the best way to represent these multi-energy systems.

The proliferation of inexpensive signal processing hardware has greatly influenced the incorporation of automatic control into all types of engineering systems. Vehicle systems, manufacturing machines, noise and vibration control systems, and even household appliances have been impacted. For control systems there is an interaction among sensors, signal processors, actuators, and the system. Modeling and understanding the overall system is essential to ensure good, reliable performance.

The word *mechatronics* has been introduced into the engineer's vocabulary and has come to mean the electronic control of mechanical systems. We believe that bond graphs are an ideal representation of mechatronic systems. Since our book is about modeling and simulation of all types of interacting physical systems, we have changed the subtitle of this edition to reflect its applicability to general mechatronic systems.

The first six chapters have been modified, and even shortened a bit, by eliminating all reference to customary English units. Cross-energy domain modeling requires power-conserving transduction, and this is best done using the International System of Units (SI). Output quantities can always be converted to units of choice, but simulations are best done using the consistent SI units. The simulation of linear systems in Chapter 4 has been modernized for better understanding. As before, the first six chapters are introductory and deal mostly with linear systems. These chapters are excellent for an undergraduate course at the senior level, after students have had some exposure to classical fluid mechanics, dynamics, thermal science, and design.

Chapters 7–12 still deal with advanced topics, but they have been improved to make them easier to understand. Chapter 9, dealing with rigid-body mechanics, has been significantly improved. These chapters are intended for a graduate-level course or for the practicing engineer involved with system design. All chapters have had new problems added, and, as before, a solution manual is available for teachers or for self-learning practicing engineers.

Chapter 13 is new and deals exclusively with simulation of nonlinear systems. Bond graphs yield equations of motion in a direct way and deliver these equations in a form perfectly suitable for computer simulation. Bond graphs also point out formulation problems resulting from perfectly reasonable modeling assumptions. These problems are addressed in Chapter 13 and simulation of a complex system is demonstrated.

Writing a text treating an advanced topic is unquestionably a labor of love. But the topic of this book is very dear to the three of us. We think the material is essential for the understanding and design of complete, engineering systems. We hope that you enjoy the book and find the topics presented as useful as we do.

CONTENTS

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 which 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, on the other hand, 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 which 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 dynamic, 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 the 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, on the other hand, 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. Also, 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 the 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 overly 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 overly simplified 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 remainder 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 all can 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 1.1*a* 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 1.1*b* 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 1.1*d* 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 Figure 1.1*d*, 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,

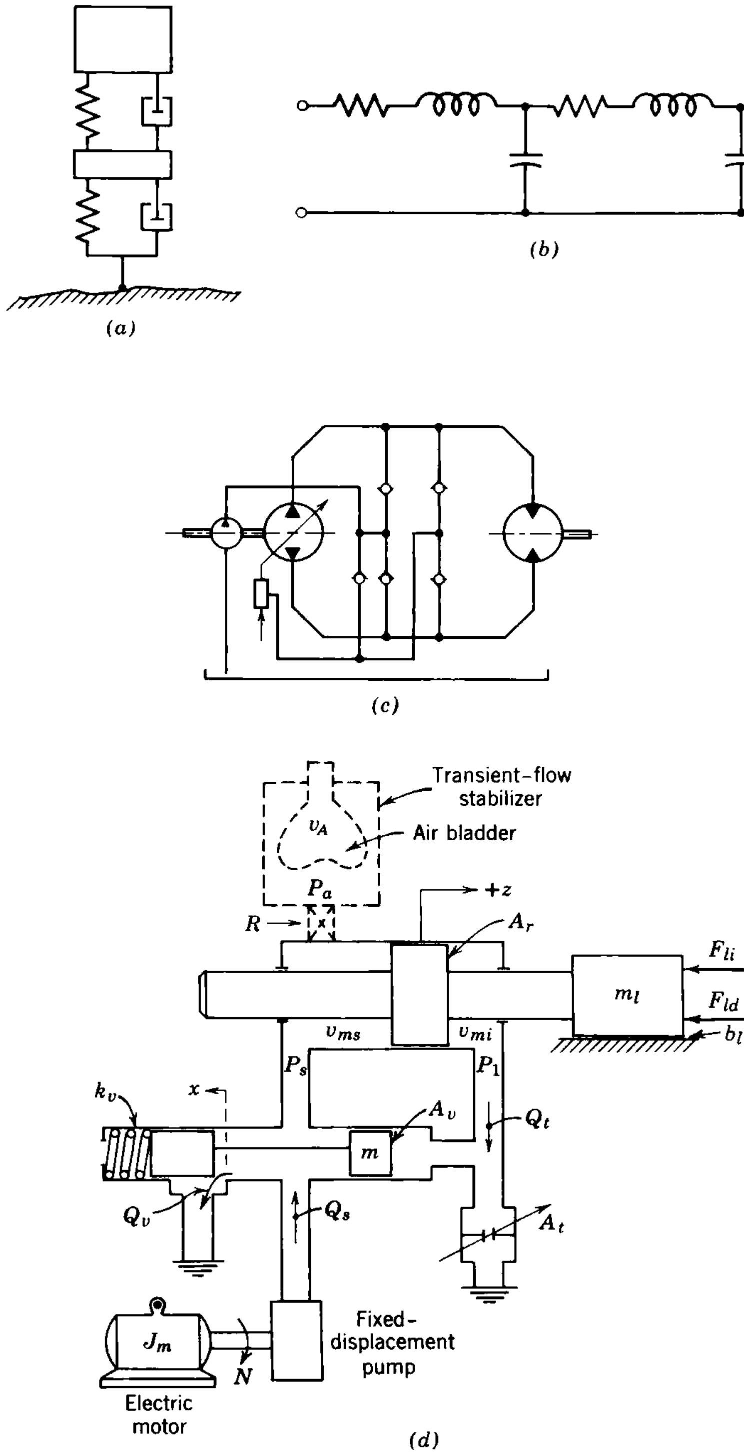

FIGURE 1.1. (*a*) Typical schematic diagram; (*b*) typical electric circuit diagram; (*c*) typical hydraulic diagram; (*d*) schematic diagram of system containing mechanical, electrical, and hydraulic components.

the hierarchy of components, subsystems, and systems can never be absolute, since even the most primitive part of a system could be modeled in such detail that it would be a complex subsystem. On the other hand, 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, on the other hand, 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.

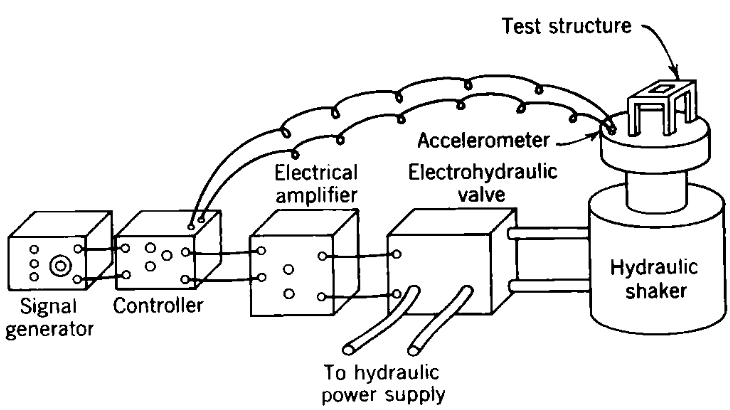

FIGURE 1.2. Vibration test system.

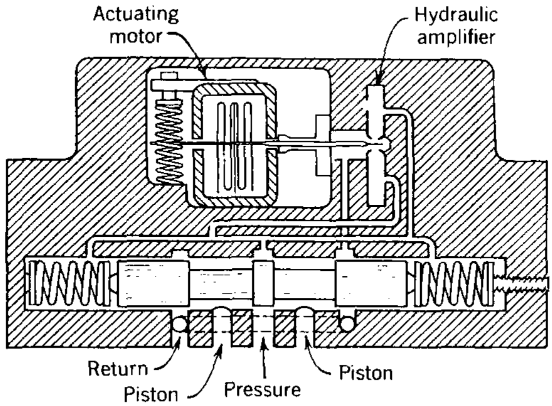

FIGURE 1.3. Electrohydraulic valve.

For this subsystem the components might be the torque motor, the hydraulic 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. On the other hand, 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 often is described as a "state-determined system." In mathematical notation, such a system model often is 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.