IRA COCHIN
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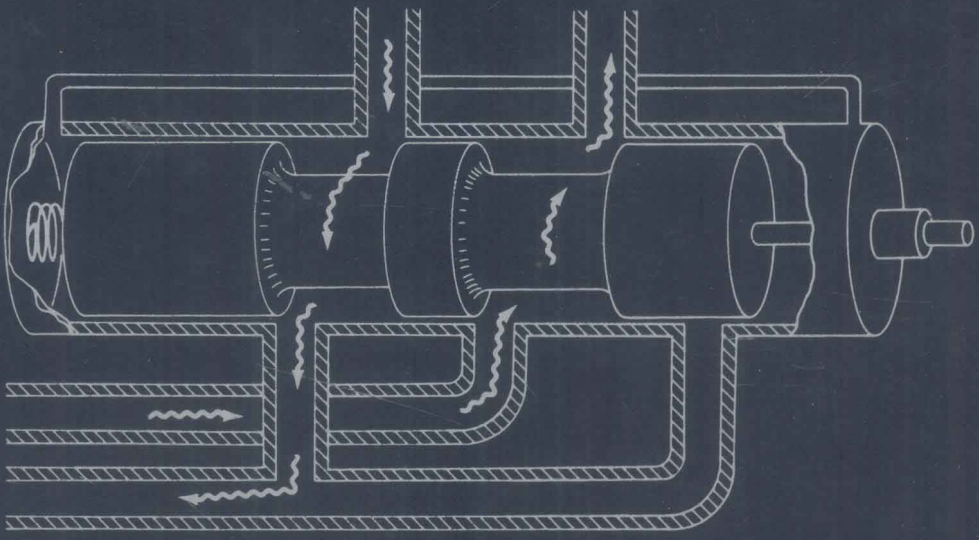

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Analysis and Design of Dynamic Systems

Preface

This text introduces fundamental systems techniques for the analysis and design of dynamic systems. The text may be used for undergraduate courses in vibrations, dynamics, systems, automatic controls, and senior design. The present text was actually developed in the process of teaching these four subjects. The text has undergone a number of changes. Many applications were added or modified, and new methods were adapted in a continuing effort to make the text more suitable for study of a difficult subject by an undergraduate audience. The present form of the text, its depth, order, treatment of many aspects of a single system, and policy of practical involvement are the logical conclusions of its inception and subsequent growth.

The objective of this text is to present a moderately complete and sufficiently sophisticated treatment of the broad class of systems. To some extent, sophisticated methods place one's head in the clouds, but the practical applications keep one's feet on the ground. Such a conflict suggests, at first, that one must either be very tall or else run up and down a lot of stairs. There is a third alternative; use the escalator. The format of this text may be regarded as a technological escalator. Simple notions are introduced at the beginning, followed by equally simple applications. In each succeeding chapter, some of these same notions are advanced and are presented again along with some new notions accompanied by comparably advanced applications. (This is done rather than present all the mathematical material at the beginning and all the applications at the end.) In this way, the student may progress in scope and magnitude, learning the mathematics and applications in a palatable manner.

It may be said that the real strengths of this text are its practical problems and devotion to design. If so, this is borne out in the illustrative examples and problems. Where appropriate, some of these are treated in detail and in depth, covering several aspects of the same system. The design techniques are presented in several forms consistent with the level of competence of the reader at that point in the curriculum. The most advanced is set in an apprentice-like atmosphere, employing actual

drawings of the system under investigation. In other cases, the sense of working in a real engineering company is simulated by cost effective design methods. In all cases, the reader has a front seat, from formulation of design criteria through the final determination of system parameters and dimensions.

The philosophy of the text is to blend techniques involving analytical, graphical, and computer methods. No one of these techniques is overemphasized in an attempt to dominate, replace, or exclude any of the others. These methods are intermixed, demonstrating that they can assist and strengthen one another.

The text has attempted to cover a fairly complete field of modern system techniques. In compiling such a work, it would appear that there is a need for an anthology of system techniques involving many disciplines. While a large portion of such an anthology exists, there are nevertheless some "windows" in the spectrum of available techniques. In an effort to fill some of these vacancies, the author would like to lay claim to the following ideas in which there is some degree of originality:

1. *One mass rule* (provides a direct relationship between the free body diagram and the system response).
2. *Synthesis of dynamic systems* (given either the performance specifications or the actual test data, this is a formal approach to establishing the system configuration).
3. *Multimass rule* (provides a direct relationship between the response of highly coupled multiple degree of freedom systems and their free body diagrams).
4. *Folding of symmetric systems* (reduces order to one-half of symmetric systems with a number of degrees of freedom).
5. Many of the design techniques in this text.

In conclusion, one might regard this text as a blend of many of the most up-to-date methods available today. Each of the techniques may have some limited area where it could stand alone, but for the most part, several techniques are used in conjunction, each one reinforcing and supporting the other. The material is seasoned with experience, and is spiced with practical illustrative examples. The text was designed to bridge the gap between theory and practice and yet remain within the corridor of time-proven methodology. Perhaps there is nothing new under the sun, but we can have a field day with innovation in the communication of these not-so-new ideas.

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Acknowledgments

An individual is the product of his environment, his associates, and the kind people who help him. A book is even more so. Those of us who have all their faculties take them for granted. How often do we offer thanks for having ten fingers, two eyes, ears, legs, a digestive system, a voice, and countless other wonders. Likewise, how often do we offer thanks to our family for their part in our lives. I consider my wife and three daughters the highest of these wonders. They gave (and are still giving) me the best of both worlds. On the one hand, they were careful not to disturb the cloud nine operation of writing, leaving me detached from the every day pressures. On the other hand, they kept me in touch with the real world with their companionship and charm. They served dinner for five on a card table, while every other horizontal surface in the house was occupied by the wall-to-wall profusion of writings and sketches. I am indeed blessed.

In the sea of scorn and dissuasion, there is a lighthouse that keeps the ship off the rocks. Such guidance was provided by Mr. Robert I. Isakower of the Scientific Engineering and Applications Division of Picatinny Arsenal. From conception up to the final draft, he read, commented, and offered suggestions. His wit made the reviews pleasant, while his perceptiveness left little unnoticed. If this book is easy to read, this is due to Mr. Isakower's scrutiny.

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It appears that with all this help, there may be a question concerning the name on the front cover. If there were a vote upon who is the author, I suppose I might win only on plurality.

Analysis and Design of Dynamic Systems

Contents

Chapter 1
Introduction to System Concepts

This chapter introduces the subjects of systems, modeling, design, analysis, and synthesis. Using a case study, a number of design concepts are highlighted in a simple gear system. First, a workable design is found. Then, cost factors are introduced. Finally, cost effective means are employed.

In the problem section for this chapter, many practical designs are outlined, giving the student an opportunity to initiate a design study.

1.1 INTRODUCTION TO SYSTEMS

The word "system" has become a household word. We hear of a plumbing system, a transportation system, an electrical system, our digestive system, our judiciary system, and our economic system. In more technical circles we hear of an ignition system, a braking system, the XYZ Broadcasting System, a communications system, a system of particles, and a navigation system. What do all of these "systems" have in common?

1.1.1 System Classification

DEFINITION OF SYSTEM

A *system* is a collection of interconnected components in which there is a specified set of dynamic variables called *inputs* (or excitations) and a

dependent set called *outputs* (or responses). Considering a hierarchy among systems, a system can be expressed as a collection of collections. On the lower level, or subsystem level, the collection of interconnected components and their behaviors can be thought of as *events*. Hence, a large system can be considered as a collection of interconnected events, where each event consists of a collection of interconnected components.

CLASSIFICATION OF SYSTEMS

The classification of systems depends upon the degree of interconnection of the events from none to total. It should be pointed out that even for no connection, there must be some relation. If the events are unrelated altogether, there is no system. Systems will be divided into three classes (for analytical and design purposes) according to the degree of interconnection of the events. The classes are: independent, cascaded, and coupled. These are discussed in turn.

• *Independent.* If the events have no effect upon one another, then the system is classified as *independent*. The events may be studied individually.

• *Cascaded.* If the effects of the events are unilateral (that is, part A affects part B, B affects C, C affects D, and so forth but not vice-versa) the system is classified as *cascaded*. For such a system, part A is studied first. Then part B is studied next, but where the effect of part A is included. Then, part C is studied next, but where the effects of parts A and B are included. And so on. Thus the events may be studied one at a time, but in the sequence dictated by the "flow" from one cascade to the next. This sequential process is referred to as the *cascade rule*.

• *Coupled.* If the events mutually affect each other, the system is classified as *coupled*. In this case, the events cannot be studied one at a time, but must be studied simultaneously. If one were to draw a "flow" line from one part to another, there will be at least one closed loop. That is, at least one sequence of events will close upon itself. Thus, if one were to study the system starting at any point in the sequence, it would be seen that the overall process is an iterative one.

1.1.2 Survey of Some Common Systems

INDEPENDENT SYSTEMS

• *Lathe Feed.* The cross feed and longitudinal feed of a machine lathe illustrate an example of related yet independent events. If the cross feed is truly perpendicular to the spindle axis, and if the longitudinal feed is truly parallel to the spindle axis, then the operator can perform facing and turning operations anywhere on the machine. If these feeds are out of line, then the operator finds that the feeds are not independent. That is, facing