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INTRODUCTORY SYSTEM ANALYSIS

Signals and Systems in Electrical Engineering

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INTRODUCTORY SYSTEM ANALYSIS

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Introductory System Analysis

SIGNALS AND SYSTEMS IN ELECTRICAL ENGINEERING

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To our wives, Clarice and Doris

Preface

This book, which is the first of two basic books,* focuses on the presentation of the fundamental concepts underlying the subjects of linear system analysis, instrumentation and control engineering, electronic circuits, and analog simulation and computation. In the present volume, the basic analysis techniques common to all of these areas are introduced at an elementary level, as a preparation for the subsequent study of specific engineering problems drawn from the areas of analog simulation, electronic instrumentation, communications, automatic control, digital computation, electrical machinery, and electric power generation and distribution.

This volume has been prepared primarily for the first course in introductory electrical engineering given to nonelectrical majors in engineering and science (with the second book or one of the several other "service-course" texts used in the second course). Secondarily, it is intended as a text for the introductory electrical engineering course for electrical majors and as a reference book for practicing engineers seeking an introductory treatment of linear system analysis. The text has been used for three years at the Polytechnic Institute of Brooklyn, where the students thus far have been primarily mechanical engineering undergraduates and physics sophomores; in addition, the two books have been used as the texts for an introductory electrical engineering course in a program leading to a master's degree in electrical engineering for graduates of other engineering and scientific curricula.

The Nature of the "Service" Course in Electrical Engineering

The book represents a rather radical departure in the selection of material for the introductory electrical engineering, or "service," course

* The second book, "Principles of Electronic Instrumentation," builds (from this book) the principles of electronics, instrumentation, and automatic control.

for nonelectrical majors. In contrast to the usual emphasis on d-c and a-c circuit analysis and electrical machinery, the book attempts to present the essential viewpoint of the electrical engineer working in those areas where the various engineering and scientific specialties are brought together (in control, instrumentation, and electronics, for example). If the present volume possesses any overemphasis, it is almost certainly in the direction of analog computers and electronic instruments, but the demands on the nonelectrical engineer for greater and greater facility in these areas will certainly grow in the future. The rather strong emphasis on linear system analysis runs somewhat counter to the recommendations of the ASEE Ad Hoc Committee on the Electrical Science course (where a much stronger emphasis on field theory was suggested). The authors believe, however, that certain factors must influence the formulation of an introductory course of a service-type, and the present volume represents an attempt to implement these factors:

1. The introduction of new concepts must be related to the past experience and knowledge of the student. For this reason we have chosen to build the initial concepts relating to circuit models around the familiar elements of mass, compliance, and friction. The students discover in this way that the fundamental techniques and viewpoints of the electrical engineer are essentially only slight modifications of those approaches with which they are already familiar in mechanics. For the same reasons there is rather strong emphasis in Chaps. 3 and 4 on the analogy between electrical and mechanical systems—not in order to exploit the analogy directly in solving problems in either field, but rather in order to emphasize the similarity of viewpoint and approach to analysis. Linear system analysis is a basic topic in mechanical engineering, chemical engineering, aeronautical engineering, civil engineering, and applied mathematics and physics, and the recognition of the essential similarity of these apparently different fields is conceptually rewarding to the student. There is also a more direct reason for emphasizing the principle of analogy, which becomes important in the work of the second book on instrumentation where mixed systems are dealt with. Today such systems are becoming the rule rather than the exception, and, as an example, many of the control systems currently being developed employ hydraulic motors or actuators to drive mechanical loads such as radar antennas and are in turn controlled by electrical subsystems often containing communication links. Here the basic system study is made tractable only by our ability to represent it in a single common analogue and it is often most expedient to employ an all-electrical representation for convenience in dealing with amplifiers, gear trains, and the like.

2. An introductory course in any area must be highly motivated. With engineering students, motivation is automatic if throughout the

course the techniques which the student is learning are applied to real-life engineering problems—problems in which the student can readily see the power and necessity of the methods and problems of sufficient importance that the student is able to derive satisfaction from their solution. Discussion of this subject of motivation is difficult, since there is certainly no argument to the fact that, in this period of rapid changes in engineering education, we cannot afford the curriculum time required for survey courses devoted exclusively to motivation. Unfortunately, electrical engineering educators all too often go to the opposite extreme, when they devote a major share of the introductory course to d-c circuits of such pathological complexity that 27 loop equations are required for description, unless the student happens to see that the sequential application of 17 otherwise trivial tricks (e.g., T–π transformations and the various network theorems) reduces the circuit to a single loop. From the standpoint of motivation, probably the most tragic discovery in electrical engineering education was that one could calculate the resistance of diagonally opposite vertices of the famous 1-ohm cube. As a consequence of this discovery, the 1-ohm cube has served as an important "motivation" in introductory courses for years, without anyone ever raising the question of what sane engineer would seriously care about the device.

3. An introductory service course should be open-ended, in the sense that the talented nonelectrical student should be prepared, after the course, for more specialized courses in electrical engineering—particularly those courses such as analog computers, introductory servo theory, and electronic circuits, which are of direct interest in the mechanical engineering profession, or additional courses on electronic instrumentation, which is of such basic importance in the applied sciences. Naturally, no service course can cover, for the nonelectrical student, the entire range of the undergraduate electrical engineering curriculum, but the service course should prepare the talented nonelectrical student to move into a master's degree program in electrical engineering with a minimum of unsatisfied undergraduate prerequisites. In the three years that the course has been given at the Polytechnic Institute of Brooklyn, several graduates in mechanical engineering have gone on to graduate work in electrical engineering and received the master's degree in one calendar year.

If the course is to fulfill this objective of open-endedness, it clearly must focus on the basic methods of analysis of the electrical engineer. If an adequate coverage is to be given to the group of topics which ordinarily requires numerous courses in the electrical engineering curriculum, there is no time for a detailed discussion of professorial, special cases or techniques peculiar only to a narrow class of problems. On the other hand, it becomes imperative to discuss the fundamental concepts in a

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manner which, while perhaps not detailed in rigorous proofs, is accurate and provides a firm, unified foundation upon which later, more specialized knowledge can be built.

The thoughts of the above paragraph are particularly important in explaining the selection of topics in this volume. Thus, while the detailed analysis of very complex electric circuits is not covered (no circuits of greater complexity than three independent nodes are considered), while there is no mention of the compensation or reciprocity theorems or the T–π transformation, and while there is no discussion at all of the matrix representation of circuit equations, the text does cover the use of the impulse function in circuit characterization and analysis, the consideration of driven circuits in which there is initial energy storage, and the simulation of linear equations of any degree on an electronic analog computer. In the second book, there are included discussions of various electronic instrumentation systems (e.g., for the measurement of temperature and acceleration), of simple feedback-control systems (including an electrohydraulic system), and of systems for electric energy generation and distribution. The possibility of discussing these varied topics in meaningful depth and correlated with actual engineering experience arises because of the focusing of attention in this first volume on the very basic concepts of linear system analysis and because of the presentation of these concepts in a unified way.

The Role of Field Theory and Materials

As a result of this emphasis on linear system analysis and the study of lumped-parameter physical systems, the book certainly represents a slighting of the role of field theory and materials engineering, at least in terms of the picture of electrical engineering which may be conveyed to the nonelectrical major. With the electrical engineering major, this distorted emphasis on one aspect of electrical engineering is not particularly troublesome, since the student is available for a number of courses and the subject matter must be compartmented for effective presentation.

The question of whether the service course should attempt to discuss the basic concepts of electromagnetic theory and the electrical properties of materials (i.e., the interaction of fields and charges in materials) is certainly open to serious differences of opinion among engineering educators. We feel rather strongly that it is simply not possible, at least in the present state of knowledge, to do anything like a reasonable job with all three topics in a single course—even a course of a year's duration. As more and more engineering departments require a course in modern physics, at least at an elementary level, it seems sensible to leave the primary burden of the materials engineering to this course, where indeed the material is perhaps presented more effectively than it can be by an engineering department. The mechanical engineering or other major department can then follow this physics course with a more specific treatment of the subject matter pertinent to its particular engineering field.

Thus, in establishing the scope of this book (and the associated course), we were left with the choice of field theory or system analysis as the primary emphasis around which the presentation would be unified. From the standpoint of correlation with the other engineering science courses in the typical undergraduate curriculum, there is little choice: the system analysis ties in closely with the dynamics and vibrations courses, the guidance work of the aeronautical engineer, and the process control work of the chemical engineer; the field theory, on the other hand, is directly related to the fluid dynamics, stress analysis, and other studies of distributed-parameter systems in the various fields.

From the standpoint of the possibility of motivation, likewise, there seems to be little choice, although it is usually somewhat more difficult to motivate the early stages of a field theory course. Certainly, however, there are exciting practical applications of field theory: in magnetohydrodynamics and plasma studies, in radiation phenomena, in the properties of electrostatic and magnetic devices (cathode-ray tubes and particle accelerators, solenoids, etc.).

The primary argument in favor of the initial emphasis on system analysis stems from the possibility of tying in the presentation closely with the previous knowledge of the student, regardless of his level (from sophomore to senior). Even first-semester sophomores are beginning to learn about differential equations (although usually after they are solved in this course), and the presentation here complements the emphasis in other courses on the properties and solution of such equations. Furthermore, the circuit-analysis viewpoint can be tied in directly with the basic work in mechanics in the freshman physics course and the work on dynamics in the later engineering science course (our own experience indicates that it is of little consequence which course comes first in the student's program, the dynamics course or this work on system analysis).

The selection of the present emphasis was certainly also based, in part, on the desire to familiarize the students in other engineering departments with the basic principles of commercial analog computers. The work of Chap. 7 provides a high point of the course (at least in terms of student motivation), and the associated opportunity in the laboratory to solve, on an analog computer, problems which would have been considered impossible in other courses in the undergraduate curriculum is a source of tremendous satisfaction to the student.

Thus, we believe that the selection of material in this volume represents a logical compromise between the desire on the one hand to present a complete survey of electrical engineering and the necessity on the other hand of restricting the scope of the book so that the material which is presented can result in a reasonable mastery of the subject rather than merely superficial knowledge. Unquestionably, a two-semester course of this nature should be followed by a third semester devoted to a consideration of the basic concepts of field theory (in which, again, there is a close correlation between the electromagnetic theory and the field theory of related and analogous areas).

The Major Emphases of the Book

The core of the material in the book can be divided into three parts:

1. The model concept.
2. The transfer-function concept.
3. Analog simulation and computation.

1. The *model concept* embraces two major aspects: the formulation of tractable, analytical models for physical signals and the formulation and exploitation of models for physical systems. In Chap. 2, we start immediately with a consideration of the types of signals which actually exist in engineering systems and place the major emphasis on the generalized exponentials (including the step function and its various derivatives and integrals as special cases). The early discussion of exponential signals (rather than a detailed analysis of d-c systems) permits immediate motivation in terms of a variety of real-life engineering examples; with this discussion inserted at the outset of the course, all of the later work on the analysis and study of simple systems and circuits can be illustrated by examples drawn from instrumentation, signal generation, and signal processing.

The system models upon which primary emphasis is placed in Chaps. 3 and 4 are the circuit diagram and the circuit equations (the integro-differential equations of motion). In Chap. 3, we focus on the viewpoints involved in the derivation of a circuit model for simple translational and rotational mechanical systems (and systems involving both types of motion). While the possibility of deriving the circuit equations through the use of the power-balance relationship is mentioned, primary emphasis is placed on those systems in which the circuit diagram can be derived from an understanding of the functioning of the system. The initial discussion of mechanical systems (before electrical circuits are even mentioned) permits a direct tie-in with the introductory mechanics course and with situations which are familiar to the student while the basic concept of a circuit-diagram model is being introduced.

Once the circuit diagram is obtained, the node equations (the equations corresponding to the application of D'Alembert's principle at each point at which the velocity is unknown) are written systematically, as the electrical engineer would do in the application of the Kirchhoff current law. Thus, the two models (the circuit diagram and the system equations) are directly related.

In Chap. 4 we begin the study of electrical systems with a development which closely parallels that of Chap. 3 for mechanical systems. Actually, the extent to which Chaps. 3 and 4 should be covered must depend to some extent upon the background of the students; certainly, if the physics background in mechanics and in electricity and magnetism is strong, a rapid coverage of the two chapters can be accomplished, since only a few new ideas are introduced. In addition, Chap. 3 can be omitted entirely, without loss of continuity, if the instructor prefers to move directly to the study of electrical systems from the original work on signal analysis; frankly, we feel that, while undue emphasis should not be placed on Chap. 3's mechanical circuits, the unity of viewpoint which is achieved in the analysis of lumped-parameter, linear systems (regardless of the particular field in which they occur) is an important lesson of undergraduate engineering education and should be a primary objective of any course in engineering science.

2. The *transfer-function concept* is the second major area of emphasis of this first book. Developed through Chaps. 5 and 6 as a basic approach to the solution of dynamics problems, the transfer function is a fundamental concept in modern system analysis, whether practiced by the electrical engineer or utilized in other fields.

Among the important transfer-function concepts presented in Chap. 5 is the carefully developed sequence of ideas built around the partial-fraction expansion of transfer functions. Starting first with initially inert systems in which there is no initial stored energy, the student sees the possibility of decomposing a system of any complexity into a parallel arrangement of trivial subsystems (usually of first order), with the combination driven by an impulse function. The next step is the introduction of the concept of a signal generator as a hypothetical system capable of generating any desired exponential signal when excited by an impulse function. At this point the student is presented with the important idea of the essential exchangeability of signals and systems and the common representation of either or both in terms of a transfer function.* The

* Our preference for the engineering-oriented concept of the signal generator to the mathematically oriented concept of a transform is based in part on our experience that this provides good motivation without at the same time evoking any strong feelings that apologies should be made for slighting the elegance of the Laplace transform. With this unrigorous, but sound, introduction, the student is well motivated for future courses in formal transform theory.

final logical step in this chain of ideas is the representation of specified, initial energy storage in terms of external sources, so that the signal-generator transfer-function concept is extended to cover all possible combinations of linear systems and signals.

In Chap. 6 the transfer function is used primarily for the interpretation of system properties without the necessity for carrying out all the detailed steps of writing differential equations and obtaining total responses. Here the forced components of response and the sinusoidal steady-state responses are found with a minimum of computational effort. As a further aid in estimating important aspects of performance, attention is focused on time constants governing response, relative damping ratios, differentiating and integrating properties, high- and low-frequency behavior, etc., and the subject of resonance is discussed in general terms with reference to both mechanical and electrical systems. With the introduction of s-plane geometry, the evaluation of time and frequency responses is further simplified and, more importantly, further unified, and the groundwork is laid for further exploitation of s-plane geometry in the second volume in connection with the dynamics of electronic instruments, the stability of feedback systems, and the response of communications and signal-processing systems.

After the analysis of relatively simple circuits is considered in detail in Chaps. 5 and 6, we turn to the consideration of analog simulation and computation in Chap. 7, primarily as a means of solution for complex systems or for systems in which several parameters are to be varied during the design. Chap. 7 presents two new and basic ideas:

1. The writing of linear algebraic equations (including the transforms of differential equations) in purely graphical form.
2. The adaptation of these graph portrayals to the operational requirements of physical analog simulations, with the ultimate objective of creating a usable analog computer "set-up."

The chapter presents the basic techniques for formulating a signal-flow graph (a set of simultaneous equations portrayed graphically) as an aid to reaching an appropriate analog computer set-up. It then continues with a discussion of various aspects of the computer simulation of linear, lumped-parameter systems as represented by linear, ordinary differential equations with constant coefficients, and it concludes with a treatment of the essentials of the algebra of signal-flow graphs, in which the flow graph is used as a general tool of analysis to prepare the student for the discussions of feedback systems in the second volume.

The signal-flow-graph techniques of Chap. 7 are by no means essential as a prelude to the formulation of analog computer simulations, and this is especially true of the rather simple systems that have been selected for examples and illustrations. However, in keeping with the objective of open-endedness, the signal-flow-graph approach is presented for the following reasons:

1. To lay a groundwork for the computer simulation of complicated systems, both linear and nonlinear, where scaling problems affecting the individual values of the variables must be dealt with and where alternate configurations must be formulated and assessed. In these complicated situations, some facility with flow-graph techniques greatly simplifies and systematizes the problems encountered. The potentialities of these techniques are barely suggested in this volume.

2. To provide a systematic approach to the portrayal of complicated systems in terms of cause-and-effect relationships (whether in block-diagram symbols or signal-flow-graph symbols is immaterial).

3. To focus attention on the feedback point of view as an alternate approach to system analysis and thereby to aid the systems engineer in viewing systems in terms of their structure or topology. (Incidentally, the portrayal of ordinary passive networks in terms of flow graphs containing feedback loops makes it a simple matter to place "feedback" in its proper perspective as a point of view.)

The last chapter of this first book presents a rather detailed discussion of a very simple example in which many of the techniques which are developed in the preceding chapters are pulled together—and an example in which a first attempt is made to indicate to the student the nature of systems or instrumentation engineering work.

The Generality

It is perhaps clear from the above brief description that there is considerable generality in the coverage and selection of material. In an attempt to achieve such generality without exceeding the bounds of complexity appropriate for a course for nonelectrical majors, we have departed in several important ways from the conventional introductory treatment of electrical engineering:

1. The use of the concept of the complex frequency from the outset greatly generalizes the various developments, without at the same time complicating the concepts involved. Actually, complex numbers are used in Chap. 2 briefly but then not again until Chaps. 5 and 6, so that there is ample time for the student to familiarize himself with this subject.

2. Network or system equations are always developed in a single, consistent way: via node equations (the summing of currents or forces at the nodes of the circuit model). Alternate methods, such as loop equations, network theorems, impedance computations, etc., are not used at all in the early sections, and when introduced are subordinated to the main theme of the node-equation approach. This approach has been demonstrated to give the student confidence in his problem-solving

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