

Preface

This book is intended for engineering undergraduate students, particularly aerospace and mechanical engineers and students in other disciplines concerned with system modeling, analysis, and control. It is intended to be a relatively comprehensive treatment of engineering undergraduate differential equations as well as two primary applications thereof: linear vibrations and classical feedback control. This material is traditionally separated into different courses in undergraduate engineering curricula, however, consistent with the theme of this book, the current trend to optimize and streamline curricula results in many programs combining courses where there is a common underlying theoretical basis. Specifically this book was developed from the materials presented in a two-course, required, junior-level sequence of courses that I developed and have taught in the Department of Aerospace and Mechanical Engineering at the University of Notre Dame over the past several years. The rationale behind the selection, arrangement, and relationship of the content of book has four primary facets.

The first facet relates to the role of mathematical analysis in modern engineering. The modern reality, especially in industry but also in academic settings, is that sophisticated software packages enabled by fast computing are starting to play a dominant role in engineering analysis. Hence, to some extent, the skill of being able to solve problems “by hand” is being displaced by computer simulation. This is not an argument for not covering what has been traditionally been the subject of engineering analysis courses, however, it can be taken as a justification for a slightly altered focus toward fundamental understanding versus problem solving by hand. Because the algorithmic aspects of many problem-solving methods are increasingly “hidden” in software, a fundamental understanding of the relationship between the attributes of a differential equation and the nature of its solution is critical; for few things are as dangerous as an engineer who places complete faith in the output of a computer.

This point may be best represented in the language of educational objectives. Perhaps the most common is due to Bloom [7], which categorizes cognitive processes in a hierarchical manner. From the lowest to highest process there are: knowledge, comprehension, application, analysis, synthesis, and evaluation. Despite the label of

“engineering analysis” many homework problems given to students fall within the application process; that is, they are asked to apply a particular solution or analysis method to a given problem. Then, through repeated exposure to a subject on the application level, it is hoped that most students develop the ability (inductively through experience) to become competent at the higher levels, at which point higher-level synthesis or evaluation problems may be addressed.

With the application level being more and more automated, an increased focus in courses on the higher cognitive levels is necessary for the students to remain competent. I cannot argue that being able to “do” problems is not a necessary skill, and it is one that certainly has not been removed from this book. However, focusing on higher-level cognitive processes is what is going to serve students best. At a minimum, it will allow them to be distinguishable from a computer, which is also able to solve differential equations [27, 55]. By combining the mathematics and the application in the same course, the full range of the theoretical mathematics can be exercised through the engineering applications for which the students will ultimately be accountable.

The second facet is pedagogical. There are several nonstandard features of the content and presentation in this book that should be highlighted. First, there is an abundance of detailed examples. These are present, not to serve as a template from which students can copy the procedure to solve a problem, but rather a recognition of the fact that, although traditionally mathematics and related application fields are taught in a deductive manner, *inductive learning* actually “promotes deeper learning and longer retention of information” [15, 16, 33]. Thus, one way to consider this abundance of examples is that they replace, to some extent, the more direct application-oriented homework problems. Second, material is sometimes covered or named in a nonstandard manner purely to promote a deeper understanding of the ultimate result, but which otherwise does not directly help one “use” the result or is otherwise nonstandard. Examples of this are found throughout the text. A superficial example would be naming the procedure normally referred to as “integrating factors” for first-order equations “variation of parameters” because it shares a common derivation with that method as typically applied to higher-order equations. A deeper example would be in the study of frequency response methods for feedback control, where emphasis is placed on the fact that what is plotted in Bode plots relates to the harmonically forced steady-state solution of the system, when the usual use of the plot for stability under unity feedback is essentially unrelated to that. Finally, an example of including a whole nonstandard section is related to Taylor series methods for numerical methods. It is included purely as a setup for the Runge–Kutta method to facilitate developing a deeper understanding by the students. This is particularly important in such a case. When the end result is just a formula to be used, without the proper development, many students would be inclined perhaps simply to be content to “use” the formula, in which case the more modern approach would be simply to bring the `ode45()` function in MATLAB® to the attention of the students.

The third facet is that this text provides a means for a streamlined and efficient treatment of material normally covered in three courses. In the author’s program it resulted in combining three courses into two courses with little lost in terms of

content coverage. With the ever-broadening scope of engineering programs to include more, for example, biological sciences and design content, this would provide a means to allocate credit hours to such content without overly substantially cutting into the traditional engineering science material.

The fourth facet relates to the motivation engineering students have for studying mathematics. Ultimately engineering students study mathematics in order to be able to solve problems that are of importance to them. Although it is certainly legitimate for engineering students to have courses solely focused on the mathematics followed by the applications, it has been my experience that engineering students approach the mathematical subjects with much greater interest and enthusiasm when they have an application immediately at hand. Assessment from the sequence of courses I teach verifies this conclusion.

Content

This book covers what is normally covered in undergraduate engineering differential equations, vibrations, and controls courses. Less emphasis is placed on “recipes” or enumerated “procedures” to solve problems than is usual, although such content is not completely missing. There are plenty of problems that ask the student to simply solve some differential equations, however, quite a few of them are, for the reasons outlined above, deeper.

In addition to the combination of subjects unified by the content of the book, there are a couple of additional unique features related to content. The final chapter on nonlinear systems is perhaps longer than what is typically covered in engineering courses. Also, in the appendix there are many computer programs that were used to solve the example problems. These are presented in both the C programming language as well as in FORTRAN. The former is included because it is still widely used. The latter is, perhaps somewhat uniquely, still used in the aerospace industry but, more important, is fairly transparent in syntax, so that a student who is not proficient in programming can still easily determine what the program is doing.

It is important to note that the chapters are not of approximately uniform length. This is particularly important for an instructor making a course syllabus from the table of contents to note.

A Web page has been created for this book that contains:

- Some media content such as movies illustrating problem solutions that are amenable to such a presentation
- Source code for computer programs
- Additional exercises
- Errata

The URL is: <http://controls.ame.nd.edu/engdiffreq/>

Prerequisites

The student is assumed to have a good background in calculus (at least through multivariable calculus) and linear algebra. A dynamics course would be useful, but the basic mechanics from the typical undergraduate engineering physics sequence seems to suffice. A basic exposure to circuit analysis along the lines of the content typical in introductory physics courses would also be helpful. Finally, a good introduction to computer programming would be very useful, but not necessarily required.

Chapter Dependencies

The book is organized in what I consider the most logical order for a fundamental treatment of the subject matter. Even if a chapter does not explicitly depend on a previous one, the general progression of understanding and sophistication that would be developed when the chapters are covered in order was carefully considered.

However, curricular realities may prevent covering the chapters in order. Although it is not ideal, it would be possible to treat some of the material out of order. Specifically, the order of the following chapters may be altered without an extreme disruption in the logical flow of the material.

- Chapter 5 considers variable-coefficient ordinary differential equations. The method used, assuming a power series, is sufficiently different from the methods that precede the chapter that it could really be considered at any point.
- Chapters 8 through 10 cover Laplace transforms and control applications. It would be possible to treat these chapters as an independent unit.
- Chapter 11 considers the simplest linear partial differential equations using the separation of variables method. Hence, as long as Chapter 3 or the equivalent has been covered, it should be possible to cover this material.
- Chapter 12 considers numerical methods, and hence really only requires an understanding of Taylor series.

In the text, these chapters do occasionally refer back to earlier chapters, however, the dependence is typically one of pedagogy, rather than of theoretical necessity. These references could typically be treated in a lecture with a relatively quick aside. In my own case, for example, because of the structure of our curriculum, I cover partial differential equations and numerical methods in the first semester of the two-semester sequence.

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And now on to business.

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