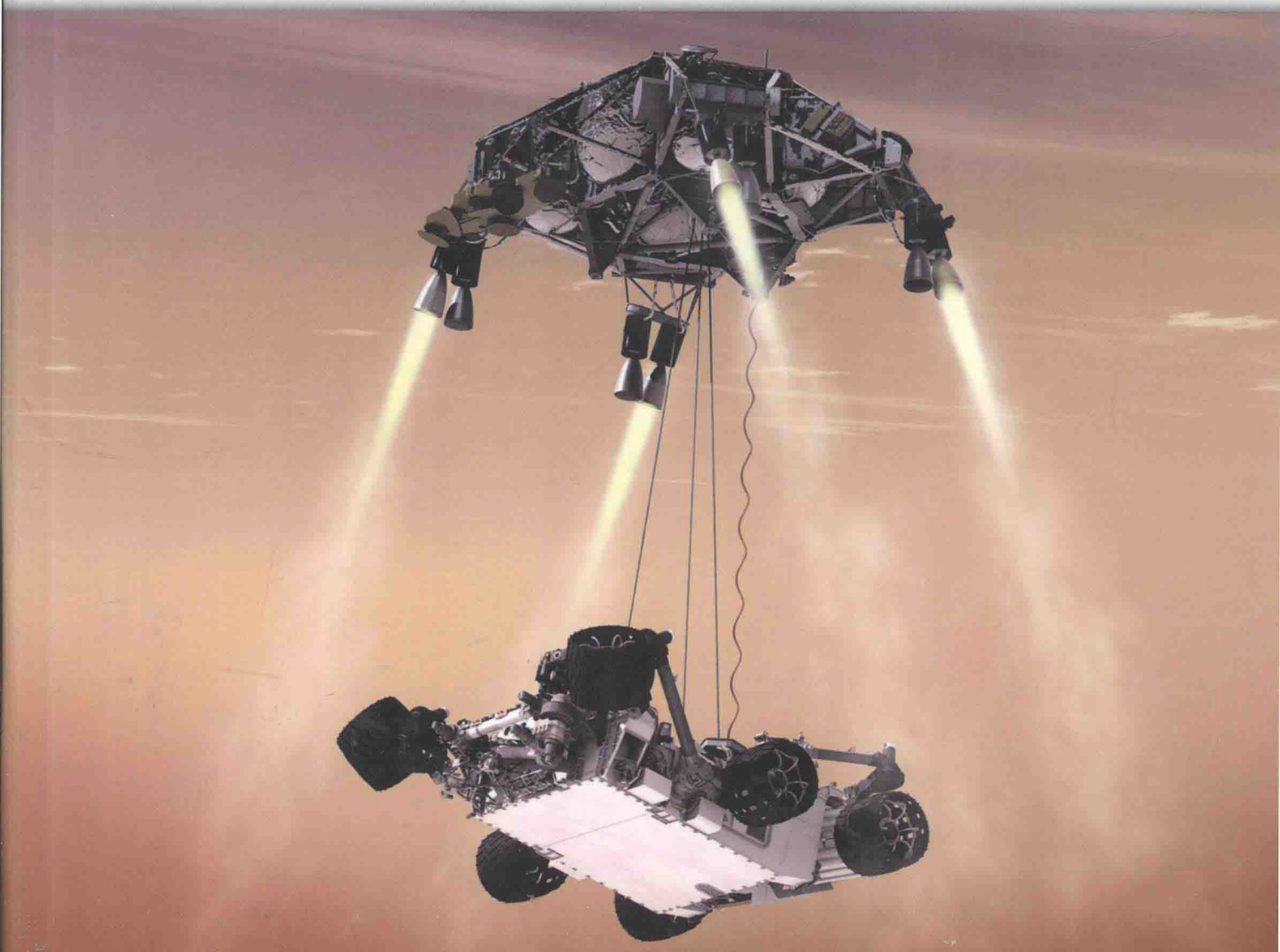
THIRD EDITION

SYSTEM Dynamics



William Palm III

System Dynamics

Third Edition

William J. Palm III
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SYSTEM DYNAMICS, THIRD EDITION

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Table 2.3.2 Solution forms for a constant input.

Equation	Solution form
First order: $\dot{x} + ax = b \quad a \neq 0$	$x(t) = \dfrac{b}{a} + Ce^{-at}$
Second order: $\ddot{x} + a\dot{x} + bx = c \quad b \neq 0$	
1. $(a^2 > 4b)$ distinct, real roots: s_1, s_2	$x(t) = C_1 e^{s_1 t} + C_2 e^{s_2 t} + \dfrac{c}{b}$
2. $(a^2 = 4b)$ repeated, real roots: s_1, s_1	$x(t) = (C_1 + tC_2)e^{s_1 t} + \dfrac{c}{b}$
3. $(a = 0, b > 0)$ imaginary roots: $s = \pm j\omega$, $\omega = \sqrt{b}$	$x(t) = C_1 \sin \omega t + C_2 \cos \omega t + \dfrac{c}{b}$
4. $(a \neq 0, a^2 < 4b)$ complex roots: $s = \sigma \pm j\omega$, $\sigma = -a/2, \omega = \sqrt{4b - a^2}/2$	$x(t) = e^{\sigma t}(C_1 \sin \omega t + C_2 \cos \omega t) + \dfrac{c}{b}$

Table 2.2.1 Table of Laplace transform pairs.

$X(s)$	$x(t), t \geq 0$
1. 1	$\delta(t)$, unit impulse
2. $\dfrac{1}{s}$	$u_s(t)$, unit step
3. $\dfrac{c}{s}$	constant, c
4. $\dfrac{e^{-sD}}{s}$	$u_s(t - D)$, shifted unit step
5. $\dfrac{n!}{s^{n+1}}$	t^n
6. $\dfrac{1}{s + a}$	e^{-at}
7. $\dfrac{1}{(s + a)^n}$	$\dfrac{1}{(n-1)!} t^{n-1} e^{-at}$
8. $\dfrac{b}{s^2 + b^2}$	$\sin bt$
9. $\dfrac{s}{s^2 + b^2}$	$\cos bt$
10. $\dfrac{b}{(s + a)^2 + b^2}$	$e^{-at} \sin bt$
11. $\dfrac{s + a}{(s + a)^2 + b^2}$	$e^{-at} \cos bt$
12. $\dfrac{a}{s(s + a)}$	$1 - e^{-at}$
13. $\dfrac{1}{(s + a)(s + b)}$	$\dfrac{1}{b - a}\left(e^{-at} - e^{-bt}\right)$
14. $\dfrac{s + p}{(s + a)(s + b)}$	$\dfrac{1}{b - a}\left[(p - a)e^{-at} - (p - b)e^{-bt}\right]$
15. $\dfrac{1}{(s + a)(s + b)(s + c)}$	$\dfrac{e^{-at}}{(b - a)(c - a)} + \dfrac{e^{-bt}}{(c - b)(a - b)} + \dfrac{e^{-ct}}{(a - c)(b - c)}$
16. $\dfrac{s + p}{(s + a)(s + b)(s + c)}$	$\dfrac{(p - a)e^{-at}}{(b - a)(c - a)} + \dfrac{(p - b)e^{-bt}}{(c - b)(a - b)} + \dfrac{(p - c)e^{-ct}}{(a - c)(b - c)}$

Table 8.1.1 Free, step, and ramp response of $\tau\dot{y} + y = r(t)$.

Free response $[r(t) = 0]$

$y(t) = y(0)e^{-t/\tau}$

$y(\tau) \approx 0.37y(0)$

$y(4\tau) \approx 0.02y(0)$

Step response $[r(t) = Ru_s(t), y(0) = 0]$

$y(t) = R(1 - e^{-t/\tau})$

$y(\infty) = y_{ss} = R$

$y(\tau) \approx 0.63y_{ss}$

$y(4\tau) \approx 0.98y_{ss}$

Ramp response $[r(t) = mt, y(0) = 0]$

$y(t) = m(t - \tau + \tau e^{-t/\tau})$

Table 2.1.2 The exponential function.

Taylor series

$$e^x = 1 + x + \frac{x^2}{2} + \frac{x^3}{6} + \cdots + \frac{x^n}{n!} + \cdots$$

Euler's identities

$e^{j\theta} = \cos\theta + j \sin\theta$

$e^{-j\theta} = \cos\theta - j \sin\theta$

Limits

$\lim_{x \to \infty} xe^{-x} = 0$ if x is real.

$\lim_{t \to \infty} e^{-st} = 0$ if the real part of s is positive.

If a is real and positive,

$e^{-at} < 0.02$ if $t > 4/a$.

$e^{-at} < 0.01$ if $t > 5/a$.

The *time constant* is $\tau = 1/a$.

Table 8.3.1 Unit step response of a stable second-order model.

Model: $m\ddot{x} + c\dot{x} + kx = u_s(t)$

Initial conditions: $x(0) = \dot{x}(0) = 0$

Characteristic roots: $s = \dfrac{-c \pm \sqrt{c^2 - 4mk}}{2m} = -r_1, -r_2$

1. Overdamped case ($\zeta > 1$): distinct, real roots: $r_1 \neq r_2$

$$x(t) = A_1 e^{-r_1 t} + A_2 e^{-r_2 t} + \frac{1}{k} = \frac{1}{k}\left(\frac{r_2}{r_1 - r_2} e^{-r_1 t} - \frac{r_1}{r_1 - r_2} e^{-r_2 t} + 1\right)$$

2. Critically damped case ($\zeta = 1$): repeated, real roots: $r_1 = r_2$

$$x(t) = (A_1 + A_2 t) e^{-r_1 t} + \frac{1}{k} = \frac{1}{k}[(-r_1 t - 1) e^{-r_1 t} + 1]$$

3. Underdamped case ($0 \leq \zeta < 1$): complex roots: $s = -\zeta\omega_n \pm j\omega_n\sqrt{1 - \zeta^2}$

$$x(t) = Be^{-t/\tau} \sin\left(\omega_n\sqrt{1 - \zeta^2}\, t + \phi\right) + \frac{1}{k}$$

$$= \frac{1}{k}\left[\frac{1}{\sqrt{1 - \zeta^2}} e^{-\zeta\omega_n t} \sin\left(\omega_n\sqrt{1 - \zeta^2}\, t + \phi\right) + 1\right]$$

$$\phi = \tan^{-1}\left(\frac{\sqrt{1 - \zeta^2}}{\zeta}\right) + \pi \quad \text{(third quadrant)}$$

Time constant: $\tau = 1/\zeta\omega_n$

Table 10.5.3 Routh-Hurwitz stability conditions.

1. **Second-Order:** $a_2 s^2 + a_1 s + a_0 = 0$
   Stable if and only if a_2, a_1, and a_0 all have the same sign.
2. **Third-Order:** $a_3 s^3 + a_2 s^2 + a_1 s + a_0 = 0$
   Assuming $a_3 > 0$, stable if and only if a_2, a_1, and a_0 are all positive and $a_2 a_1 > a_3 a_0$.
3. **Fourth-Order:** $a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0 = 0$
   Assuming $a_4 > 0$, stable if and only if a_3, a_2, a_1, and a_0 are all positive, $a_2 a_3 > a_1 a_4$, and

$$a_1(a_2 a_3 - a_1 a_4) - a_0 a_3^2 > 0$$

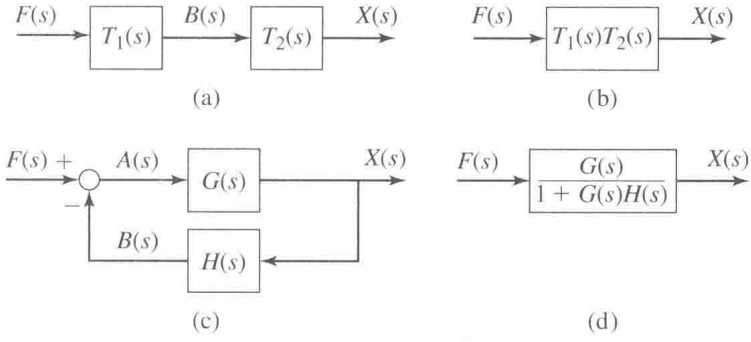

Figure 5.1.4 (a) and (b) Simplification of series blocks. (c) and (d) Simplification of a feedback loop.

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To my wife, Mary Louise; and to my children, Aileene, Bill, and Andrew.

PREFACE

System dynamics deals with mathematical modeling and analysis of devices and processes for the purpose of understanding their time-dependent behavior. While other subjects, such as Newtonian dynamics and electrical circuit theory, also deal with time-dependent behavior, system dynamics emphasizes methods for handling applications containing multiple types of components and processes such as electromechanical devices, electrohydraulic devices, and fluid-thermal processes. Because the goal of system dynamics is to understand the time-dependent behavior of a system of interconnected devices and processes as a whole, the modeling and analysis methods used in system dynamics must be properly selected to reveal how the connections between the system elements affect its overall behavior. Because systems of interconnected elements often require a control system to work properly, control system design is a major application area in system dynamics.

TEXT PHILOSOPHY

This text is an introduction to system dynamics and is suitable for such courses commonly found in engineering curricula. It is assumed that the student has a background in elementary differential and integral calculus and college physics (dynamics, mechanics of materials, thermodynamics, and electrical circuits). A previous course in differential equations is desirable but not necessary, as the required material on differential equations, as well as Laplace transforms and matrices, is developed in the text.

The decision to write a textbook often comes from the author's desire to improve on available texts. The decisions as to what topics to include and what approach to take emerge from the author's teaching experiences that give insight as to what is needed for students to master the subject. This text is based on the author's forty-one years of experience in teaching system dynamics.

This experience shows that typical students in a system dynamics course are not yet comfortable with applying the relevant concepts from earlier courses in dynamics and differential equations. Therefore, this text reviews and reinforces these important topics early on. Students often lack sufficient physical insight to relate the mathematical results to applications. The text therefore uses everyday illustrations of system dynamics to help students to understand the material and its relevance.

If laboratory sessions accompany the system dynamics course, many of the text's examples can be used as the basis for experiments. The text is also a suitable reference on hardware and on parameter estimation methods.

MATLAB® AND SIMULINK®[1]

MATLAB and Simulink are used to illustrate how modern computer tools can be applied in system dynamics.[2] MATLAB was chosen because it is the most widely

[1]MATLAB and Simulink are registered trademarks of The MathWorks, Inc.

[2]The programs in this text will work with the following software versions, or higher versions: Version 8 of MATLAB, Version 8 of Simulink, and Version 9.4 of the Control Systems Toolbox.

used program in system dynamics courses and by practitioners in the field. Simulink, which is based on MATLAB and uses a diagram-based interface, is increasing in popularity because of its power and ease of use. In fact, students convinced the author to use Simulink after they discovered it on their own and learned how easy it is to use! It provides a useful and motivational tool.

It is, however, not necessary to cover MATLAB or Simulink in order to use the text, and it is shown how to do this later in the Preface.

TEXT OVERVIEW

Chapter 1 introduces the basic terminology of system dynamics, covers commonly used functions, and reviews the two systems of units used in the text: British Engineering (FPS) units and SI units. These are the unit systems most commonly used in system dynamics applications. The examples and homework problems employ both sets of units so that the student will become comfortable with both. Chapter 1 also introduces methods for parameter estimation. These methods are particularly useful for obtaining spring constants and damping coefficients.

Chapter 2 develops the Laplace transform method for solving differential equations and applies it to equations having step, ramp, sine, impulse, and other types of forcing functions. It also introduces transfer function models.

Chapter 3 covers rigid-body dynamics, including planar motion.

Chapter 4 covers modeling of mechanical systems having stiffness and damping, and it applies the analytical methods developed in Chapter 2 to solve the models.

Chapter 5 develops block diagrams and the state-variable model, which is useful for certain analytical techniques as well as for numerical solutions. The optional sections of this chapter introduce Simulink, which is based on block diagram descriptions, and apply the chapter's concepts using MATLAB.

Chapter 6 treats modeling of electric circuits, operational amplifiers, electromechanical devices, sensors, and electroacoustic devices. It also discusses how motor parameters can be obtained, and it shows how to analyze motor performance.

Part I of Chapter 7 covers fluid systems. Part II covers thermal systems. These two parts are independent of each other. A background in fluid mechanics or heat transfer is not required to understand this chapter, but students should have had elementary thermodynamics before covering the material on pneumatic systems in Section 7.5.

Chapters 8 and 9 cover analysis methods in the time domain and the frequency domain, respectively.

Chapter 8 integrates the modeling and analysis techniques of earlier chapters with an emphasis on understanding system behavior in the time domain, using step, ramp, and impulse functions primarily. The chapter covers step response specifications such as maximum overshoot, peak time, delay time, rise time, and settling time.

Chapter 9 demonstrates the usefulness of the transfer function for understanding and analyzing a system's frequency response. It introduces Bode plots and shows how they are sketched and interpreted to obtain information about time constants, resonant frequencies, and bandwidth.

Chapters 10, 11, and 12 deal with a major application of system dynamics, namely, control systems. Chapter 10 is an introduction to feedback control systems, including the PID control algorithm applied to first- and second-order plants. Chapter 11 deals with control systems in more depth and includes design methods based on the root locus plot and practical topics such as compensation, controller tuning, actuator saturation,

reset wind-up, and state-variable feedback, with emphasis on motion control systems. Chapter 12 covers series compensation methods and design with the Bode plot.

Chapter 13 covers another major application area, vibrations. Important practical applications covered are vibration isolators, vibration absorbers, modes, and suspension system design.

ALTERNATIVE COURSES IN SYSTEM DYNAMICS

The choice of topics depends partly on the desired course emphasis and partly on whether the course is a quarter or semester course.

Some courses omit fluid and thermal systems, which are covered in Chapter 7. This chapter can be skipped if necessary because only some examples in the remaining chapters, and not the theory and methods, depend on it.

In the author's opinion, a basic semester course in system dynamics should include most of the material in Chapters 1 through 6, and Chapters 9 and 10. At the author's institution, the system dynamics course is a junior course required for mechanical engineering majors, who have already had courses in dynamics and differential equations. It covers Chapters 1 through 10, with brief coverage of Chapter 7 and Chapter 8, and with some MATLAB and Simulink sections omitted. This optional material is then covered in a senior elective course in control systems, which also covers Chapters 11 and 12.

The text is flexible enough to support a variety of courses. The sections dealing with MATLAB and Simulink are at the end of the chapters and may be omitted. If students are familiar with Laplace transform methods and linear differential equations, Chapter 2 may be covered quickly. If students are comfortable with rigid body planar motion, Chapter 3 may be used for a quick review.

GLOSSARY AND APPENDICES

There is a glossary containing the definitions of important terms, five appendices, and an index. Appendices D and E are on the text website.

Appendix A is a collection of tables of MATLAB commands and functions, organized by category. The purpose of each command and function is briefly described in the tables.

Appendix B is a brief summary of the Fourier series, which is used to represent a periodic function as a series consisting of a constant plus a sum of sine terms and cosine terms. It provides the background for some applications of the material in Chapter 9.

Appendix C shows how to use MATLAB to fit models to scattered data using the least-squares method.

Appendix D is a self-contained introduction to MATLAB, and it should be read first by anyone unfamiliar with MATLAB if they intend to cover the MATLAB and Simulink sections. It also provides a useful review for those students having prior experience with MATLAB.

Appendix E covers numerical methods, such as the Runge-Kutta algorithms, that form the basis for the differential equation solvers of MATLAB. It is not necessary to master this material to use the MATLAB solvers, but the appendix provides a background for the interested reader.

Answers to selected homework problems are given following Appendix C.

CHAPTER FORMAT

The format of each chapter follows the same pattern, which is

1. Chapter outline
2. Chapter objectives
3. Chapter sections
4. MATLAB sections (in most chapters)
5. Simulink section (in most chapters)
6. Chapter review
7. References
8. Problems

This structure has been designed partly to accommodate those courses that do not cover MATLAB and/or Simulink, by placing the optional MATLAB and Simulink material at the end of the chapter. Chapter problems are arranged according to the chapter section whose concepts they illustrate. All problems requiring MATLAB and/or Simulink have thus been placed in separate, identifiable groups.

OPTIONAL TOPICS

In addition to the optional chapters (11, 12, and 13), some chapters have sections dealing with material other than MATLAB and Simulink that can be omitted without affecting understanding of the core material in subsequent chapters. All such optional material has been placed in sections near the end of the chapter. This optional material includes:

1. Function discovery, parameter estimation, and system identification techniques (Sections 1.4, 8.4, and 9.5)
2. General theory of partial fraction expansion (Section 2.5)
3. Impulse response (Sections 3.6 and 4.6)
4. Motor performance (Section 6.5)
5. Sensors and electroacoustic devices (Section 6.6)

DISTINGUISHING FEATURES

The following are considered to be the major distinguishing features of the text.

1. **MATLAB.** Stand-alone sections in most chapters provide concise summaries and illustrations of MATLAB features relevant to the chapter's topics.
2. **Simulink.** Stand-alone sections in Chapters 5 through 12 provide extensive Simulink coverage not found in most system dynamics texts.
3. **Parameter estimation.** Coverage of function discovery, parameter estimation, and system identification techniques is given in Sections 1.4, 8.4, and 9.5. Students are uneasy when they are given parameter values such as spring stiffness and damping coefficients in examples and homework problems, because they want to know how they will obtain such values in practice. These sections show how this is done.
4. **Motor performance evaluation.** Section 6.5 discusses the effect of motor dynamics on practical considerations for motor and amplifier applications, such as motion profiles and the required peak and rated continuous current and torque,

and maximum required voltage and motor speed. These considerations offer excellent examples of practical applications of system dynamics but are not discussed in most system dynamics texts.

5. **System dynamics in everyday life.** Commonly found illustrations of system dynamics are important for helping students to understand the material and its relevance. This text provides examples drawn from objects encountered in everyday life. These examples include a storm door closer, fluid flow from a bottle, shock absorbers and suspension springs, motors, systems with gearing, chain drives, belt drives, a backhoe, a water tower, and cooling of liquid in a cup.
6. **Theme applications.** Two common applications provide themes for examples and problems throughout the text. These are motion control systems, such as a conveyor system and a robot arm, and vehicle suspension systems.

WEBSITE

The publisher maintains a website for this text at www.mhhe.com/palm. An online instructors manual is available at this site. It contains solutions to the problems and other pedagogical aids, and is accessible to instructors who have adopted the text for their course. The site is also home to Appendices D and E.

ELECTRONIC TEXTBOOK OPTION

This text is offered through CourseSmart for both instructors and students. CourseSmart is an online resource where students can purchase access to this and other McGraw-Hill textbooks in a digital format. Through their browsers, students can access the complete text online for almost half the cost of a traditional text. Purchasing the eTextbook also allows students to take advantage of CourseSmart's web tools for learning, which include full text search, notes and highlighting, and email tools for sharing notes among classmates. To learn more about CourseSmart options, contact your sales representative or visit www.CourseSmart.com.

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The University of Rhode Island provided an atmosphere that encourages teaching excellence, course development, and writing, and for that I am grateful.

Finally, I thank my wife, Mary Louise; and my children, Aileene, Bill, and Andrew, for their support, patience, and understanding.

William J. Palm III
Kingston, Rhode Island
December 2012

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ABOUT THE AUTHOR

William J. Palm III is Professor of Mechanical, Industrial, and Systems Engineering at the University of Rhode Island. In 1966 he received a B.S. from Loyola College in Baltimore, and in 1971 a Ph.D. in Mechanical Engineering and Astronautical Sciences from Northwestern University in Evanston, Illinois.

During his forty-two years as a faculty member, he has taught nineteen courses. One of these is a junior system dynamics course, which he developed. He has authored nine textbooks dealing with modeling and simulation, system dynamics, control systems, vibrations, and MATLAB. These include *Introduction to MATLAB for Engineers*, third edition (McGraw-Hill, 2011), *A Concise Introduction to MATLAB* (McGraw-Hill, 2008), and *Differential Equations for Engineers and Scientists* (McGraw-Hill, 2013) with Yunus Çengel. He wrote a chapter on control systems in the *Mechanical Engineers' Handbook*, fourth edition, (M. Kutz, ed., Wiley, 2014), and was a special contributor to the fifth editions of *Statics* and *Dynamics,* both by J. L. Meriam and L. G. Kraige (Wiley, 2002).

Professor Palm's research and industrial experience are in control systems, robotics, vibrations, and system modeling. He was the Director of the Robotics Research Center at the University of Rhode Island from 1985 to 1993, and is the co-holder of a patent for a robot hand. He served as Acting Department Chair from 2002 to 2003. His industrial experience is in automated manufacturing; modeling and simulation of naval systems, including underwater vehicles and tracking systems; and design of control systems for underwater vehicle engine test facilities.

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CHAPTER OBJECTIVES

When you have finished this chapter, you should be able to

1. Define the basic terminology of system dynamics.
2. Apply the basic steps used for engineering problem solving.
3. Apply the necessary steps for developing a computer solution.
4. Use units in both the FPS and the SI systems.
5. Develop linear models from given algebraic expressions.
6. Identify the algebraic form and obtain the coefficient values of a model, given a set of data containing little scatter.

This chapter introduces the basic terminology of system dynamics, which includes the notions of *system, static* and *dynamic elements, input,* and *output*. Because we will use both the foot-pound-second (FPS) and the metric (SI) systems of units, the chapter introduces these two systems. Developing mathematical models of input-output relations is essential to the applications of system dynamics. Therefore, we begin our study by introducing some basic methods for developing algebraic models of static elements. We show how to use the methods of function identification and parameter estimation to develop models from data, and how to fit models to data that has little scatter.

Although Section 1.4 provides the foundation for understanding how to develop models of static elements, coverage of this section is not required to understand the methods of the remaining chapters, because the appropriate models will be supplied in the examples and chapter problems and thus need not be derived. ■

1.1 INTRODUCTION TO SYSTEM DYNAMICS

This text is an introduction to system dynamics. We presume that the reader has some background in calculus (specifically, differentiation and integration of functions of a single variable) and in physics (specifically, free body diagrams, Newton's laws of motion for a particle, and elementary dc electricity). In this section we establish some basic terminology and discuss the meaning of the topic "system dynamics," its methodology, and its applications.

1.1.1 SYSTEMS

The meaning of the term *system* has become somewhat vague because of overuse. The original meaning of the term is a *combination of elements intended to act together to accomplish an objective*. For example, a link in a bicycle chain is usually not considered to be a system. However, when it is used with other links to form a chain, it becomes part of a system. The objective for the chain is to transmit force. When the chain is combined with gears, wheels, crank, handlebars, and other elements, it becomes part of a larger system whose purpose is to transport a person.

The system designer must focus on how all the elements act together to achieve the system's intended purpose, keeping in mind other important factors such as safety, cost, and so forth. Thus, the system designer often cannot afford to spend time on the details of designing the system elements. For example, our bicycle designer might not have time to study the metallurgy involved with link design; that is the role of the chain designer. All the systems designer needs to know about the chain is its strength, its weight, and its cost, because these are the factors that influence its role in the system.

With this "systems point of view," we focus on how *connections* between the elements influence the *overall* behavior of the system. This means that sometimes we must accept a less-detailed description of the operation of the individual elements to achieve an overall understanding of the system's performance.

Figure 1.1.1 illustrates a liquid-filled tank with a volume inflow f (say in cubic feet per second). The liquid height is h (say in feet). We see in Example 1.4.2 that the functional relationship between f and h has the form $f = bh^m$, where b and m are constants. We would not call this a "system." However, if two tanks are connected as shown in Figure 1.1.2, this connection forms a "system." Each tank is a "subsystem"

Figure 1.1.1 The effect of liquid height h on the out flow rate f.

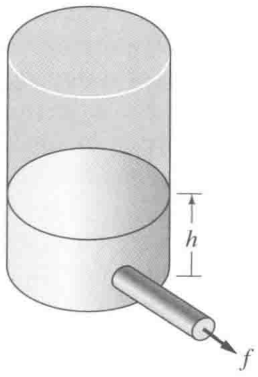
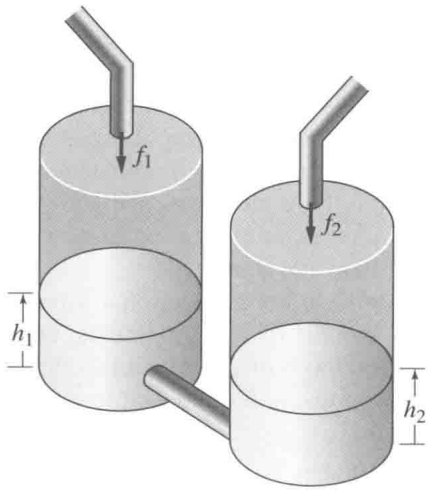


Figure 1.1.2 Two connected tanks.



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