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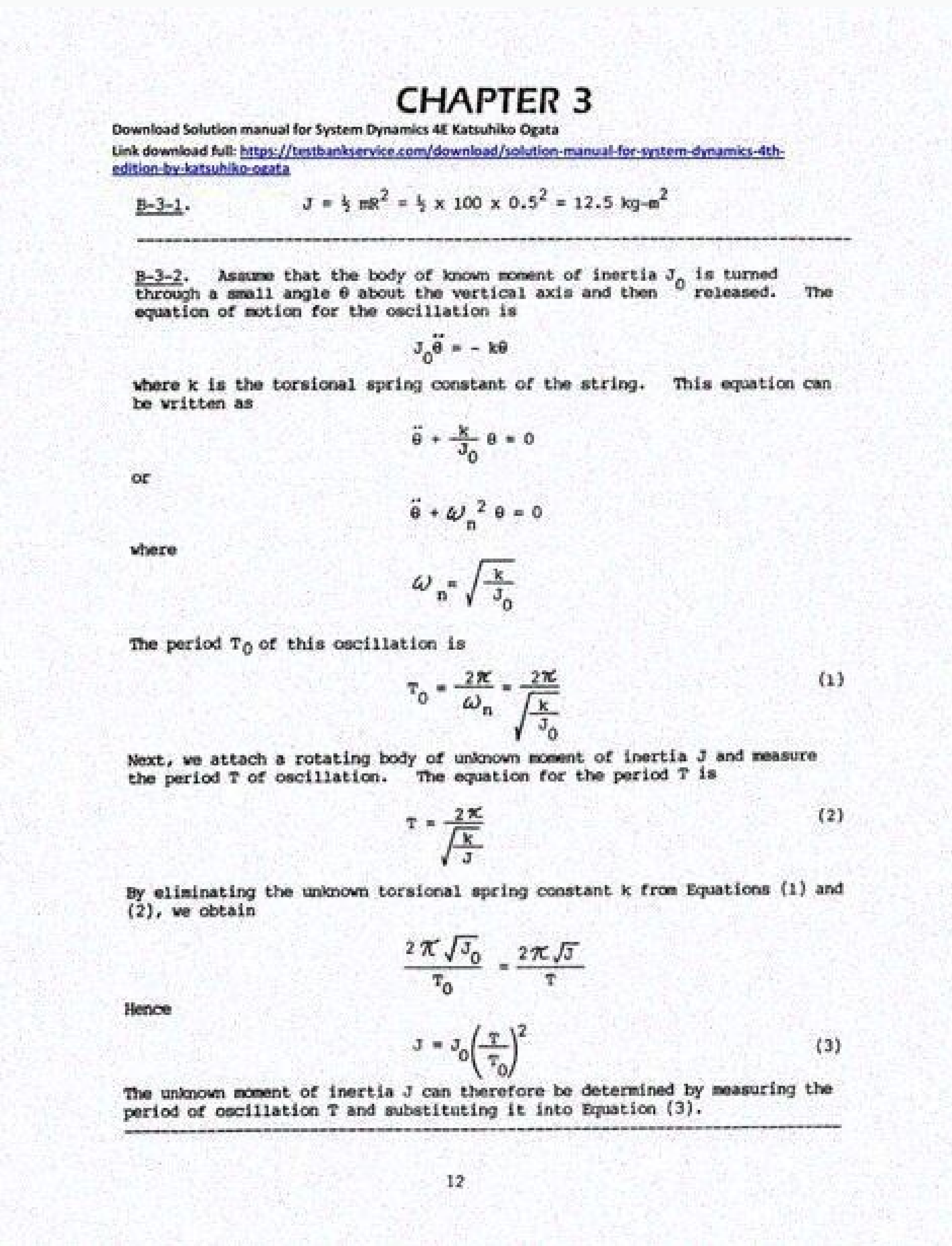

CHAPTER 3

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B-3-1. $J = \frac{1}{2} mR^2 = \frac{1}{2} \times 100 \times 0.5^2 = 12.5 \text{ kg-m}^2$

B-3-2. Assume that the body of known moment of inertia J_0 is turned through a small angle θ about the vertical axis and then released. The equation of motion for the oscillation is

$$J_0 \ddot{\theta} = -k\theta$$

where k is the torsional spring constant of the string. This equation can be written as

$$\ddot{\theta} + \frac{k}{J_0}\theta = 0$$

or

$$\ddot{\theta} + \omega_n^2 \theta = 0$$

where

$$\omega_n = \sqrt{\frac{k}{J_0}}$$

The period T_0 of this oscillation is

$$T_0 = \frac{2\pi}{\omega_n} = \frac{2\pi}{\sqrt{\frac{k}{J_0}}} \qquad (1)$$

Next, we attach a rotating body of unknown moment of inertia J and measure the period T of oscillation. The equation for the period T is

$$T = \frac{2\pi}{\sqrt{\frac{k}{J}}} \qquad (2)$$

By eliminating the unknown torsional spring constant k from Equations (1) and (2), we obtain

$$\frac{2\pi\sqrt{J_0}}{T_0} = \frac{2\pi\sqrt{J}}{T}$$

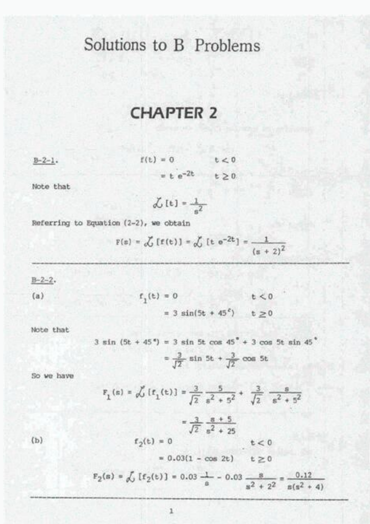
Hence

$$J = J_0\left(\frac{T}{T_0}\right)^2 \qquad (3)$$

The unknown moment of inertia J can therefore be determined by measuring the period of oscillation T and substituting it into Equation (3).

12

 1 Introduction to System Dynamics 1–1 INTRODUCTION System dynamics deals with the mathematical modeling of dynamic systems and response analyses of such systems with a view toward understanding the dynamic nature of each system and improving the system's performance.Response analyses are frequently made through computer simulations of dynamic systems. Because many physical systems involve various types of components,a wide variety of different types of dynamic systems will be examined in this book.The analysis and design methods presented can be applied to mechanical, electrical, pneumatic,and hydraulic systems,as well as nonengineering systems,such as eco- nomic systems and biological systems.It is important that the mechanical engineer- ing student be able to determine dynamic responses of such systems. We shall begin this chapter by defining several terms that must be understood in discussing system dynamics. Systems. A systemis a combination of components acting together to per- form a specific objective.A componentis a single functioning unit of a system.By no means limited to the realm of the physical phenomena,the concept of a system can be extended to abstract dynamic phenomena, such as those encountered in eco- nomics,transportation,population growth,and biology. From Chapter 1 of System Dynamics, Fourth Edition. Katsuhiko Ogata.



Solutions to B Problems

CHAPTER 2

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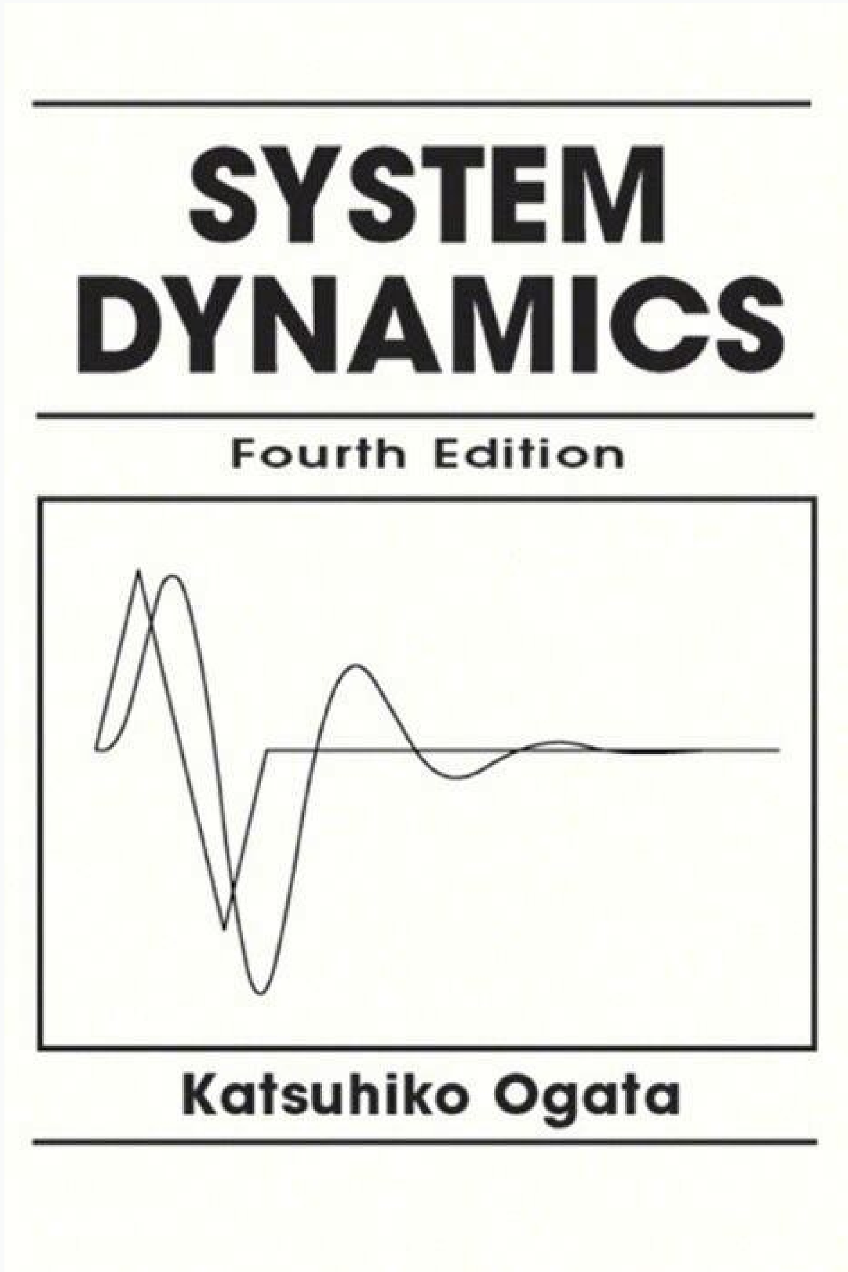

System dynamics model example.

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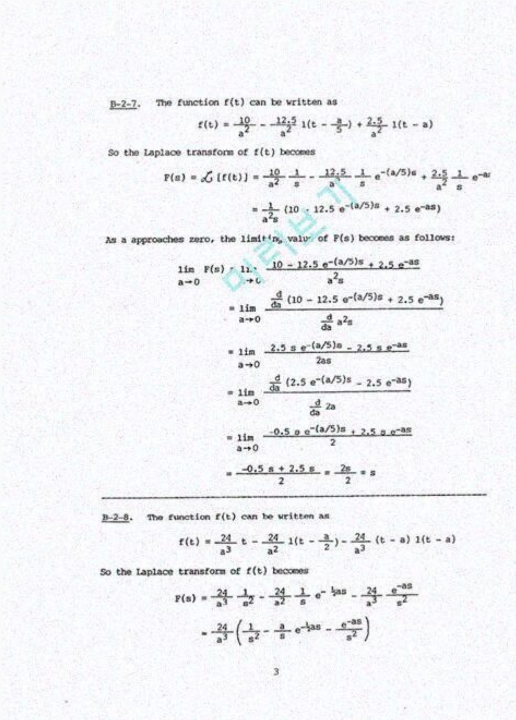
B-2-7. The function f(t) can be written as

$$f(t) = \frac{10}{a^2} - \frac{12.5}{a^2} 1(t - \frac{a}{5}) + \frac{2.5}{a^2} 1(t - a)$$

So the Laplace transform of f(t) becomes

$$F(s) = \mathcal{L}[f(t)] = \frac{10}{a^2}\frac{1}{s} - \frac{12.5}{a^2}\frac{1}{s}e^{-(a/5)s} + \frac{2.5}{a^2}\frac{1}{s}e^{-as}$$

$$= \frac{1}{a^2 s}(10 - 12.5 e^{-(a/5)s} + 2.5 e^{-as})$$

As a approaches zero, the limiting value of F(s) becomes as follows:

$$\lim_{a\to 0} F(s) = \lim_{a\to 0} \frac{10 - 12.5 e^{-(a/5)s} + 2.5 e^{-as}}{a^2 s}$$

$$= \lim_{a\to 0} \frac{\frac{d}{da}(10 - 12.5 e^{-(a/5)s} + 2.5 e^{-as})}{\frac{d}{da} a^2 s}$$

$$= \lim_{a\to 0} \frac{2.5 s e^{-(a/5)s} - 2.5 s e^{-as}}{2as}$$

$$= \lim_{a\to 0} \frac{\frac{d}{da}(2.5 e^{-(a/5)s} - 2.5 e^{-as})}{\frac{d}{da} 2a}$$

$$= \lim_{a\to 0} \frac{-0.5 s e^{-(a/5)s} + 2.5 s e^{-as}}{2}$$

$$= \frac{-0.5 s + 2.5 s}{2} = \frac{2s}{2} = s$$

B-2-8. The function f(t) can be written as

$$f(t) = \frac{24}{a^3} t - \frac{24}{a^2} 1(t - \frac{a}{2}) - \frac{24}{a^3}(t - a) 1(t - a)$$

So the Laplace transform of f(t) becomes

$$F(s) = \frac{24}{a^3}\frac{1}{s^2} - \frac{24}{a^2}\frac{1}{s}e^{-\frac{1}{2}as} - \frac{24}{a^3}\frac{e^{-as}}{s^2}$$

$$= \frac{24}{a^3}\left(\frac{1}{s^2} - \frac{a}{s}e^{-\frac{1}{2}as} - \frac{e^{-as}}{s^2}\right)$$

3

System dynamics model example.

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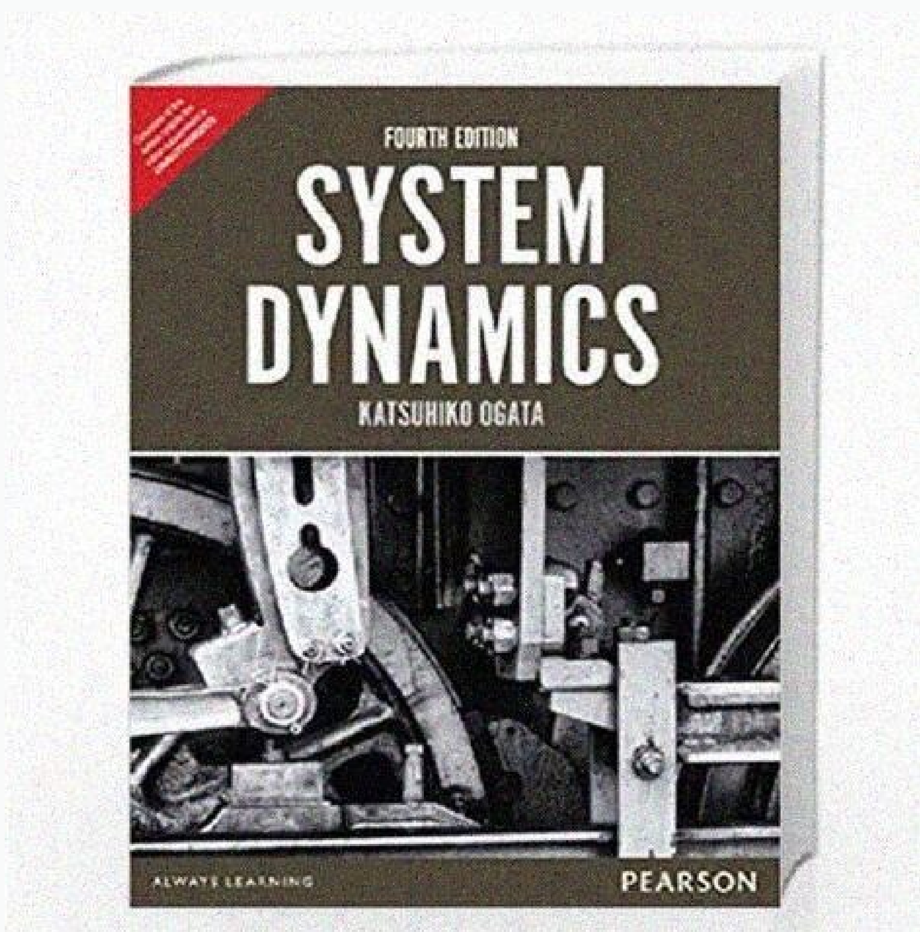

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A differential equation is called nonlinear if it is not linear.Two examples of nonlinear differential equations are d2x dx + x2 - 1 + x = 0 dt2 1 2 dt and d2x dx + + x + x3 = sin vt dt2 dt 2 Sec.

1–2 Mathematical Modeling of Dynamic Systems Linear systems and nonlinear systems. For linear systems,the equations that constitute the model are linear.In this book,we shall deal mostly with linear sys- tems that can be represented by linear,time-invariant ordinary differential equations. The most important property of linear systems is that the principle of superpo- sitionis applicable.This principle states that the response produced by simultaneous applications of two different forcing functions or inputs is the sum of two individual responses.Consequently,for linear systems,the response to several inputs can be calculated by dealing with one input at a time and then adding the results.As a result of superposition,complicated solutions to linear differential equations can be derived as a sum of simple solutions. In an experimental investigation of a dynamic system,if cause and effect are proportional,thereby implying that the principle of superposition holds,the system can be considered linear. Although physical relationships are often represented by linear equations,in many instances the actual relationships may not be quite linear. In fact, a careful study of physical systems reveals that so-called linear systems are actually linear only within limited operating ranges. For instance, many hydraulic systems and pneumatic systems involve nonlinear relationships among their variables,but they are frequently represented by linear equations within limited operating ranges. For nonlinear systems,the most important characteristic is that the principle of superposition is not applicable.In general,procedures for finding the solutions of problems involving such systems are extremely complicated.Because of the mathe- matical difficulty involved,it is frequently necessary to linearize a nonlinear system near the operating condition.Once a nonlinear system is approximated by a linear mathematical model,a number of linear techniques may be used for analysis and design purposes. Continuous-time systems and discrete-time systems. Continuous-time systems are systems in which the signals involved are continuous in time.These sys- tems may be described by differential equations. Discrete-time systems are systems in which one or more variables can change only at discrete instants of time.(These instants may specify the times at which some physical measurement is performed or the times at which the memory of a digital computer is read out.) Discrete-time systems that involve digital signals and,possi- bly,continuous-time signals as well may be described by difference equations after the appropriate discretization of the continuous-time signals. The materials presented in this text apply to continuous-time systems;discrete- time systems are not discussed. 1–2 MATHEMATICAL MODELING OF DYNAMIC SYSTEMS Mathematical modeling.

Mathematical modeling involves descriptions of important system characteristics by sets of equations.By applying physical laws to a specific system,it may be possible to develop a mathematical model that describes the dynamics of the system.Such a model may include unknown parameters,which 3 Introduction to System Dynamics Chap. 1 must then be evaluated through actual tests.Sometimes,however,the physical laws governing the behavior of a system are not completely defined,and formulating a mathematical model may be impossible.If so,an experimental modeling process can be used.In this process,the system is subjected to a set of known inputs,and its out- puts are measured.Then a mathematical model is derived from the input–output re- lationships obtained.

Simplicity of mathematical model versus accuracy of results of analysis. In attempting to build a mathematical model,a compromise must be made between the simplicity of the model and the accuracy of the results of the analysis.It is im- portant to note that the results obtained from the analysis are valid only to the ex- tent that the model approximates a given physical system.

In determining a reasonably simplified model,we must decide which physical variables and relationships are negligible and which are crucial to the accuracy of the model.To obtain a model in the form of linear differential equations,any dis- tributed parameters and nonlinearities that may be present in the physical system must be ignored.If the effects that these ignored properties have on the response are small,then the results of the analysis of a mathematical model and the results of the experimental study of the physical system will be in good agreement.Whether any particular features are important may be obvious in some cases, but may, in other instances,require physical insight and intuition.Experience is an important factor in this connection. Usually, in solving a new problem, it is desirable first to build a simplified model to obtain a general idea about the solution.Afterward,a more detailed math- ematical model can be built and used for a more complete analysis. Remarks on mathematical models. The engineer must always keep in mind that the model he or she is analyzing is an approximate mathematical descrip- tion of the physical system;it is not the physical system itself.In reality,no mathe- matical model can represent any physical component or system precisely. Approximations and assumptions are always involved.Such approximations and as- sumptions restrict the range of validity of the mathematical model.(The degree of approximation can be determined only by experiments.) So,in making a prediction about a system's performance,any approximations and assumptions involved in the model must be kept in mind.

Mathematical modeling procedure.

The procedure for obtaining a math- ematical model for a system can be summarized as follows: 1. Draw a schematic diagram of the system,and define variables. 2. Using physical laws, write equations for each component, combine them according to the system diagram,and obtain a mathematical model. 3. To verify the validity of the model, its predicted performance, obtained by solving the equations of the model, is compared with experimental results. (The question of the validity of any mathematical model can be answered only by experiment.) If the experimental results deviate from the prediction 4 Sec.

1–3 Analysis and Design of Dynamic Systems to a great extent,the model must be modified.A new model is then derived and a new prediction compared with experimental results.The process is re- peated until satisfactory agreement is obtained between the predictions and the experimental results. 1–3 ANALYSIS AND DESIGN OF DYNAMIC SYSTEMS This section briefly explains what is involved in the analysis and design of dynamic systems. Analysis. System analysis means the investigation, under specified condi- tions,of the performance of a system whose mathematical model is known. The first step in analyzing a dynamic system is to derive its mathematical model.Since any system is made up of components,analysis must start by developing a mathematical model for each component and combining all the models in order to build a model of the complete system.Once the latter model is obtained,the analysis may be formulated in such a way that system parameters in the model are varied to produce a number of solutions. The engineer then compares these solutions and interprets and applies the results of his or her analysis to the basic task. It should always be remembered that deriving a reasonable model for the complete system is the most important part of the entire analysis. Once such a model is available,various analytical and computer techniques can be used to ana- lyze it.The manner in which analysis is carried out is independent of the type of physical system involved—mechanical,electrical,hydraulic,and so on. Design. System designrefers to the process of finding a system that accom- plishes a given task.In general,the design procedure is not straightforward and will require trial and error. Synthesis. By synthesis,we mean the use of an explicit procedure to find a system that will perform in a specified way.Here the desired system characteristics are postulated at the outset,and then various mathematical techniques are used to synthesize a system having those characteristics.Generally,such a procedure is com- pletely mathematical from the start to the end of the design process. Basic approach to system design. The basic approach to the design of any dynamic system necessarily involves trial-and-error procedures.Theoretically,a synthesis of linear systems is possible, and the engineer can systematically deter- mine the components necessary to realize the system’s objective.In practice,howev- er,the system may be subject to many constraints or may be nonlinear;in such cases, no synthesis methods are currently applicable.Moreover,the features of the com- ponents may not be precisely known.Thus,trial-and-error techniques are almost al- ways needed. Design procedures. Frequently,the design of a system proceeds as follows: The engineer begins the design procedure knowing the specifications to be met and 5