Control System Engineering Principles and Design

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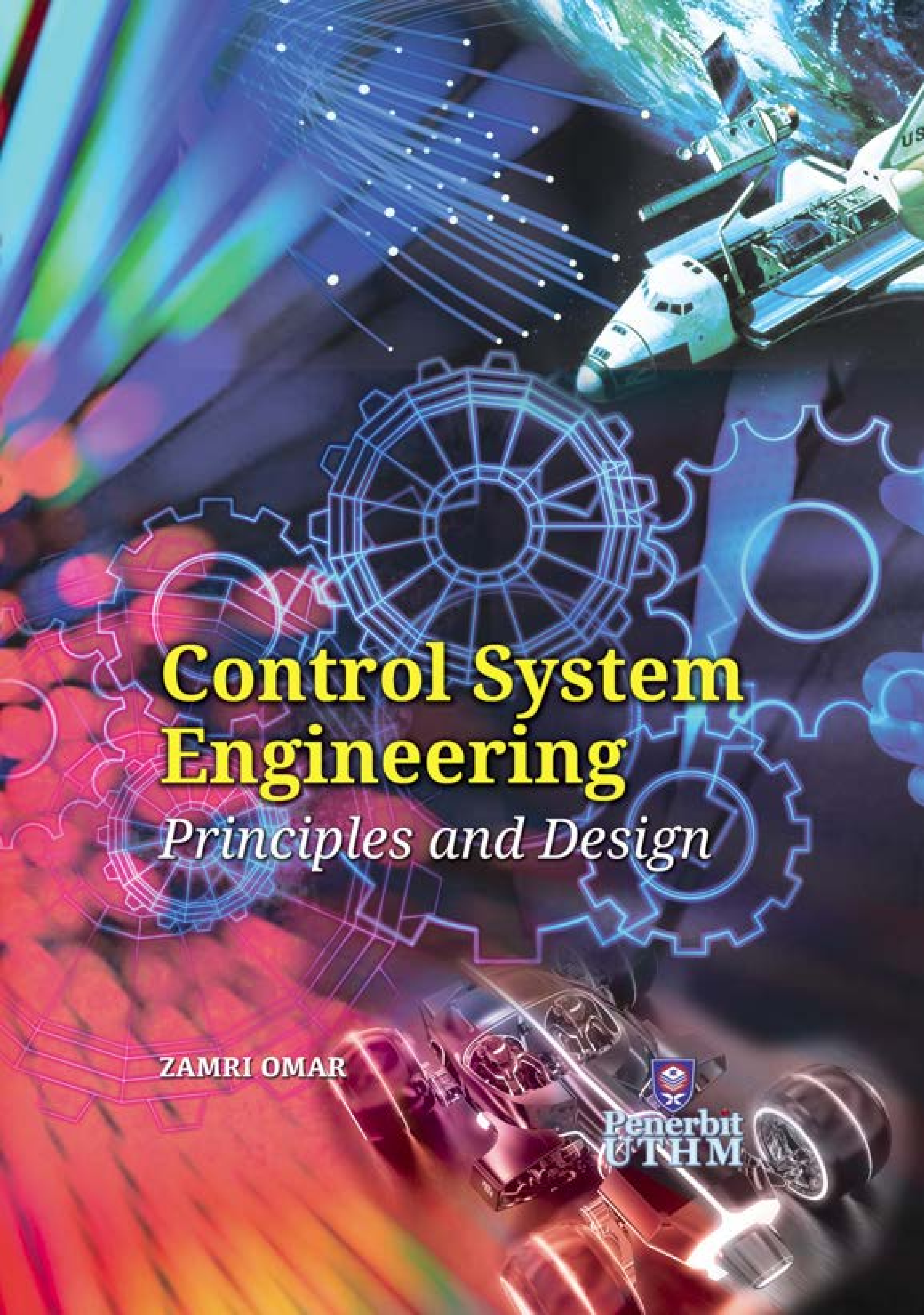
Abstract: The study of control system engineering is essential for mechanical, aerospace and electrical engineering students. This book presents an elementary treatment to the concept and design of control systems engineering. It is suitable to be used as a text for senior students pursuing diploma or bachelor degree, and as essential compact reference for postgraduate students. This book is also for anyone who desires to know the fundamental of control systems engineering.

Keywords: Dynamic, time, stability, Root Locus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2015

Perpustakaan Negara Malaysia Cataloguing—in—Publication Data

Zamri Omar
Control System Engineering: Principles and Design / ZAMRI OMAR
Includes index
Bibliography: pages 193
ISBN 978-967-0468-96-9
1. System engineering. 2. Automatic control. Title.
629.8

Published by:
Penerbit UTHM
Universiti Tun Hussein Onn Malaysia
86400 Parit Raja,
Batu Pahat, Johor
No. Tel: 07-453 7051 / 7454
No. Faks: 07-453 6145

Website: http://penerbit.uthm.edu.my
E-mail: pt@uthm.edu.my
http://e-bookstore.uthm.edu.my

Penerbit UTHM is a member of
Majlis Penerbitan Ilmiah Malaysia
(MAPIM)

Printed by:
AWIJAYA ENTERPRISE
No. 15, Jalan Budi Utara
Taman Wawasan Perindustrian
83000 Batu Pahat, Johor

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Preface

This book presents an elementary treatment to the concept and design of control systems engineering. The study of this subject is substantive for students in mechanical, aerospace and electrical engineering because control system is found in broad applications within these disciplines. This book is intended to be used as a text for senior students pursuing diploma, bachelor degree students and as essential compact reference for postgraduate students. Generally, this book is for anyone who desires to know the fundamental of control systems engineering.

The book is writing in a way such that the theoretical is precise and concise, so that the readers are able to grasp the central idea promptly. The process to understand the subject matter is quite straightforward, with the help of many discussions on the practical applications of the subject in the control system design. For maximum benefits, the readers should have some experiences in basic calculus and engineering mechanics. The text is organized into six chapters as follows;

Chapter 1 presents the introduction of control system; from the general concept to the specific area of interest. We explain open and closed loop control system. We discuss the method used to represent the physical systems, the dynamics of the system and control system design. Elements that relate the input and output of the systems are introduced, known as the transfer function. We discuss how to obtain transfer function from the block diagram.

Chapter 2 brings the readers to the actuality of many engineering systems on how and why they really behave in certain manners. It is the study of the system's dynamics, which is to explore the application of mathematical equations, engineering and science laws in modeling the systems. Then we demonstrate how to develop the system's block diagram based on the mathematical equations related to those systems. In Chapter 1 we work on the system's block diagram without knowing how these diagrams are really obtained. Now in this chapter, that question will be answered.

Chapter 3 details the importance and application of the mathematical model of the systems developed in Chapter 2. The model, which in an ordinary differential equation (ODE) is closely related to the system's transfer function. Here we discuss how to use Laplace transform as a tool to solve the ODE. To solve ODE means to obtain the system's output response towards certain type of input signals. Then we see how systems are classified according to their order and class, and to understand on the factors that affect the characteristic and performance of control systems. Here we establish the foundation of the control system design by introducing design requirements or specifications which has two parts; transient response and steady-state response.

Chapter 4 moves with the essential element in control system design, which is the system's stability. We explain the concept of absolute stability (stable or unstable) in control systems and how to determine system's stability by using Routh criterion. This criterion needs the readiness of the system's characteristic equation. Each system has a unique characteristic equation, which is self-explanatory; the equation that characterizes the system. The root of this equation is known as poles. Although this method is mainly to determine absolute stability, it also helpful for preliminary control system design by letting us know the suitable range for the system's gain to ensure system's stability.

Chapter 5 is the essential of the control system design. We already know that characteristic equation is very important equation that describes the system's behavior. Here we discus how root locus method can tell us the actual values of poles and other system parameters that fulfill the control system design specifications. We explain the concept of relative stability, which explains how stable or how unstable a system is. Then, if control system does not meet the design specification or we want to improve the system's performance, we will discuss how we can solve this by adding compensator to the system.

Chapter 6 concludes the book by presenting the analysis and control system design based on frequency response, which complements the root locus method. To design a control system through root locus, we must have an accurate closed loop model of the system, where in many cases they are very hard to obtain. Here we discuss the frequency response techniques that use only the information of the open loop transfer function. Out of several choices available in the techniques, we choose Bode diagram for this subject. Stability in describes in terms of gain margin and phase margin. This method is quite powerful because it can fulfill the transient and steady-state design specification, although the closed-loop model of the system in not available. However, Bode diagram does not give direct information on the system's transient response. Therefore, root locus method and frequency response technique are to complement each other.

The use of computer packages in control system design is very important in this era. One of them is MATLAB, which is likely has become a standard in the control system community. Therefore, we also include some MATLAB examples in our discussion, particularly in root locus and Bode diagram chapters. This book is developed from class materials, and the organization of chapters in this manner has enabled students to better understand the subject of control system engineering. Finally, generous recommendation to improve the presentation of this book is very much welcomed.

Acknowledgement

I would like to thank all people for their contributions in many ways to this book. They are my colleagues in the mechanical and manufacturing engineering faculty for their support and encouragement to the completion of this book. I would like to acknowledge the support from the university who provided me with the book's writing funding scheme. Thank you also to all staff at University's Publisher Office who have guided me throughout the process of producing this book. I wish to extend special thanks my family for their love and assistance. Most of all, the most greatest thank is to The Almighty, that is Him who has made this book a reality. To all readers, I hope you will get as much from reading this book as I did from writing it.

CHAPTER 1

Introduction to Control Systems

1.10 CONTROL SYSTEM

We normally experience the result of control systems, sometimes without realizing it. Control system exists in very broad systems surrounding us, ranging from, for examples engineering system, social system, economics, ecological, politics to weather, solar and astronomy systems. During space shuttle launching, the thrust should be controlled to maintain the vehicle in the upright attitude. In economics, the share price is controlled by many factors. Our solar system still in a perfect controlled motion until today. All planets circumambulating the sun in their orbits. Evidently, the universe system is far beyond human capability to control, but this system is just another amazing example of controlled motion systems.

Basically, our discussion here is limited to the control of engineering systems. Think about computers, domestic appliances, cars, airplanes, communication system, power generation plant or manufacturing process. All these systems are dynamic, which have certain variables of interest need to be controlled. The common approach in control system design is to understand how these systems behave, and then find out how to control the variables or parameters associated with these systems. The system behavior are governed by the physical science. Each of these systems has engineering or science laws behind it. Newton's laws, thermodynamics laws and Kirchhoff's laws are a few of them.

CHAPTER 2

Modeling of Dynamic Systems

2.1 INTRODUCTION

The physical system is modeled in terms of mathematical equations, which is required for the study of system's dynamic and control system design. The mathematical model, whether they are for mechanical, electrical, thermal, biological, and so on, consists of ordinary differential equation that shows the relationships that relate the output of a system to its input. The model is developed by using science and engineering laws of the system, for examples, any motion in the engineering system is governed by Newton's laws, electrical system is based on Kirchhoff's laws, and liquid level system is based on mass conservation laws.

Although the physical systems can be modeled mathematically, it should be noted that there is no exact mathematical model of a physical system. Even so, it is sufficient enough to enable us to explore, observe, understand and deduce the control engineering problems at hand. This chapter deals with a wide range of engineering systems, including mechanical, electrical, electromechanical and liquid level. These are the most important and common engineering systems. We will derive the mathematical model of these dynamic systems.

In previous chapter, we have discussed the system representation by block diagram, and have demonstrated how to simplify the block diagram in order to obtain the system's transfer function. We did this without examining the details how such diagrams are developed

CHAPTER 3

Time Response Analysis

3.1 INTRODUCTION

In the previous chapter, we have seen how to develop a mathematical model for a given dynamic system. The mathematical model is very useful to study the system's dynamic, where it should be well understood before we can design a controller for that system. Once a mathematical model has been derived for a control system, a number of techniques can be applied to analyze the system performances. Time response analysis is the study of the output response with respect to time, when the system is given with an input. The inputs to the control system vary and sometimes are unpredictable. For example, in radar tracking system on a combat aircraft, the position, speed and attitude of the target plane are always changing in random fashion.

However, in many systems we can observe the patterns of the actual input signals may be in the forms of sudden shock, a change of amplitude, a constant velocity or a constant acceleration. If we are able to figure out that the input to the control systems are in the form of these signals, then it is very helpful because we can model these signals mathematically. Generally, a sudden shock can be modeled as impulse signal, a sudden change can be modeled as step signal and a constant acceleration can be modeled as ramp signal.

For example, if we activate an air conditioning system by applying a constant voltage, it means we are applying a step function to the

CHAPTER 4

Stability of Control Systems

4.1 INTRODUCTION

It is important to ensure the stability of dynamic systems. The terms stability and control are closely related to each other. Stability characteristic could result from the nature of the system, which is refer to as inherent stability and also affected by the input given to the system. On the other hand, instability could lead to the self-destruction of the system. For example, an aircraft would go into uncontrollable pitch, or a car would keep bouncing up and down after hitting a bump, or a washing machine drum would stay in spinning mode. A classic example of instability due to the system's nature is the collapse of Tacoma Bridge in 1940, where the wind had caused an oscillation that grew in amplitude, caused the bridge to sway violently from side to side until it broken apart.

Generally, control is the ability for us to alter the system's motion as we desired and it is very much depends on the system's stability. A stable open loop system can become unstable when a feedback control system is implemented. In another circumstance, an unstable process can be stabilized by implementing a feedback control scheme. By definition, a system is stable if a bounded input signal is excited into the system, the resulting output signal should also bounded, as depicted in Fig. 4.1. On the other hand, if the system is given with bounded input produces unbounded output, the system is unstable as shown in Fig. 4.2.

CHAPTER 5

Control System Design Using Root Locus

5.1 INTRODUCTION

In control system design, it is often necessary for us to evaluate the control system performance when the system parameters are changed. Most of dynamic systems have one or more parameters that are not fixed. For examples, the mass and center of gravity of a rocket vehicle are altered after part of the rocket fuel was used, the car's weight will depend on the number of passengers, and the resistance and inductance of electrical components are changed when there is a changing on the load. In late 40's, W.R Evans introduced a graphical method known as Root Locus, used to study the changes of linear systems performance due to the changing of system parameters.

In the previous sections, we have discussed that the characteristic equation determines the system's stability. Generally, the system stability is directly related to the value or position of the poles, such as the properties of transient response are influenced by the values of the roots of the characteristic equation. The stability region on the s-plane is shown in Fig. 5.1. The s-plane is a complex plane which represents the poles location (x) of the system. The system is stable if all poles lie on the left side of imaginary axis. If any pole is located on the imaginary axis, with other poles in the left half plane, the system has the marginal stability, which means the response neither decays nor grows as time approaches infinity. The value of zeros gives effect

CHAPTER 6

Control System Design Using Frequency Response

6.1 INTRODUCTION

In the previous chapter, we have discussed the design of control system based on the root locus. Construction of the root locus plot is quite straightforward. However, the success of this method depends on the availability of accurate plant model, in terms of transfer functions for the components such as actuators, subsystems and sensors. We now consider the control system design approach that uses only the information of the open loop transfer function along positive imaginary axis, which is known as frequency response technique.

Root locus gives us direct information on the performance of the system's transient response, while frequency response gives us the information on the steady state and stability margins. Therefore, root locus and frequency response technique complement each other. Theoretically, frequency response covers the entire frequency spectrum from zero to infinity. In Chapter 3, we have examined the response of dynamics systems due to step and ramp inputs. Now we consider an open loop system in Fig. 6.1a is given with sinusoidal input.

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