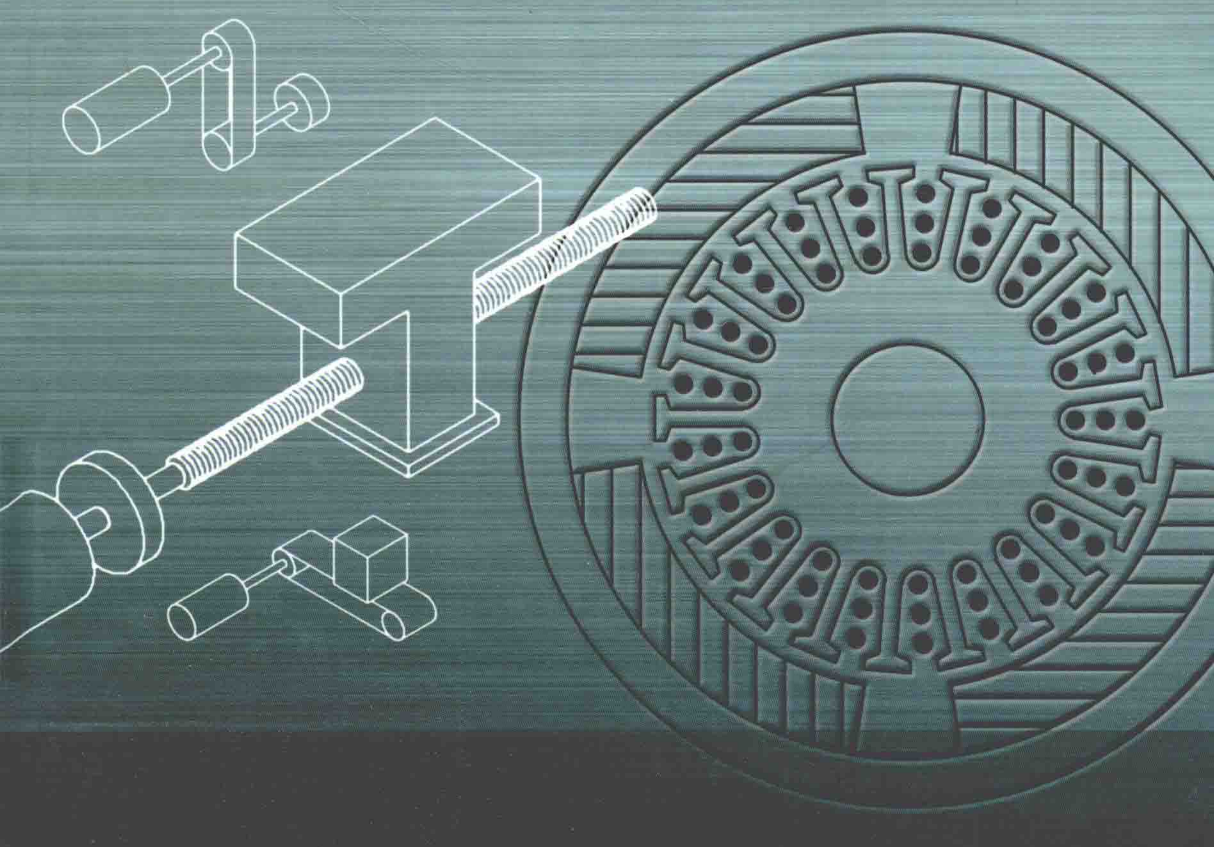
Electromechanical Motion Systems - Design and Simulation

Frederick G. Moritz



WILEY

ELECTROMECHANICAL MOTION SYSTEMS

DESIGN AND SIMULATION

Frederick G. Moritz
FM Systems, Ohio, USA

WILEY

This edition first published 2014

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Moritz, Frederick G.
Electromechanical motion systems : design and simulation / Frederick G. Moritz.
pages cm
Includes bibliographical references and index.
ISBN 978-1-119-99274-5 (hardback)
1. Servomechanisms. 2. Robotics. I. Title.
TJ214.M6576 2013
629.8′323–dc23

2013023514

A catalogue record for this book is available from the British Library.

ISBN: 9781119992745

Typeset in 10/12pt Times by Aptara Inc., New Delhi, India
Printed and bound in Malaysia by Vivar Printing Sdn Bhd

1 2014

ELECTROMECHANICAL MOTION SYSTEMS

To my wife,

Louise,

For her enthusiastic support and encouragement

Acknowledgements

To Roger Mosciatti and Thomas Foley, my partners for over 25 years at MFM Technology; the two most inventive and dedicated engineers it has been my pleasure to know. Our efforts individually and together led to over 20 US patents and a highly successful manufacturer of motion control products and systems.

To Hans Waagen, an engineer who combines an in-depth knowledge of motion control with an ability to concisely analyze and interpret a customers' product requirements.

To Avi Telyas, founder of the Bayside Motion Group, an entrepreneur who understands and supports the engineers' contribution to the success of high tech business ventures.

To Dr. Duane Henselman, University of Maine, who has the ability to combine theory with the practical requirements of product design and manufacturing.

To Art Shoemake, for supplying many of the illustrations in this book.

To Visual Solutions, Inc., creator of the VisSim simulation software used throughout the book, for their encouragement and support in the creation of the product and system simulation diagrams.

To my wife Louise and son Peter for their able participation in checking the manuscript and proofs of the complete book.

Contents

1

Introduction

Having spent the first half of my engineering career in the design of motion control systems in computer peripheral equipment (digital tape recorders, disc memories and high speed line printers) and the second half in the design, manufacture and application of brushless motors, gearheads and slides, I have been both a user and a supplier of the various components used in high performance servo/control systems.

Time restraints in a typical one or two semester motion control/servo system course require that the text and class time devote a majority of their content to topics such as pertinent mathematics, LaPlace transform, linear system analysis, closed loop control theory and stabilization techniques. Little time can be devoted to a detailed presentation of the system components, which are typically presented in a cursory fashion only as needed to aid in the discussion of the system theory.

This book will extend such course work by providing an introduction to the technology of the major components that are used in every motion system.

A website is available (www.wiley.com/go/moritz) which will allow you to access a number of the figures in this book. You will be able to activate them, observe simulation activity, modify system parameters to observe the effect on system performance and print out the results. For example, in Figure 4.13 you can change the motor parameters (R, L, torque constant, etc.) or the load torque or the PI values to observe the effect on performance and stability. The figures that are accessible are identified throughout the book with (available at www.wiley.com/go/moritz) appended to their captions.

A system designer cannot become an expert in the design of system components. He will never fabricate his own motor or encoder, but he must understand the basics of those components in order to properly apply them and have successful discussions with his component suppliers.

I have found that one of the best sources of information about component technology is from the well written and timely application notes and white papers from component suppliers. Over the years I have accumulated a valuable file of such information and encourage everyone engaged in system design to do the same.

Electromechanical Motion Systems: Design and Simulation, First Edition. Frederick G. Moritz.

Companion Website: www.wiley.com/go/moritz

Since the time I used a Bendix G15 computer in the 1960s there have been amazing advances in computer technology and application software that now allow simulation of complete electromechanical systems, including both linear and nonlinear characteristics of all the components. Throughout this book, component and system simulation is used to demonstrate the use of this technology to display system operation. A number of programs, such as MATLAB® and Simulink® by The Mathworks, MapleSim by Maplesoft, Ansys by Ansoft and VisSim by Visual Solutions are available to perform such simulations. The simulations in this book have been created with VisSim.

The book consists of the following chapters:

Chapter 2 – A brief review of servo/motion control theory, including an introduction to the use of simulation for root solving and a review of sampled data technology.

Chapter 3 – Detailed descriptions of the main components used in the fabrication of electromechanical motion control systems.

Chapter 4 – A review of the various system characteristic functions showing how they can be described and analyzed by the use of computer simulation techniques. It also contains a summary of the dynamic equations describing eight basic building blocks, which form the foundation of most motion systems.

Chapter 5 – Contains design notes and simulations of five of the many systems I helped create.

1.1 Targeted Readership

This book will be useful to:

- Students at the senior undergraduate or graduate school level to supplement their standard systems text to provide detailed component and simulation information as an aid in the design and analysis of prototype systems.
- As a reference text for graduate school students in advanced system courses involved in detailed system design and component selection.
- Practicing engineers initiating a system design requiring background information about components unfamiliar to them and/or an introduction in the use of simulation techniques.

1.2 Motion System History

A detailed and complete history of the motion control field would alone require a book larger than this one. Therefore the following just covers some highlights in the field and some of the pioneers and their accomplishments and contributions to motion control.

Since the late 1800s mathematical analysis and design of motion control has been limited to modeling the system in terms of its classical Newtonian differential equations with constant coefficients since no method existed to model nonlinearites (saturation, dead band, hysteresis, etc.) At best, linear approximations of nonlinearities have been made and designs modified once prototype test results are obtained.

This approach resulted in the mathematical representation of the system being mostly correct for small signal excitation and having errors and unpredictability for large signals.

As of 1955, Truxal summed up the status as: "The highly developed design and analysis theories for linear systems, in contrast to the rather inadequate state of the art of analysis of non-linear systems, are a natural result of the well-behaved characteristics of a linear system.Techniques for the description of non-linear systems are still in the early stage of development, with only a limited range of problems susceptible to satisfactory analysis at this time" [1].

A considerable amount of work in analysis was devoted to creating various methods of predicting stability using graphical methods showing the characteristics of the poles and zeros of the system as a result of parameter variations. Once modeled this way, a prototype system was fabricated and tested to determine what modifications to the design were necessary to account for the nonlinearities, and these were then incorporated in the calculations to more closely model the system. As the technology advanced, methods were created to analyze nonlinearities, as represented by Phase-Plane analysis (1945) (limited to second order systems) and Describing Function analysis (1950) (subject to certain system frequency characteristics).

Obviously, the reason for "designing" a system on paper is to specify the various components and predict their ability to provide proper operation before expending the time and funds to actually fabricate the system. The more accurate the "prediction", the less time it will take to complete the design.

By 1972, Tymshare Inc. of Palo Alto CA provided CSMP (Continuous System Modeling Program) which allowed simulation of systems with both linear and nonlinear blocks, operating from a main frame computer via I/O access by Teletype terminal and X/Y plotter. Bi-directional transmission of data over conventional telephone lines was slow; even a single loop simulation took as long as one hour to run and provide listed and graphical results.

Today, with the advent of the microprocessor, the PC and a wide range of simulation software, it is possible to simulate both the linear and nonlinear functionality of a complete system, combining the electrical and mechanical components and run a simulation in a matter of seconds. The "inadequate state of the art of the analysis of nonlinear systems" has been overcome.

System controllers now have rapid enough processing time such that they can perform their two main functions, that is, axis loop closure and stabilization, together with control of the functionality and interaction of all the machine axes in real time. Controllers are available that can perform such action with up to 64 axes. In addition, they can modify axis characteristics as a result of changing performance requirements; for example, software modification of stability parameters as load inertia changes.

Defining an exact time when the motion control field was started is of course not possible. It is a technology that has evolved over the past 200 years and advanced rapidly starting in the 1900s.

It is interesting that two of the earliest contemporaries in the field were James Watt (1736–1819) and Pierre-Simon, marquis de LaPlace (1749–1827). They most likely did not know each other, certainly did not consider themselves as "motion control designers" and were involved in totally opposite ends of the technology.

Watt was a "hands on" engineer, active in various aspects of the application of steam to industrial requirements. He invented an early feedback device, the fly-ball governor, which regulated the speed of an engine by controlling its supply of steam. The problem with this system was that it was often subject to oscillations; typically resolved by trial and error modifications, with no mathematical analysis involved.

LaPlace, on the other hand, was a famous French mathematician who was deeply involved in celestial mechanics, probability and field theory. He and Simeon-Denis Poisson (1781–1840) were involved with various transforms while working on probability. Although never involved in what we call motion control, one of the transforms named after him, the LaPlace Transform, is used routinely in motion control design and analysis.

Edward Routh (1831–1907) and Adolph Hurwitz (1859–1919) were also contemporaries who were specifically involved in motion control theory. Hurwitz polynomials are those which have all their zeros in the left half of the complex plane. Using this information Routh created the Routh–Hurwitz criteria, which is a simple test to determine whether a polynomial is a Hurwitz polynomial and, in turn, became the first practical test to determine the stability of a feedback control system.

Oliver Heaviside (1850–1925) was a self-educated mathematician who developed an operational calculus to solve differential equations by substituting "p" for the derivative term and thereby converting the differential equation into an algebraic equation. Although used successfully his methods were subject to much criticism by strict academics.

Harry Nyquist (1889–1976) performed work in 1932 on the use of feedback to stabilize telephone line repeater amplifiers used in long distance communications. He developed the well known Nyquist Stability Criteria which carried over into electromechanical system design. During World War II he was active in developing control systems for artillery equipment.

Harold Black (1898–1983) invented the negative feedback amplifier in 1927 which he described in a 1934 paper. He credited using Nyquist Stability Criteria to attack the stability problem created by negative feedback and discussed the effects of negative feedback, namely higher linearity, lower gain, lower distortion, higher bandwidth and reduction of nonlinearities in the forward path.

Hendrick Bode (1905–1982) extended Nyquist's work on feedback amplifier design and created the well known Bode Gain/Phase plot used to graph the gain and phase of a system as a function of frequency. This allowed the determination of the gain and phase margin of the system or how to determine its conditional stability. In 1939 he worked on military fire control systems. He authored one of the classic texts in the field, *Network Analysis and Feedback Amplifier Design*.

Walter Evans (1920–1999) developed the technique of Root Locus analysis, which shows the variation of the poles of the closed loop system with changes in the open loop gain, providing a simple means of determining how to add compensation to improve stability and performance. He authored a classic text, *Control System Dynamics*, McGraw-Hill, 1954.

Nicholas Minorsky (1885–1970) performed extensive work in analysis and design of ship steering technology. In a 1922 paper he analyzed the properties of a "three term" controller which we today call PID compensation.

Harold Hazen (1901–1980) published papers in 1934 covering the theory and design of high performance servomechanisms as a result of his work on ship shaft positioning systems.

Krylov (1879–1955) and Bogoliubov (1909–1992) developed the concept of the describing function to be used in analyzing nonlinearities. They took the approach that the system acts like a low pass or band pass filter but is limited by the transfer function being dependent on the amplitude of the input waveform. Authors of *Introduction to Nonlinear Mechanics*, Princeton University Press, 1947.

R.J. Kochenburger was the first in the United States to show the use of the describing function in his 1950 PhD thesis and in a paper,A Frequency Response Method for Analyzing and Synthesizing Contactor Servomechanisms", Trans. AIEE, Vol. 69, Part I, 1950.

H. Harris (MIT) introduced the general idea of the transfer function with respect to servomechanisms in a NRDC report in 1942.

L.A. MacColl first described the use of the phase plane to characterize a nonlinear system. *Fundamental Theory of Servomechanisms*, D. Van Nostrand, 1945.

1.3 Suggested Library for Motion System Design

There have been many books written covering various aspects of servo and control system theory and any list will be subjective and based on individual experience.

The following list is the basis for a comprehensive motion system library

- Golnaraghi, F. and Kuo, B.C. (2010) *Automatic Control Systems*, 9th edn., J. Wiley & Sons.

An up-to-date comprehensive text, covering both theory and applications.

Includes MATLAB®, ACSYS, SIMlab and Virtual Lab for on-line problem solving and application examples.

- Hanselman, D. (2003) *Brushless Permanent Magnet Motor Design*, 2nd edn, The Writers Collective.
- Bateson, R.N. (2001) *Introduction to Control System Technology*, 7th edn, Prentice-Hall.
- Doebelin, E. (1998) *System Dynamics*, CRC Press.
- Leenhouts, A. (1997) *Step Motor System Design Handbook*, 2nd edn, Litchfield Engineering Co.

A summary of the authors many years of activity in the application of stepper motors with a large number of applications.

- Levine, W.S. (ed.) (1996) *The Control Handbook*, CRC Press.

Contains an extensive summary (1500 pages, 200 authors) of modern control technology covering fundamentals, advanced methods and applications.

- Åström, K.J. and Hägglund, T. (1995) *PID Controllers*, Instrument Society of America.

In depth review of PID theory and various methods of manual and automatic tuning (Ziegler–Nichols, step response and frequency response methods).

- Kuo, B.C. and Tal, J. (1978) *Incremental Motion Control, Vol I – DC Motors and Control Systems*, SRC Publishing.
- Kuo, B.C. (1979) *Incremental Motion Control, Vol II – Step Motors and Control Systems*, SRC Publishing.

A two volume set covering DC and stepper motor driven incremental systems, with in-depth theory and a wide range of examples from actual applications

- Thaler, G.J. and Pastel, M.P. (1962) *Analysis and Design of Nonlinear Feedback Control Systems*, McGraw-Hill.

Complete coverage of the theory of the Phase-Plane and Describing Function applied to nonlinear systems including Relay (bang-bang) servomechanisms and nonlinear compensation techniques.

- Tou, J.T. (1959) *Digital and Sampled-Data Control Systems*, McGraw-Hill.

Covers the theory of sampling, the Z transform theorem and analysis, sampling frequency and root locus in the Z plane.

- Truxal, J.G. (1955) *Automatic Feedback Control System Synthesis*, McGraw-Hill.

Provides a comprehensive review of all the theory available at the time: LaPlace, RC network synthesis, Root Locus, Pole/Zero, S plane design, Z transform, Describing Function and Phase Plane analysis.

- Chestnut, H. and Mayer, R. (1951) *Servomechanism and Regulating System Design*, Vol. I & II, John Wiley & Sons.

Classic texts in the field, used for many years in senior level servo system design courses.

- James, H.M., Nichols, N.B., and Phillips, R.S. (1947) *Theory of Servomechanisms*, McGraw-Hill, 1947a volume in the MIT Radiation Laboratory Series.

An old classic covering work done during WWII on radar, gun control, torpedo and ship steering systems.

Basically treats all elements as filters with lead or derivative control and integral equalization compensation described in terms of filter theory.

No mention of nonlinearity except for a single sentence concerning backlash.

Reference

[1] Truxal, J.G. (1955) *Control System Synthesis*, McGraw-Hill, pp. 560–561.