Intelligent Systems, Control and Automation: Science and Engineering

Volume 77

More information about this series at http://www.springer.com/series/6259

Jocelyn Sabatier • Patrick Lanusse • Pierre Melchior
Alain Oustaloup

Fractional Order Differentiation and Robust Control Design

CRONE, H-infinity and Motion Control

With contributions by
Chapter 1: C. Farges
Chapter 3: D. Nelson Gruel
Chapter 4: L. Fadiga
Chapter 5: S. Victor

Springer

Jocelyn Sabatier
LAPS - Bat A4
IMS Laboratory - CNRS UMR 5218 – Bordeaux INP – Bordeaux University
Talence, France

Pierre Melchior
Universite Bordeaux 1-IPB/Enseirb-Matmec LAPS - Bat A4
IMS Laboratory - CNRS UMR 5218 – Bordeaux INP – Bordeaux University
Talence, France

Patrick Lanusse
LAPS - Bat A4
IMS Laboratory - CNRS UMR 5218 – Bordeaux INP – Bordeaux University
Talence, France

Alain Oustaloup
IMS Laboratory LAPS - Bat A4
IMS Laboratory - CNRS UMR 5218 – Bordeaux INP – Bordeaux University
Talence, France

ISSN 2213-8986 ISSN 2213-8994 (electronic)
Intelligent Systems, Control and Automation: Science and Engineering
ISBN 978-94-017-9806-8 ISBN 978-94-017-9807-5 (eBook)
DOI 10.1007/978-94-017-9807-5

Library of Congress Control Number: 2015938444

Springer Dordrecht Heidelberg New York London

Printed on acid-free paper

Springer Science+Business Media B.V. Dordrecht is part of Springer Science+Business Media (www.springer.com)

Preface

Application of Fractional Differentiation in Systems and Control Theory

This book is dedicated to several applications of fractional derivative equations to systems and control theory. It also proposes a very detailed description of the CRONE control methodology.

Since the second half of the twentieth century, the study of fractional derivative and fractional differential equations has made great strides (Oldham and Spanier 1974; Samko et al. 1993; Miller and Ross 1993; Kiryakova 1994; Gorenflo and Mainardi 1997; Podlubny 1999; Kilbas et al. 2006).

Thanks to these advances, fractional differentiation has been applied in many areas:

- Electrical engineering (modeling of motors, modeling of transformers, skin effect)
- Electronics, telecommunications (phase locking loops)
- Electromagnetism (modeling of complex dielectric materials)
- Electrochemistry (modeling of batteries, fuel cells and ultracapacitors)
- Thermal engineering (modeling and identification of thermal systems)
- Mechanics, mechatronics (vibration insulation, suspension)
- Rheology (behaviour identification of materials, viscoelastic properties)
- Automatic control (fractional order PID, robust control, system identification, observation and control of fractional systems)
- Robotics (modeling, path tracking, path planning, obstacle avoidance)
- Signal processing (filtering, restoration, reconstruction, analysis of fractal noise)
- Image processing (fractal environment modeling, pattern recognition, edge detection)
- Biology, biophysics (electrical conductance of biological systems, fractional modeling of neurons, muscle modeling, lung modeling)
- Physics (analysis and modeling of diffusion phenomenon)
- Economics (analysis of stock exchange signals)

In these applications, fractional differentiation is often used to model phenomena that exhibit nonstandard dynamical behaviors, with long memory or with hereditary effects. Sometimes these behaviors are associated with constant phase element (CPE) or Warburg's systems. These modeling applications gave rise to the notion of fractional order models, i.e. models described by an integro-differential equation involving fractional order derivatives of its input(s) and/or output(s). Linear fractional differentiation order models are not quite conventional linear models and not quite conventional distributed parameter models described by a diffusion equation. They are in fact halfway between these two classes of systems and that explains why they are particularly suited for diffusion phenomena modeling, although there is still a debate on the physical interpretation of these models, as shown at the end of the first chapter.

Among all these applications of fractional differentiation and fractional models, automatic control is no exception. One can even say that it was this area that caused the renewed interest in fractional differentiations and fractional models that appeared in the 1970s. In this area, pioneering work focused on simulation and approximations of fractional integrators (Carlson and Halijak 1961, 1964; Jones and Shenoi 1970) and also on applications in controller design (Tustin et al. 1958; Manabe 1961). Nowadays, there are many applications in the field of automatic control, such as:

- PI and PID control
- Robust control
- Pole placement methods
- Internal model control
- Optimal control
- Adaptive control and automatic gain control
- Sliding mode control
- Reset control
- Nonlinear control
- Fuzzy control
- Chaotic system control

With fractional PID, fractional robust control is the application that has given rise to the most numerous and most advanced developments. Mainly through CRONE control, fractional robust control has been the subject of theoretical developments, academic design, and industrial implementations. CRONE control has been popularized by several monographs in French (Oustaloup 1983, 1991; Oustaloup and Mathieu 1999) and by numerous papers published in international journals or conference proceedings. One goal of this book is thus to present an updated and exhaustive overview of CRONE control with examples that can be reworked using the CRONE toolbox. This toolbox has recently been developed in Matlab and is freely distributed. As the literature now abounds in fractional models for various dynamical systems, another goal of the book is to present another robust control methodology specially dedicated to fractional models: an extension to fractional models of H_∞ control and flatness control. As a prefilter offers an additional degree of freedom to enhance closed loop performance, the third objective of the book is to propose path tracking (motion control) design methodologies based on fractional differentiation.

Organization of the Book

This book is written so that novices can understand what fractional differentiation and fractional models are and how they can be used in robust control. As such, the theoretical developments are illustrated by numerous examples and applications. The book is organized as follows.

Chapter 1 is dedicated to the definition of fractional differentiation. Approximation of fractional differentiation is also addressed in this chapter with an application to the ignition prediction of active materials. Fractional models, i.e. models described by differential equations involving fractional derivatives of the input and output, are then introduced. Based on the interpretation of fractional models, a distinction is made between the model pseudo-state and the "real state," in order to discuss the fractional model initialization problem and also to analyze model observability with an application to transistor junction temperature estimation. To conclude this chapter, a stability analysis method involving Linear Matrix Inequalities (LMI) is presented and applied to stability margin computation for a CRONE suspension.

Chapter 2 first gives an overview of the notions of robustness, stability margins, and model uncertainty. Then, before introducing CRONE control methodologies and in order to highlight the interest of robust controllers, Integer PID and Fractional PID controller design methodologies are presented. Unlike a first generation CRONE controller whose design methodology is presented at the end of this chapter, the (integer or fractional) PID controller cannot ensure closed loop stability degree robustness versus pure plant gain variation. The first generation CRONE methodology is thus an initial improvement to fight against controlled plant uncertainty. The robustness of PID and first generation CRONE controllers is assessed by using a comparative example.

Chapter 3 presents the second generation of the CRONE methodology that extends the field of application of the first generation one. By replacing the real fractional order by a complex order, the third generation of the CRONE methodology is defined for any perturbed SISO system and is finally used to extend the CRONE approach to the design of robust controllers for multi-input/multi-output (MIMO) systems. Several academic examples, treated with the CRONE control Matlab toolbox, illustrate in detail the various control strategies presented. Other experimental and industrial applications are presented in the references listed in the bibliography.

Despite the high level of performance obtained on several industrial applications, third generation CRONE control cannot be addressed as a convex control problem. Thus to offer a convex counterpart (not necessarily easier to implement and not necessarily more efficient), Chap. 4 offers an extension to commensurate fractional order models of H_∞ control. First, LMI conditions are presented for the computation of a fractional order model $H\infty$ norm. Then, from the previous analysis conditions, synthesis LMI conditions are derived for pseudo state space control and dynamic output control of commensurate fractional order models. An application to the seismic isolation of a bridge structure is studied as an illustrative example.

While the previous chapters were devoted to the design of the feedback controller inside the control loop (single input/single output (SISO) or MIMO), Chap. 5 concerns path tracking design or motion control methodologies involving fractional differentiation. For the SISO case, the goal is to design a prefilter that simultaneously reduces the output closed loop overshoot and speeds up the tracking of the closed loop time response by taking into account the plant input limitations. Three different approaches are presented: fractional prefilter, input shaping, and flatness principles. All these approaches are applied on experimental closed loop systems.

References

Carlson GE, Halijak CA (1961) Simulation of the fractional derivative operator $\sqrt{s}$. Proc of the CSSCM, Kansas State U B 45(7):1–22

Carlson GE, Halijak CA (1964) Approximation of fractional capacitors $(1/s)^{1/n}$ by a regular Newton process. IEEE Trans Circ Sys., CT-11 2:210–213

Gorenflo R, Mainardi F (1997) Fractional calculus: integral and differential equations of fractional order. In: Carpintieri A, Mainardi F (eds) Fractals and fractional calculus in continuum mechanics. Springer Verlag, New York

Jones HE, Shenoi BA (1970) Maximum flat lumped-element approximation to fractional operator inmitance function. IEEE Trans Circ Sys 17(1):125–128

Kilbas AA, Srivastava HM, Trujillo JJ (2006) Theory and applications of fractional differential equations. Elsevier, Amsterdam

Kiryakova V (1994) Generalized fractional calculus and applications. Number 301 in pitman research notes in mathematics. Longman Scientific & Technical, Essex

Manabe S (1961) The non integer integral and its application to control systems. ETJ of Japan 6(3–4):83–87

Miller K, Ross B (1993) An introduction to the fractional calculus and fractional differential equations. John Wiley & Sons, New York

Oldham KB, Spanier J (1974) The fractional calculus; Theory and applications of differentiation and integration to arbitrary order (Mathematics in Science and Engineering, V). Academic Press, New York

Oustaloup A (1983) Systèmes asservis linéaire d'ordre fractionnaire. Masson Editions, Paris

Oustaloup A (1991) La commande CRONE. Hermès Editions, Paris

Oustaloup A, Mathieu B (1999) La commande CRONE: du scalaire au multivariable. HERMES, Paris

Podlubny I (1999) Fractional differential equations. Academic Press, San Diego

Samko S, Kilbas A, Marichev O (1993) Fractional integrals and derivatives: theory and applications. Gordon and Breach Science Publishers, Amsterdam

Tustin A, Allanson JT, Layton JM, Jakeways RJ (1958) The design of systems for automatic control of the position of massive objects (Citations: 14). Proceedings of the IEEE Part C: Monographs 105(1S). doi: 10.1049/pi-c.1958.0001

Contents