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Process Control

The Passive Systems Approach

Springer

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To the memory of my mother, Professor Linxian Feng
Jie Bao

To my wife Janet and my son Geoffrey
Peter L. Lee

Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies…, new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

Seminal contributions to the theory of dissipative and passive systems date from the early 1970s. Since that time the concepts have been used to design controllers for robotic systems and more recently, the thrust by control system design has led to some new contributions to the literature.

A key concept in dissipative systems theory is that of a storage function. This may be considered to be an abstraction of the idea of a store of energy within the system. The second key concept is a supply rate function and this can be viewed as an abstraction of the supply rate of energy to a system. Although the storage function and the supply rate function are abstract ideas, their value lies in the fact that they can often be identified with physical energy quantities within a real system.

Thus, a dissipative system is one for which the increase in internal energy is no greater than the energy supplied to it so the storage function quantifies internal energy or stored energy and the supply rate function prescribes the rate of energy supplied to the system. A passive system is then a dissipative system having a particular form of supply rate function, namely one expressed as an inner product of system input and output vectors.

The power of these dissipative system quantities lies in their links with system stability results and their ability to analyse physical systems described by nonlinear and linear models. In the field of process control, B.E. Ydstie and colleagues have demonstrated deep but natural links between thermodynamical systems and the notions of dissipative and passive systems theory. This *Advances in Industrial*

Control monograph by Jie Bao and Peter Lee makes a major step-forward in the literature of the passive systems approach to process control.

The monograph opens with a chapter on the fundamental ideas of dissipative and passive systems which covers the basic definitions and system properties before moving on to define passivity indices, and the methods of input feed forward and output feedback to create passivity. A gravity-feed tank system and heat exchanger process are used to illustrate the fundamental results of the chapter.

The next chapters explore the implications of the passivity systems approach to four key process control topics: robust control design, decentralised control, fault-tolerant control design and process controllability analysis; one chapter is devoted to each topic. These are all topics from the mainstream of process control applications and new results and insights are found in all four chapters of the volume. Passivity-based robust control designs are compared with H_∞ control designs in Chapter 3. Some of the decentralized and block-decentralised passivity-based robust controllers designed in Chapter 4 use PI controllers reflecting the widespread industrial use of these controllers. The fault-tolerant control designs of Chapter 5 attempts to achieve fault tolerance whilst avoiding or minimising controller redundancy. Finally, considerable academic and industrial interest in integrated process and controller design methods has motivated the use of passivity concepts in assessing process controllability; this forward-looking material is presented in Chapter 6.

The last chapter of the monograph, Chapter 7, is authored by Katalin Hangos and Gábor Szederkényi and this chapter delves into the fundamental links between the notions of thermodynamics and the constructs of passivity systems theory. It is an illuminating chapter that also considers the ideas of Hamiltonian system models and how models of process industry systems are constructed.

This excellent entry to the *Advances in Industrial Control* series contains new theoretical and applications-related results. It collects together the recent work of the authors to permit a cohesive presentation of passivity system theory as applied to process control. It is useful to note the wide range of industrial process models used in the examples. These include heat exchangers, a continuous stirred-tank reactor, distillation column, supercritical fluid extraction process, boiler furnace control, high-purity distillation column along with some purely academic examples. Many of these process models are standard in the process control literature and this facilitates comparisons of the results of the new methods with those already found in the published literature.

The potential readership for the monograph includes engineers and researchers from the process industries who may wish to exploit the methods and results directly. Research students on Masters and doctoral programmes in process and individual control will find the monograph an inspiring and interesting addition to their research literature. The wider readership of the control engineering and academic community may well find knowledge in this monograph that will transfer to other application fields; consequently the monograph is a very welcome new addition to the *Advances in Industrial Control* series.

M.J. Grimble and M.A. Johnson
Glasgow, Scotland, U.K.

Preface

Passive systems are intuitively appealing. Such systems do not "generate" energy internally, and hence are easier to control and to guarantee that the controlled response is stable. An understanding of the conditions that govern when and how any given system may be passive is thus an important approach in designing control systems. It is only in recent times that interest in using such approaches in the process industries has emerged.

This book is the first attempt to address passivity-based developments systematically in process control. It is written for a wide readership, including the industrial, engineering and academic communities. We have made an effort to present the theory backed by intuitive explanations, illustrative examples and/or case studies in all main chapters. The MATLAB® routines and controller parameters for all examples as well as a library of functions that implement the system analysis and control design methods developed in this book are available at http://www.springer.com/978-1-84628-892-0.

We have assumed that the readers have a working knowledge of engineering mathematics and that they have had some exposure to linear control theory. Some more advanced mathematical tools are introduced when necessary. This book presents the reader with both the conceptual framework and practical tools for passivity-based system analysis and control.

The authors are grateful for the contribution of Professor Katalin M. Hangos and Dr Gábor Szederkényi of the Systems and Control Laboratory, Computer and Automation Research Institute, Hungarian Academy of Sciences, who have written Chapter 7 of this book. This chapter makes clear the link between thermodynamics, Hamiltonian systems and passivity and how this linkage can be exploited in the design of passivity-based control systems.

This book is largely based on our recent research results. We wish to thank our co-workers and students, Dr Osvaldo Rojas, Dr Wenzhen Zhang, Dr Steven W. Su, Mr Kwong Ho Chan and Mr Herry Santoso for their contributions on the projects related to the subject of the present book. Dr Osvaldo Rojas also helped in proofreading some of the chapters.

We wish to express our gratitude to Professor Michael Johnson for his inspiration to prepare the book. Most importantly, we would like to thank our wives, who have continued to support us through the long hours that any such effort requires.

The University of New South Wales, Australia *Jie Bao*
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February 2007

Contents

Notation

Abbreviations

AS	asymptotically stable
BDIC	block decentralized integral controllable
BMI	bilinear matrix inequality
BRG	block relative gain
DCLI	decentralized closed-loop integrity
DIC	decentralized integral controllable
DUS	decentralized unconditional stability
ESPR	extended strictly positive real
GAS	globally asymptotically stable
GES	globally exponentially stable
IFP	input feedforward passivity
IMC	internal model control
ISE	integral square error
ITAE	integral time-weighted absolute error
LES	locally exponentially stable
LHP	left half plane
LMI	linear matrix inequality
LQG	linear quadratic Gaussian
LTI	linear time invariant
MIMO	multi-input multi-output
MP	minimum phase
NI	Niederlinski index
NMP	nonminimum phase
OFP	output feedback passivity
PID	proportional-integral-derivative
PR	positive real
RGA	relative gain array
RHP	right half plane
SDP	semidefinite programming

SISO	single-input single-output
SPR	strictly positive real
SSDP	successive semidefinite programming
SVD	singular value decomposition
ZSD	zero state detectable
ZSO	zero state observable

Symbols

A^T	transpose of matrix A
A^{-1}	inverse of matrix A
A^{-T}	transpose of inverse of matrix A
$A > 0$	matrix A is positive definite
$A \geq 0$	matrix A is positive semidefinite
A^*	complex conjugate transpose of complex matrix A
$\arg(c)$	angle of complex number c
$\mathbb{C}$	field of complex numbers
$\mathbb{C}^{m\times n}$	field of complex matrices of dimension $m \times n$
C^0 function	a function which is continuous
C^n function	a function which can be differentiated n times ($n > 1$), leaving a continuous nth derivative
$\det(A)$	determinant of matrix A
$\dim(A)$	dimension of matrix A
$\mathcal{F}_l$	lower linear fractional transformation
$f_T(t)$	truncation operator of function $f(t)$
$\mathrm{Im}(A)$	imaginary part of complex matrix A
$\mathrm{In}(A)$	inertia of matrix A
$H : u \mapsto y$	mapping H from u to y
I	identity matrix
$\mathcal{L}_2^m$	$\mathcal{L}_2$ space with dimension m
$\mathcal{L}_{2e}^m$	extended $\mathcal{L}_2$ space with dimension m
$\mathbb{R}$	field of real numbers
$\mathbb{R}^{m\times n}$	field of real matrices of dimension $m \times n$
$\mathrm{Re}(A)$	real part of complex matrix A
sup	supremum (the least upper bound)
$\mathrm{Tr}(A)$	trace of matrix A
$\Delta(s)$	uncertainty system
$\Delta_A(s)$	additive uncertainty
$\Delta_M(s)$	multiplicative uncertainty
$\bar{\sigma}(A)$	maximum singular value of matrix A
$\underline{\sigma}(A)$	minimum singular value of matrix A
$\sigma_i(A)$	ith singular value of matrix A
$\bar{\lambda}(A)$	maximum eigenvalue of matrix A

$\underline{\lambda}(A)$	minimum eigenvalue of matrix A
$\lambda_i(A)$	ith eigenvalue of matrix A
$\Lambda(A)$	RGA matrix of matrix A
$\lambda_{ij}(A)$	the ijth element of $\Lambda(A)$
$\Lambda_i\,(G(0))$	block relative gain (BRG) of the ith block $G_{ii}(0)$
$\mu(A)$	structured singular value of matrix A
ν	IFP index
ν_F	frequency-dependent IFP index
ν_{FB-}	passivity-based uncertainty measure in a frequency band
ν_I	passivity-based interaction measure
ν_{IA}	passivity-based interaction measure (additive uncertainty)
ν_{IM}	passivity-based interaction measure (multiplicative uncertainty)
ν_{S-}	sector bounded IFP measure (shortage of IFP)
ν_{sIA}	sector-based interaction measure (additive uncertainty)
ν_{sIM}	sector-based interaction measure (multiplicative uncertainty)
$\nu_-(G(s),\omega)$	shortage of IFP of $G(s)$ at frequency ω
ω	frequency
$:=$	state-space realization of a transfer function
$\triangleq$	defined as
$\\|f\\|_2$	2-norm of a function $f(t)$
$\\|f\\|_\infty$	∞-norm of a function $f(t)$
$\\|f\\|_{\infty-2}$	$\infty - 2$ norm of a function $f(t)$
$\\|G\\|_2$	2-norm of a system $G(s)$
$\\|G\\|_g$	generalized $\mathcal{H}_2$-norm of a system $G(s)$
$\\|G\\|_\infty$	$\mathcal{H}_\infty$-norm of a system $G(s)$
$< f, g >$	inner production of f and g
$\forall$	for all