

Advances in Industrial Control

Other titles published in this Series:

Digital Controller Implementation and Fragility

Robert S.H. Istepanian and James F. Whidborne (Eds.)

Optimisation of Industrial Processes at Supervisory Level

Doris Sáez, Aldo Cipriano and Andrzej W. Ordys

Robust Control of Diesel Ship Propulsion

Nikolaos Xiros

Hydraulic Servo-systems

Mohieddine Jelali and Andreas Kroll

Strategies for Feedback Linearisation

Freddy Garces, Victor M. Becerra, Chandrasekhar Kambhampati and Kevin Warwick

Robust Autonomous Guidance

Alberto Isidori, Lorenzo Marconi and Andrea Serrani

Dynamic Modelling of Gas Turbines

Gennady G. Kulikov and Haydn A. Thompson (Eds.)

Control of Fuel Cell Power Systems

Jay T. Pukrushpan, Anna G. Stefanopoulou and Huei Peng

Fuzzy Logic, Identification and Predictive Control

Jairo Espinosa, Joos Vandewalle and Vincent Wertz

Optimal Real-time Control of Sewer Networks

Magdalene Marinaki and Markos Papageorgiou

Process Modelling for Control

Benoît Codrons

Computational Intelligence in Time Series Forecasting

Ajoy K. Palit and Dobrivoje Popovic

Modelling and Control of mini-Flying Machines

Pedro Castillo, Rogelio Lozano and Alejandro Dzul

Rudder and Fin Ship Roll Stabilization

Tristan Perez

Hard Disk Drive Servo Systems (2nd Ed.)

Ben M. Chen, Tong H. Lee, Kemao Peng and Venkatakrishnan Venkataramanan

Measurement, Control, and Communication Using IEEE 1588

John Eidson

Piezoelectric Transducers for Vibration Control and Damping

S.O. Reza Moheimani and Andrew J. Fleming

Manufacturing Systems Control Design

Stjepan Bogdan, Frank L. Lewis, Zdenko Kovačić and José Mireles Jr.

Windup in Control

Peter Hippe

Nonlinear H_2/H_∞ Constrained Feedback Control

Murad Abu-Khalaf, Jie Huang and Frank L. Lewis

Practical Grey-box Process Identification

Torsten Bohlin

Modern Supervisory and Optimal Control

Sandor Markon, Hajime Kita, Hiroshi Kise and Thomas Bartz-Beielstein

Wind Turbine Control Systems

Fernando D. Bianchi, Hernán De Battista and Ricardo J. Mantz

Advanced Fuzzy Logic Technologies in Industrial Applications

Ying Bai, Hanqi Zhuang and Dali Wang (Eds.)

Practical PID Control

Antonio Visioli

Soft Sensors for Monitoring and Control of Industrial Processes

Luigi Fortuna, Salvatore Graziani, Alessandro Rizzo and Maria Gabriella Xibilia

Jie Bao and Peter L. Lee

Process Control

The Passive Systems Approach

 Springer

Jie Bao, PhD
School of Chemical Sciences
and Engineering
The University of New South Wales
Sydney
New South Wales
Australia

Peter L. Lee, PhD
The University of South Australia
Adelaide, South Australia
Australia

British Library Cataloguing in Publication Data

Bao, Jie

Process control : the passive systems approach. - (Advances
in industrial control)

1. Passivity-based control 2. Process control

I. Title II. Lee, Peter L., 1954-
629.8

ISBN-13: 9781846288920

Library of Congress Control Number: 2007928319

Advances in Industrial Control series ISSN 1430-9491

ISBN 978-1-84628-892-0

e-ISBN 978-1-84628-893-7

Printed on acid-free paper

© Springer-Verlag London Limited 2007

MATLAB® is a registered trademark of The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098, USA. <http://www.mathworks.com>

Aspen Plus® is a registered trademark of Aspen Technology, Inc., Ten Canal Park, Cambridge, MA 02141-2201, USA. <http://www.aspentech.com/>

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency. Enquiries concerning reproduction outside those terms should be sent to the publishers.

The use of registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant laws and regulations and therefore free for general use.

The publisher makes no representation, express or implied, with regard to the accuracy of the information contained in this book and cannot accept any legal responsibility or liability for any errors or omissions that may be made.

9 8 7 6 5 4 3 2 1

Springer Science+Business Media
springer.com

Advances in Industrial Control

Series Editors

Professor Michael J. Grimble, Professor of Industrial Systems and Director
Professor Michael A. Johnson, Professor (Emeritus) of Control Systems
and Deputy Director

Industrial Control Centre
Department of Electronic and Electrical Engineering
University of Strathclyde
Graham Hills Building
50 George Street
Glasgow G1 1QE
United Kingdom

Series Advisory Board

Professor E.F. Camacho
Escuela Superior de Ingenieros
Universidad de Sevilla
Camino de los Descubrimientos s/n
41092 Sevilla
Spain

Professor S. Engell
Lehrstuhl für Anlagensteuerungstechnik
Fachbereich Chemietechnik
Universität Dortmund
44221 Dortmund
Germany

Professor G. Goodwin
Department of Electrical and Computer Engineering
The University of Newcastle
Callaghan
NSW 2308
Australia

Professor T.J. Harris
Department of Chemical Engineering
Queen's University
Kingston, Ontario
K7L 3N6
Canada

Professor T.H. Lee
Department of Electrical Engineering
National University of Singapore
4 Engineering Drive 3
Singapore 117576

Professor Emeritus O.P. Malik
Department of Electrical and Computer Engineering
University of Calgary
2500, University Drive, NW
Calgary
Alberta
T2N 1N4
Canada

Professor K.-F. Man
Electronic Engineering Department
City University of Hong Kong
Tat Chee Avenue
Kowloon
Hong Kong

Professor G. Olsson
Department of Industrial Electrical Engineering and Automation
Lund Institute of Technology
Box 118
S-221 00 Lund
Sweden

Professor A. Ray
Pennsylvania State University
Department of Mechanical Engineering
0329 Reber Building
University Park
PA 16802
USA

Professor D.E. Seborg
Chemical Engineering
3335 Engineering II
University of California Santa Barbara
Santa Barbara
CA 93106
USA

Doctor K.K. Tan
Department of Electrical Engineering
National University of Singapore
4 Engineering Drive 3
Singapore 117576

Professor Ikuo Yamamoto
The University of Kitakyushu
Department of Mechanical Systems and Environmental Engineering
Faculty of Environmental Engineering
1-1, Hibikino, Wakamatsu-ku
Kitakyushu, Fukuoka, 808-0135
Japan

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
University of South Australia, Australia
February 2007

Jie Bao
Peter L. Lee

Contents

1	Introduction	1
2	Dissipativity and Passivity	5
2.1	Concept of Passive Systems	5
2.2	Properties of Passive Systems	11
2.2.1	Stability of Passive Systems	11
2.2.2	Kalman–Yacubovich–Popov Property	12
2.2.3	Input-Output Property	14
2.2.4	Phase-related Properties	17
2.3	Interconnection of Passive Systems	21
2.4	Passivity Indices	24
2.4.1	Excess and Shortage of Passivity	24
2.4.2	Passivity Indices for Linear Systems	28
2.5	Passivation	29
2.5.1	Input Feedforward Passivation	29
2.5.2	Output Feedback Passivation	30
2.6	Passivity Theorem	32
2.7	Heat Exchanger Example	36
2.8	Summary	41
3	Passivity-based Robust Control	43
3.1	Introduction	43
3.1.1	Uncertainties	44
3.1.2	Robust Stability	46
3.2	Characterization of Uncertainties	47
3.2.1	Uncertainty Bound Based on IFP	47
3.2.2	Uncertainty Bounds Based on Simultaneous IFP and OFP	51
3.3	Passivity-based Robust Control Framework	56
3.3.1	Robust Stability Condition	56
3.3.2	Robust Stability and Nominal Performance	57

3.3.3	Advantages and Limitations of Passivity-based Robust Control	59
3.3.4	Robust Control Design	59
3.3.5	Example of CSTR Control	65
3.4	Combining Passivity with the Small Gain Condition	69
3.4.1	Robust Stability Condition Based on Passivity and Gain	70
3.4.2	Control Synthesis	73
3.4.3	Robust Control of a Mixing System	77
3.5	Passive Controller Design	80
3.5.1	Problem Formulation	83
3.5.2	Contraction Map	84
3.5.3	Synthesis of SPR/ \mathcal{H}_∞ Control	84
3.5.4	Control Design Procedure	85
3.5.5	Illustrative Example	86
3.6	Summary	87
4	Passivity-based Decentralized Control	89
4.1	Introduction	89
4.2	Decentralized Integral Controllability	91
4.2.1	Passivity-based DIC Condition	93
4.2.2	Computational Methods	94
4.3	DIC Analysis for Nonlinear Processes	97
4.3.1	DIC for Nonlinear Systems	97
4.3.2	Sufficient DIC Condition for Nonlinear Processes	98
4.3.3	Computational Method for Nonlinear DIC Analysis	100
4.3.4	Nonlinear DIC Analysis for a Dual Tank System	101
4.4	Block Decentralized Integral Controllability	103
4.4.1	Conditions for BDIC	105
4.4.2	Pairing Based on BDIC	107
4.4.3	BDIC Analysis of the SFE Process	108
4.5	Dynamic Interaction Measure	110
4.5.1	Representing Dynamic Interactions	110
4.5.2	Passivity-based Interaction Measure	112
4.5.3	Examples	117
4.6	Decentralized Control Based on Passivity	120
4.6.1	Problem Formulation	120
4.6.2	Decentralized Control of Boiler Furnace	121
4.7	Summary	122
5	Passivity-based Fault-tolerant Control	125
5.1	Introduction	125
5.2	Representation of Sensor/Actuator Faults	126
5.3	Decentralized Unconditional Stability Condition	128
5.3.1	Passivity-based DUS Condition	128
5.3.2	Diagonal Scaling	130

5.3.3	Achievable Control Performance	131
5.3.4	Pairing for Dynamic Performance	132
5.4	Fault-tolerant Control Design for Stable Processes	135
5.4.1	Fault-tolerant PI Control	135
5.4.2	Decentralized Fault-tolerant \mathcal{H}_2 Control Design	139
5.4.3	Selecting the Weighting Function $w(s)$	140
5.4.4	Control Synthesis	141
5.4.5	Illustrative Example	146
5.5	Fault-tolerant Control Design for Unstable Processes	149
5.5.1	Static Output Feedback Stabilization	150
5.5.2	Fault-tolerant Control Synthesis	152
5.5.3	Illustrative Example	153
5.6	Hybrid Active-Passive Fault-tolerant Control Approach	156
5.6.1	Failure Mode and Effects Analysis	156
5.6.2	Fault Detection and Accommodation	157
5.6.3	Control Framework	159
5.7	Summary	160
6	Process Controllability Analysis Based on Passivity	161
6.1	Introduction	161
6.2	Analysis Based on Extended Internal Model Control	163
6.2.1	Extended Internal Model Control Framework	163
6.2.2	Controllability Analysis for Stable Linear Processes	166
6.3	Regions of Steady-state Attainability	171
6.3.1	Steady-state Region of Attraction	172
6.3.2	Steady-state Output Space Achievable via Linear Feedback Control	178
6.3.3	Steady-state Attainability by Nonlinear Control	181
6.3.4	Numerical Procedure	184
6.3.5	Case Study of a High-purity Distillation Column	185
6.4	Dynamic Controllability Analysis for Nonlinear Processes	187
6.5	Summary and Discussion	191
7	Process Control Based on Physically Inherent Passivity	
	<i>by K.M. Hangos and G. Szederkényi</i>	193
7.1	Thermodynamic Variables and the Laws of Thermodynamics	194
7.1.1	Extensive Variables, Entropy, Intensive Variables	194
7.1.2	Laws of Thermodynamics	197
7.1.3	Nonequilibrium Thermodynamics	198
7.2	The Structure of State Equations of Process Systems	199
7.2.1	State Variables and Order of Systems	200
7.2.2	Conservation Balances and Mechanisms	201
7.2.3	Constitutive Equations	202
7.2.4	State Equations of Process Systems	203
7.2.5	Implications in Process Control	204

7.2.6	Heat Exchanger Example	205
7.3	Physically Motivated Supply Rates and Storage Functions	207
7.3.1	Entropy-based Storage Functions	207
7.3.2	Possible Choices of Inputs and Outputs	210
7.3.3	Storage Function of the Heat Exchanger Example	210
7.4	Hamiltonian Process Models	212
7.4.1	System Structure and Variables	212
7.4.2	Generalized Hamiltonian Systems	213
7.4.3	Generalized Hamiltonian Systems with Dissipation	214
7.4.4	Hamiltonian Description of the Heat Exchanger Example	215
7.5	Case Study: Reaction Kinetic Systems	216
7.5.1	System Description, Thermodynamic Variables and State-space Model	217
7.5.2	The Reaction Simplex and the Structure of Equilibrium Points	217
7.5.3	Physically Motivated Storage Function	218
7.5.4	Passive Input-output Structure	219
7.5.5	Local Hamiltonian Description of Reversible Reaction Networks	221
7.6	Summary	224
A	Detailed Control Design Algorithms	225
A.1	Solution to the BMI Problem in SPR/ \mathcal{H}_∞ Control Design	225
A.2	DUS \mathcal{H}_2 Control Synthesis	226
A.2.1	Final LMI	226
A.2.2	SSDP Procedure	228
B	Mathematical Proofs	231
B.1	Phase Condition for MIMO Systems	231
B.2	Proof of Theorem 4.4	232
B.3	Proof of Theorem 4.8	235
B.4	Region of Steady-state Attainability	237
B.4.1	Nominal Stability of Nonlinear IMC	237
B.4.2	Proof of Theorem 6.6	239
B.4.3	Positive Invariance of Region of Attraction	240
B.4.4	Proof of Theorem 6.10	240
	References	243
	Index	251

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 n th 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 $f(t)$
$\text{Im}(A)$	imaginary part of complex matrix A
$\text{In}(A)$	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 $m \times n$
$\text{Re}(A)$	real part of complex matrix A
\sup	supremum (the least upper bound)
$\text{Tr}(A)$	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
$\sigma_i(A)$	i th singular value of matrix A
$\bar{\lambda}(A)$	maximum eigenvalue of matrix A

$\underline{\lambda}(A)$	minimum eigenvalue of matrix A
$\lambda_i(A)$	i th eigenvalue of matrix A
$\Lambda(A)$	RGA matrix of matrix A
$\lambda_{ij}(A)$	the ij th element of $\Lambda(A)$
$\Lambda_i(G(0))$	block relative gain (BRG) of the i th 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}_∞ -norm of a system $G(s)$
$\langle f, g \rangle$	inner production of f and g
\forall	for all