## Robust Industrial Control Systems: Optimal Design Approach for Polynomial Systems

Michael J. Grimble

University of Strathclyde, UK



**Robust Industrial Control Systems** 

## Robust Industrial Control Systems: Optimal Design Approach for Polynomial Systems

Michael J. Grimble

University of Strathclyde, UK



Copyright © 2006 John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk Visit our Home Page on www.wiley.com

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

#### Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

#### Library of Congress Cataloging-in-Publication Data

Grimble, Michael J.
Robust industrial control systems: optimal design approach for polynomial systems/Michael J. Grimble.
p. cm.
Includes bibliographical references and index.
ISBN 0-470-02073-3 (cloth: alk. paper)
Process control–Automation. I. Title.
TS156.8.G76 2006

2005031937

### British Library Cataloguing in Publication Data

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

ISBN-13 978-0-470-02073-9 (HB) ISBN-10 0-470-02073-3 (HB)

670.42'7-dc22

Typeset in 10/12pt Times by Thomson Press (India) Limited, New Delhi, India. Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production. To my dear family Wendy Claire, Mark and Callum Andrew and Christie

# **Contents**

Pr	reface				
Ac	Acknowledgements				
1	Introduction to Optimal and Robust Control			1	
	1.1 Introduction		luction	1	
		1.1.1	Optimality, Feedback and Robustness	2	
		1.1.2	High-integrity and Fault-tolerant Control Systems	3	
		1.1.3	Self-healing Control Systems	4	
		1.1.4	Fault Monitoring and Detection	5	
		1.1.5	Adaptive versus Robust Control	5	
		1.1.6	Artificial Intelligence, Neural Networks and Fuzzy Control	5	
		1.1.7	Discrete-time Systems	7	
	1.2	The <i>H</i>	$H_2$ and $H_\infty$ Spaces and Norms	8	
		1.2.1	Graphical Interpretation of the $H_{\infty}$ Norm	9	
		1.2.2	Terms Used in $H_{\infty}$ Robust Control Systems Design	9	
	1.3	Introd	luction to $H_{\infty}$ Control Design	9	
		1.3.1	Properties of $H_{\infty}$ Robust Control Design	11	
		1.3.2	Comparison of $H_{\infty}$ and $H_2/LQG$ Controllers	12	
		1.3.3	Relationships between Classical Design and $H_{\infty}$ Robust Control	13	
		1.3.4	$H_2$ and $H_\infty$ Design and Relationship to PID Control	13	
		1.3.5	$H_{\infty}$ Polynomial Systems Synthesis Theory	13	
	1.4	State-	Space Modelling and Synthesis Theory	14	
		1.4.1	State-space Solution of Discrete-time $H_{\infty}$ Control Problem	14	
		1.4.2	$H_{\infty}$ Control Design Objectives	15	
		1.4.3	State-feedback Control Solution	15	
		1.4.4	State-feedback Control Problem: Cross-product Costing Case	18	
		1.4.5	State-space Solution of Discrete-time $H_{\infty}$ Filtering Problem	19	
		1.4.0	Bounded Real Lemma	21	
	15	1.4.7	Output Feedback $H_{\infty}$ Control Problem	24	
	1.5	Introd	Suction to $H_2$ or LQG Polynomial Synthesis	29	
		1.5.1	System Description	29	
		1.5.2	Cost Function and Solution	31 21	
		1.5.3	Minimisation of the Performance Criterion	31	

		1.5.4	Solution of the Diophantine Equations and Stability	34
		1.5.5	$H_2/LQG$ Design Examples	35
	1.6	Bench	nmarking	40
		1.6.1	Restricted Structure Benchmarking	41
		1.6.2	Rules for Benchmark Cost Function Selection	42
	1.7	Condi	ition Monitoring	44
	1.8	Comb	bining $H_2$ , $H_\infty$ and $\ell_1$ Optimal Control Designs	45
	1.9	Linea	r Matrix Inequalities	46
	1.10	Concl	luding Remarks	47
	1.11	Proble	ems	48
	1.12	Refer	ences	51
2	Sca	lar H	2 and LQG Optimal Control	57
	2.1	Introd	luction	57
		2.1.1	Industrial Controller Structures	58
		2.1.2	The 2 <sup>1</sup> / <sub>2</sub> -DOF Structure	59
		2.1.3	Restricted Structure Control Laws	60
	2.2	Stoch	astic System Description	60
		2.2.1	Ideal Response Models	62
		2.2.2	System Equations	62
		2.2.3	Cost Function Weighting Terms	63
	2.3	Dual-	criterion Cost-minimisation Problem	64
		2.3.1	Solution of the Dual-criterion Minimisation Problem	66
		2.3.2	Theorem Summarising LQG Controller	71
		2.3.3	Remarks on the Equations and Solution	73
		2.3.4	Design Guidelines	76
		2.3.5	Controller Implementation	77
		2.3.6	LQG Ship-steering Autopilot Application	78
	2.4	LQG	Controller with Robust Weighting Function	82
		2.4.1	Youla Parameterisation	82
		2.4.2	Cost Function with Robust Weighting Function	83
		2.4.3	Solution of the Dual-criterion Problem	
			with Robust Weighting	84
		2.4.4	Summary of $H_2/LQG$ Synthesis Problem	
			with Robust Weighting	86
		2.4.5	Comments on the Solution	88
	2.5	Introd	luction to the Standard System Model	89
		2.5.1	Standard System Model	89
	2.6	The S	Standard System Model Structure	91
		2.6.1	Polynomial System Models	92
		2.6.2	Reference Model	93
		2.6.3	Cost Function Signals to be Weighted	94
	2.7	Gener	ralised H <sub>2</sub> Optimal Control: Standard System Model	95
		2.7.1	Optimal Control Solution of the Standard System	
			Model Problem	96

		2.7.2	Summary of $H_2/LQG$ Controller for Standard	
			System Results	102
		2.7.3	Remarks on the Solution	104
	2.8	Concl	uding Remarks	105
	2.9	Proble	ems	105
	2.10	Refer	ences	109
3	$H_\infty$	Opti	mal Control of Scalar Systems	113
	3.1	Introd	luction	113
		3.1.1	Links Between $LQG$ and $H_{\infty}$ Solutions	114
		3.1.2	Reference and Feedback Controller Designs	115
	3.2	System	m Description	115
	3.3	Lemn	na Linking $H_{\infty}$ and LQG Control Problems	115
	3.4	Calcu	lation of the $H_{\infty}$ Optimal Controller	116
		3.4.1	Simple $H_{\infty}$ Controller Structures and Calculations	117
		3.4.2	Zero Measurement Noise Case	117
		3.4.3	Solution for the $H_{\infty}$ Optimal Controller	118
		3.4.4	Stability Robustness of Mixed-sensitivity $H_{\infty}$ Designs	121
		3.4.5	One-block $H_{\infty}$ Control Problems	122
	3.5	The C	$GH_{\infty}$ Control Problem	123
		3.5.1	$GH_{\infty}$ Cost Function Definition	124
		3.5.2	Youla Parameterised Form of the $GH_{\infty}$ Controller	126
		3.5.3	Calculation of the $GH_{\infty}$ Controller	128
	3.6	Stabil	ity Robustness of $GH_{\infty}$ Designs	136
		3.6.1	Structure of the Uncertain System	136
		3.6.2	Rational Uncertainty Structure	137
		3.6.3	Stability Lemma	139
		3.6.4	Influence of the Uncertainty Model	140
		3.6.5	Design Procedure for Uncertain Systems	140
		3.6.6	$H_{\infty}$ Self-Tuning Controller for Systems with	1 47
	27	G ( 1	Parametric Uncertainty	147
	3.7	Stand	ard System and Cost Function Description	147
	3.8		lation of $H_{\infty}$ Controller for the Standard System	14/
		3.8.1	F-iteration Method of Solving the Robust weighting Equation	148
	2.0	J.ð.Z Droha	$H_2/H_\infty$ If a de-off bilistic System Descriptions and $H_\infty$ Control	149
	5.9	2 0 1	Uncertain System Model	150
		2.9.1	Cost Function Definition	151
		3.9.2	Uncertain System and Polynomial Equation Depresentation	155
		5.9.5 2.0.4	Discussion of Probabilistic Uncertainty Modelling	155
		5.7.4	and Control	150
	3 10	Concl	and Control	150
	3.10	Proble		150
	3 12	Refer	ences	163

4	Mu	ltivariable <i>H</i> <sub>2</sub> / <i>LQG</i> Optimal Control	167
	4.1	Introduction	167
		4.1.1 Matrix Fraction Descriptions	168
	4.2	Multivariable System Description	168
		4.2.1 Multivariable Sensitivity Matrices and Signal Spectra	170
		4.2.2 Choice of Noise and Cost Function Weightings	171
	4.3	LQG Optimal Control Problem and Solution	171
		4.3.1 Solution of the $H_2/LQG$ Problem	172
		4.3.2 Solution of the Diophantine Equations	175
	4.4	Youla Parameterisation and Auxiliary Problem	182
		4.4.1 Youla Parameterisation for the Auxiliary Problem	184
		4.4.2 Summary of Multivariable Problem Results	
		with Robust Weighting	186
	4.5	H <sub>2</sub> /LQG Optimal Control Problem: Measurement Noise Case	187
		4.5.1 Predictive Optimal Control	190
		4.5.2 SIMO Predictive Optimal Control Problem	190
		4.5.3 Probabilistic Description of Uncertainty	196
	4.6	The GLQG Optimal Control Problem	196
		4.6.1 Solution of the GLQG Problem	197
		4.6.2 Modified GLQG Cost Function and Youla Parameterisation	199
	4.7	Design of Automatic Voltage Regulators	200
	4.8	Pseudo-state Modelling and Separation Principle	210
		4.8.1 Introduction to Pseudo-state Methods	210
		4.8.2 Pseudo-state Discrete-time Plant Model	211
		4.8.3 Discrete Pseudo-state Feedback Optimal Control	215
		4.8.4 Solution of the Pseudo-state Feedback Control Problem	217
		4.8.5 Discrete Pseudo-state Estimation Problem	222
		4.8.6 Solution of the Discrete-time pseudo-state Estimation Problem	224
		4.8.7 Output Feedback Control Problem and Separation Principle	230
		4.8.8 Computational Example	235
		4.8.9 Pseudo-state Approach Remarks	240
	4.9	Concluding Remarks	240
	4.10	Problems	241
	4.11	References	245
5	Mu	ltivariable $H_\infty$ Optimal Control	249
	5.1	Introduction	249
		5.1.1 Suboptimal $H_{\infty}$ Control Problems	250
	5.2	$H_{\infty}$ Multivariable Controllers	250
		5.2.1 Derivation of the Weighting Filter $W_{\sigma}$	251
		5.2.2 Robust Weighting Equation	252
		5.2.3 Calculation of the $H_{\infty}$ Optimal Controller	253
		5.2.4 Superoptimality in $H_{\infty}$ Design	258
		5.2.5 Single-input Multi-output Systems	259

	5.3	One-b	lock and $GH_{\infty}$ Optimal Control Problems	259
		5.3.1	One-block Nehari Problems	259
		5.3.2	Categories of Nehari Problem	260
		5.3.3	Constraint on the Choice of Weights for Simplified Design	261
		5.3.4	$GH_{\infty}$ Optimal Control Problem	262
		5.3.5	Final Remarks on LQG Embedding $H_{\infty}$ Solution	267
	5.4	Subop	timal $H_{\infty}$ Multivariable Controllers	268
		5.4.1	System Description and Game Problem	269
		5.4.2	Linear Fractional Transformation	271
		5.4.3	Signals and Bounded Power Property	271
		5.4.4	System and Cost Weighting Function Definitions	272
	5.5	Polyne	omial System for Suboptimal $H_{\infty}$ Control Problem	273
		5.5.1	J-spectral Factorisation	274
		5.5.2	Diophantine Equations for Causal and Noncausal	
			Decomposition	274
	5.6	Soluti	on of Suboptimal $H_\infty$ State Feedback Problem	275
		5.6.1	Discrete-time Game Problem	275
		5.6.2	Relationship Between the Game and $H_{\infty}$ Problems	276
		5.6.3	Standard System Model Equations and Sensitivity	277
		5.6.4	Completing-the-squares	277
		5.6.5	Cost Index Terms	278
		5.6.6	Cost Integrand Simplification	279
		5.6.7	Contour Integral Simplification	279
		5.6.8	Optimal Control Law Calculation	280
		5.6.9	Expression for $H_0^T J H_0$	281
		5.6.10	Saddle-point Solution	282
		5.6.11	Expression for the Minimum Cost	283
	5.7	Subop	timal $H_{\infty}$ State-feedback Control Problem	284
		5.7.1	Remarks on the Solution	285
	5.8	Relati	onship Between Polynomial and State-Space Results	287
		5.8.1	J-spectral Factorisation Using Riccati Equation	288
		5.8.2	Relationship between the Polynomial and	
			State-space Equations	290
	5.9	Soluti	on of Suboptimal Output Feedback Control Problem	291
		5.9.1	Final Remarks on the Suboptimal $H_\infty$ Solution	291
	5.10	Proble	ems	292
	5.11	Refere	ences	295
6	Rok	oust C	Control Systems Design and Implementation	299
	6.1	Introd	uction	299
		6.1.1	The Control Design Problem	300
		6.1.2	Justification for $H_{\infty}$ Control Design	302
		6.1.3	Dynamic Cost Function Weightings	303
		6.1.4	Properties of Sensitivity Functions for	
			Discrete-time Systems	304

6.2	Avoid	ing Impractical $H_{\infty}$ Designs	306
	6.2.1	Equalising $H_{\infty}$ Solutions and Implications for	
		Multivariable Design	307
6.3	Pole-z	zero Cancellation Properties of LQG and $H_{\infty}$ Designs	308
	6.3.1	Polynomial Systems Approach	308
	6.3.2	$H_2/LQG$ Optimal Control Problem	308
	6.3.3	$H_{\infty}$ Optimal Control Problem	310
	6.3.4	Cancellation of Minimum-phase Plant Zeros	311
	6.3.5	Cancellation of Stable Plant Poles	312
	6.3.6	Sendzimir Steel Rolling Mill Results	314
6.4	Syster	n Pole and Zero Properties	314
	6.4.1	Controller Poles and Zeros due to Weightings	314
	6.4.2	Poles of the Closed-loop System	315
6.5	Influe	nce of Weightings on Frequency Responses	316
	6.5.1	Stability Criterion and Cost Function Weighting Selection	316
	6.5.2	Influence of the Choice of Weights on the Sensitivity	
		Functions	317
	6.5.3	Use of Constant Cost Weightings in $H_{\infty}$ Design	319
	6.5.4	Poor Robustness due to Unrealistic Weightings	320
6.6	Loop	Shaping Design for Multivariable Systems	324
	6.6.1	Singular Value Approximations	324
	6.6.2	Robustness and Loop Shaping	326
	6.6.3	Stability and Performance Boundaries	327
	6.6.4	Robust Design for Systems in Standard Model Form	328
	6.6.5	Structured Singular Values	330
6.7	Forma	alised Design Procedures	331
	6.7.1	Steps in a $H_{\infty}$ Design Procedure	331
	6.7.2	Cost Function Weighting Selection for Scalar Systems	332
6.8	Mutiv	ariable Robust Control Design Problem	334
	6.8.1	Problems in Multivariable Control	335
	6.8.2	Poles and Zeros of Multivariable Systems	336
	6.8.3	Interaction Measures	337
6.9	Multi	variable Control of Submarine Depth and Pitch	337
	6.9.1	Selection of Weights in Multivariable Problems	337
	6.9.2	Multivariable Submarine Motion Control	338
	6.9.3	Multivariable Submarine Control Design Results	340
	6.9.4	Speed of Response and Interaction	343
	6.9.5	Order of the Weighting Terms	346
	6.9.6	Two-degree-of-freedom Submarine Control	346
6.10	Restri	cted Structure and Multiple Model Control	346
	6.10.1	Feedforward and Feedback Polynomial System Plant	347
	6.10.2	$H_2/LQG$ Restricted Structure Optimal Control Problem	350
	6.10.3	Numerical Algorithm for Single- and Multi-model Systems	362
	6.10.4	Hot Strip Finishing Mill Tension Control	370
	6.10.5	Benefits of Multiple-model Approach	379
	6.10.6	Restricted Structure Benchmarking	379

	6.11 6.12	Concluding Remarks	381 382
	6.13	References	384
7	$H_2$	Filtering, Smoothing and Prediction	389
	7.1	Introduction	389
		7.1.1 Standard Signal Processing Model	390
	7.2	Signal Processing System Description	390
		7.2.1 Summary of Estimation Problem Assumptions	391
		7.2.2 Optimal Estimator Transfer-function	392
		7.2.3 System Equations	392
		7.2.4 Polynomial Matrix Descriptions	392
		7.2.5 Spectral Factorisation	393
	7.3	The Standard $H_2$ Optimal Estimation Problem	393
		7.3.1 $H_2$ Standard System Model Estimation Problem Solution	394
		7.3.2 Estimation Error Power Spectrum: Completion of Squares	394
		7.3.3 Wiener Filtering Solution	395
		7.3.4 Introduction of the First Diophantine Equation	396
		7.3.5 Optimal Estimator when Signal Model Stable	396
		7.3.6 Optimal Estimator when Signal Model can be Unstable	399
		7.3.7 Optimal Estimator when Signal Model can be Unstable	404
	7.4	Solution of Filtering, Smoothing and Predication Problems	408
		7.4.1 State Estimation Problem	408
		7.4.2 Output Filtering and Prediction	409
		7.4.3 Deconvolution Estimation	410
		7.4.4 Robust Weighting Function $W_{\sigma}$	413
		7.4.5 Extensions of the Estimator Capabilities	414
	7.5	Strip Thickness Estimation from Roll Force Measurements	415
		7.5.1 Rolling Mill Model	416
		7.5.2 Continuous-time Dynamic Mill Model	416
	7.6	Strip Thickness Estimation Using Force Measurments	418
	7.7	Strip Thickness Estimation Using X-Ray Gauge Measurements	421
	7.8	Strip Thickness Estimation Using Gauge Measurements	422
	7.9	Time-Varying and Nonstationary Filtering	426
		7.9.1 Linear Multichannel Estimation Problem	428
		7.9.2 Output Estimation Problem	431
	= 10	7.9.3 Relationship to the Kalman Filtering Problem	435
	7.10	Conclusions	440
	7.11	Problems	441
	7.12	References	442
8	$H_\infty$	Filtering, Smoothing and Prediction	445
	8.1	Introduction	445
		8.1.1 The $H_{\infty}$ Filtering Problem	446