

Editors

Professor Dr.-Ing. Manfred Thoma
Institut fuer Regelungstechnik, Universität Hannover, Appelstr. 11, 30167 Hannover,
Germany
E-mail: thoma@irt.uni-hannover.de

Professor Dr. Frank Allgöwer
Institute for Systems Theory and Automatic Control, University of Stuttgart,
Pfaffenwaldring 9, 70550 Stuttgart, Germany
E-mail: allgower@ist.uni-stuttgart.de

Professor Dr. Manfred Morari
ETH/ETL I 29, Physikstr. 3, 8092 Zürich, Switzerland
E-mail: morari@aut.ee.ethz.ch

Series Advisory Board

P. Fleming
University of Sheffield, UK

P. Kokotovic
University of California, Santa Barbara, CA, USA

A.B. Kurzhanski
Moscow State University, Russia

H. Kwakernaak
University of Twente, Enschede, The Netherlands

A. Rantzer
Lund Institute of Technology, Sweden

J.N. Tsitsiklis
MIT, Cambridge, MA, USA

Chunyu Yang, Qingling Zhang, and Linna Zhou

Stability Analysis and Design for Nonlinear Singular Systems

 Springer

Authors

Chunyu Yang
School of Information and Electrical
Engineering
China University of Mining and Technology
Xuzhou
P.R. China

Linna Zhou
School of Information and Electrical
Engineering
China University of Mining and Technology
Xuzhou
P.R. China

Qingling Zhang
Institute of Systems Science
Northeastern University
Shenyang
P.R. China

ISSN 0170-8643
ISBN 978-3-642-32143-6
DOI 10.1007/978-3-642-32144-3
Springer Heidelberg New York Dordrecht London

e-ISSN 1610-7411
e-ISBN 978-3-642-32144-3

Library of Congress Control Number: 2012942952

© Springer-Verlag Berlin Heidelberg 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

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

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

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

Preface

In the past several decades, singular systems have been one of the major research fields of control theory because of their extensive applications in the Leontief dynamic model, electrical and mechanical models, etc. Depending on the area of applications, these models are also called descriptor systems, semi-state systems, differential-algebraic systems or generalized state-space systems. On the stability of linear time-invariant singular systems, many necessary and sufficient conditions have been reported. However, the stability problem for nonlinear singular systems has not been thoroughly investigated. This monograph aims to present up-to-date research developments and references on stability analysis and design of nonlinear singular systems. It investigates the problems of practical stability, strongly absolute stability, input-state stability and observer design for nonlinear singular systems and the problems of absolute stability and multi-objective control for nonlinear singularly perturbed systems by using Lyapunov stability theory, comparison principle, S-procedure and linear matrix inequality (LMI) etc.. It contains valuable reference material for researchers wishing to explore the area of singular systems, and its contents are also suitable for a one-semester graduate course.

In this monograph, practical stability of nonlinear singular systems is firstly studied. The basic concepts and results on practical stability for standard state-space systems are generalized to singular systems. Then, strongly absolute stability of Lur'e singular systems is defined. Circle criterion and Popov criterion are derived. The notion of input-state stability (ISS) for nonlinear singular systems is defined based on the concept of ISS for standard state-space systems and the characteristics of singular systems. LMI-based sufficient conditions for ISS of Lur'e singular systems are proposed. Furthermore, observer design for nonlinear singular systems is studied and some observer design methods are proposed by the obtained stability results and convex optimization algorithms. Finally, absolute stability and multi-objective control of nonlinear singularly perturbed systems are studied. Using ε -dependent Lyapunov functions, absolute stability criteria of Lur'e singularly perturbed systems are derived and multi-objective control of T-S fuzzy singularly perturbed systems is achieved. Compared with the existing results, the obtained methods do not depend

on the decomposition of the original system and can produce a determinate upper bound for the singular perturbation parameter.

The work was partially supported by the National Natural Science Foundation of China (60904009, 60904079, 60974004, 61020106003), the Fundamental Research Funds for the Central Universities (N110408001, N100406010), the National Basic Research Program of China (2009CB320601) and the 111 project (B08015).

Xuzhou, China
June, 2012

Chunyu Yang
Qingling Zhang
Linna Zhou

Contents

1	Introduction	1
1.1	Models for Singular Systems	1
1.2	Singular Systems	5
1.2.1	Linear Singular Systems	6
1.2.2	Nonlinear Singular Systems	7
1.3	Singularly Perturbed Systems	8
1.4	Overview of the Monograph	9
2	Practical Stability Analysis and Synthesis for Nonlinear Singular Systems	13
2.1	Introduction	13
2.2	Preliminaries	14
2.3	Practical Stability Analysis for Nonlinear Singular Systems	16
2.3.1	Problem Formation	16
2.3.2	Main Results	17
2.3.3	Example	20
2.3.4	Concluding Remarks	24
2.4	Practical Stability Analysis for Nonlinear Singular Systems with Disturbance Input	25
2.4.1	Problem Formation	25
2.4.2	Main Results	26
2.4.3	Example	28
2.4.4	Concluding Remarks	34
2.5	Practical Stability of Singular Systems with Time Delays in Terms of Two Measurements	34
2.5.1	Problem Formation	34
2.5.2	Main Results	35
2.5.3	Example	38
2.5.4	Concluding Remark	40
2.6	Practical Stabilization for Nonlinear Singular Systems	40
2.6.1	Problem Formation	40
2.6.2	Comparison Principle	42

2.6.3	Main Results	43
2.6.4	Concluding Remark	47
3	Strongly Absolute Stability Analysis for Lur'e Singular Systems	49
3.1	Introduction	49
3.2	Preliminaries	50
3.2.1	Basic Definitions	50
3.2.2	Basic Lemmas	52
3.2.3	Positive Realness of Singular Systems	54
3.3	Circle Criterion: SISO Case	56
3.3.1	Problem Formation	56
3.3.2	Main Results	57
3.3.3	Examples	64
3.3.4	Concluding Remarks	66
3.4	Circle Criterion: MIMO Case	67
3.4.1	Problem Formation	67
3.4.2	Main Results	67
3.4.3	Examples	72
3.4.4	Concluding Remarks	73
3.5	Popov Criterion	73
3.5.1	Problem Formation	73
3.5.2	Main Results	74
3.5.3	Example	82
3.5.4	Concluding Remarks	84
3.6	Popov-Like Criterion	85
3.6.1	Problem Formulation	85
3.6.2	Generalized Lur'e Lyapunov Function	85
3.6.3	Main Results	87
3.6.4	Examples	96
3.6.5	Concluding Remarks	99
4	Input-to-State Stability Analysis and Design for Lur'e Singular Systems	101
4.1	Introduction	101
4.2	Preliminaries	102
4.3	Input-to-State Stability Analysis and Design for a Class of Lur'e Singular Systems	103
4.3.1	Problem Formulation	103
4.3.2	Main Results	104
4.3.3	Example	110
4.3.4	Concluding Remark	111
4.4	Input-to-State Stability for Lur'e Singular Systems with Unstable Linear Subsystems	112
4.4.1	Problem Formulation	112
4.4.2	Main Results	113

4.4.3	Example	122
4.4.4	Concluding Remark	123
5	Observer Design for Nonlinear Singular Systems	125
5.1	Introduction	125
5.2	Observer Design for a Class of Nonlinear Singular Systems	127
5.2.1	Preliminaries	127
5.2.2	Main Results	128
5.2.3	Example	135
5.2.4	Concluding Remark	137
5.3	H_∞ Observer Design for Singular Systems with Slope-Restricted Nonlinearities	138
5.3.1	Preliminaries	138
5.3.2	Main Results	139
5.3.3	Examples	147
5.3.4	Concluding Remarks	153
6	Absolute Stability of Lur'e Singularly Perturbed Systems	155
6.1	Introduction	155
6.2	Preliminaries	157
6.3	Circle Criterion	158
6.3.1	Problem Formulation	158
6.3.2	Main Results	159
6.3.3	Example	161
6.4	Popov Criterion	163
6.4.1	Problem Formulation	163
6.4.2	A Lur'e Lyapunov Function for Lur'e SPSs	164
6.4.3	Main Results	167
6.4.4	Examples	170
6.5	Concluding Remarks	173
7	Multi-objective Control for T-S Fuzzy Singularly Perturbed Systems	175
7.1	Introduction	175
7.2	Problem Formulation	177
7.3	Main Results	180
7.4	Example	189
7.4.1	Case I: \mathbf{D} Is the Open Left-Half Plane	191
7.4.2	Case II: \mathbf{D} Is a Conic Sector Region	191
7.5	Concluding Remarks	195
	References	197
	Index	209

Acronyms

PR	positive real
SPR	strictly positive real
ESPR	extended strictly positive real
LMI	linear matrix inequality
KYP	Kalman-Yakubovich-Popov
SPS	singularly perturbed system
ISS	input-to-state stability
GLLF	generalized Lur'e Lyapunov function
SISO	single-input-single-output
MIMO	multiple-input-multiple-output