

SINGULARLY PERTURBATION METHOD FOR MULTIVARIABLE
PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROLLER TUNING

MASHITAH BINTI CHE RAZALI

UNIVERSITI TEKNOLOGI MALAYSIA

UNIVERSITI TEKNOLOGI MALAYSIA

DECLARATION OF THESIS / UNDERGRADUATE PROJECT PAPER AND COPYRIGHT

Author's full name : MASHITAH BINTI CHE RAZALI

Date of Birth : 16 SEPTEMBER 1988

Title : SINGULARLY PERTURBATION METHOD FOR MULTIVARIABLE PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROLLER TUNING

Academic Session : 2014/2015 -1

I declare that this thesis is classified as:

- CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*
- RESTRICTED** (Contains restricted information as specified by the organization where research was done)*
- OPEN ACCESS** I agree that my thesis to be published as online open access (full text)

I acknowledged that Universiti Teknologi Malaysia reserves the right as follows:

1. The thesis is the property of Universiti Teknologi Malaysia
2. The Library of Universiti Teknologi Malaysia has the right to make copies for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by:

SIGNATURE

880916115288

(NEW IC NO. /PASSPORT NO.)

Date: **14 OCTOBER 2014**

SIGNATURE OF SUPERVISOR

ASSOC. PROF. DR. NORHALIZA ABD
WAHAB

NAME OF SUPERVISOR

Date: **14 OCTOBER 2014**

NOTES: * If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentiality or restriction.

“I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of the degree of Master of Engineering (Electrical)”



Signature :
Name of Supervisor : Assoc. Prof. Dr. Norhaliza Abd Wahab
Date : October 14, 2014

BAHAGIAN A – Pengesahan Kerjasama*

Adalah disahkan bahawa projek penyelidikan tesis ini telah dilaksanakan melalui kerjasama antara _____ dengan _____

Disahkan oleh:

Tandatangan : Tarikh :

Nama :

Jawatan :

(Cop rasmi)

** Jika penyediaan tesis/projek melibatkan kerjasama.*

BAHAGIAN B – Untuk Kegunaan Pejabat Fakulti Kejuruteraan Elektrik

Tesis ini telah diperiksa dan diakui oleh:

Nama dan Alamat : **Prof. Madya Dr. Samsul Bahari bin Mohd Noor**
Pemeriksa Luar **Jabatan Kejuruteraan Elektrik & Elektronik,**
Fakulti Kejuruteraan,
Universiti Putra Malaysia,
43400 Serdang, Selangor.

Nama dan Alamat : **Prof. Madya Dr. Yahaya bin Md Sam**
Pemeriksa Dalam I **Fakulti Kejuruteraan Elektrik,**
Universiti Teknologi Malaysia,
81310 UTM Johor Bahru.

Pemeriksa Dalam II :

Nama Penyelia lain :
(jika ada)

Disahkan oleh Timbalan Dekan (Pengajian Siswazah & Penyelidikan) / Ketua Jabatan Program Pengajian Siswazah:

Tandatangan : Tarikh :

Nama :

SINGULARLY PERTURBATION METHOD FOR MULTIVARIABLE
PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROLLER TUNING


MASHITAH BINTI CHE RAZALI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

OCTOBER 2014

“I declare that this thesis entitled “*Singularly Perturbation Method for Multivariable Proportional-Integral-Derivative Controller Tuning*” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree”

Signature : 

Name : Mashitah Binti Che Razali

Date : October 14, 2014

I lovingly dedicate this thesis:

To my beloved husband who supported me each step of the way,
To my beloved mum who cheer me with endless support and enthusiasm,
To my beloved family and family in law who encourage me in everything,
To my beloved friends who helped a lot during finished this research.

Without those caring support,
It would not have been possible for me to complete this research.

Thank you with love.

ACKNOWLEDGMENTS

I would like to thank my supervisor Assoc. Prof. Dr. Norhaliza Abdul Wahab for her guidance and encouragement throughout the period of conducting this research which gave me the experience and knowledge in the field of singularly perturbation system and multivariable PID controller tuning.

My special thanks go to my husband, Mohd Haziq Mahmud, who were more than generous with her boundless care and precious time. I also wish million thanks to my mother, Madam Melah Salleh for her great support morally and educationally. Additionally, I am deeply grateful to my beloved family and family in law who has been a great source of inspiration and cooperation during undergoing the research study.

I am also indebted to Universiti Teknikal Malaysia Melaka (UTeM) for funding my master study. Deepest thanks to the postgraduate students, technician at Process Control Laboratory at UTM and those that their names were not mentioned for their support and assistance in making this thesis real.

ABSTRACT

Efficient controls of industrial processes are of great importance. The industrial control performance has to be met with the desired optimum operation. However, the tuning process always becomes a challenging matter especially for Multiple-Input Multiple-Output (MIMO) system with two-time scale characteristic. This motivates the use of singularly perturbation method into the designs of Multivariable Proportional-Integral-Derivative (MPID) controller tuning. The singularly perturbation method based on Naidu and Jian Niu were considered and tested. It is observed that singularly perturbation system by Naidu method gives a good approximation at low, middle and high frequencies. Two MIMO systems with two-time scale characteristic, wastewater treatment plant and Newell and Lee evaporator were used as a test bed. Traditionally, the MPID controller tuning namely Davison, Penttinen-Koivo, Maciejowski and Combined are based on full order static matrix inverse model. In this work, the singularly perturbed MPID controller tuning methods were proposed based on the dynamic matrix inverse to improve the tuning of the system. Furthermore, Particle Swarm Optimization has been applied in tuning the parameters for an optimum control performance. Comparing the closed loop performance and process interaction presented by the traditional MPID and singularly perturbed MPID controller methods, the latter method is able to improve the transient responses, provide low steady state error and reduce the process interaction.

ABSTRAK

Kawalan yang berkesan memainkan peranan yang sangat penting di dalam sesebuah proses industri. Prestasi kawalan bagi setiap industri hendaklah mencapai tahap operasi optimum yang diperlukan. Walau bagaimanapun, proses penalaan sering menjadi satu perkara yang mencabar terutamanya apabila melibatkan sistem yang mempunyai pembolehubah yang Berbilang-Input Berbilang-Output (MIMO) dengan ciri skala dua-kali. Ini mendorong kepada penggunaan kaedah usikan bersendirian ke dalam strategi mereka bentuk pengawal penalaan Pembolehubah Pelbagai Terbitan Penting Seimbang (MPID). Kaedah usikan bersendirian berdasarkan Naidu dan Jian Niu telah diguna dan diuji. Adalah diperhatikan bahawa kaedah usikan bersendirian oleh Naidu menawarkan anggaran yang baik pada frekuensi yang rendah, sederhana dan tinggi. Dua sistem MIMO dengan ciri skala dua-kali, iaitu loji rawatan air kumbahan dan penyejat Newell dan Lee telah digunakan untuk ujikaji. Pengawal penalaan tradisional MPID, Davison, Penttinen-Koivo, Maciejowski dan Combine adalah berdasarkan kepada model asal matrik statik songsang. Di sini, kaedah pengawal penalaan MPID usikan bersendirian berdasarkan matrik dinamik songsang telah dicadangkan bagi memperbaiki proses penalaan. Selain itu, Pengoptimuman Zarah Terkumpul telah diguna untuk mendapatkan parameter penalaan untuk kawalan yang optimum. Berdasarkan perbandingan bagi prestasi gelung tertutup dan proses interaksi di antara MPID tradisional dan MPID usikan bersendirian, kaedah yang kedua dapat meningkatkan tindak balas sementara, memberikan ralat keadaan mantap yang rendah dan mengurangkan proses interaksi.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xi
	LIST OF FIGURES	xiii
	LIST OF ABBREVIATIONS	xvi
	LIST OF SYMBOLS	xviii
	LIST OF APPENDICES	xx
1	INTRODUCTION	1
	1.1 Problem Statement	2
	1.2 Research Objectives	3
	1.3 Research Scope	4
	1.4 Contribution of the Research Work	4
	1.5 Outline of the Thesis	5
2	LITERATURE REVIEW	6
	2.1 Introduction	6
	2.2 Multivariable PID Control	6

2.3	Conventional MPID Controller	9
2.4	Singularly Perturbed Multivariable Controller	10
2.5	Singularly Perturbation Method for Continuous System	13
2.5.1	Naidu Method	14
2.5.2	Jian Niu Method	17
2.6	Optimized Singularly Perturbed MPID Tuning	21
2.6.1	Particle Swarm Optimization (PSO)	22
2.6.2	Particle Swarm Optimization (PSO) Algorithm	24
2.7	Summary	28
3	SINGULARLY PERTURBED MPID CONTROLLER DESIGN	29
3.1	Introduction	29
3.2	MPID Controller Design Technique	30
3.2.1	Davison Method	30
3.2.2	Penttinen-Koivo Method	31
3.2.3	Maciejowski Method	32
3.2.4	Combined Method	33
3.3	Framework	33
3.4	Summary	34
4	CASE STUDY I: WASTEWATER TREATMENT PLANT (WWTP)	35
4.1	Introduction	35
4.2	Activated Sludge Wastewater Treatment Plant	35
4.3	Linearized Model	38
4.4	Time Scale Analysis	41
4.5	Singularly Perturbation Method Applied to Wastewater Treatment Plant	43
4.5.1	Singularly Perturbation Method	43

	by Naidu	
	4.5.2 Singularly Perturbation Method by Jian Niu	44
	4.5.3 Model Validation	45
4.6	Controllability Analysis	48
4.7	Relative Gain Array (RGA) Analysis	49
4.8	Result and Discussion	51
	4.8.1 MPID Control for Full Order and Singularly Perturbed System Based on Particle Swarm Optimization	52
	4.8.2 Implementation of Singularly Perturbed MPID Control	62
	4.8.3 Closed Loop Stability Analysis	75
4.9	Summary	79
5	CASE STUDY II: NEWELL AND LEE EVAPORATOR	80
5.1	Introduction	80
5.2	Newell and Lee Evaporator System	81
5.3	Linearized Model	85
5.4	Time Scale Analysis	88
5.5	Singularly Perturbation Method for Newell and Lee Evaporator	89
	5.5.1 Model Validation	91
5.6	Controllability Analysis	94
5.7	Relative Gain Array (RGA) Analysis	95
5.8	Result and Discussion	96
	5.8.1 MPID Control for Full Order and Singularly Perturbed System Based on Particle Swarm Optimization	97
	5.8.2 Implementation of Singularly Perturbed MPID Control	104
5.9	Closed Loop Stability Analysis	117

5.10	Summary	118
6	CONCLUSION AND FUTURE WORK	120
6.1	Conclusion	120
6.2	Future Work	122
	REFERENCES	123
	Appendices A-D	131-151

LIST OF TABLES

TABLE NO.	TITLE	PAGE
4.1	Possible controller pairings of WWTP	49
4.2	Input-output pairs of WWTP	51
4.3	Simulation parameters of PSO for WWTP	53
4.4	WWTP - Optimum PID parameter for Davison method based on PSO	55
4.5	WWTP - Optimum PID parameters for Penttinen- Koivo method based on PSO	56
4.6	WWTP - Optimum PID parameters for Maciejowski method based on PSO	57
4.7	WWTP - Optimum PID parameters for Combined method based on PSO	58
4.8	Optimal tuning parameters	62
4.9	Singularly perturbed MPID controller matrix	63
4.10	Characteristic of closed loop response	74
5.1	Description and value of the constant parameters [83]	84
5.2	Possible controller pairings of Newell and Lee evaporator	95
5.3	Input-output pairs of Newell and Lee evaporator	96
5.4	Evaporator: Optimum PID parameter for Davison method	98
5.5	Evaporator: Optimum PID parameters for Penttinen- Koivo method	99

5.6	Evaporator: Optimum PID parameters for Combined method	100
5.7	Optimal tuning parameters	104
5.8	Singularly perturbed MPID controller matrix	105
5.9	Step point change	107
5.10	Performance indices	116

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Concept of PSO search	23
2.2	Flowchart of the PSO algorithm	27
4.1	Activated sludge process	36
4.2	Eigenvalue plots on s-plane	42
4.3	Comparison of magnitude analysis for different methods	46
4.4	Comparison of phase analysis for different methods	47
4.5	Substrate responses between full order and singularly perturbed system during substrate set point change	60
4.6	Interaction in dissolved oxygen level due to the substrate set point change	60
4.7	Dissolved oxygen responses between full order and singularly perturbed system during dissolved oxygen set point change	61
4.8	Interaction in substrate level due to the dissolved oxygen set point change	61
4.9	Simulink block diagram of closed loop WWTP with PRBS input	64
4.10	Concentration of substrate based on PRBS input	65
4.11	Concentration of dissolved oxygen based on PRBS input	65
4.12	Closed loop responses of substrate during substrate	67

	set point change	
4.13	Process interactions during substrate set point change	68
4.14	Dilution rate responses during substrate set point change	69
4.15	Air flow rate responses during substrate set point change	70
4.16	Closed loop responses of dissolved oxygen during dissolved oxygen set point change	71
4.17	Process interactions during dissolved oxygen set point change	72
4.18	Dilution rate responses during dissolved oxygen set point change	73
4.19	Air flow rate responses during dissolved oxygen set point change	73
4.20	Closed loop multivariable system	75
4.21	Closed loop pole-zero	78
5.1	Newell and Lee evaporator	82
5.2	Eigenvalue plots on s-plane for Newell and Lee evaporator	89
5.3	Comparison of magnitude analysis for different methods	92
5.4	Comparison of phase analysis for different methods	93
5.5	Separator level responses between full order and singularly perturbed system during separator level set point change	102
5.6	Interaction in operating pressure due to the separator level set point change	102
5.7	Operating pressure responses between full order and singularly perturbed system during operating pressure set point change	103
5.8	Interaction in separator level due to the operating pressure set point change	103
5.9	Simulink block diagram of closed loop Newell and	106

	Lee evaporator	
5.10	Closed loop responses of separator level during separator level set point change	108
5.11	Process interactions during separator level set point change	110
5.12	Product flow rate responses during separator level set point change	111
5.13	Cooling water flow rate responses during separator level set point change	111
5.14	Closed loop responses of operating pressure during operating pressure set point change	113
5.15	Process interactions during operating pressure set point change	114
5.16	Product flow rate responses during operating pressure set point change	115
5.17	Cooling water flow rate responses during operating pressure set point change	115
5.18	Closed loop pole-zero plot of Newell and Lee evaporator	118

LIST OF ABBREVIATIONS

BIBO	-	Boundary Input Boundary Output
CLCP	-	Closed Loop Characteristic Polynomial
CMAES	-	Covariance Matrix Adaptation Evolutionary Strategy
CSTR	-	Continuously Stirred Tank Reactor
GA	-	Genetic Algorithm
IAE	-	Integral Absolute Error
IMC	-	Internal Model Control
ISE	-	Integral Squared Error
ITAE	-	Integral Time Weighted Absolute Error
ITSE	-	Integral Time Weighted Squared Error
I/O	-	Input/Output
LQG	-	Linear-Quadratic-Gaussian
MIMO	-	Multiple-Input Multiple-Output
MLSS	-	Mixed Liquor Suspended Solid
MPC	-	Model Predictive Controller
MPID	-	Multivariable PID
OLCP	-	Open Loop Characteristic Polynomial
ORSF	-	Order Real Schur Form
P	-	Proportional
PI	-	Proportional Integral
PID	-	Proportional Integral Derivative
PRBS	-	Pseudo Random Binary Sequence
PSO	-	Particle Swarm Optimization

RGA	-	Relative Gain Array
RNGA	-	Relative Normalize Gain Array Concept
SGA	-	Successive Galerkin Approximation
SISO	-	Single-Input Single-Output
SPA	-	Singularly Perturbation Analysis
SPM	-	Singularly Perturbation Method
SPS	-	Singularly Perturbation System
WWTP	-	Wastewater Treatment Plant

LIST OF SYMBOLS

C_M	-	Controllable matrix
DO	-	Dissolved oxygen
D	-	Dilution rate
dB	-	Decibel
e_{ss}	-	Steady state error
F_2	-	Product flow rate
F_{200}	-	Cooling water flow rate
g_{best}	-	Global best
h	-	Hour
h^{-1}	-	Per hour
iter	-	Number of iteration
iter _{max}	-	Maximum number of iteration
K	-	Controller matrix
K_d	-	Derivative gain
K_i	-	Integral gain
K_p	-	Proportional gain
kg	-	Kilogram
kg/kPa	-	Kilogram per kilopascal
kg/m	-	Kilogram per meter
kg/min	-	Kilogram per minute
kW/K	-	Kilowatt per kelvin
kPa	-	Kilopascal
L_2	-	Separator level
m	-	Number of slow eigenvalue

M	-	Meters
mg/l	-	Milligrams per liters
mg^{-1}	-	Meters per gram
m^3/h	-	Meters cube per hour
N	-	Number of fast eigenvalue
P_{best}	-	Particle's local best known position
P_c	-	Random probability
P_m	-	Mutation probability
P_2	-	Operating pressure
rad/s	-	Radius per seconds
r_1/ r_2	-	Random variable
S	-	Substrate
S	-	Seconds
Sec	-	Seconds
T	-	Time
T_r	-	Rise time
T_s	-	Settling time
W	-	Air flow rate
w	-	Inertia weigh
W_{max}	-	Maximum inertia weight
W_{min}	-	Minimum inertia weight
X	-	Biomass
X_r	-	Recycled biomass
α	-	Tuning parameter of Maciejowski method
φ	-	Tuning parameter of integral gain
ρ	-	Tuning parameter of proportional gain
δ	-	Tuning parameter of derivative gain
ω_B	-	Specific bandwidth frequency
%	-	Percent
% OS	-	Percentage overshoot
*	-	Unstable

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Two Stage Linear Transformations	131
B	Model of Wastewater Treatment Plant	133
C	Model of Newell And Lee Evaporator	137
D	Data of Routh-Hurwitz	138