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

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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.

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ABSTRACT

Efficient control of industrial processes is of great importance. The industrial control performance has to meet the desired optimum operation. However, the tuning process 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 in the design of Multivariable Proportional-Integral-Derivative (MPID) controller tuning. The singularly perturbation methods based on Naidu and Jian Niu were considered and tested. It is observed that singularly perturbation system by method of Naidu gives a good approximation at low, middle and high frequencies. Two MIMO systems with two-time scale characteristic that are wastewater treatment plant, and Newell and Lee evaporator were used as test beds. 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 are proposed based on the dynamic matric inverse to improve the tuning of MIMO system. Furthermore, Particle Swarm Optimization has been applied in the tuning of the parameters for an optimum control performance. Comparing the closed loop performance and process interaction of traditional MPID and the proposed singularly perturbed MPID controller methods, the latter methods are able to improve 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 sistem MIMO. 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.

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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
gbest	-	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
Pbest	-	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

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CHAPTER 1

INTRODUCTION

Proportional-integral-derivative (PID) controller is the most preferable in industrial process control [1]. PID involves three separate constant parameters, which are proportional (P), integral (I) and derivative (D). By tuning the three parameters of a PID controller algorithm, the controller can provide the control action designed for specific system requirements. Due to its simple structure [2], easiness to understand and ability to give good stability and high reliability to the system [3], PID is known as one of the powerful control designs. PID controller is widely used in both single-input single-output (SISO) and multiple-input multiple-output (MIMO) systems.

Tuning of PID parameter for SISO system is frequently based on Zeigler Nichol, Cohen Coon, pole placement and gain-phase margin methods. Tunings of PID parameter for MIMO systems are also usually involved with the conventional method as performed to SISO systems [4]. However, this method is only applicable for decentralized multivariable controller which involves several numbers of individual PID controllers. This application can cause extreme problems due to the existence of interaction [5]. Therefore, better tuning method is highly required to achieve great performance for MIMO system [6].

Multivariable PID (MPID) control usually uses to control more than one control variables. Some of the control design purposes are to improve the manufacturing process, increase efficiency in terms of energy usage, reduce cost and alleviate time constraints. For example, industrial process control involves multiple control objectives such as to control level, temperature and outlet concentration, which can possibly be attained by adjusting selected manipulated variables during the process.

Industrial process control essentially involves multivariable system, some of them have different dynamic characteristics (two-time scale characteristic) for each control variable including slow and fast variables. This characteristic causes difficulties in finding the optimal control tuning. Considering slow variable will deteriorate the performance of fast variable control and vice versa.

1.1 Problem Statement

Owing to the various industrial process controls based on MIMO systems, multivariable control tuning becoming the preferred tuning control. Existing multivariable control are based on a number of control techniques such as PID, model predictive control (MPC), internal model control (IMC), linear-quadratic-Gaussian (LQG) and inferential control. Today, PID controller is still the most applied [7]. However, due to the presence of process interaction and different dynamic characteristic in the multivariable system, the tuning of PID parameters has always been a challenging and crucial matter for optimum operations [4]. Therefore, this thesis presents MPID control tuning methodology which exploits the properties of a singularly perturbation method.

The MPID methods involved are Davison, Penttinen-Koivo, Maciejowski and Combined methods. The conventional MPID control tuning designs were performed at a steady state response, which is at zero frequency gain. In this work, the MPID control tuning was designed based on dynamic inverse matrix. The proposed designs are able to provide dynamic output responses with good tracking ability, which is more practical in real application.

Since the considered multivariable systems involve two-time scale characteristic, the method of singularly perturbed is desired. By having the MPID based on singularly perturbation method, it is able to provide easiness in the optimization process and reduce the existence of process interaction between controlled and manipulated variables.

1.2 Research Objectives

The objectives that are bound to be answered throughout the research are:

i. To analyze multivariable process control with two-time scale characteristic by exploiting the singularly perturbation method.
ii. To enhanced the tuning method for MPID controller design using dynamic inverse matrix approach – Davison, Penttinen-Koivo, Maciejowski and Combined methods.
iii. To apply controller tuning parameters based on particle swarm optimization (PSO).
iv. To evaluate and compare the effectiveness of the proposed MPID control tuning designs in two case studies – Activated sludge wastewater treatment plant and Newell and Lee evaporator system.

1.3 Research Scope

This project will be focus on the control performance and process interaction of multivariable system with two-time scale characteristic. Two case studies presented, wastewater treatment plant and Newell and Lee evaporator. For each system, two control variables and two manipulate variables are considered. To analyze multivariable system with two-time scale characteristic, singularly perturbation method by Naidu and Jian Niu are implemented.

Once the implementation was completed, MPID control tuning designs which are Davison, Penttinen-Koivo, Maciejowski and Combined method are enhanced based on the dynamic inverse matrix using the obtained singularly perturbed system. Since it involve with several tuning parameter, particle swarm optimization (PSO) was applied. In this study, linearly decreasing inertia weight and integral time square error (ITSE) fitness function are considered. To measure the effectiveness of the proposed methods, all of the output response and process interaction for both case studies are evaluate and compare accordingly. It is based on the simulation studies by using Matlab/Simulink software.

1.4 Contribution of the Research Work

The main contributions of this research can be concluded as follows:

i. Enhanced MPID tuning framework using singularly perturbation method based on Naidu and Jian Niu.
ii. Provide ease of tuning based on the design of enhanced MPID control using dynamic inverse matrix of singularly perturbed system.
iii. Attained optimum tuning parameters for each MPID controller designs using particle swarm optimization (PSO).

iv. Provide efficient control for wastewater treatment plant and Newell and Lee evaporator. Successfully controlled the output responses at the desired value and minimized the process interactions that exist between the system variables.

1.5 Outline of the Thesis

Chapter 2 represents the literature review of the conventional MPID controller, singularly perturbed multivariable controller, singularly perturbation method by Naidu and Jian Niu, optimization technique and PSO algorithms.

The research methodology will take place in Chapter 3 in which the research activities will be described in detail. The sequences of multivariable PID control based on four different methods are discussed.

The simulation results and discussion for multivariable PID control for activated sludge wastewater treatment plant will be discussed thoroughly in Chapter 4.

Chapter 5 reports the results and discussion for the second case study which is an evaporator system.

Finally, chapter 6 concludes the research work. Recommendations for future works are also listed down in this chapter.

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