NONLINEAR PROPORTIONAL INTEGRAL CONTROLLER WITH ADAPTIVE INTERACTION ALGORITHM FOR NONLINEAR ACTIVATED SLUDGE PROCESS

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DEDICATION

This work is dedicated to my family whom I thank for all of their love and support.

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Praise to the Almighty...

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ABSTRACT

Wastewater Treatment Plant (WWTP) is highly complex with the nonlinearity of control parameters and difficult to be controlled. The need for simple but effective control strategy to handle the nonlinearities of the wastewater plant is obviously demanded. The thesis emphasizes on multivariable model identification and nonlinear proportional integral (PI) controller to improve the operation of wastewater plant. Good models were resulted by subspace method based on N4SID algorithm with generated multi-level input signal. The nonlinear PI controller (Non-PI) with adaptive rate variation was developed to accommodate the nonlinearity of the WWTP, and hence, improving the adaptability and robustness of the classical linear PI controller. The Non-PI was designed by cascading a sector-bounded nonlinear gain to linear PI while the rate variation is adapted based on adaptive interaction algorithm. The effectiveness of the Non-PI has been proven by significant improvement under various dynamic influents. In the process of activated sludge, better average effluent qualities, less number and percentage of effluent violations were resulted. Besides, more than 30% of integral squared error and 14% of integral absolute error were reduced by the Non-PI controller compared to the benchmark PI for dissolved oxygen control and nitrate in nitrogen removal control, respectively.

ABSTRAK

Loji Rawatan Sisa Air (WWTP) adalah sangat kompleks dengan parameter pengawal tak linear dan sukar untuk dikawal. Keperluan strategi pengawal yang mudah tetapi berkesan bagi mengatasi ketaklelurusan loji air sisa adalah sangat diperlukan. Tesis ini menekankan pengenalpastian model berbilang pemboleh ubah dan reka bentuk pengawal kadar kamir (PI) tak linear bagi memperbaiki operasi WWTP. Model terbaik dihasilkan melalui kaedah keadaan-ruang berdasarkan algoritma N4SID dengan menggunakan isyarat masukan pelbagai aras yang dihasilkan. Pengawal PI tak linear (Non-PI) dengan pengubahsuain kadar perubahan gandaan dibangunkan bagi menampung kesan tak linear WWTP seterusnya memperbaiki penyesuaian dan keteguhan pengawal klasik PI linear. Pengawal Non-PI dibangunkan secara lata dengan disempadani gandaan tak linear kepada PI linear sementara kadar perubahan gandaan diubah suai berdasarkan algoritma hubungan pengubahsuaian. Keberkesanan pengawal Non-PI berjaya dibuktikan dengan penambahbaikan yang jelas di bawah keadaan cuaca yang berbeza. Bagi proses enap cemar teraktif, purata kualiti kumbahan yang lebih baik dan bilangan pelanggaran kumbahan yang lebih rendah dapat dihasilkan. Sementara itu, lebih daripada 30% ralat kamiran kuasa dua dan 14% ralat kamiran nyata telah dikurangkan oleh pengawal Non-PI berbanding penanda aras PI bagi pengawal oksigen terlarut dan nitrat dalam pengawal pembuangan nitrat setiap satu.

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LIST OF ABBREBRIVATIONS

AE	-	aeration energy
AIA	-	adaptive interaction algorithm
AGA	-	adaptive genetic algorithm
ANN	-	artificial neural network
ASM1	-	Activated Sludge Model No. 1
ASM2	-	Activated Sludge Model No. 2
ASM2d	-	Activated Sludge Model No. 2d
ASM3	-	activated Sludge Model No. 3
ASP	-	activated sludge process
BSM1	-	Benchmark Simulation Model No. 1
BOD_5	-	biochemical oxygen demand of tank 5
COD	-	chemical oxygen demand
CVA		canonical variate analysis
DO	-	dissolved oxygen
DO_i	-	dissolved oxygen of tank i; i=1, 2, 3, 4, 5
DO_{345}	-	dissolved oxygen control of tank i; i= 3, 4 and 5
FLC	-	fuzzy logic control
IAE	-	integral of absolute error

ISE	-	integral of square error
IWA	-	International Water Association
LTI	-	linear time-invariant
MIMO	-	multiple-input multiple-output
MOESP	-	multivariable output-error state-space model identification
MPC	-	model predictive control
MRSE	-	mean relative squared error
MVAF	-	mean variance–accounted-for
Nitrate-DO_5	-	nitrate and DO_5 control
Non-PI	-	nonlinear PI controller
Non-PI_i	-	nonlinear PI controller tank *i*; *i*=1, 2, 3, 4, 5
N4SID	-	numerical subspace state-space system identification
N_{tot}	-	total nitrogen
PEM	-	predictive error method
PI	-	proportional integral
PI_i	-	proportional integral applied to tank *i*; *i*=1, 2, 3, 4, 5
PID	-	proportional integral derivative
PRBS	-	pseudorandom binary sequences
SIM	-	subspace identification method
SISO	-	single-input single-output
S_{NH}	-	ammonia
TSS	-	total suspended solids
WWTP	-	wastewater treatment plant
ZOH	-	zero order hold

LIST OF SYMBOLS

e - error

e_{knon} - error of nonlinear gain function

e_{max} - maximum error of nonlinear gain function

F_n - Frechet derivative

d - day

k_n - rate variation of nonlinear gain

k_{non} - nonlinear gain function

k_{nond} - desired nonlinear gain function

K_La - oxygen transfer coefficient

K_La_i - oxygen transfer coefficient of tank i; i=1, 2, 3, 4, 5

K_p - proportional gain

K_i - integral gain

M - maximum length sequence

mean(|e|) - mean of absolute error

max(e) - maximum absolute deviation from set-point

n - no. of shift register

q - number level of MPRS

Q_i - flow rate of tank i; i=1, 2, 3, 4, 5

Q_{intr} - internal recycle flow rate

$std(e)$ - standard deviation of error

T_{cyc} - duration one cycle of *m*-sequences

T_i - integral time constant

T_{SW} - switching time

V_i - volume of tank *i*; *i*=1, 2, 3, 4, 5

Z_i - concentrations of tank *i*; *i*=1, 2, 3, 4, 5

u - input variable

ω_{low} - lower frequency limit

ω_{up} - upper frequency limit

ω_s - excitation signal bandwidth

x_i - signal sequences

y - output variable

y_d - output desired

y_m - output measured

y_{knon} - output nonlinear gain function

y_{knond} - output desired nonlinear gain function

α_c - connection weights

o - functional composition

α_s - high frequency content

β_s - low frequency content

τ^{H}_{dom} - fastest dominant time constant

τ^{L}_{dom} - slowest dominant time constant

γ - adaptive constant

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Wastewater treatment plant (WWTP) is subject to large disturbances in flows and loads together with uncertainties concerning the composition of the influent wastewater. The aim of WWTP is to remove the suspended substances, organic material and phosphate from the water before releasing it to the recipient. Several stages of the treatment are carried out in the WWTP. These basically include the mechanical removal of floating and settle able solids as the first treatment, continued by a biological treatment for nutrients and organic matter abatement, sludge processing and chemical treatment. However, the best technology available shall be used to control the discharge of pollutants emphasized in biological process; called activated sludge process (ASP) (Vlad *et al.*, 2012; Wu and Luo, 2012). In ASP, the organic matters from raw water (influent) in generally are oxidized by microorganisms to producing treated water (effluent). Some of the organic matters are converted to carbon dioxide while the remaining is integrated into new cell mass. A sludge that contains both living and dead microorganisms thus containing phosphorous and nitrogen are then produced by the new cell mass (Rehnström, 2000).

Benchmark Simulation Model No. 1 (BSM1) is a preferable platform to evaluate the effectiveness of the control design strategies for the activated sludge system (Yong *et al.*, 2006). The initial BSM1 was developed by COST 264 and COST 682 Working Group No. 2, but now is under the IWA Task Group. The BSM1 is in general a simulation environment which integrated with a plant layout, a simulation model, influent loads, test procedures and evaluation criteria. These items have been pursued to mimic the accepted standards and realism of the WWTP. Nitrification process with predenitrification configuration that is regularly applied to achieve biological nitrogen removal in full-scale plants are developed in the plant. The detail of BSM1 can be referred in Alex *et al*. (2008).

According to BSM1, two important processes are involved; nitrification and denitrification. Nitrification is a process in which ammonium is oxidized to nitrate. The nitrification is implemented under aerobic conditions with the presence of oxygen. However, the nitrate formed by nitrification process, sequentially is converted into gaseous nitrogen in denitrification process (Samuelsson *et al.*, 2005). Note that the denitrification is conducted under anoxic condition with absence of oxygen. In nitrification, DO is needed by microorganisms and control of this variable is of significant importance to ensure that all the reactions operate effectively. The DO control has been practiced for many years in wastewater control. In fact, the nitrogen removal in ASP requires a two-step procedure which takes place simultaneously nitrification and denitrification processes.

In fact, the WWTP is significantly known as a complex multivariable or a large-scale plant that asks for great demands on control design strategy. The main goal for a wastewater control is generally to satisfy strict effluent requirements and minimize costs while maintaining water quality (Amand, 2011). Due to continuously changing conditions with the nonlinearity effect of the control parameters, the proposed control strategy that is potential to maintain a balance of DO concentration and nitrogen removal process during the set-point changes is highly necessitated**.** Further, enhancement of the nonlinear PI controller with adaptive features is aimed for effective wastewater control strategy.

1.2 Problem Statement and Significance of the Research

A basic knowledge of biotechnology of the WWTP that covers model identification and control design strategies aiming to improve the process of activated sludge is highlighted in the study. Modelling can be defined as a process to describe the dynamic behaviour of a system (Ljung, 1998)**.** Two basic ways of modelling includes the mathematical modelling which is analytical approach that commonly use the physics law to represents the process' behavious. Another is system identification that referred to experimental approach. The experiments are performed on the system while the model is then fitted based on the data recorded (Soderstrom and Stoica, 2001). The biological process of the ASP was first developed on IAWQ's Activated Sludge Model No. 1 (ASM1) (Henze *et al.,* 1987). It then continued by a series of mathematical models known as Activated Sludge Model No. 1 (ASM2) and Activated Sludge Model No. 3 (ASM3). Among them, the ASM1 is the most successful one used to represent the processes dynamics of the ASP (Yang *et al.*, 2014; Wu and Luo, 2012). Undoubtly, derivation on physical behaviour of the system offering more exciting appearances, but it is clearly difficult and time consuming specifically when dealing with a large system. The direct usage of the ASM1 is difficult for control purposes since more computer intensive, hardest calibration and longer time consuming will be asked (Yang *et al.*, 2014; Samuelsson, 2005; Stare *et al.,* 2007). Therefore, system identification technique becomes a good alternative in predicting the behaviour of the activated sludge. To compensate for the nonlinearity effect in signal excitation caused by multi-level signal of the wastewater data, a multi-level pseudo random input signals is generated and applied in model identification.

The development of the control design strategies and the ability to perform in the process of activated sludge is next covered. In general, a multi-input multi-output (MIMO) system is visibly described as a system with more than one control loop. Changes in any input will generally affect all the outputs due to interaction between the inputs and outputs variables (Wang *et al.*, 2005)**.** However, a non-interacting plant would be resulted if the first input signal only effects the first output signal, similarly the second input signal only effects the second output signal and so on (Skogestad and Postlethwaite, 2005). Two solution packages referring to central control structure and decentralized control structure that are always proposed to tackle the stability and the improvement of the MIMO control performances (Khaki-Sedigh and Moaveni, 2009). Each of them has their advantages and deficiencies to effectively operate the WWTP. Basically, a non-diagonal transfer function matrices refer to centralized controllers that describing the highly interactive loops in the process. Meanwhile, independent feedback controllers are normally used to control a subgroup of the plant outputs with a subgroup of the plant inputs in decentralized control.

The WWTP has very wide dynamic time scales thus can be divided into three different scales; slow processes, medium scale processes and fast processes (Steffens and Lant, 1999; Wahab, 2009). The growth of biological processes such as biomass growth is considered as a slow process. The medium scale processes refer to the dynamic concentrations and nutrient removal while the fast scale processes denote the flow dynamics and the DO. The slow process has a time constant of days or even up to months and regularly handled by supervisory control. The medium scale processes has a time constant of minutes or up to hours are normally asked for more advanced process control while the basic control strategies may be considered for the fast process with in minutes of the time constant. Useful review related to biological activated sludge process can be referred to the work presented by Jeppsson (1996). The dynamic natures of the WWTP time scales challenge the development of the controller thus ask for simple but effective controller design strategies.

The interest in more advanced control strategies is always demanded due to the tighter effluent quality of the WWTP (Samuelsson, 2005). It was observed that aeration process is a vital part of the whole function of the ASP (Amand, 2011; Holenda, 2007; Wu and Luo, 2012). Surface mechanical type aerators or diffused aeration systems is typically applied to deliver oxygen to the aeration system. In order to break the air into bubbles as they are dispersed through the aeration tank, the aerators or diffused aeration system with a high volume air compressor (blower), low pressure, air piping system and diffusers are commonly applied. However, it is a nontrivial task to transport the oxygen from the air bubbles to the cells of the microorganisms, thus the process is commonly described by the oxygen mass transfer coefficient, K_La. K_La, in general is nonlinear and depends on the aeration actuating system and the sludge conditions (Holenda *et al.*, 2008). The K_La indicates the rate at which the oxygen is transferred to the wastewater by aeration system and it is always used as a manipulated variable for DO control. To explain the aeration model, a DO mass balance around complete stirred tank reactor is usually presented (Alex *et al.,* 2008). The DO concentration in the aerobic part should be sufficiently high, so that enough oxygen can be supplied to the microorganisms in the sludge. The organic matter is then degraded and ammonium is adequately converted to nitrate. However, an excessively high DO will ask for higher airflow rate, thus leading to higher energy consumption and deteriorating the sludge quality. The importance of DO control is heavily discussed such the work by Lindberg (1997); Carlsson and Lindberg (2004); Brdys *et al.* (2002), and Sanchez *et al*. (2003).

Meanwhile, extreme concentration of nitrogen in the effluent invites several drawbacks. The growth of algae and aquatic plants are strongly inspired by nitrogen. This may causes deficiency of oxygen due to the degradation process (Lindberg, 1997; Samuelsson, 2005). Consequently, minimization of the nitrogen level in the incoming wastewater is obviously required thus can be solved by nitrogen removal control.

The improvement of balance DO concentration in aerated tanks and the nitrogen removal process contribute to a big interest in activated sludge control. However, one of the main problems in controlling the DO concentration is the nonlinear natures of the process dynamic (Piotrowski *et al.,* 2008; Han *et al.,* 2008; Holenda, 2007). Consequently, it is hard to achieve high control performance in all operating conditions with a linear controller. A controller that is capable to maintain a balance of DO level during the set-point changes is highly demanded. In fact, the biological nitrogen removal in activated sludge WWTP requires a two-step procedure taking place simultaneously, nitrification and denitrification. The relationships between the control inputs and the outputs in both processes are complex whereas, the biological nitrogen removal itself is nonlinear and time varying (Samuelsson, 2005;

Lindberg, 1997). To these reasons, a simple but effective controller that has potential to handle the complexity of both processes are aimed in this work.

The proportional-integral-derivative (PID) technique is one of the control strategies that are frequently applied in industrial (Mcmillan, 2012), specifically for WWTP. The dominative usage of the PID control is undeniably even with the advances of modern control techniques. However, the PID controller is still faces with a great challenge to control a complex nonlinear system; specifically with randomness of the external disturbances. The classical PID controller is regularly adequate to control of a nominal physical process. Difficulties may come to the classical PID to perform well in high-performance control with changes operating conditions (Seraji, 1998). Besides, the fixed control parameters in the classical PID controller lead to poor performance of transient response. This was supported by the limitation in the operating range of the controller specifically when it deals with complex nonlinear system (Aydogdu and Korkmaz, 2011). But, the design and analysis of the nonlinear PID controller are strongly complicated and difficult to be implemented (Yongping, 2010) while the question to design simple architecture of effective PID controller was appointed (Wang, 2012). In conjunction to these issues, modification of a linear PI controller using special nonlinear functions is claimed to be more attractive in engineering applications (Yongping, 2010).

Based on the above discussion, a dynamic nonlinear PI (Non-PI) controller with changed parameters over time with respect to the error response based on the nonlinear function is proposed. The aim here is to compensate the nonlinearities behaviours of the WWTP and hence to improve the adaptability and robustness of the classical PI controller. Furthermore, initiative enhancement to simplify the Non-PI control structure by adapting the rate variation of the nonlinear gain is also targeted. The proposed Non-PI is focused on improving the balance of DO concentration in aerated tanks and the nitrogen removal process for effective activated sludge control.

1.3 Research Objectives

The objectives of this research can be outlined as follows:

(i) To obtain linear state-space model with developed multi-level input signal for nonlinear activated sludge process.

(ii) To design a nonlinear PI controller that is potential to accomodate the dynamic natures of the activated sludge.

(iii) To test the nonlinear PI controller to the nonlinear activated sludge process under different variations and disturbances.

1.4 Research Scope and Limitation

The research scope and limitation of this work can be described as follows:

(i) The model identification is implemented by subspace based method with N4SID algorithm. To obtain more information data in signal excitation, a multi-level perturbation input signal is generated.

(ii) The simulation is emphasizes on the updated version of Benchmark Simulation Model No. 1 (BSM1) with updated sensors and noises as described in Alex *et al.* (2008) using Matlab@Simulink simulation platform.

(iii) The biological parameter values of the BSM1 are correspond approximately to a temperature of 15^{o}C.

(iv) The work concerns on the improvement of two case studies. Case I refers to the aeration process where the DO in all aerated tanks are considered. The Case II highlights on the nitrogen removal process which involve the simultaneous nitrification and denitrification processes.

(v) For Case I, the manipulation of the oxygen mass transfer coefficient, K_La is constrained at 360/day in controlling each DO tank. The sensor of class A with a measurement range of 0 to 10 mg/l and a measurement noise of 0.25 mg/l was applied.

(vi) For Case II, the internal recycle flowrate, Q_{intr} and the K_La were manipulated in controlling the nitrate and the DO control loops, respectively. Again, the K_La was constrained at 360 day^{-1} while the Q_{intr} was restricted up to 5 times of stabilized input flow rate, 92230 m^3/day. A class B0 sensor with a measurement range of 0 to 20 mg/l and measurement noise of 0.5 mg/l was applied in nitrate control while similar sensor of class A in Case I is used for DO control.

(vii) The improvement of the five effluents water quality are considered in the simulation. The flow-weighted average of the five effluent concentrations; total nitrogen (N_{tot}), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia (S_{NH}), and total suspended solids (TSS) are constrained to 18 g/l, 100 g/l, 4 g/l, 30 g/l and 10 g/l, respectively (Alex *et al.,* 2008).

(viii) The effectiveness of developed nonlinear PI is always compared to the performances of default benchmark PI controller; which is tuned and recommended by Alex *et al.* (2008).

1.5 Organization of the Thesis

Chapter 1 presents a brief introduction of the process of wastewater treatment plant. The problem statement, the objective , the scope and limitation of the research are discussed.

In Chapter 2, the literature study on the wastewater treatment plant (WWTP), the system identification and control design techniques are presented. It then continued by critical literatures that motivates the implementation of the project. The theoretical part on multilevel pseudorandom input signal and the nonlinear PI controller are also discussed.

Chapter 3 explaines the methodology part of the project that starts with the flow of project implementation. The simulation procedures, the exclusive study of the Benchmark Simulation Model No. 1 (BSM1) and the case studies involved are next presented. It then followed by the implementation of the state-space modelling, the development of the MPRS input signal and the nonlinear PI controller to the activated sludge process (ASP).

Chapter 4 presents the simulation result of model identification and control design application. It discuss the performance of identified model, the results on RGA test continued by the performances of the proposed nonlinear PI controller under various weather condition and disturbances.

The summary of the research findings and the recommendation of future research based on this study are presented in Chapter 5.

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4. **S. I. Samsudin,** M. F. Rahmat, Norhaliza Abdul Wahab, Mashitah Che Razali, Muhamad Sani Gaya, A Study on Controller Design Strategies for TITO Plant, 8th IEEE Conference on Industrial Electronics and Applications, (ICIEA 2013), 19- 21 June 2013, Melbourne, Australia.