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Self-Tuning PID Based on Adaptive Genetic Algorithms with the Application of Activated Sludge Aeration Process

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***Abstract* - Activated sludge aeration process is a non-linear system subject to large perturbations in flow and load, together with uncertainties on the composition of the incoming wastewater. Traditional PID control lacks the ability to overcome these disturbances. In order to achieve adaptive process performances, an adaptive genetic algorithm (AGA) was proposed to tune the parameters of an activated sludge aeration PID controller. Several self-tuning algorithms, specifically Ziegler-Nichols (Z-N), internal model control (IMC) and Kappa-tau were also applied in order to tune an activated sludge aeration PID controller. Performance results of these controllers were compared by simulation with those obtained by using an adaptive genetic algorithm (AGA) to tune PID controller. By comparing, the proposed algorithm, which is used to tune the parameters of PID controller, achieves satisfactory response of a PID controller actuating over the aeration process in an activated sludge process.**

***Index Terms* - Adaptive genetic algorithm, Ziegler-Nichols, internal model control, Kappa-tau, activated sludge aeration process.**

I. INTRODUCTION

The activated sludge is one of the most widely used biological wastewater treatment processes (WWTP). The dissolved oxygen (DO) concentration in WWTP has been recognized as an important variable to be controlled both for economical and process efficiency purpose. The proper control of DO could achieve adaptive process performances and there is an economic incentive to minimize excess oxygenation by supplying only necessary air to meet the time-varying oxygen demand of the mixed liquors. Despite the relatively simple dynamics of the DO mass balance, the control may be known difficult because of time-varying influent wastewater conditions, nonlinearity, time delay, sensor noise and slow sensor dynamics. To overcome these problems, several adaptive control strategies have been suggested recently to the control of DO concentration in the aeration basin [1]-[3]. The previous works with advanced control algorithm require detailed process information such as oxygen transfer rate, respiration rate, reactor volume, wastewater flow rate and use a mathematically complex algorithm that is difficult to be implemented in on-line manner [4] and [5]. Moreover, these cannot be implemented with the PID controller that is the most common controller in the real WWTP. Therefore, a method of improving the PID controller performance is required to use only the process input-output data without requiring any complicated algorithm. It is an automatic tuning of PID controller (self-tuning). In WWTP, PID controllers are familiar to process operators and very popular because of its simplicity, easiness in operation and robustness to modeling error. But it is well known that the DO concentration cannot be controlled effectively by using the PID controller with fixed gain parameters. And the manual tuning of PID controller is tedious and laborious. Furthermore, from the viewpoint of control, the aeration process is characterized by its nonlinear dynamics. In this situation, high control performance for all operating conditions may be hard to achieve with linear controllers [6]. In spite of that, the open loop dynamic response of this system can be approximated, over a limited range, as a first order function plus deadtime (FOPDT). In this function [Eq. (1)] K is the static gain, T is the time constant and τ is the deadtime.

$$G(s) = Ke^{-\tau s} \big/ (Ts+1) \tag{1}$$

And then PID controller is tuned based on the reduced method. The aim of this paper is to apply a self-tuning to actual DO control system in the full-scale WWTP.

II. SELF-TUNING METHOD

In order to obtain an adequate closed loop response of the biological process actuated by the control systems, the aeration controller must be tuned to a given performing mechanism. Thus, Seborg et al give six performance criteria that a closed loop system has to satisfy [7]:

a) The closed loop system must be stable.
b) The effects of disturbance have to be minimized.
c) Rapid and smooth responses to setpoint changes must be obtained.
d) Offset has to be eliminated
e) Excessive control action has to be avoided, and
f) The control system has to be robust, that is, it has to be insensitive to changes in process conditions and to errors in the assumed process model.

To accomplish this performance, many kinds of controllers have been developed. Among them the PID controller is the best known. This controller has three adjustable parameters (K_p or controller gain, T_i or integral time and T_d or derivative time), whose values can be obtained by using different tuning methodologies. In this work three methodologies have been used [8]:

a) Z-N (open-loop): the PID tuning method presented by Ziegler and Nichols is based on the system's open-loop step response. It uses the fact that many systems in the process industry can be approximated by a first-order lag plus a time delay as in (1). Where K and T can be determined by simply plotting the step response of the plant. Then the PID tuning parameters can be obtained by the Z-N step response method.

b) Kappa-tau tuning: the dynamics of a system can be described more accurately if three parameters are used in the design instead of two. The kappa-tau tuning method is a method in that direction and is used in automatic tuning [8]. As in the Z-N method it comes in two versions. One is based on the step response, in which the process is characterized by a static gain K_p, a gain α (the gain of the transient part of the open-loop response), and a dead time L. The controller parameters are a function of the normalized dead time τ given by

$$\tau = L/(L+T) \tag{2}$$

With T being the dominant time constant of the process.

c) IMC: which is based on an assumed process model, relating the controller settings to the model parameters in a straightforward manner. If the open loop response of the system can be fitted to FOPDT, this method can be easily simplified to a PID controller.

For a system, which can be fitted well to (1), PID parameter values calculated with these tuning methodologies are shown in Table. I.

TABLE I

PID PRAMETER VALUES OBTAINED BY USING DIFFERENT METHODOLOGIES

	K_p	T_i	T_d
Z-N(open-loop)	$1.2/K$	2τ	$\tau/2$
Kappa-tau	$\frac{8.4\cdot T}{K\tau}e^{[-9.6(\frac{\tau}{T+\tau})+9.8(\frac{\tau}{T+\tau})^2]}$	$3.2\cdot\tau e^{[-1.5\cdot(\frac{\tau}{T+\tau})-0.93\cdot(\frac{\tau}{T+\tau})^2]}$	$0.86\cdot\tau e^{[-1.9\cdot(\frac{\tau}{T+\tau})-0.44\cdot(\frac{\tau}{T+\tau})^2]}$
IMC	$\frac{1}{K}\frac{2\cdot(T/\tau)+1}{2\cdot(\tau_c/\tau)+1}$	$\frac{\tau}{2}+T$	$\frac{T}{2\cdot(T/\tau)+1}$

III. ADAPTIVE GENETIC ALGORITHMS FOR TUNING PID

Genetic algorithm (GA) is a directed random search technique that is widely applied in optimization problems and uses principles inspired by natural genetics to evolve solutions to problems. The basic idea is to maintain a population of chromosomes (representing candidate solutions to the concrete problem being solved) that evolves over time through a process of competition and controlled variation. This is especially useful for complex optimization problems where the number of parameters is large and the analytical global solutions are difficult to obtain [9]. A lot of research efforts have been spent to improve the performance of GA. Different selection schemes and genetic operators have been proposed. In this paper, the standard GA is modified and new genetic operators are introduced to improve its performance. The details of the AGA are shown given as follows:

A. Adaptive Tuning for Probability of Crossover and Mutation

Adaptation tuning probability of crossover and mutation is one of the effective methods improving search arithmetic. The tuning arithmetic as follows:

$$p_c = \begin{cases} k_1(f_{\max} - f_c^{'})/(f_{\max} - \overline{f}), f_c^{'} \geq \overline{f} \\ k_3, f_c^{'} < \overline{f} \end{cases} \tag{3}$$

$$p_m = \begin{cases} k_2(f_{\max} - f)/(f_{\max} - \overline{f}), f \geq \overline{f} \\ k_4, f < \overline{f} \end{cases} \tag{4}$$

with: $f_c^{'}$: maximum fitness values among parents without crossover;

f: fitness value of individual needing mutation;

f_{ma}: maximum fitness value;

$\overline{f}$: average fitness value;

$k_1 = k_3 = 1, k_2 = k_4 = 0.5$.

For high quality individual(fitness values higher than average values)，if the values of p_c and p_m are adopted small that will accelerate GA to converge. For low quality individual (fitness values lower than average value), the values of p_c and p_m are adopted big that will prevent GA from getting into local minimum.

B. Coding Methods

There are two types of coding methods for GA. They are binary and real-coded GA, respectively. Since the parameters that we are interested in the present study are real numbers, the latter is applied for evolution. However, the advantages of real-coded GA compared to binary GA are its speed and accuracy, since it is not necessary to transform the real numbers into binary numbers. So in this paper, real-coded method is adopted.

C Design of Fitness Function

In order to achieve satisfactory response, the following equation is selected to act as optimal index for parameters selecting.

$$J = \int_0^\infty (\omega_1|e(t)| + \omega_2 u^2(t))dt + \omega_3 \cdot t_u \tag{5}$$

With: $e(t)$: system error;

$u(t)$: output of controller;

t_u: rise time;

$\omega_1, \omega_2, \omega_3$: weight values

In order to avoid overshoot, punish function is adopted. In case overshoot coming into being, the value of overshoot will become a part of optimal index. Then the optimal index as follows: if $e(t)>0$ $\quad J=\int_0^{\infty}(\omega_1|e(t)|+\omega_2 u^2(t)+\omega_4|e(t)|)dt+\omega_3\cdot t_u$ (6)

IV. Results And Discussion

A Simulation System

In order to evaluate and verify the effectiveness of the proposed AGA Self-tuning PID controller, and to compare its performance to those of other three methods tuned PID controllers, an activated sludge process model was applied and the model is shown in Fig. 1.

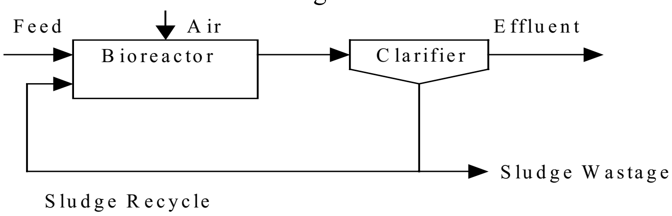


Fig. 1 Activated sludge process model

In this activated sludge process, three variables [biomass (X), substrate (S_S) and oxygen (S_O)] and two processes (growth and decay of micro-organisms) are considered.

It is important to note that for aeration control purposes the dynamics of the activated sludge treatment can be well described by this model, more complex models not being needed. From a chemical engineering point of view, this system constitutes a continuous stirred tank reactor and a decanter [6]. Oxygen for the bio-oxidation process is supplied by a compressor. The application of mass balance to the system shown in Fig. 1 gives the following set of equations:

$$\frac{dX}{dt}=Q_0X_0-QX+V[\mu(\frac{S_S}{K_S+S_S})\cdot(\frac{S_O}{K_{O,H}+S_O})X-bX \tag{7}$$

$$\frac{dS_S}{dt}=Q_0\cdot S_0-Q\cdot S+V\cdot[-\frac{1}{Y}\cdot\mu\cdot(\frac{S_S}{K_S+S_S})\cdot(\frac{S_O}{K_{O,H}+S_O})\cdot X \tag{8}$$

$$\frac{dS_O}{dt}=Q_0\cdot S_{O_0}-Q\cdot S_O+V\cdot[-\frac{1-Y}{Y}\mu\cdot(\frac{S_S}{K_S+S_S})\cdot(\frac{S_O}{K_{O,H}+S_O})\cdot X-b\cdot X$$
$$+k_La\cdot(S_{O,sat}-S_O)] \tag{9}$$

Where Q_0 is influent flow rate, $K_{O,H}$, K_S , b and Y are coefficient representing, saturation coefficient for oxygen, saturation coefficient for substrate, rate constant for lysis and yield coefficient. The term k_La represents the oxygen mass transfer and $S_{O,sat}$ is the maximum dissolved oxygen concentration.

The structure of control system for the activated sludge system is shown in Fig. 2. A compressor supplies oxygen for the bio-reactor-tank process. The oxygen flowrate can be modified by means of a control valve.

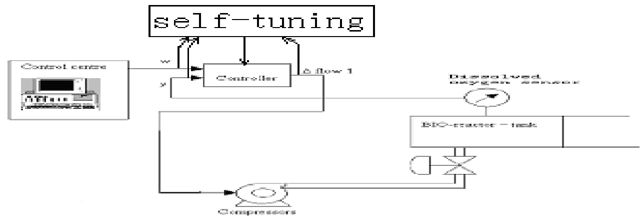


Fig. 2 The structure of control system

In this paper, by applying step response test for the aeration process of an activated sludge and identification of a reduced first-order plus time delay (FOPDT) model using the method of the areas is used as the object for studying. The reduced model is as follows and the time unit is minutes:

$$G_p(s)\cong 0.015\,e^{-8s}/(8.33s+1) \tag{10}$$

B Results and Discussion

As mentioned in the first section, The DO concentration is an important variable to be controlled both for economical and process efficiency purpose. Moreover, DO concentration is influenced by several factors, for example, temperature, sludge concentration, and composition of influent. So it is very essential to change setpoint of DO concentration according to environment. In this section, In order to study the behavior of the system, the simulation was performed. The object of the simulation was to compute the evolution of the dissolved oxygen concentration, in a three dissolved oxygen concentration setpoint change sequence.

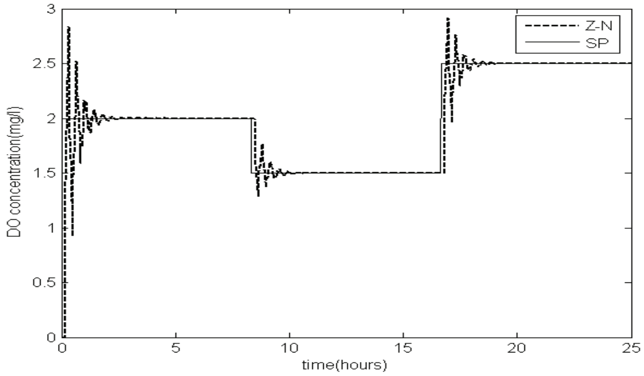
The results of simulation are shown in Fig. 3. In Table II are shown the rise time (RT), the settling time (ST) and overshoot (OS). As it can be seen, great improvements in both parameters can be obtained by using the AGA tuned PID controller. Table III presents the calculated parameters of the PID controller for the different algorithms described in the second section self-tuning methods of this paper (Table II).

TABLE II
RISE TIME, SETTLING TIME AND OVERSHOOT

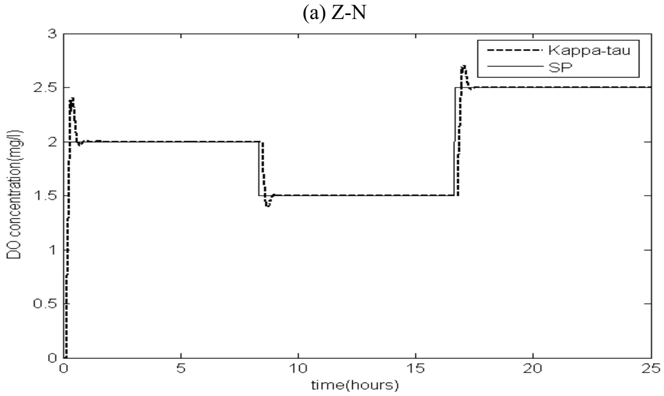
	AGA			Kappa-tau			IMC			Z-N		
	RT	ST	OS(%)	RT	ST	OS	RT	ST	OS	RT	ST	OS
SP change from 0 to 2.0	0.51	0.59	3.8%	0.35	0.60	20%	0.36	0.62	12%	0.23	1.85	42%
SP change from 2.0 to 1.5	0.5	0.51	0.8%	0.32	0.54	13%	0.35	0.53	4%	0.21	1.31	20%
SP change from 1.5 to 2.5	0.51	0.54	1.5%	0.35	0.58	8.1%	0.35	0.61	5%	0.18	1.63	37%

TABLE III
PID PARAMETER ACCORDING TO DIFFERENT METHODOLOGIES

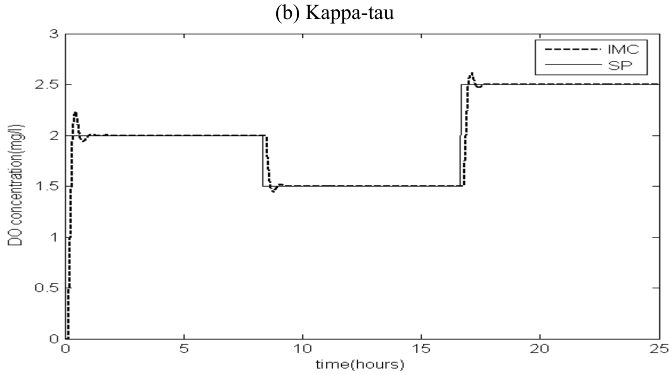
	AGA	Kappa-tau	IMC	Z-N
K_p	35.825	63.515	55.358	83.333
T_i	555.56	589.42	647.69	960.00
T_d	2.2500	146.47	92.965	240.00



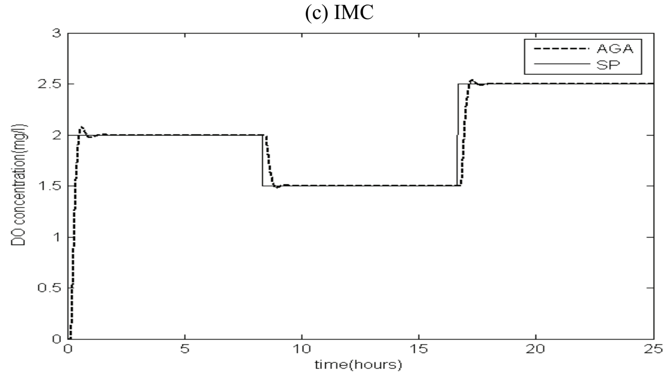
(a) Z-N



(b) Kappa-tau



(c) IMC



(d) AGA

Fig. 3 DO concentration maintained with each of the four controllers used in a three steps setpoint change sequence.

According to Table II and Table III, the following remarks can be made:

a) The Z-N tuned PID controller achieves an oscillatory response, due to the high controller gain used.

b) In the same way that in the previous setpoint change simulations, the Kappa-tau and IMC tuned controllers obtain closer results. The initial rise time of both system is better than that obtained with the AGA controller.

c) On the contrary, it can be observed that when the operation time increases and setpoint changes, the AGA tuned controller quickly improves its response and reaches steady state. The overshoot and the settling time of AGA tuned PID controllers are better than those obtained with other three methods.

d) The system of AGA tuned controller has the smoother responses, not being oscillatory in any of the simulation cases studied.

e) It can be seen from the whole that the AGA tuned PID controller obtained better performance of dynamic response by using the method mentioned in the third section than those obtained with other three methods.

f) It is also indicated that the AGA can obtain a global best solution in searching the parameters of the PID controller.

Ⅴ. CONCLUSION

A new structure for control of activated sludge aeration process has been discussed. A PID controller and a self-tuning algorithm compose this structure. Here an AGA is used as self-tuning algorithm to obtain values of the different parameters of the PID controller. From the simulations performed, it was found that it is possible to control the activated sludge aeration process using an AGA tuned PID controller which outperforms other three methods tuned PID controllers. Simulation results are quite encouraging.

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