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COMPARISONS OF PROCESS IDENTIFICATION METHODS AND SUPERVISORY DO CONTROL IN THE FULLSCALE WASTEWATER TREATMENT PLANT

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Abstract: Dissolved oxygen (DO) control in the wastewater treatment plant (WWTP) has been the most critical factor in terms of improving the wastewater treatment efficiency and energy saving. However, the result of DO control with simple PID controller is not satisfactory since the dynamics of DO show some time-varying and nonlinear characteristics. The objectives of this study are as follows. First aim is to apply and compare some process identification methods of PID autotuning for stable DO control in a real coke WWTP. Second, a simple algorithm for the supervisory control of set point decision is proposed to decide a proper DO set point for the current operation condition of the aeration basin by estimating the respiration rate simultaneously during process identification step. The key idea in this method is that the DO set point is proportional to the respiration rate, which is the indicator of the biologically degradable load. In the experimental results, process identification methods have been practiced and compared at the modeling and control performance and supervisory control reduced the aeration cost in the full-scale WWTP. *Copyright © 2002 IFAC*

Keywords: Auto-tuning; dissolved oxygen (DO) control; Kalman filter, respiration rate estimation; supervisory control, wastewater treatment plant (WWTP);

1. INTRODUCTION

Various advanced automatic control methods have been reported to improve the wastewater treatment efficiency and reduce operating costs with the advancement of automatic instruments and computer technologies. Specially, DO concentration in the biological WWTP has been the most critical factor. Excessively high DO concentration increased energy consumption and deteriorate the process performance since they reduce the sludge quality and make the denitrification less efficient. Likewise, low DO concentration lead to both bad quality sludge and less efficient pollutant removal. In summary, DO control purposes are to keep DO concentration sufficiently high level to support the growth of adequate organisms, keep DO concentration sufficiently low for energy saving and avoiding the excess mixing, and keep DO concentration low for nitrate recirculation in the advanced nutrient process.

The PID controller has been best known and is familiar to the process operator because it has a simple linear structure and a robustness property. But in the aspect of control engineering, DO process is classified by its nonlinear dynamics. So, DO control result with a simple PID controller has been not satisfactory since DO dynamics show non-linear and bi-linear characteristics. Moreover, conventional fixed gain PID controllers may not be directly applicable since it does not provide satisfactory regulatory performance against various operation changes. In order to obtain an adequate closed loop response of the biological process, the optimally tuned parameters of the PID controller (autotuning) to be compatible with various process variations are required for DO control system. Several techniques have been tried to increase DO control efficiency (Lee *et al.,* 1994; Diue *et al.,* 1995; Carlsson *et al.,* 1996; Yoo *et al.,* 2001a).

In this research, we use the process identification method for tuning of PID controller (Yoo *et al.* 2001b). It can identify general time-invariant linear systems with a frequency weighting, while retaining simplicity. The frequency weighting makes it possible to improve the robustness to under-parameterization and uncertainties such as disturbances and noises. Then it uses a model reduction method to tune the PID controller using usual tuning rules based on the first or the second order plus time delay model.

The low-level feedback control is usually sufficient under normal conditions when the flowrate and composition of influent wastewater are reasonably constant. However, the operational conditions change, it is favorable for setpoint to be changed adequately for the desired operation. The setpoint change is performed as frequently as necessary, depending on changes in operating conditions or constraints. So, the on-line calculation of setpoints, called *supervisory control*, should allow the unit or plant to achieve maximum profits and minimum pollutant effluents while satisfying operating constraints. The proper aeration in the WWTP is crucial to the treatment and the proper DO setpoint control gives or may give the following advantages such as better control of effluent and energy saving from the lower average DO setpoint. And there is a need to shift the operation condition by the change of setpoints during extreme operational condition such as hydraulic shocks or toxicity. Moreover, WWTP displays nonlinear behaviour when the operational conditions are far from the normal operating point, requiring changes to control setpoints (Seborg *et al.* 1989; Rosen and Yuan 2000).

On the other hand, the supervisory control in the WWTP has been problematic because of its difficulty and hardness. To know which setpoint is the best from a microbiological point of view is a much more complex question. Therefore, there have been few guidelines for the suitable DO setpoint until now (Cardello and San 1988; Lindberg*,* 1997; Rosen and Yuan 2000). Cardello and San (1988) developed the control algorithms to batch bioreactor by incorporating the static feedforword-feedback control and gain scheduling control. Lindberg (1997) suggested a setpoint controller which utilizes measurements of ammonium concentration in the end of aeration basin. The controller tries to maintain a prespecified ammonium concentration by varying DO setpoint. If the ammonium concentration is too high, then DO setpoint is increased and vice versa. Their idea was tested in a pilot plant. But it must be established if the biomass floc properties will be negatively affected by proposed algorithm. Rosen and Yuan (2000) suggested the method for integrated multivariate monitoring and control of biological WWTP during extreme events. They used the dynamic principal component analysis (PCA) and Fuzzy c-means (FCM) for monitoring and classification of the process state. The class membership function of FCM is used to derive adequate control setpoint for the local control loops.

In this research, first, we practiced and compared several process identification methods for the PID controller design which has been used in the most WWTP. We experimented and compared some exciting input signals such as relay feedback, proportional (P) control, relay plus P-controller signal, and setpoint change to activate the DO process in the WWTP. Second, we suggest the supervisory control algorithm to give reasonable setpoint of current operating condition in the WWTP by estimating the respiration rate simultaneously during process identification step.

2. PROPOSED METHOD

2.1 Process Identification Method for PID autotuning

There are some reasons considering automatic tuning in the DO control system. First, the DO dynamics is slow which makes a manual tuning tedious. Second, the operator in wastewater plants often has a rather limited knowledge in automatic control and how to manually tune a controller.

We used a process identification method for the automatic design of the PID controller (Yoo *et al.*, 2001b). It can identify effectively a desired frequency region of the process and utilize any type of test signal generators such as the controller itself, relay, P controller, pulse or step signal generator. Since it considers all measured data sets in estimating several parameters of the process, it shows a good robustness to measurement noises. Even though the proposed identification is simple and does not require any complicated numerical techniques it provides better model accuracy compared with previous methods for the autotuning. Also, the used method provides a good accuracy for under-parameterization and uncertainties like disturbances and noises since it uses a frequency weighting.

Consider the following transform for a signal $y(t)$ before we develop a new process identification method.

$$L_f\{y(t)\} = y_f(s) = \int_0^{t_f} \exp(-st)y(t)dt \qquad (1)$$

Here, if we choose t_f as infinite the above transform is the same as the Laplace transform. From a simple manipulation, the following equation can be obtained when initial values of the signal and its derivative values are all zero.

$$L_f\{I_n\_y(t)\} = \frac{1}{s^n} L_f\{y(t)\} - \exp(-st_f)\sum_{i=1}^{n} \frac{1}{s^i} I_{n-i+1}\_y(t_f) \qquad (2)$$

where $I_n\_y(t)$ denotes the n-th integral of the process output $y(t)$. That is,

$$I_n\_y(t) = \underbrace{\int_0^t \cdots \int}_{n} y(t_1)dt_1 \cdots dt_n \tag{3}$$

Now, consider the following general time-invariant linear system.

$$G_p(s) = \frac{y(s)}{u(s)} = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots + b_1 s + b_0}{a_n s^n + a_{n-1}s^{n-1} + \cdots + a_1 s + 1} \tag{4}$$

where $G_p(s)$ is proper, that is, $m \le n$. $u(s), y(s)$ denote the Laplace transforms of the process input (or controller output) and the process output, respectively. $G_p(s)$ represents the transfer function of the process. The above system (4) can approximate usual processes including time delay terms, nonminimum phase zeroes as accurately as desired since the time delay term can be approximated effectively by just increasing the order like the Pade approximation. It can be rewritten as follows.

$$G_p(s) = \frac{\frac{b_m}{s^{n-m}} + \frac{b_{m-1}}{s^{n-m+1}} + \cdots + \frac{b_1}{s^{n-1}} + \frac{b_0}{s^n}}{a_n + \frac{a_{n-1}}{s} + \cdots + \frac{a_1}{s^{n-1}} + \frac{1}{s^n}} \tag{5}$$

By applying the previously defined transform to the above system, the following algebraic equation is obtained.

$$a_n y_f(s) + a_{n-1}I_1\_y_f(s) + \cdots + a_1 I_{n-1}\_y_f(s) + I_n\_y_f(s) =$$
$$b_m I_{n-m}\_u_f(s) + b_{m-1}I_{n-m+1}\_u_f(s) + \cdots + b_1 I_{n-1}\_u_f(s) + b_0 I_n\_u_f(s)$$
(6)

Our objective is to identify the coefficients of *a* and *b*. In Eq. (6), only if the process output is measurable, we can calculate $y_f(s), u_f(s)$ and $I\_y_f(s), I\_u_f(s)$ for various s values using Eqs. (1) and (2) with a numerical integration method. Therefore, we can estimate the coefficients of *a* and *b* from the linear Eq. (6) with a least squares method. In this research, we choose s value as a complex number $j\omega$. Physically, ω means a frequency. Eq. (1) is similar to the Fourier transform since $s = j\omega$. Here, the objective function for the least squares method is the Euclidean norm of the difference between the left-hand side and the right-hand side of Eq. (6). That is,

$$\begin{aligned} e(j\omega_k) &= I_n\_y_f(j\omega_k) - a_n y_f(j\omega_k) \\ &- a_{n-1}I_1\_y_f(j\omega_k) - \cdots - a_1 I_{n-1}\_y_f(j\omega_k) + \\ &b_m I_{n-m}\_u_f(j\omega_k) + b_{m-1}I_{n-m+1}\_u_f(j\omega_k) \\ &+ \cdots + b_1 I_{n-1}\_u_f(j\omega_k) + b_0 I_n\_u_f(j\omega_k) \end{aligned} \tag{7}$$

$$\begin{aligned} &\underset{a,b}{\mathrm{MIN}}\left\{\sum_{k=1}^{N}\left\|e(j\omega_k)\right\|^2\right\} = \\ &\underset{a,b}{\mathrm{MIN}}\left\{\sum_{k=1}^{N} Re(e(j\omega_k))^2 + Im(e(j\omega_k))^2\right\} \end{aligned} \tag{8}$$

where ω_k is the *k*-th desired frequency and *N* is the number of the desired frequencies. The least squares-optimization problem can be solved directly so that any complicated numerical techniques are not required.

In summary, after activating the process using an appropriate activation-signal-generator we numerically calculate the integrals of the process output, the process input and the corresponding transforms, $y_f(j\omega_k)$ and $u_f(j\omega_k)$ for desired frequencies ω_k's. And then we estimate the coefficients of Eq. (4) by minimizing the Euclidean norm of Eq. (8).

On the other hand, we should reduce the identified model to the FOPTD or SOPTD model to tune the PID controller automatically because many developed on-line PID tuning methods such as internal model control (IMC), the Integral of time-weighted absolute value of the error (ITAE) and Cohen-Coon (C-C) are based on these models. Here, we used a simple model reduction method to reduce the high order model to a lower (Sung *et al.*, 1996).

2.2 Supervisory Control

The supervisory control to recommend a proper DO setpoint in the aeration basin's current operation condition has been problematic in the advanced wastewater treatment process. However, there have been few guidelines for the proper DO setpoint until now. The proper aeration is crucial to treatment efficiency since an insufficient dissolved oxygen level impairs the oxidation process and eventually leads to biomass death. Whereas too high DO concentration may cause the sludge to settle poorly and excessive aeration is also undesirable from an economic point of view since the oxygen in excess is lost to the atmosphere. Therefore, The proper DO setpoint control gives or may give the following advantages such as better control of effluent, lower average DO setpoint which saves energy.

On the other hand, the respiration rate of activated sludge has generated much interest, as it is an essential variable in the activated sludge process and provides information on activity and concentration of the biomass, influent wastewater concentration and composition, toxicity and concentration of biomass degradable matter in the effluent. However, there has been some controversy as the utility of the respiration rate in control systems (Spanjers *et al.*, 1998). The calculation of the respiration rate can be used in several ways: a) estimation of the overall activity in the aerated basin. b) calculation of the load of oxygen consumption substances on the aeration basin c) calculation of nitrification rate d) estimation of necessary aerated volume e) rapid detection of inhibition of the nitrification and other oxygen consuming reactions. One advantage with these calculations is the fast response to changes (Bjorlenius and Reinius, 1998).

The key idea is that DO setpoint is determined in proportion to the respiration rate and influent loading because the respiration rate is the important variable that characterizes the DO process and the associated removal and degradation of biodegradable matter and is the only indicator of biologically degradable load. That is, if toxic matter enters the plant, for example, this can be detected as a decrease in the respiration rate, since the microorganisms degrade their activity or some of them die. Then, a rapid decrease in the respiration rate may hence be used as a warning that toxic matter has entered the plant. In this case, we should increase the DO set point. Therefore, we can suggest the following decision rule that "*The higher respiration rate, the lower DO setpoint. The lower respiration rate, the higher DO setpoint*". Fig. 1 shows the scheme of the supervisory control to decide the setpoint of DO controller. Supervisory control is based on *in-situ* estimation of respiration rate during the process identification, where whole aerator in the real plant is used as a respirometer. Afterwards, the operator included the influent loads and temperature effect into the supervisory DO control. In the case of the high influent load and the abnormal temperature change, a by-pass action should be taken to save the microorganisms.

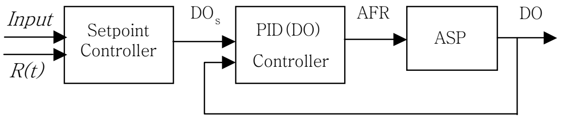

Fig. 1 Supervisory DO control scheme.

Because we didn't have the real-time respiration rate meter in the waste loading state, we used the well-known respiration rate estimation algorithm with Kalman filter approach suitable to the surface aerator type of full-scale WWTP. And the estimated parameter is also used to give judgment of the present operation states and process load. There are several different approaches such as recursive method in order to estimate oxygen transfer rate and respiration rate from measurements of DO and airflow rate. In this paper, we used the Lindberg's method (Marsili-Libelli, 1990; Lindberg, 1997). The respiration rate is tracked by a Kalman filter by using measurements of DO and air flow rate, $u(t)$. During the autotuning phase, the airflow rate or aerator speed variation is given a high excitation both in amplitude and frequency. The estimation procedure is performed on a relatively short date set, in our case, autotuning's identification time. Then, the estimated models of the respiration rate and oxygen transfer rate could be used to the other controller design. The estimated value of the respiration rate would be used as a base rule in the set point decision.

3. EXPERIMENTAL RESULTS

We have applied several process identification methods and compared their performances to verify the effectiveness of the auto-tuning method in the fullscale wastewater treatment plant which is located in Pohang, Korea. The plant has treated the cokes wastewater from the steel industry and had the highly dynamic variation characteristics. It is extremely difficult to treat the cokes wastewater because of large quantities of toxic compounds and coal-derived liquors (e.g. phenols, ammonia, nitrate, cyanides and naphthalene). Furthermore, the quantity and quality of wastewater varies frequently in upstream, which causes troublesome in controlling DO of aeration basin with a conventional method.

Fig. 2 shows a schematic diagram of the WWTP considered in this study. The plant is made of two parts: one is the biological process that composed of the activated sludge process. The other is the chemical treatment part. The studied wastewater treatment plant consists of five aerators and two settling tanks. Each aerator was equipped with 4 types of sensors (pH, DO, ORP, MLSS) and a speed controllable surface aerator in order to supply the dissolved oxygen in the aeration basin. The automatic control system has PC/PLC structure. It was designed as the user-friendly control system using the commercial man machine interface (MMI) software known as FIX DMACS 7.0. The PID control algorithm was been installed in the MMI where the process identification and supervisory control were implemented with the visual basic 6.0. We have applied the proposed methods into the fifth aerator to verify the effectiveness of the auto-tuning method and the supervisory control algorithm.

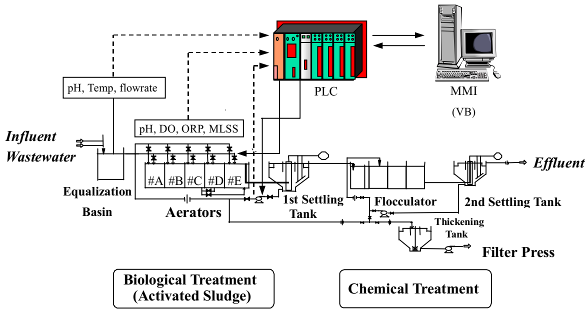

Fig. 2. Schematic diagram of the coke wastewater treatment plant.

We experimented three input signals of setpoint change of PID controller, relay feedback, and relay plus P-controller signal to activate the DO process in the real plant. The tested aeration basin was the last basin. Fig. 3 shows the experimental results of three process identification methods in full-scale WWTP, where are shown the aerator speed (RPM) and DO concentration basin for each three activating signals.

The sampling time was 3 seconds and the signal from the DO sensor was filtered using exponential filter. A simple setpoint change of PID controller itself was chosen as the activation signal without any control mode change (Fig. 3a). It is simple, stable and easy to implement the proposed on-line identification method. Moreover, this closed-loop identification method can be used when that the process receives any unintentional disturbance during the identification.

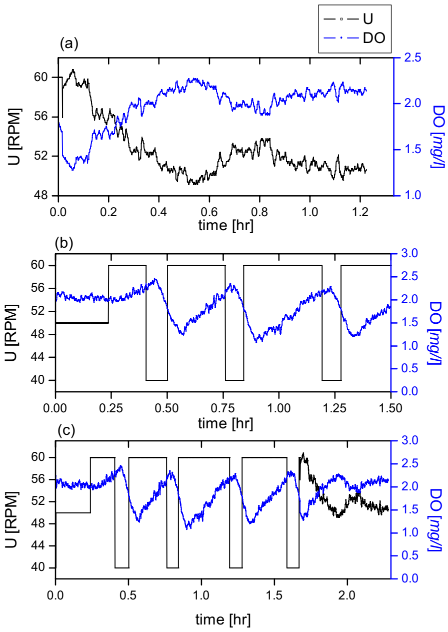

Fig. 3. Experimental results of some process identification methods in full-scale WWTP. (a) setpoint change of PID controller, (b) relay feedback, (c) relay plus P-controller.

On the other hand, if we select the relay feedback as an activation signal of the process identification, the classical method for the respiration estimation can also be used. The relay feedback as a process identification makes the DO concentration the cyclic behavior (Fig.3b). The respiration rate is calculated from the observed rate of decrease of the DO concentration. This decrease represents the respiration rate only, if the rate of change of DO concentration inside the reactor due to incoming and outgoing flows in negligible. The respiration rate is estimated as the slope of a regression line fitted to a series of DO signal (in our case, filtered data). That is, the relay feedback identification makes the additional estimation method for the respiration rate possible. We will implement this approach in the future. And if we want good controller performances in spite of the long identification time, we can select the relay plus proportional controller as the activation signal to acquire much frequency information (Fig.3c). However, these two relay identification methods have some constraint requirements, which the autotuning method may fail if a sudden disturbance occurs during the identification phase.

Using the acquired data, we identified the high order model through the explained identification method. And then we reduced the high order model into the first and second order plus time delay model using the model reduction technique for the PID controller tuning (Sung *et al.*, 1996).. As a tuning rule, the ITAE disturbance rejection rule is selected because it is appropriate for the step input disturbance that occurs frequently in the WWTP. Fig. 4 shows the control performances of DO concentration based on PID autotuning and supervisory control in the full-scale WWTP for 50 days. The experimental results showed good control performance and showed robustness to measurement noises since it considers all measured data sets to estimate several adjustable parameters. In spite of the frequent load change, the characteristics of coke making plant, the control performance. The abrupt change of DO concentration is due to the a stoppage of electric power.

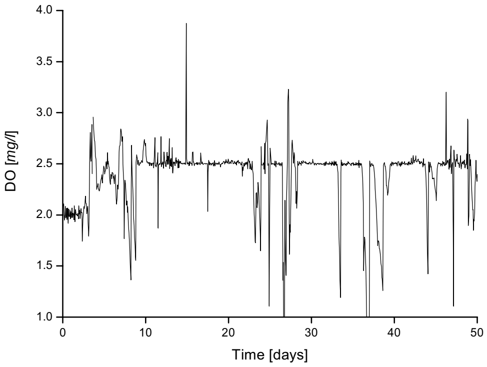

Fig. 4. Control performances using the proposed method for 50 days.

In the supervisory control, we determined the previous simple set point decision rule, "*The higher respiration rate, the lower DO set point. The lower respiration rate, the higher DO set point*". To avoid the DO set point becomes too high or too low, it should be only be allowed to vary in an interval, 0.5-4.0 mg/l in our case. And the respiration rate range is 10-60 *mg/l/h*. In our coke WWTP, we suggested following simple set point decision rule during the normal influent load.

$$\boldsymbol{DO}_s = -0.024\hat{\boldsymbol{R}}(\boldsymbol{t}) + 1.75 \qquad (9)$$

During the identification phase of the setpoint change PID controller, we estimated the respiration rate using the Kalman filter approach. In addition, the operators has included to temperature effect and influent characteristics (high, normal ,low influent load) into the supervisory control considering the environmental condition since the DO dynamics is influenced by aeration basin's temperature and influent loading. The supervisory control has been modified and revised according to the operator's experiences.

In this coke WWTP, the ammonia concentration has been high compared with the readily biodegradable chemical oxygen (COD). This is a good environmental condition for the growth of nitrifying bacteria. Before the application of PID autotuning, it was difficult to maintain DO concentration constant in order to inhibit the growth of nitrifying bacteria by poor control performances. After PID autotuning and supervisory control, operators could maintain the DO concentration lower than the past by the increased controller's stability and adjust the operating condition efficiently, which in extended the operator's the liberty of choice.

Fig. 5 shows the change of electricity consumption in this treatment plant for four years. Note that new utility equipment was installed in 600 days and large electricity consumption was necessary. As shown in this Fig. 5, there was rapid of electricity saving after applying the PID autotuning and supervisory control. This is 5% of the total electricity consumption and 15% of the electricity cost when considering only the surface aerators. Moreover, as a result of improved control performance, the fluctuation of effluent quality has been decreased and overall improvement of the effluent water quality was achieved.

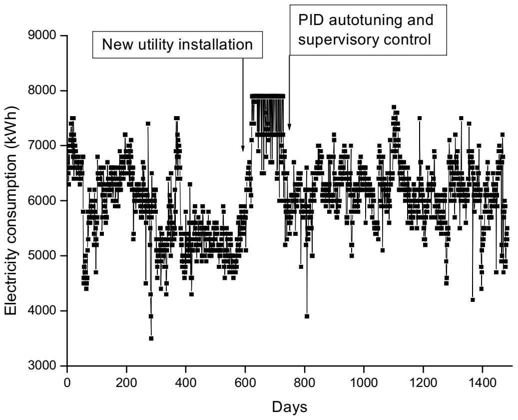

Fig. 5. Change of electricity consumption in fullscale WWTP during four years.

4. CONCLUSIONS

In this work, we compared some process identification methods of PID autotuning for stable DO control and applied the supervisory control to give reasonable setpoint of current operating condition and save the operating cost, which were based on simultaneous process identification and *in-situ* estimation of respiration rate in the. In the experimental results, process identification methods and supervisory control have been practiced and compared at the modeling and control performance and reduced the electricity cost in the full-scale WWTP.

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