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DISSOLVED OXYGEN CONCENTRATION REGULATION USING AUTO–TUNING PID CONTROLLER IN FERMENTATION PROCESS.

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ABSTRACT: A novel control method involving an automatic tuning of digital PID controller parameters has been developed for better regulation of DO (dissolved oxygen) concentration in batch fermentation processes. Heuristic reasoning allows the PID controller to reach improved tuning decisions based upon the supervision of certain control performance indices in the same cognitive manner as in an expert control.

INTRODUCTION

With recent improvements in sensor reliability and digital computer systems, digital process control is unanimously accepted as an effective way of improving the performance and reducing the operating costs of fermentation processes. One of the most important computer applications in fermentation processes is DO (dissolved oxygen) concentration control. Since a small change of DO level may bring about a significant physiological alteration in cell metabolism, the control of DO concentration level in aerobic fermentation media has a profound effect on the rates of microbial metabolism and product formation.

Fermentation systems are complex, time–varying, and highly nonlinear. Especially, in a batch culture system, its dynamic behaviors significantly change during the fermentation as a result of antifoam addition, biomass accumulation, product formation, and nutrient depletion. Therefore, in general controllers which have fixed tuning parameter values such as conventional PID controller are considered to be insufficient to cover a wide range of dynamic changes in fermentation processes. New schemes to compensate for changes in the process dynamics need to be developed for better regulatory performance.

This tuning problems has spurred development of a number of methods for automatic tuning of PID loops. Most of the method proposed upto date rely either on identification of an explicit model [1–4], or on identification of parameters such as critical gain and period [5] or overshoot and damping ratios [6], which characterize the control loop dynamics. These methods are reported to work well in many applications, but inherent assumptions about the form of the model or the form of the disturbance patterns may cause difficulties in certain applications [7]. Also, in some cases the performance criterion does not directly relate to optimal performance of the control loop.

The auto–tuning PID controller proposed in the present study is based on the supervision of certain control performance indices in the same cognitive manner as in an expert control, which obviates the need for assumptions about the process or disturbance patterns.

DESIGN OF AUTO–TUNING PID CONTROLLER

Digital PID control

Discretization with rectangular integration and backward differentiation of the canonical equation of conventional analog PID controller leads to

$$U(k) = K_c\,[e(k)+\frac{T}{\tau_i}\sum_{i=0}^{k-1}e(k)+\frac{\tau_d}{T}\{e(k)-e(k-1)\}] \quad (1)$$

where $U(k)$ is control input; $e(k) = C_s - C(k)$ control deviation; C_s set point; T sampling time; K_c proportional gain; τ_d derivative time; and τ_i integral time. Because a position type of PID controller as in eq.(1) is not appropriate for programming on a digital computer, the PID feedback control algorithm employed in this study was of a velocity form which could be obtained through the subtraction from eq.(1) of the corresponding equation for $U(k-1)$ as follows.

$$U(k) = U(k-1)+K_c\,[\{e(k)-e(k-1)\}+\frac{T}{\tau_i}\,e(k) + \frac{\tau_d}{T}\{e(k)-2e(k-1)+e(k-2)\}] \quad (2)$$

To avoid large changes in the control input after a step change in the set–point, C_s has been removed from the derivative and the proportional terms. In which case we have the following equation.

$$U(k) = U(k-1)+K_c\,[\{C(k)-C(k-1)\}+\frac{T}{\tau_i}\,e(k) + \frac{\tau_d}{T}\{C(k)-2C(k-1)+C(k-2)\}] \quad (3)$$

At this point, the most important task is tuning of the controller parameters K_c, τ_i, and τ_d and the sampling time T.

Tuning Decision with Heuristics

In the present study the controller parameter tuning was carried out using a heuristic rule based on the supervision of three performance indices. For adaptation of the proportional gain K_c, Marsik and Strejc proposed several heuristic rules [8]. However these rules are too complicated to implement. Furthermore, it is not clear which rule should be chosen in certain situation.

A new heuristic reasoning rule has been proposed for the adaptation of proportional gain in the present study. The performance indices chosen for the heuristic reasoning for K_c adaptation are the output error covariance, the average value of the error, and the input covariance which are calculated on-line using a moving window. The moving window covariances of the input and the output are expressed as

$$CovC(k) = S_1(k) - S_2(k) * S_2(k) \tag{4}$$

$$CovU(k) = S_3(k) - S_4(k) * S_4(k) \tag{5}$$

where $S_1(k)$, $S_2(k)$, $S_3(k)$ and $S_4(k)$ are defined by

$$S_1(k) = \frac{1}{n}\{\sum_{l=k-n}^{k-1} C(k-l)^2\} \tag{6}$$

$$S_2(k) = \frac{1}{n}\{\sum_{l=k-n}^{k-1} C(k-l)\} \tag{7}$$

$$S_3(k) = \frac{1}{n}\{\sum_{l=k-n}^{k-1} U(k-l)^2\} \tag{8}$$

$$S_4(k) = \frac{1}{n}\{\sum_{l=k-n}^{k-1} U(k-l)\} \tag{9}$$

Here, n is an integer which determines the moving window length. These two performance indices correspond to ISE (integral-squared-error) tuning criteria in principle. However, their calculations are recurrently performed over a finite time interval based on normal process disturbances and control actions, while the ISE tuning criteria are calculated over an infinite time interval after an artificially introduced step change in the control input or the set point. The third index is the moving window offset of the output:

$$Offset(k) = C_s - S_2(k) \tag{10}$$

By using these three performance indices, the following simple heuristic rule was proposed for the automatic tuning of the proportional gain, K_c.

$$\textbf{IF } CovC(k) \geq CovC_{max} \textbf{ AND } CovU(k) > CovU_{max} \tag{11}$$

$$\textbf{THEN } K_c(k) = K_c(k-1) - \alpha_{pi} \cdot Cov(k)$$

$$\textbf{IF } Cov(k) < Cov_{min} \textbf{ AND } |Offset(k)| > Offset_{crit}$$

$$\textbf{THEN } K_c(k) = K_c(k-1) + \alpha_{pd} \cdot |Offset(k)|$$

$$\textbf{OTHERWISE} \quad K_c(k) = K_c(k-1)$$

where a_{pi} and a_{pd} are the weighting factors. Once an adjustment is made in K_c, the next decision was reserved for certain number of sampling instants in order to allow the process enough time to respond to the adjustment and thus accurately analyze its effects.

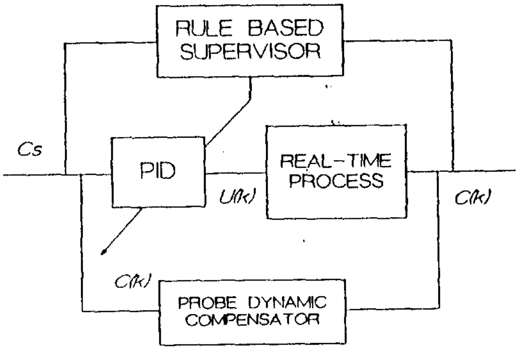

Figure 1. Block diagram of PID control based of heuristic rule.

DO Electrode Dynamics Compensation

The most popular DO electrode for industrial fermentation processes is of membrane-sheathed type. The membrane causes complex electrode dynamics including the response time delay. In Koizumi and Aiba [9], the following relation between the actual DO concentration of the fermenter broth, $C(t)$ and the output signal from the DO electrode, $C_e(t)$ was proposed.

$$C(t-\tau) = C_e(t) + \frac{1}{k_c}\frac{dC_e(t)}{dt} \tag{12}$$

If τ is d times of the sampling period T, eq. (12) can be digitized to give eq. (13) by using a first-order backward difference approximation.

$$C(k-d) = C_e(k) + \frac{1}{T \cdot k_c}\{C_e(k) - C_e(k-1)\} \tag{13}$$

Here, the most recent data available at time $t(= kT)$ is d-step delayed value. Thus, the simple extrapolation procedure in eq. (14) was employed for d-step ahead prediction.

$$\hat{C}(k) = C(k-d) + d \cdot \{C(k-d) - C(k-d-1)\} \tag{14}$$

Without considering the electrode dynamics, stability of the control algorithm will be decreased due to inherently incorrect measurements which are mainly caused by the response time delay.

A block diagram of the proposed DO concentration control algorithm is presented in Figure 1.

MATERIALS AND METHODS

A schematic diagram of the bioreactor control system is shown in Figure 2. The fermenter system was a Bio-Stat E model (B. Braun Biotech.) and the working volume was 2 L. All measurement and regulation modules on the Bio-Stat E model are equipped with input and output ports which are indispensable for computer interface. An IBM-XT personal computer thus could be readily and successfully connected to the fermenter system with a data interface. The data interface consists of 16 channel multiplexed 12 bits A/D converter (conversion time 20 mS), 8 channel 12 bits D/A converter, and a clock. Real time peripherals such as printer and hard disk were employed for data acquisition. All necessary computer programs involved were written in Quick–BASIC.

Measurement of the DO concentration was performed using a sterilizable polarographic DO electrode. The agitation speed was manipulated through a thyrister controller of which set point was provided by the computer. In practice, the control action is commonly constrained by mechanical limitations. This situation is reflected in the control as follows.

$$\begin{aligned} &\textbf{IF } U(k) < U_{min} (= 150) \textbf{ THEN } U_f(k) = U_{min} \qquad (15)\\ &\textbf{IF } U(k) > U_{max} (=1000) \textbf{ THEN } U_f(k) = U_{max}\\ &\quad \textbf{OTHERWISE} \qquad U_f(k) = U(k) \end{aligned}$$

where $U_f(k)$ denotes the actual control input. The air flow rate was fixed at 1 vvm. The temperature and the pH of the culture broth were maintained at 37°C and 7, respectively by the built–in regulation modules on the fermenter system. The microorganism was *Escherichia coli* K–12. The growth medium consisted of glucose, yeast extract, K_2HPO_4, KH_2PO_4, NH_4Cl, and $MgSO_4 \cdot 7H_2O$ which were dissolved in distilled water.

RESULTS AND DISCUSSION

To use a digital PID controller, appropriate values of the tuning parameters, T, Kc, τ_i, and τ_d should be chosen first. In general, the sampling time can be determined with the following rule of thumb suggested by Isermann [10]

$$T_{95}/4 \geq T \geq T_{95}/15 \qquad (16)$$

where T_{95} is the 95% settling time. In the present case T_{95} was about 60 sec, which resulted in 4–15 sec of sampling time. However, use of a shorter sampling time usually improves the digital PID control performance due to increases in the amount of available information and the number of control actions. A sampling time of 5 sec was used throughout the PID control experiments.

Figure 3 shows typical results obtained from the conventional PID control. In this experiment, K_c, τ_i, and τ_d are chosen to be *0.5*, *12*, and *2.4*, respectively. These values were determined by using transient–response tuning methods, such as Cohen–Coon criteria [11] as the first approximation. The fine tuning procedure was done manually at a DO concentration of 50%. The DO concentration was represented as percentage of the saturated DO concentration, $C*$. When the set point was 50% of DO concentration at which the controller parameters had been tuned, the controlled DO concentration rapidly converge to the set point with no significant overshoot.

However, after a negative step change in the set point from 50% to 30%, DO concentration showed a very slow convergence with considerable oscillation. This result seems to be caused by the dependence of process dynamics on the magnitude and the direction of a step change in the input variable, in other word, nonlinearity which is one of the well–known characteristics of bioreactor systems. Another possible cause is the response time delay (or measurement lag) which is one of the intrinsic characteristics of menbrane type DO electrodes. Doebelin proposed that if the time lag in measurement device is larger than the sampling period, it brings about instability within the closed control loop, which is coupled with relatively large sensitivity [12]. Therefore, with no compensation procedure for the DO electrode dynamics such as response time delay, the oscillation phenomenon in DO concentration (Fig. 3) did not seem to vanish.

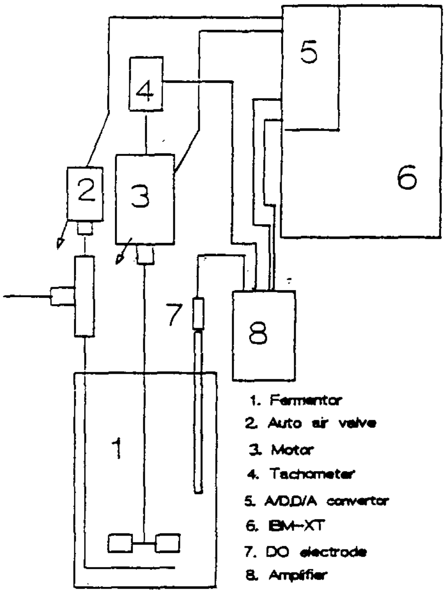

Figure 2. Schematic diagram of computer installed fermenter.

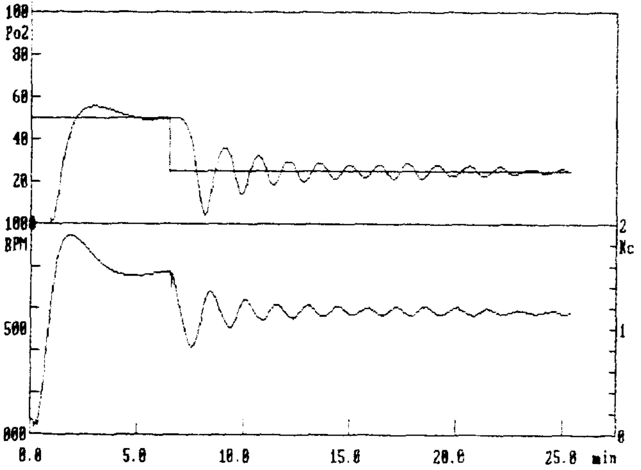

Figure 3. DO concentration control with digital PID controller (tuning parameters; K_c=*0.5*, τ_i=*12*, τ_d=*2.4*)

With this in mind, a PID controller complemented not only with an automatic tuner involving an heuristic rule but also with a compensation procedure for the DO electrode dynamics was tried and the result for a square wave set point is shown in Figure 4.
The heuristic reasoning rule described by eq.(11), the velocity form of digital PID controller as in eq.(2), and the DO electrode dynamic compensation procedure of eq.(4) were employed. Though some minute oscillations were observed, the DO concentration converged to the set point very fast with a zero steady state offset. However, a large fluctuation in the control input took place after a step change in the set point C_s. Furthermore, the variation of control parameter, K_c was also dramatic. As mentioned early in the section for **Digital PID Control**, this result seemed to be due to the sudden change of C_s in the derivative term in the controller eq.(2), which causes excessive control actions.

Figure 5 shows PID control results in the case in which eq.(2) is replaced with eq.(3). In this particular case, no compensation for dynamic characteristics of the DO electrode was involved. A relatively small initial value for the proportional gain, $K_c(0) = 0.05$, was appropriated. In the beginning, the rising time was large and the output convergence was very slow because the initial value of K_c was too small. Even though a number of K_c readjustments were carried out by the controller itself, the oscillations in the input and the output variables last for a long time and an overshoot was observed whenever a set point change was introduced. Such a result is due to the fact that no compensation for the DO electrode dynamics is included in the control loop.

Figure 6 shows PID control results in the case of using the PID control algorithm of eq. (3) compensated for the dynamic characteristics of the DO electrode and of starting with a very small value of the proportional gain, $K_c(0) = 0.05$. Though some oscillations were observed during the initial transient period, overall response was fairly improved with nearly zero steady state offset and no overshoot. With the electrode dynamics compensator included in the control loop, the convergence of the controlled output was much faster than that of the previous case (Figure 5). Once the K_c was readjusted to an optimal value, no overshoot appear any longer and very good control performance was obtained. The final K_c value was smaller than that in the case of figure 5.

Figure 7 shows PID control results in the case of starting with a very large value of the proportional gain, $K_c(0) = 1.5$. As in the case of figure 5, no compensation procedure for the DO electrode dynamics was include in the control loop. As shown in this figure, the first overshoot is very large and an overshoot always appeared whenever the set point was changed. Furthermore, the adaptation of K_c value was very slow.

Figure 8 represents results of PID control using the same algorithm as in Figure 6 except a much larger value of $K_c(0)(= 1.5)$ was used. In this experiment, no overshoot appeared. The convergence rate of K_c was very fast, *i.e.* after only 4 steps of readjustment procedure the value of K_c converged to a reasonable level of *0.35*.

Figure 9 shows the time profiles of DO concentration $C(k)$, the agitation speed $U(k)$, and the proportional gain $K_c(k)$ over the entire period of a batch fermentation of *E. coli*. The same control algorithm as in Figure 8 was implemented. A very large initial value of K_c ($K_c(0) = 2.0$) was appropriated. With the exponential growth of cells, dynamic characteristics of oxygen transfer in the reactor significantly changed and thus the K_c value of the PID controller was continuously readjusted. The overall performance was found to be quite robust despite the time–varying nature of the fermentation process.

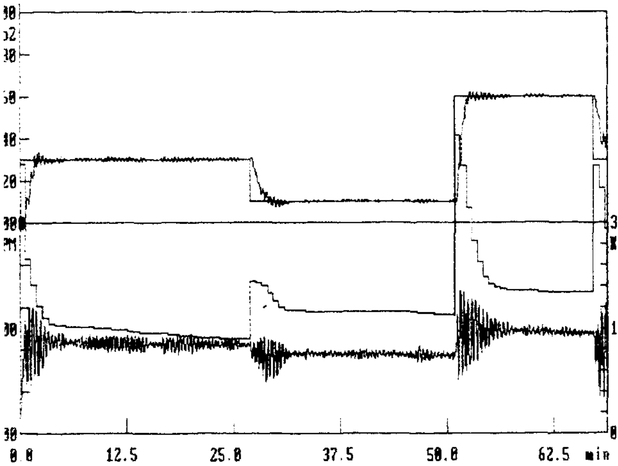

Figure 4. The rule based PID control of DO concentration. (eq.(2) is used and probe dynamics considered; $K_c(0)=0.05$, $\tau_i=12$, $\tau_d=2.4$)

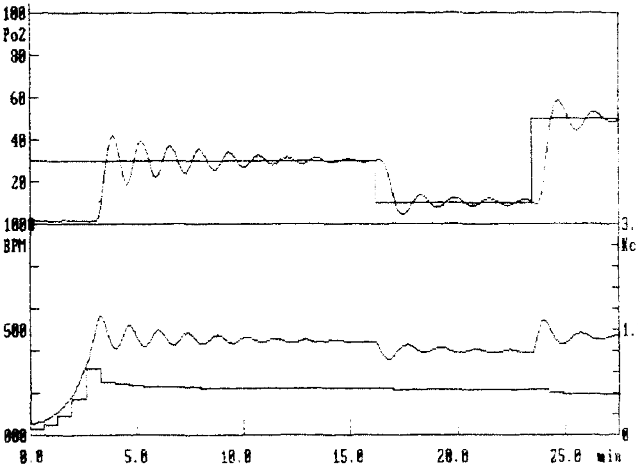

Figure 5. The rule based PID control of DO concentration. (eq.(3) is used and no probe dynamics are considered; $K_c(0)=0.05$, $\tau_i=12$, $\tau_d=2.4$)

CONCLUSIONS

In the present study a new auto–tuning rule has been developed, which is based on the supervision of three control performance indices in the same cognitive manner as in an expert control and has been applied for automatic tuning of digital PID control parameters.

Experimental results indicated that the auto–tuning PID controller worked extremely well requiring no initial tuning step for the proportional gain in controlling the DO concentration in a batch fermentation process in spite of a large variation in the process load. This is due to its ability to readjust its parameters and thereby to compensate for changes in the process dynamics.

The main advantages of this method stem from the fact that it does not need repeated artificial disturbances during the operation such as set point change which are introduced to readjust the controller gain as in some conventional auto–tuning PID controllers. These advantages include a wide range applicability and ease of use.

The proposed auto–tuning PID control algorithm can be a useful tool in handling processes of strongly time–variant nature as in most biological systems.

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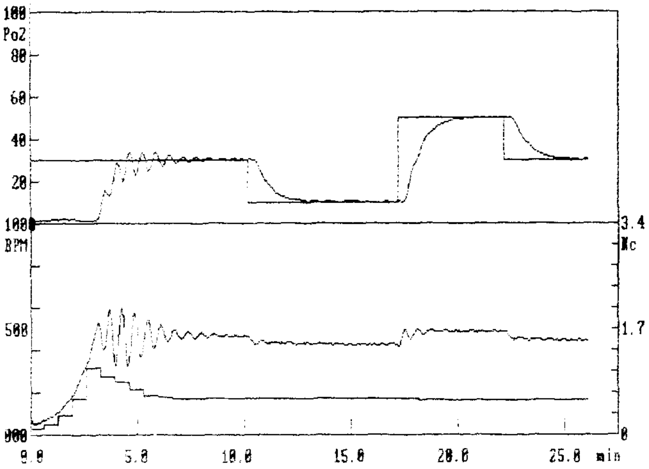

Figure 6. The rule based PID control of DO concentration. (probe dynamics are considered; $K_c(0)=0.05$, $\tau_i=12$, $\tau_d=2.4$)

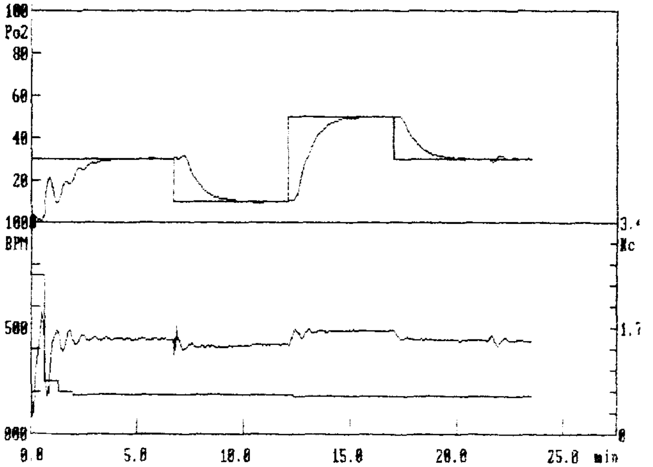

Figure 8. The rule based PID control of DO concentration. (probe dynamics considered; $K_c(0) = 1.5$, $\tau_i=12$, $\tau_d=2.4$)

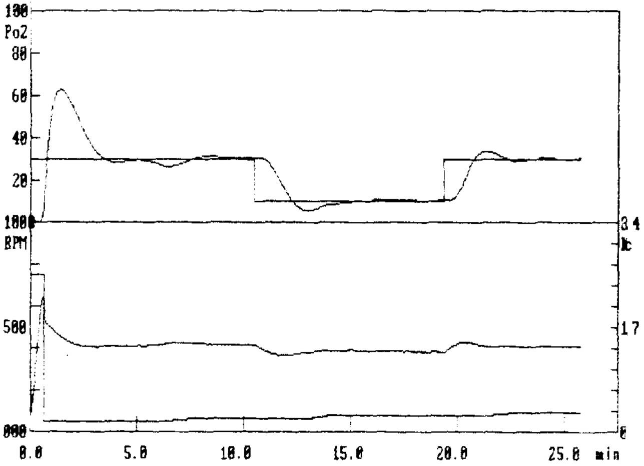

Figure 7. The rule based PID control of DO concentration. (no probe dynamics considered; $K_c(0)=1.5$, $\tau_i=12$, $\tau_d=2.4$)

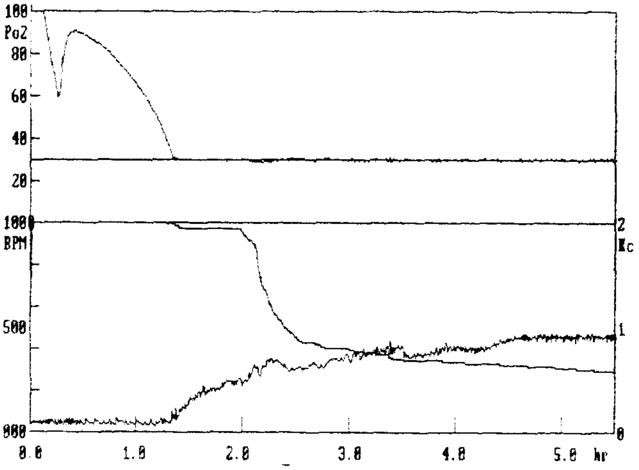

Figure 9. The time profile of DO concentration control results with rule based PID controller in batch culture (probe dynamics considered; $K_c(0)=2.$, $\tau_i=12$, $\tau_d=2.4$)