'87 韓國自動制御學術會議論文集 1987. 10.16~17

연속 교반 발효조에서 균체농도의 단순 디지탈 제어

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Simple Digital Control of Cell Mass in Biological CSTR

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Abstract

Yeast biomass in a biological continuous stirred tank reactor was controlled with an APPLE II microcomputer using adaptive control theory of bilinear systems. The controller used is as simple as a PID controller, but required less information. Cell concentration was well controlled by adjusting the inlet flow rate following the algorithm.

I. Introduction

The complex nature of biological systems makes it difficult to construct a good model describing the dynamics of general continuous stirred tank biological reactors(CSTBR). It is usually a tedious and time consuming job to formulate a dynamic model for a specific CSTBR. Hence, for better regulation we need a controller which is robust enough to handle uncertainties in CSTBR dynamic models and preferably requires less information about individual reactors.

Here we propose a controller to regulate cell concentration in a CSTBR, using the concepts of the self tuning regulator and known bilinear structure of the CSTBR.[1] It is as simple as a PID controller, but it requires less information. Experimental results show that this controller is as competent as the PID controller to control the yeast cell concentration in a CSTBR.

II. Controller Design

The cell mass balance equation for the CSTBR is

$$dX(t)/dt = \mu(t)\cdot X(t) - D(t)\cdot X(t) \qquad (1)$$

where X(t) is the cell mass concentration used as the output variable, D(t) is the dilution rate used as the input variable, and $\mu(t)$ is the time-varying growth rate coefficient which contains the effects of substrate dynamics.[2]

Equation(1) can be discretized with the rectangular integration rule to

$$\begin{aligned} X(k+1) &= (1+\mu(k)\cdot T)\cdot X(t) - T\cdot D(k)\cdot X(k) \\ &= a(k)\cdot X(k) - T\cdot D(k)\cdot X(k) \qquad (2) \end{aligned}$$

where T is the sampling time. Since in equation (2) only one parameter a(k) is not known, we can trace it without using a complicated identification procedure as follows

$$\hat{a}(k) = X(k)/X(k-1) + T\cdot D(k-1) \qquad (3)$$

A dead beat control law with $\hat{a}(k)$ instead of $a(k)$ can be constructed as it is done in the self-tuning regulator. In other words, let $a(k) \doteq \hat{a}(k)$ and $X(k+1) = Xs$, then

$$\begin{aligned} D(k) &= \hat{a}(k)/T - Xs/T{\cdot}X(k) \\ &= D(k-1) + \{X(k)/X(k-1) - Xs/X(k)\}/T \qquad (4) \end{aligned}$$

If a(k) is a unknown constant, it takes two steps for the control law of eq.(4) to settle the discrete time system of eq.(2) to a desired nonzero set point Xs. However, it is probable that the controller will be sensitive to measurement noises. Thus we introduce a tuning parameter λ to retard the control effects:

$$\begin{aligned} D(k) &= D(k-1) + \lambda\{X(k)/X(k-1) - Xs/X(k)\}/T \\ &\quad 0 \le \lambda \le 1 \qquad (5) \end{aligned}$$

We intend to test the control mode of eq.(5) and investigate the effects of λ by controlling a small laboratory scale CSTBR. If we replace Xs by Xs(k), the control law of eq.(5) can be used in the tracking problems. This algorithm is directly applicable to the control of product or substrate in a CSTBR if a proper sensor is present.

III. Experimental

A schematic diagram of experimental apparatus is shown in Figure 1. The medium consisted of glucose (20 g/L), yeast extract (5 g/L), malt extract (3 g/L) and Bacto-peptone(5 g/L) dissolved in distilled water. The medium was autoclaved 20 min at 2 atm and 121 °C.

A strain of yeast(Saccharomyces cerevisiae, ATCC 24858) was grown aerobically(2vvm) in a 2L fermenter of our own construction. The reactor was operated batchwise untill the cell mass reached a certain level , and then was switched to continuous operation. The temperature and the pH of the reactor were maintained at 30 °C and pH 5 respectivly by on-off control with the APPLEII microcomputer through the separate control algorithm. Cell concentration was monitored by optical density with a Spectronic 100 with the recycle of the broth through the photocell.

The controller was composed of an APPLE II microcomputer, peripherals and A/D, D/A convertors of 12 bits resolution of our own construction. Signals were gathered every 3 min by the analog means and were averaged digitally. Dilution rate was controlled with a peristaltic pump(7016 head, Cole-Parmer). The interfacing circuits were constructed in the authors' laboratory. The BASIC and ASSEMBLY languages were used in programming. The structure of the program is shown in Figure 2.

IV. Results and Discussion

Equation (1) resembles a bilinear system equation solved analytically by Svoronos.[1] And using a highly output-weighted quadratic cost regulator as the controller of this bilinear system resulted in proportional control with high gain. Dibiasio et al. [2,4] also showed through elaborate simulations and experimental studies that a sufficiently high gain P controller could stabilize a CSTBR. However, for more safety and better regulation, some information about $\mu(k)$ is required.

In the present experiment some setting of the PID controller failed to give stable responses. Therefore experiments with only the P-mode were carried out to see whether the control theory of Svoronos [1] could be applied to the present system. Sampling the cell mass was done every 3 min since the theory was based on discreate time version. After an on-line run about 10 hours, relatively good control with P-mode (gain = 25 L/g h) was obtained and it is shown in Figure 3. There was no overshoot or steady-state off set, but a high level of disturbance owing to high gain of controller was unavoidable.

Figure 4 shows that better results with a low disturbance in the level of cell concentration could be obtained with direct application of the control law of eq. (5) with $\lambda = 1$. However, there still existed heavy fluctuations in the dilution rate.

Further improvement could be made by adjusting the tuning parameter to 0.1 as shown in figure 5. Figure 6 shows that the controller could trace the changes of the set point Xs. The disturbances seem to have originated from sensing the cell concentration. The foam dispersed in the broth during the aeration was not completely removed at the recycle shunt and also fed to the spectrophotometer. However the present control law was successful in damping a great part of these disturbances.

In conclusion, the present control law gave better results than the PID controller. Furthermore, the parameter λ was easier to tune than the gain of the PID controller due to its finite bound ($0 \leq \lambda \leq 1$).

The procedure for obtaining the present control law can also be applied to processes such as fed-batch systems, whose system dynamics can be described or approximated via the scalar system with one unknown parameter.

Nomenclature

a = time-varying parameter
$\hat{a}$ = estimate of a
D = dilution rate, 1/h
k = discrete-time instance
t = time index
T = sampling time, min
X = cell mass concentration, g/L
X_s = set point of X

Greek Letters

μ = specific growth rate, 1/h
λ = tuning parameter
τ_I = integral time constant for the PID controller
τ_D = derivative time constant for the PID controller

References

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이 논문은 아산사회복지사업재단의 1986년도 연구비 지원에 의하여 연구되었음.

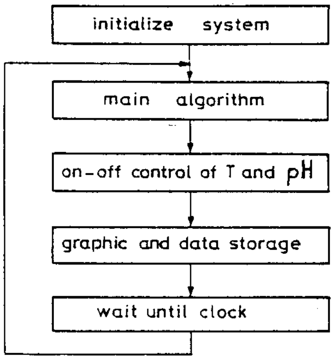
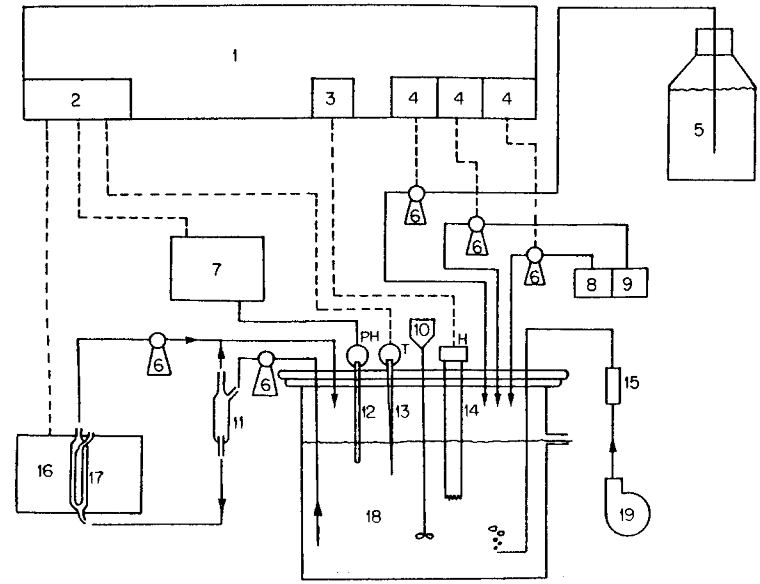


Fig. 2. Control program structure.



1. Microcomputer Apple II and peripherals.
2. Amps, filters and A/D converter.
3. Heat controller and D/A converter.
4. Motor drivers and D/A converters.
5. Medium reservoir.
6. Peristaltic pump.
7. pH meter.
8. 0.1 N NaOH solution.
9. 0.1 N HCl solution.
10. Stirrer.
11. Bubble trap.
12. pH electrode.
13. Thermocouple.
14. Heater.
15. Air filter.
16. Spectrophotomer
17. Photo-cell.
18. Bioreactor.
19. Air pump.

Fig. 1. Apparatus for microcomputer-controlled yeast culture system.

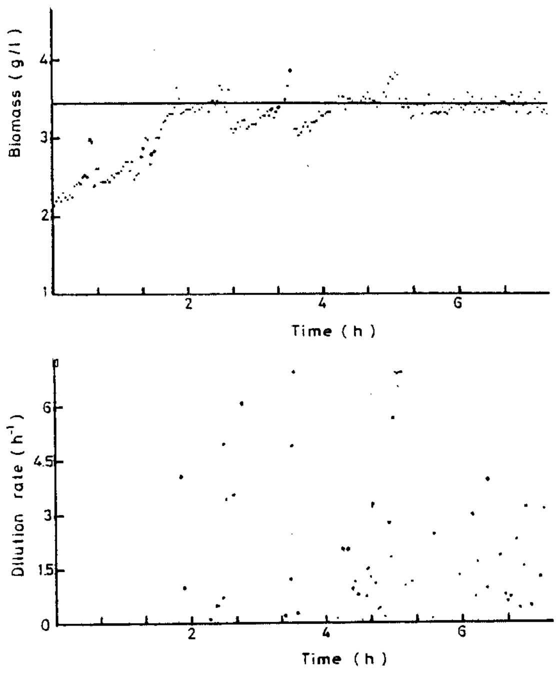


Fig. 3. Biomass output and controlled dilution rate by the discretized PID controller (gain=25, $1/\tau_i = \tau_D = 0$)

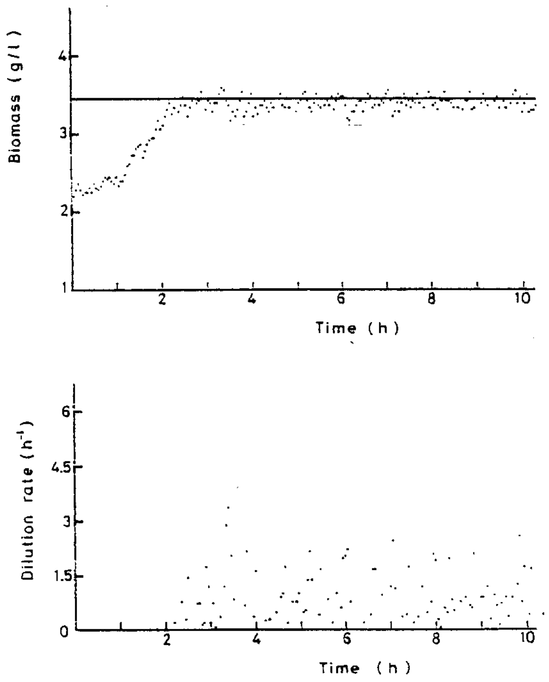


Fig. 4. Biomass output and dilution rate by the new controller with $\lambda = 1.0$

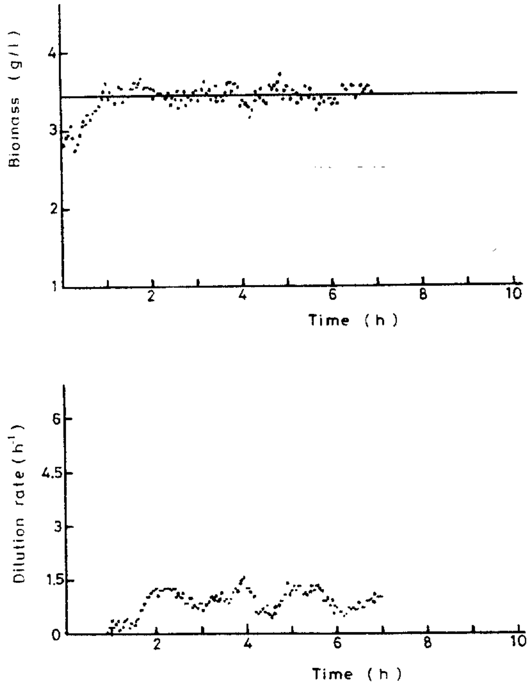


Fig. 5. Biomass output and dilution rate by the new controller with $\lambda = 0.1$

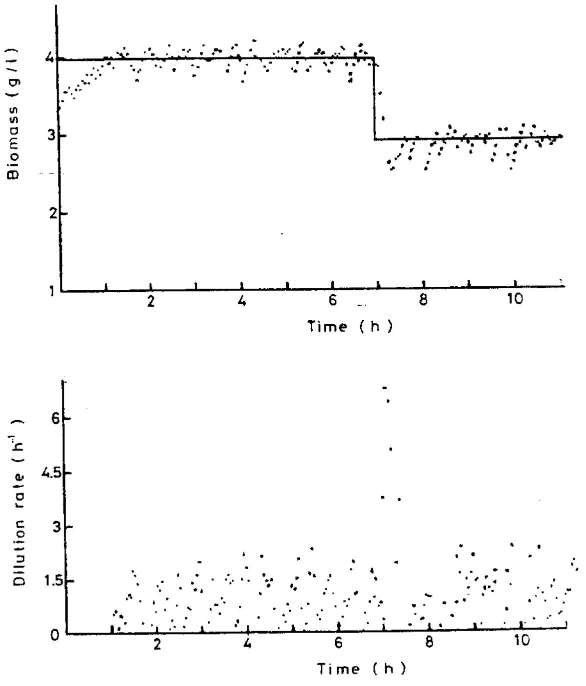


Fig. 6. Biomass output and dilution rate by the new controller with $\lambda = 0.5$ for swing program.