Variable Structure Control for a Continuous Bioreactor

H.J.Tham, M.A.Hussain*, K.B.Ramachandran
Department of Chemical Engineering
University of Malaya, 50603, Kuala Lumpur, Malaysia
*E-mail:azlan@fk.um.edu.my

Abstract: Fermentation is known to be a highly nonlinear process and it requires a nonlinear controller for effective control. This paper studies the application of variable structure control or sliding mode control with direct use of nonlinear model to a continuous baker's yeast production. Lyapunov's theorem is used to ensure asymptotic stability of the system, and also to determine the switching coefficients of the controller. The switching coefficients are calculated and determined during the process. To overcome chattering, the control input derivative is used as an auxiliary variable. The simulation results show smooth response for set point change. For external disturbance rejection, it was found that the controller is able to bring the state back to the sliding surface, and the state is maintained there for the subsequent time.

Keywords
Nonlinear control, variable structure control, sliding mode control, fermentation processes.

I. INTRODUCTION

Variable structure system with sliding mode was first studied in Russia in the 1950s. However, this technique did not receive world wide attention and was not investigated extensively. Among the reasons being are there were lack of practical design procedures and shortage of literature in English language. During the late 70's, additional properties of variable structure system were developed, and advances in computer technology also enabled practical implementation of such system. Since then, variable structure system has gained increasing interest among scientists and control engineers. Today variable structure system is widely applied and still extensively studied in the control of robot, electrical motor, aircraft, spacecraft, power system and other engineering field.

The most important merit and well known advantage of variable structure system is its robustness against parameter uncertainties and disturbances. It is a high-speed switching feedback control system, consisting of subsystems supplied with switching rules. The control law drives the state's trajectory on to the sliding surface. The dynamics restricted on this surface are actually the controlled system's behaviour.

II. FERMENTATION PROCESS

This paper considers the application of sliding mode control to a continuous bioreactor. With the presence of living organism, the control of bioreactor is more complex than the conventional chemical reactor. The dynamics of fermentation processes are highly nonlinear and poorly understood. The reproducibility of results is unreliable. Besides being influenced by external condition such as temperature, pH, dissolved oxygen etc, microorganism also has their own regulatory mechanism, which means that the model parameters may not remain unchanged over long time. Therefore we can only change the extracellular environment, which we hope it would affect the mechanism rightly.

The sliding mode control algorithm is applied to a continuous fermentation process described by the following nonlinear differential equations [1]:

$$\frac{dX}{dt} = \mu(S)X - DX\,; \tag{1}$$

$$\frac{dS}{dt} = -k\mu(S)X + D(S_{in} - S)\,. \tag{2}$$

where X and S are cell and substrate concentration respectively, D=F/V is the dilution rate, S_{in} is the feed substrate concentration and k is the characteristic coefficient. The specific growth rate,μ is a growth model dependence on substrate concentration. The most commonly used model is the Monod model. In our study, we are taking into account the substrate inhibition effect by using the Haldane Law:

$$\mu = \frac{\mu_m S}{K_s + S + S^2/K_i} \tag{3}$$

where μ_m is the maximum specific growth rate, K_s is the saturation constant and K_i is the inhibition coefficient. The control strategy is to regulate S as the controlled variable (y) by manipulating D (u). It is assumed in this work that the substrate concentration in the reactor and feed line are measured.

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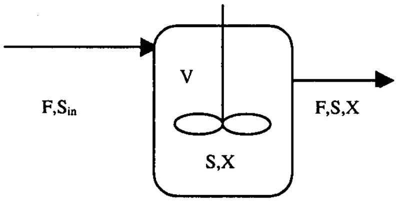

Fig.1 Stirred tank bioreactor

III. CONTROLLER DESIGN

The design of variable structure system is such that it uses high speed switching control logic to drive a nonlinear plant's state trajectory onto a user specified surface in state space called switching or sliding surface. When the state trajectory reaches the sliding surface, control switches between 2 values at high speed and sliding motion occurs. The plant's state trajectory is then maintained on this surface for the subsequent time. In this study, it is assumed that the variable structure system is ideal, i.e. the switching occurs infinitely fast.

A. Sliding Surface

The first stage in variable structure control design is to construct the sliding surface. $\sigma(x)$ is the sliding function and sliding surface is where $\sigma(x)=0$. The sliding surface is designed in a way that the closed loop plant dynamic restricted on this surface is actually represented by the equation governing the sliding surface. In other words, set point and trajectory tracking or other desired dynamic responses are embedded in the design of sliding surface. Sliding surface can be linear or nonlinear in nature. In this paper, we are looking into the linear surface $\sigma=cX_1+X_2$ where c is the design parameter. From the equation, it can be deduced that during sliding mode, system dynamics governed by $\sigma=0$ is only influenced by the design parameter c, and hence closed loop dynamics are not affected by perturbation.

B. Control law

Upon designing the switching surface, the second stage is to develop a control law which guarantees existence of sliding mode. The method of equivalent control proposed by Utkin [2] is the technique used to determine system motion restricted to the switching surface. It is actually a geometric interpretation of average system dynamics on both side of the surface. The equivalent control can be obtained when $\dot{\sigma}(x)=0$. For simplicity, we are only considering single input system.

In the methodology, the two differential equations above are first transformed into a second order differentiation equation:

$$\frac{d^2y}{dt}=-k\alpha X\frac{dy}{dt}-k\frac{d(\alpha X)}{dt}y+(S_0-S)\frac{du}{dt}-\frac{dS}{dt}u \tag{4}$$

with

$$\alpha=\frac{\mu_m}{K_s+S+S^2/K_i} \tag{5}$$

Then it can be written in error state with e = y-y$_d$ where y$_d$ is the set point. The resulting second order differential equation is then represented in Fliess's Generalised Canonical Form [3]. With the mathematical transformation, the process model in state space now has a lower order than the original system.

$$\frac{de_1}{dt}=e_2 \tag{6}$$

$$\frac{de_2}{dt}=-k\frac{d(\alpha X)}{dt}e_1-k\alpha Xe_2+(S_0-S)\frac{du}{dt}-\frac{dS}{dt}u-k\frac{d(\alpha X)}{dt}y_d \tag{7}$$

C. Chattering

Chattering is always a problem in sliding mode system. It is caused by discontinuous control. It can cause unmodelled dynamic which is undesirable. There are many ways suggested to overcome this problem which hindered the development of this algorithm at its early stage. To obtain a smooth control input (D), is very important in delicate processes such as fermentation processes and also for reason of physical constrain. Hence, the sliding mode is realised with respect to the control input derivative [4]. The control law is designed on the basis of variable structure system theory,

$$\frac{du}{dt}=\psi_1e_1+\psi_2e_2+\psi_3u+\psi_4y_d \tag{8}$$

where ψ_i (i=1-4) are switching coefficients. The coefficients are determined from the stability analysis using Lyapunov theorem. If the Lyapunov function is chosen as

$$V=0.5\sigma^2 \tag{9}$$

and

$$\sigma=ce_1+e_2. \tag{10}$$

where c is an arbitrary positive scalar design parameter mentioned in section III.A, which ensure asymptotically stable dynamics. The value of c determines the time taken to reach the sliding surface.

The first derivative of V with respect to time is

$$\frac{dV}{dt}=\sigma(c\dot{e}_1+\dot{e}_2) \tag{11}$$

To ensure the reaching condition is fulfilled, the reaching condition $\sigma\dot{\sigma} < 0$ is required and the switching coefficients are calculated based on this inequality. This controller design does not take into account the range of process parameter variation and external disturbance, but the switching coefficient is calculated as the process proceeds.

IV. SIMULATION INVESTIGATION

The variable structure controller designed is applied to a continuous baker's yeast cultivation process. The characteristic coefficients are as follows [5], μ_m=0.3/h, Ks=0.1g/l, Ki=50g/l, k=2, while the inlet substrate concentration is 20g/l. The controller design parameter c was chosen to be 3.

The results are shown through simulation study using MATLAB. Fig. 2 shows changes in control input and output with respect to set point change. The set point is changed from 0.15 to 0.5 and dropped to 0.3. The evolution of sliding surface is also shown. It can be seen that the response is stable and the control action is good.

The performance of the controller against external disturbance is also investigated. The external disturbance, which is the feed substrate concentration was changed by 10% and 20%. It can be observed that the response deviates from the setpoint when the disturbance is introduced, but the deviation is very small and acceptable. The external disturbance is rejected and the control output is brought back to the set point. The results are depicted in fig.3.

V. CONCLUSION

The application of variable structure control to continuous fermentation process is investigated. Although the test model chosen for the controller is Bakers Yeast fermentation system, but it is generally applicable for all type of fermentation processes. The proposed controller was tested for set point change and disturbance rejection. It was found that this controller actually guaranteed that the error goes to zero as $t \rightarrow \infty$. Upper and lower bound of process parameter and disturbances has not been taken into account in this approach, and yet still able to show good and reasonable response.

VI. REFERENCES

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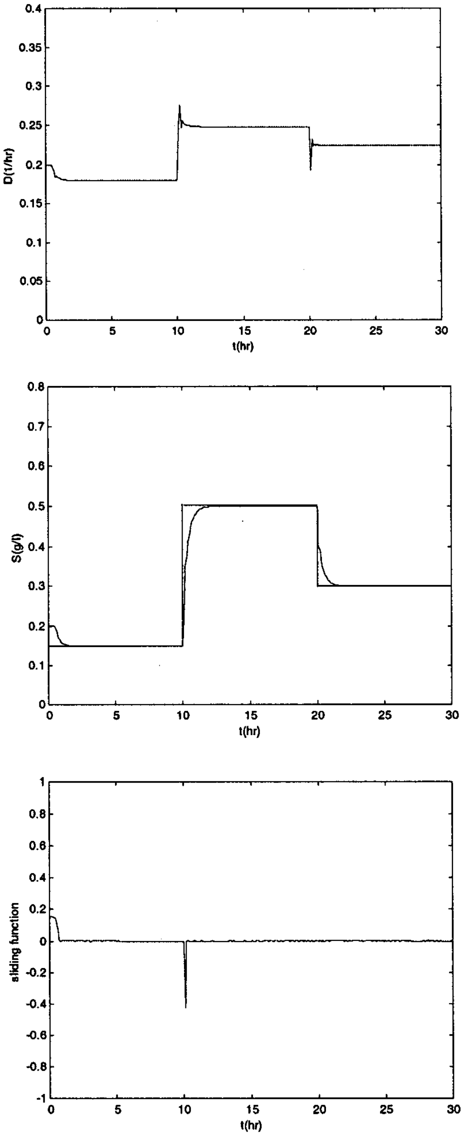

Fig.2 System behaviour for set point change

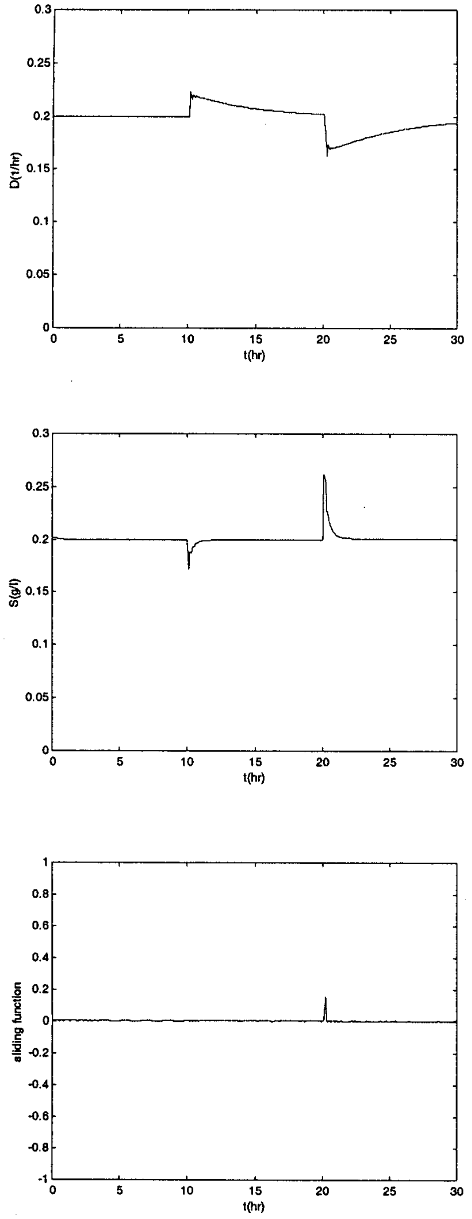

Fig.3 System behaviour during disturbance rejection