CHEMICAL ENGINEERING TRANSACTIONS
VOL. 32, 2013
Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-23-5; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1332203

Sliding Mode Fuzzy Logic Control of an Unstable Bioreactor

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The design of a Sliding Mode Fuzzy Logic Controller (SMFLC) is considered for the control of the biomass in an unstable continuous bioreactor exhibiting output multiplicity. Bioreactors are characterized by high nonlinearities and are often subjected to parameter uncertainties and disturbances. The control of such processes is often difficult to achieve with traditional linear control techniques. A conventional Sliding Mode Controller (SMC) is first designed and integrated with fuzzy logic to achieve a SMFLC. The controllers are then compared by simulation. Set point step changes and external disturbances are considered in the study. The good performance of the SMFLC for the nonlinear system is demonstrated, especially for its ability to reject disturbances. Compared to the SMC, the SMFLC is faster and more robust, showing the best values of the performance indexes.

1. Introduction

The use of biological processes is growing rapidly due to the increasing demand in products such as pharmaceuticals, foods, alcoholic beverages, enzymes and others. Since bioprocesses involve living organisms, they often experience nonlinear behaviors which may include output multiplicity, bifurcations, chaos, unstable dynamic response to disturbances and changes in system parameters; all these phenomena can lead to instability and ultimately affect the yield of production. For this reason the application of traditional linear controllers is limited since they are not able to cope with the high nonlinear behavior of biological processes. To deal with uncertainties and nonlinearities, significant results can be obtained with Sliding Mode Controllers (SMC), that represent a simple approach to robust control. The sliding mode control was first studied by Emelyanov (1967) and then by Utkin (1977) and Slotine (1985). A review on the uses of the sliding mode control and its main characteristics can be found in Fridmann et al. (2011). The sliding mode control is a fast control action that adapts the control signal to the dynamics of a nonlinear system in order to drive the states along a sliding surface. Once the sliding surface has been reached, the system response is insensitive to parameter uncertainties and disturbances. Despite its robust character, in a SMC a high frequency motion, known as chattering, may occur, due to the drastic switching of the control action and this could not allow to achieve the predefined sliding surface. Many techniques that avoid chattering have been suggested. These include the introduction of boundary layers near the sliding surface, that modify the control switching law and dampen the dynamics of the controlled variable. Chattering affecting the SMC can be also overcome if the traditional sliding mode control is integrated with the fuzzy logic to develop a sliding mode fuzzy logic controller (SMFLC) as proposed by Palm (1992). One can easily create the fuzzy rule base that guarantees the stability and robustness of the closed loop system with a SMFLC. SMFLCs have been mainly used on mechanical or electrical systems such as robots (Palm et al., 1997), servo motors (Suyintno et al., 1993) or satellites (Guan and Pan, 2008). More recently Shahraz and Bozorgmehry Boozarjomehry (2009) have proposed the use of SMFLC to the control of chemical processes whose internal states are either unknown or have no significant meaning. In this work a SMFLC is proposed for the control of an unstable bioreactor. The control objective is to control the biomass concentration by manipulating the dilution rate with inlet substrate concentration as external process disturbance. It will be also assumed that the model used is subjected to uncertainty in the yield factor and the closed loop is affected by a dead time due to the measurement device. A traditional SMC is also designed. The performances of both these schemes are evaluated and compared by simulation.

Please cite this article as: Galluzzo M., Cirino C., 2013, Sliding mode fuzzy logic control of an unstable bioreactor, Chemical Engineering Transactions, 32, 1213-1218 DOI: 10.3303/CET1332203

2. Bioprocess model

A second order continuous stirred tank bioreactor is used for the study. The model, proposed by Agrawal and Lim (1989), exhibits substrate inhibition and output multiplicity. The biomass and substrate concentration are described by the following differential equations:

$$\frac{dB}{dt}=\left(\frac{\mu_{max}S}{k_m+S+k_1S^2}-D\right)B \qquad (1)$$

$$\frac{dS}{dt}=\left(S_f-S\right)D-\left(\frac{\mu_{max}S}{k_m+S+k_1S^2}-D\right)\frac{B}{\gamma} \qquad (2)$$

The parameters and initial conditions of the model can be found in Table 1. With the given parameter values, the bioreactor has three different equilibrium points:

$[B_1,S_1]$ = [0; 4] stable wash out condition;
$[B_2,S_2]$ = [1.530; 0.174] stable condition;
$[B_3,S_3]$ = [0.998; 1.512] unstable condition.

In the stable equilibrium point the high substrate conversion can inhibit the biomass causing oscillations in the states. To avoid this behavior it is desirable to stabilize the process in the unstable equilibrium point. The control aim is to lead the biomass concentration from the stable equilibrium point, at high conversion, to the unstable one, at lower conversion, despite the disturbances and uncertainties in the model. The dilution rate will be used as the manipulated variable, S_f is the main process disturbance, the yield γ is considered uncertain. A measurement delay is also introduced in the closed loop in order to simulate a more realistic system.

3. SMC and SMFLC design

The design of the SMC and SMFLC requires an approximation of the real process and the knowledge of the upper and lower values of disturbances to determine the control law that stabilizes the bioreactor. In general, the real process can be described by the following nonlinear scalar equation:

$$\ddot{B}=f(\dot{B},B,\boldsymbol{p})+b(\dot{B},B,\boldsymbol{p},D)\cdot D \qquad (3)$$

where f and b are nonlinear functions, $\ddot{B}$ and $\dot{B}$ are the second and first derivate of B and $\boldsymbol{p}$ represents the parameter vector and D is the dilution rate. For a SMC, the control problem is to define a control law such that for a desired set point trajectory the error tends to zero following a sliding line of slope λ defined as (Palm et al., 1997):

$$s(\dot{B},B)=\lambda e+\dot{e} \qquad (4)$$

Here e is the error and $\dot{e}$ its first time derivate. The control law can be defined so that the closed loop response always satisfies the Lyapunov criterion

$$\frac{1}{2}\frac{d}{dt}s^2\leq\eta\left|s\right| \qquad (5)$$

or alternatively

$$\dot{s}\cdot sng(s)\leq\eta \qquad (6)$$

Table 1: Bioprocess parameters and initial conditions.

PARAMETER	γ [g/g]	S_f [g/L]	μ_{max} [L/h]	k_m [g/L]	k_1 [g/L]	D [1/h]	$B(0)$ [g/L]	$S(0)$[g/L]
NOMINAL VALUE	0.4	4	0.53	0.12	0.4545	0.3	1.530	0.174

In Eq (6) $sgn(s)$ is the sign function and η is a strictly positive constant that guarantees a finite approaching time to the sliding line (Utkin, 1977). The inequality Eq (6) represents the so called *reaching condition* and ensures the stability of the closed loop. Introducing (4) into (6) and deriving, the SMC law for a second order system becomes (Palm et al., 1997):

$$D = \hat{b}^{-1}[-\hat{f} + G\cdot(\ddot{B}_d - \lambda\dot{e}) - G\cdot K(s)\cdot sng(s)] \quad (7)$$

where $\ddot{B}_d$ is the second derivate of the desired trajectory (set-point), $\hat{b}$ and $\hat{f}$ are approximations of b and f while $K(s)$ is a positive constant to be chosen in such a way that Eq (6) is always verified. Due to the sign function, the control law Eq (7) can be source of chattering, leading to drastic changes of the control input that may negatively affect the control of the process. However chattering can be avoided by introducing a boundary layer near the sliding line that dampens the dynamics of the controller output and ensures that the system states remain inside the layer. The width of the layer is denoted as 2ϕ. The control law Eq (7) than becomes:

$$D = \hat{b}^{-1}[-\hat{f} + G\cdot(\ddot{B}_d - \lambda\dot{e}) - G\cdot K(s)\cdot sat(s/\phi)] \quad (8)$$

with

$$sat\left(\frac{s}{\phi}\right) = \begin{cases} s/\phi & if \quad |s/\phi| < 1 \\ \mathrm{sgn}(s/\phi) & if \quad |s/\phi| \geq 1 \end{cases} \quad (9)$$

To determine the multiplier term G the following bonds are defined:

$$0 \leq \beta^{min} \leq b\cdot\hat{b}^{-1} \leq \beta^{max} \quad (10)$$

and

$$G = (\beta^{\min}\cdot\beta^{\max})^{-0.5} \quad (11)$$

For the design of the conventional SMC the control parameters are found using a trial and error method minimizing the IAE index and the settling time of the controlled variable during the simulation. The stability of the SMC is achieved with the control parameters given in Table 2.

The Sliding Mode Fuzzy Logic Control is an extension of the SMC with boundary layer. The design of the SMFLC integrates the SMC with the fuzzy logic. The structures of both controllers are very similar. For the SMFLC the control Eq (8) is changed into:

$$D_N = \hat{b}^{-1}[-\hat{f} + G\cdot(\ddot{B}_d - \lambda\dot{e}) - G\cdot K_{fuzzy}(s)\cdot sat(s/\varphi)] \quad (12)$$

where $K_{fuzzy}(s)$ is a nonlinear and positive function of the sliding line described by the fuzzy rules.

The usual design steps for a SMFLC consist in the normalization of the sliding line s into s_N by means of an input factor N_S, the fuzzification of s_N and the computation of the fuzzy output, the defuzzification into a normalized output D_N and denormalization into a physical control output D_{fuzz} by N_u. The rules are conditioned so that above the sliding line a negative control action is generated and a positive one below it (Palm et al., 1997). The SMFLC designed uses a Sugeno type inference. The general *i-th* rule R^i has the form:

$$R^i : if \quad s_N = s_N^i \quad then \quad D_N = Singletone^i \quad (13)$$

The weighted sum is used as defuzzification method. Five singletons [-100, -20, 0, 20, 100] for the output and five triangular sets (NB, NS, Z, PS, PB) for the input are used. For the unstable bioreactor the fuzzy sets and the sliding mode transfer characteristics are shown in Figure 1. In order to have a valid comparison of the controlled process dynamics, most of the parameters of the SMFLC were chosen to be the same as those estimated for the SMC. Table 2 collects all the design data. The fuzzy rules are instead shown in Table 3.

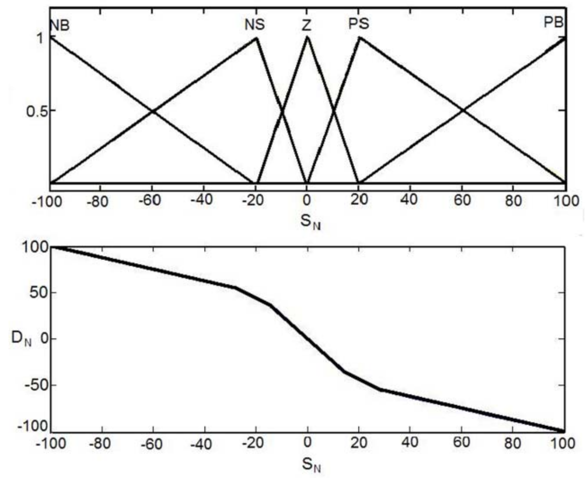

Figure 1: Membership functions and sliding mode fuzzy transfer characteristic.

4. Simulation results and discussion

The simulation study was carried out by MATLAB®.

The performances of the controllers are evaluated by forcing the bioreactor to move from the stable equilibrium point [B_2; S_2] = [1.530; 0.174] to the unstable one [B_3; S_3] = [0.998; 1.512]. To compare the different dynamics, the settling time t_s and the integral of the absolute error IAE are used as performance indexes. The controllers are tested in two different cases; servo response and ability to contrast the disturbances. The first simulation regards a step servo response from the stable to the unstable operating point. In this case no disturbance neither uncertainty affect the bioreactor. The result of the simulation is shown in Figure 2 - left where the response of *B* and the manipulated variable *D* are shown. Here the SMFLC has a better performance over the SMC. The superiority of the fuzzy logic controller is confirmed by the performance index that are t_s = 15 h and IAE = 0.595 for the SMFLC, and t_s = 20 h and IAE = 0.993 for the SMC. In order to verify their robustness, a second simulation was carried out assuming that the process is affected by variations in some parameters. In particular the inlet substrate concentration varies in the interval 3.8 < S_f < 5.2 g/L as a sinusoidal wave of frequency 5 h^{-1} and the yield factor randomly in the interval 0.3 < γ < 0.5 g/g. In this case the closed loop includes a dead time of 0.1 h due to the measuring device. The result is shown in Figure 2 -right.

Table 2: SMC/SMFLC design parameters.

	λ	ϕ	N_S	N_u	K	G	$\ddot{B}_d$
SMC	0.002	1.25	-	-	22.84	0.833	0
SMFLC	0.002	1.25	155.02	-0.085	-	0.1224	0

Table 3: SMFLC Fuzzy Rules.

SINGLETON	100	20	0	-20	-100
S_N	NB	NS	Z	PS	PB

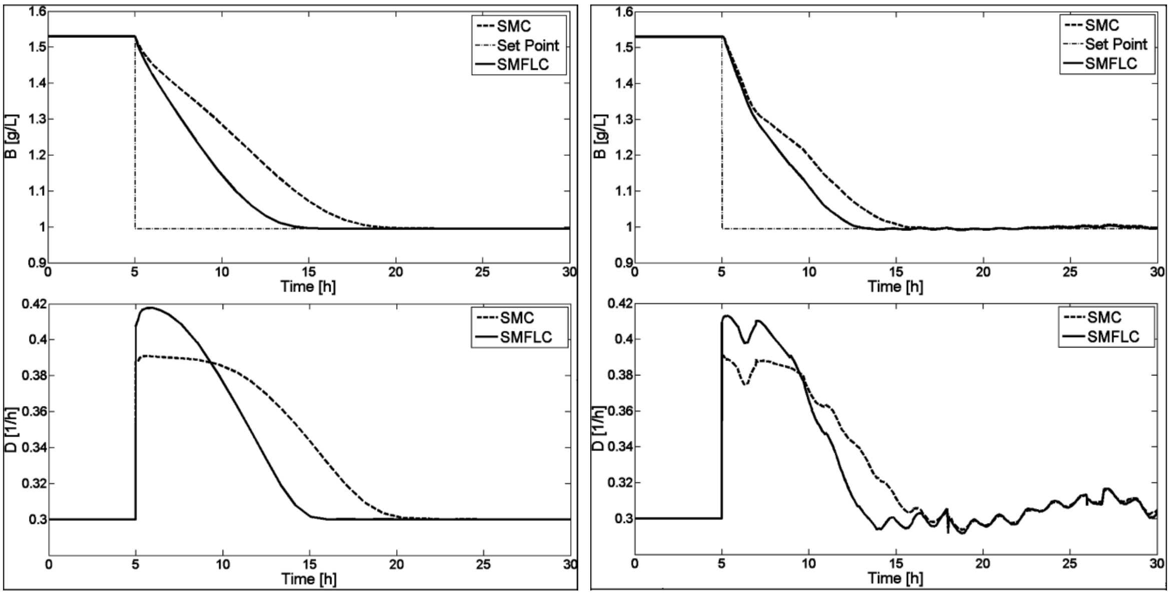

Figure 2: Controlled and manipulated variables for a set point change from 1.530 to 0.998 g/L at t = 5 h –(left) with no disturbances and uncertainties affecting the bioprocess and –(right) with simultaneous sinusoidal oscillation in S_f and random variation in γ.

In this case a set point change and the disturbances affect the process at t = 5 h simultaneously. The SMFLC again confirms to perform better than the conventional SMC. This is further underlined by the performance indexes that are t_s = 14 h and IAE = 0.574 for the SMFLC and t_s = 18.5 h and IAE = 0.868 for the SMC. With reference to the second simulation the distance of the error state from the sliding line (4) is shown in Figure 3. The SMFLC is always closer to the line than the SMC. In both cases the steady state condition corresponds to a zero distance condition.

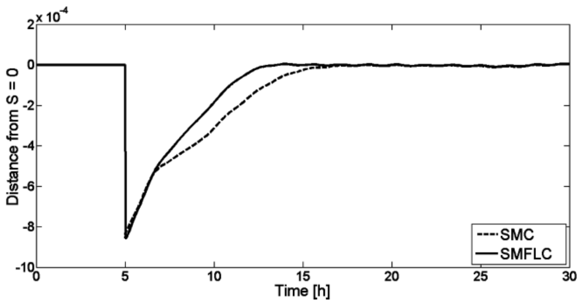

Figure 3: Distance of the error states from the sliding line s = 0.

The effect of the slope value of the sliding line of the SMFLC was investigated by simulation of the controlled process with other values of λ. The results can be seen in Figure 4. Here the SMFLC is subjected to the same set point change as in the previous case shown in Figure 2 – (right). It is clear that a higher sliding slope improves the behaviour of the controlled variable. However the manipulated variable D for the simulation with λ = 0.003 shows the highest overshoot and an unexpected peak at t = 5 h that can damage the actuator.

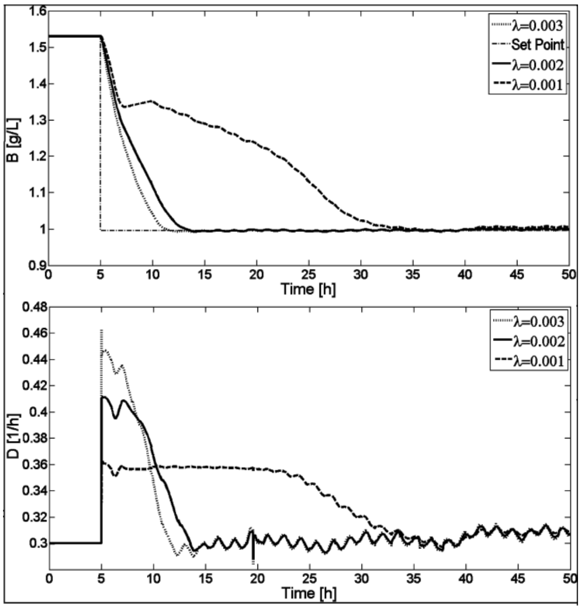

Figure 4: SMFLC response for different values of the slope λ, when affected by set point variation from 1.530 to 0.998 g/L, a sinusoidal oscillation in S_f and a randomic variation in γ simultaneously.

5. Conclusions

A SMFLC for an unstable bioprocess was designed and used for controlling the biomass concentration. A conventional SMC was also developed in order to have a comparison with the SMFLC. The controllers appear to be robust when tested with a step change in the set point, a sinusoidal disturbance and a random parameter variation simultaneously. A dead time in the measuring device was also introduced in the closed loop in order to further stress the controllers and simulate a more realistic case. In the case of the SMFLC, the controlled variable reaches always the set point faster than the SMC, as confirmed by the evaluated settling time. Moreover the lower IAE index obtained with the SMFLC confirms its better performance in reducing the error. The superiority of the SMFLC over the SMC indicates that uncertainties in loads and parameters would not affect the closed loop system, proving the robustness of the fuzzy controller. Therefore the SMFLC can be considered as a good alternative for controlling systems such bioreactors. The design and implementation of the SMFLC are relatively simple even if they require the knowledge of the process model and the conversion of the mathematical form given by Eq (1) – Eq (2) into the Eq (3). This last operation could be hard especially if the model presents a high degree of nonlinearity.

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