Optimal Control Strategy of a Biotechnological Process Using a Fuzzy Zonal Model

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Abstract

This paper deals with the zonal modelling and the optimal control of the biosynthesis processes that take place inside discontinuous bioreactors. There are used fuzzy techniques in order to obtain a general model, no matter of the bioreactor functioning conditions. Using the fuzzy zonal model an algorithm for determining the batch stopping time so that an optimal cost criterion is met was implemented. The fuzzy zonal model and the optimal algorithm were validated based on the experimental data provided by the Food Industry Institute from Bucharest, regarding the biosynthesis process of alpha-amylase with Bacillus subtilis microorganisms.

Keywords: Model based control, Biosynthesis process, Zonal modelling, Optimal control, Fuzzy techniques.

Introduction

The main difficulty in dealing with enzyme biosynthesis process control is the development of a model, which is able to reflect accurately enough the bioreactor dynamics. Here are several observations that render the difficulty of the obtaining of a model for a biosynthesis process:

1. The complexity of the biosynthesis processes. In most cases, the variables that describe the dynamics of the microorganism populations and of the biosynthesis products are not directly measurable. They are controlled by a number of physical parameters such as temperature, pH, aeration etc., associated with heat and mass transfer subsystems. These stand for the "interface" subsystems of the bioreactor, with which the subsystems of the microbiological and biochemical processes interact and which are inaccessible to direct measurements [1].
2. There are many aspects insufficiently treated regarding the inoculums quality and the heterogeneous nature of the substrate (these may be considered as uncertainties of the process).
3. The "interface" subsystems should also explicit the reaction rates as functions of physical and chemical parameters, that representing a very difficult problem. This fact leads to the obtaining of some mathematical models valuable only in certain conditions of the bioreactor functioning. Every modification of the bioreactor functioning conditions (for example the composition of the culture environment) leads to an essential modification of the bioreactor dynamics.

In these circumstances, there are some approaches focused on the modeling of the biosynthesis processes aiming the automatic control. References are often made to the state models designed upon the biochemical reactions schemes or the mass-balance equations [2]. Other authors use neural and fuzzy methods to design biosynthesis models, based on process measured data [3], [4], or modelling techniques based on knowledge [5], [6].

This paper deals with the zonal modelling using fuzzy techniques and with the optimal control of a batch bioprocess, the biosynthesis process of alpha-amylase with the microorganism *Bacillus subtilis*.

Materials and methods

The zonal modelling of the biosynthesis processes that take place inside discontinuous bioreactors

The lot of experimental data consists in numeric value sets that represent the evolutions of a microbial population, in certain conditions of temperature (T), inoculums (X_0), initial substrate (s_0), stirring speed (V_a) and aeration (q_a). Let:

$$\underline{Q} = (T,\, X_0,\, s_0,\, V_a,\, q_a)^{\mathrm{T}} \qquad (1)$$

be the vector of variables that reveal an experiment conditions regarding the dynamics of the microbial population from the bioreactor. A modelling technique that is adequate to biotechnological processes consists in the process structuring in many phases. Each phase corresponds to one physiological state of the cell and it is distinctly modelled. The global model represents a variable structure system.

Let us consider $x(t)$ the evolution of the microbial population (the cell concentration) in a batch bioreactor, experimentally obtained in the conditions characterized by vector $\underline{Q}$. The graphic representation of $x(t)$ and the analysis of the respective variation form, correlated with phenomenological aspects of the microorganisms growth allow the zoning of the curve $x(t)$, so that each zone may be easy analytically described. For example, Figure 1 presents the zoning of the response curve $x(t)$, marking four phases: induction (lag) (1), transitory (2), exponential (3) and decay (4). During each phase (zone) the analytical description of the curve $x(t)$ is as follows:

$$x_i(t) = f_i(t); \quad t_{i-1} \le t < t_i, \quad i = 1, 2, \mathrm{K}\ , n_f \qquad (2)$$

where n_f is the zone number considered in the bioreactor dynamics and the index i points out to the current zone. The functions $f_i(t)$ are treated as responses to step signals of some linear systems, having the initial conditions equal to the measured values of the respective physical values at the end of the previous phase. In this way, the evolution of $x(t)$, according to Figure 1, may be interpreted as the response of a variable structure system, with the property that the system is linear between the structure changing moments.

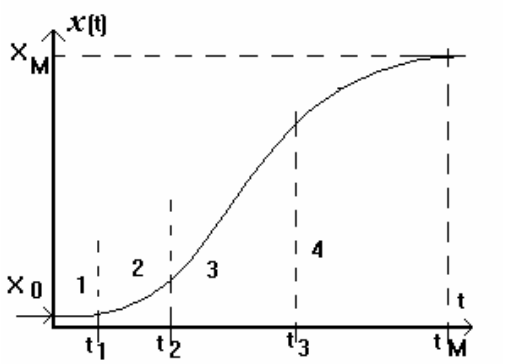

Figure 1. The evolution of total biomass $X(t)$ during the biosynthesis process

Let $\underline{p}_i$ be the parameters vector (the model coefficients) that appear in the function $f_i(t)$. It results that, for a vector $\underline{Q}$ stated by the conditions of the experiment, the equation (2) becomes:

$$x_i(t) = f_i(t, \underline{p}_i(\underline{Q})); \quad t \in [t_{i-1}, t_i], \quad i = 1,2,\text{K}\ ,n_f \tag{3}$$

A very well known zonal model of the cellular biomass evolution is the Kono's [7]. Kono uses a model based on the chemical kinetics principles, stating the concepts of *critical concentration* and *consuming coefficient*. The equation that describes the biosynthesis process during the induction, transitory and exponential phases is the following:

$$\dot{x}(t) = k \cdot \phi(t) \cdot x(t) \tag{4}$$

where ϕ is the consuming coefficient and it is defined as the cell set that consumes the substrate, conveying in the entire biosynthesis medium ($\phi = 0$ in the induction phase, ϕ=1 in the exponential phase and $0<\phi<1$ in the transitory phase). Further on the equations that describe the cellular biomass evolution for each zone are presented.

In *the induction phase*:

$$\phi(t) = 0\text{, so } \dot{x}(t) = 0 \text{ and } x(t) = X_0 \tag{5}$$

In *the transitory phase* more versions of mathematical description of the microorganism growth process could exist. The expression of the function $\phi(t)$ must have a physical meaning and leads to an evolution of the solution $x(t)$ as much closer as the experimental data. The following variation form leads to the fast evolutions of the variable $x(t)$, which are very close to the experimentally determined variations, so it will be considered in this paper:

$$\phi(t) = 1 - e^{-\gamma \cdot t} \tag{6}$$

Equation (6) shows that the consuming coefficient has the form of the step response of a first order element with the time constant $T_L = 1/\gamma$. It results the solution:

$$x(t) = X_0 \cdot \exp(k \cdot t) \cdot \exp\left[\frac{k}{\gamma}\left(1 - e^{-\gamma \cdot t}\right)\right] \tag{7}$$

In *the exponential phase* $\phi(t) = 1$ is been replaced in equation (4), resulting:

$$x(t) = x(t_2) \cdot \exp\left(k \cdot \left(t - t_2\right)\right) \tag{8}$$

In *the decay phase* the following equation is valid:

$$x(t) = X_M - \left(X_M - X_m\right) \cdot \exp\left(-k \cdot \frac{X_m \cdot \left(t - t_3\right)}{X_M - X_m}\right) \tag{9}$$

where t_3 corresponds to the final moment of the exponential phase, and $X_m = x(t_3)$, where X_M is the maximum value of the cellular biomass.

The optimal control of the biosynthesis processes

The objective of the optimal control in the case of a discontinuous bioreactor is to determine the batch stop time so that the greatest amount of enzymes with minimum resource consumption to be obtained. Because that the process is of batch type, there are several constrains regarding the command definition, meaning that there are not many free choices in the modification of the base values (temperature, stirring, pH etc.). They must be kept at values considered "optimal", provided by the technologist operator and based on his expertise, the only way of action being the bioreactor shutdown at an optimum moment, when the cost function is minimum.

The following expression for the profit obtained within a batch is considered:

$$B = \frac{V_{PB} - C_{MP} - C_{OA} - q_{ER}T_R}{T_A + t_f} - q_{FM} - q_A \tag{10}$$

where V_{PB} – the total values of the biosynthesis products obtained during one batch; C_{MP} – the total cost of the materials used during one batch; C_{OA} – the total cost of the auxiliary operations during one batch; q_{ER} - the cost of the consumed energy by the bioreactor during the batch; q_{EM} – the cost of the human work used for a bioreactor batch; q_A – the amortization of the bioreactor equipment within the time period; t_f – the final period of time needed for the biosynthesis reactions development; T_A – the necessary time for the auxiliary operations.

It can be noticed that, for a certain biosynthesis product, C_{MP}, C_{OA}, q_{FM}, q_A and T_A are constant, q_{ER} depends on the stirring and aeration intensity, while V_{PB} and t_f essentially depend on the development conditions of the biosynthesis process. The total amount of the biosynthesis products is:

$$V_{PB} = x_\alpha(t_f) P_{u\alpha} \tag{11}$$

where $x_\alpha(t_f)$ is the quantity of alpha-amylase produced at the moment t_f and $P_{u\alpha}$ is the unit price of the biosynthesis product. Consequently, the specific cost of the biosynthesis products has been adopted as criterion function, having the following expression:

$$I = \frac{C_{MP} + C_{OA} + c_{ut}t_f + q_{FM}t_f + q_A t_f}{x_\alpha(t_f)} \tag{12}$$

where c_{ut} is the cost of the utilities within the time period. Taking into account the numerical values of the costs in equation (11), the following expression of the performance criterion is obtained:

$$I(u) = \frac{\eta_0 + \eta_1 u}{x_\alpha(u)} \tag{13}$$

In the case of the discontinuous bioreactor, the command consists in the batch stop time:

$$u = t_f \tag{14}$$

Results and Discussion

The zonal model using fuzzy techniques for the global description of system dynamics

Figure 2 shows the comparison of the zonal model with experimental data for the biosynthesis process of alpha amylase with the microorganism *Bacillus subtilis*. With respect to Figure 2 it is to be noticed that the model approximates very well the data coming from the real process. It has to be mentioned that the experimental data shown in Figure 2 represent an average of all experiments carried through within a year by the Food Industry Institute from Bucharest.

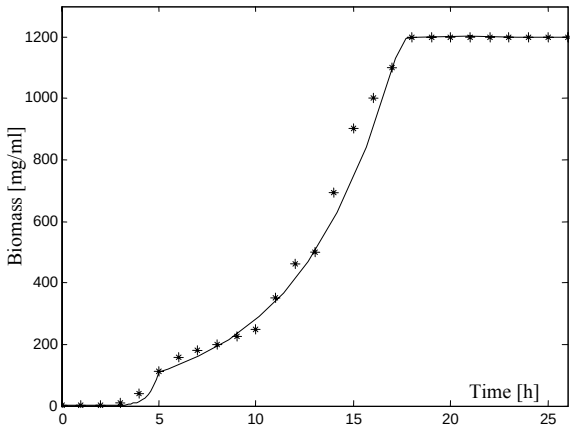

Figure 2. The evolution of the total biomass $x(t)$: zonal model (continuous line) and real data (*)

Taking into account the results obtained from the experimental data the following conclusions for the zonal modelling can be drawn:

1) The spoiling of the experiment conditions (vector $\underline{Q}$) should not affect the number of zones and the (zonal) local structure of the model, but only $\underline{p}_i$ vectors of the parameters.
2) The t_i moments preserving the borders of the phases are not guaranteed at the changing of the vector $\underline{Q}$.

Based on these facts, a system that allows the global description of the biosynthesis processes was built. The system consists in two blocks:

1. A block based on fuzzy techniques of Sugeno type [8]. This block has as input (fuzzy variable) the CO_2 derivative and the right member of the compounding rules contained in the rule-base is represented by the equations that describe the process dynamics inside each phase. So, the transition from one zone to another is not done at predefined moments, but accordingly to the CO_2 information (more precisely the CO_2 derivative).
2. A block that, at each step of the exponential zone, adapts the coefficient k of the model aiming a very good match between the model outputs and the experimental data. Only the exponential phase was chosen for the implementation of this block, because in this phase the total biomass values are much greater comparing to the similar values from other phases. Moreover, this phase is the most important from the point of view of the proposed

model. This coefficient is reported to the experiment shown in Figure 2 considered as a standard one. In this case the coefficient at the current step is obtained from the coefficient at the previous step, corrected by ratio between the measured CO_2 level and the standard one.

The membership functions of the fuzzy variable CO_2-derivative are shown in Figure 3. The Sugeno rule block determines the global output of the model (the total number of germs), using a relation of gravity center type. The Sugeno rule block of the fuzzy system contains the following rules:

IF (dCO_2=Zero) AND (phase(k-1)=lag) THEN $x(t) = X_0$

IF (dCO_2=Small) AND (phase(k-1)= lag) OR (phase(k-1)= transitory) THEN

$$x(t) = X_0 \cdot \exp\left(k \cdot t\right) \cdot \exp\left[\frac{k}{\gamma}\left(1 - e^{-\gamma \cdot t}\right)\right]$$

IF (dCO_2=Big) AND (phase(k-1) = transitory) OR (phase(k-1) =exponential) THEN

$$x(t) = x(t_2) \cdot \exp\left(k \cdot \left(t - t_2\right)\right)$$

IF (dCO_2=Small) OR (dCO_2=Zero) OR (dCO_2=Negative) AND (phase(k-1) = exponential) OR (phase(k-1)=lethal) THEN $x(t) = X_M - \left(X_M - X_m\right) \cdot \exp\left(-k \cdot \frac{X_m \cdot \left(t - t_3\right)}{X_M - X_m}\right)$

where *der[CO_2]* represents the CO_2-derivative variable; *phase(k)* represents the phase at the current moment; *phase(k-1)* represents the phase at the previous moment.

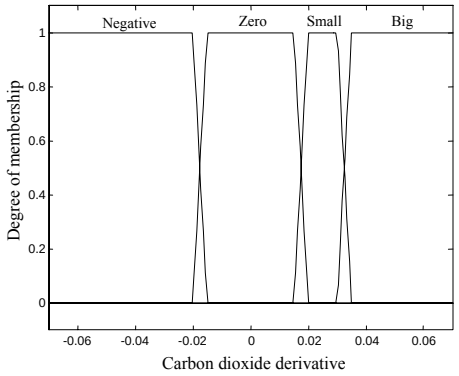

Figure 3. The membership functions of *der[CO_2]*

Figure 4 presents the validation of the zonal fuzzy model with experimental data for the biosynthesis process of alpha amylase with *Bacillus subtilis* microorganism. It can be noticed that the results are very good, the fuzzy zonal model being accordingly to the experimental data.

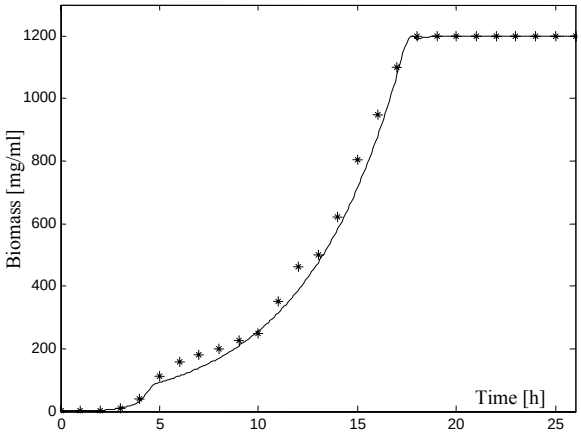

Figure 4. The evolution of the total biomass $x(t)$: fuzzy zonal model (continuous line) and real data (*)

The optimal control of the biosynthesis process of the alpha-amylase with the *Bacillus subtilis* microorganism

The analysis of the experimental data from the biosynthesis process of the alpha-amylase with the microorganism *Bacillus subtilis* leads to the following conclusions:

1. In the event of growing of a very great quantity of biomass, the quantity of the product (alpha-amylase) obtained in the batch is unsatisfying (Table 1). Practically, it is considered that a batch is "satisfying" when a minimum of approx. 5000-5500 relative units of alpha-amylase quantity is obtained;

Table 1. The evolution of the total microorganism number and of the quantity of alpha-amylase for different experiments of the biosynthesis process of the alpha-amylase with *Bacillus subtilis* microorganism

Total microorganism number	Alpha-amylase quantity
1200	8233
360	14619
1730	9286
7050	5296
7500	4943
12900	4634
39000	3900

2. After the moment when the exponential zone has ended, the optimum, from the productivity point of view (the minimizing of the criterion given by equation (20)), is obtained after a variable time period that depends on the environment conditions. pH is the physical variable that can be linked to the period of time between the two important moments: the moment when the exponential zone has ended and one when the criterion is minimum. Therefore, if at the end of the exponential zone, pH had a great value (the environment is strongly alkaline) there weren't conditions for the microorganisms to continue the enzyme production, so that the bioreactor must be immediately shutdown. But if at the end of the exponential zone, pH had a small value (the environment is nearly

acid), the microorganisms are still producing alpha-amylase, although they met the decay zone. In this case, the decision of shutting-down the bioreactor should be taken after a significant number of hours. Table 2 presents the correspondence between the bioreactor functioning time periods after the end of the exponential zone, in order to obtain the maximum productivity.

Table 2. The pH influence upon the functioning duration of the bioreactor after the exponential zone has ended

The pH level in the bioreactor at end of the exponential zone	The bioreactor functioning duration after the end of the exponential zone
7.8	4
6.5	8
8.3	1
8	2

Based on the conclusions stated before for the biosynthesis process of the alpha-amylase with the microorganism *Bacillus subtilis*, the following model based control structure has been proposed: the system develops accordingly to the fuzzy zonal model up to the moment of reaching the exponential phase. In this moment an analysis of the possibility to obtain a productive enough batch is performed. The analysis considers the number of microorganisms that exist in the bioreactor at that moment. In case the number of microorganisms is very big, a small productivity will be achieved and, for economical reason, the decision of the batch stop will be taken.

If the decision is to continue the batch, the fuzzy zonal model is set again, up to the moment of the end of the exponential zone. In that moment, considering the second conclusion, based on the pH level of the culture inside the bioreactor at that time, the moment of the batch stop is determined. The decision is taken within a fuzzy block of Mamdani type, having as input the pH level measured in the bioreactor and as output the functioning time period of the bioreactor, after the exponential zone has ended.

The following membership functions have been chosen for the input and output (Figures 7 and 8). The rule-base contains two rules:

IF (pH = Small) THEN (Time = Positive)
IF (pH = Big) THEN (Time = Zero)

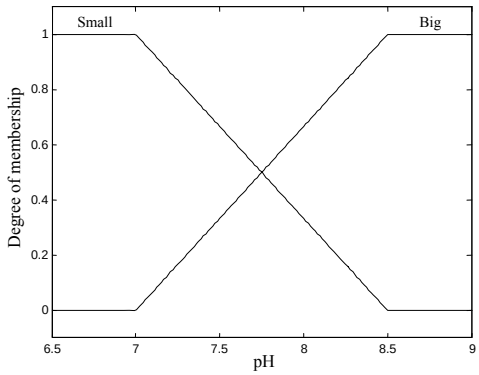

Figure 7. The membership functions used for input

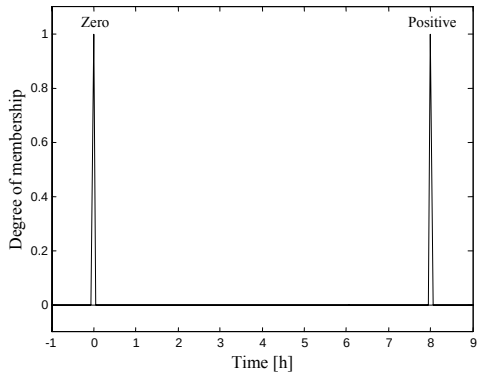

Figure 8. The membership functions used for output

Based on the fuzzy block presented before, the functioning periods of the bioreactor, after the moment of the end of the exponential zone, have been determined. It can be noticed that the results obtained with the optimal control structure (presented in Table 3) are very close to those obtained within the experimental data (Table 2).

Table 3. The pH influence upon the bioreactor functioning duration after the exponential zone has ended using fuzzy logic block

The pH level in the bioreactor at end of the exponential zone	The bioreactor functioning duration after the end of the exponential zone using fuzzy logic block
7.8	3.73
6.5	8
8.3	1.07
8	2.67

Conclusions

In the paper a fuzzy zonal model based on the CO_2 information taken on-line from the process was proposed. This model has several advantages: it is very general (it does not depend on the bioreactor functioning conditions), simplicity, the transition moments from one zone to another are not fixed (they depend on the CO_2 information) and the transitions from one zone to another are smoothly done (due to the use of the fuzzy techniques).

Based on the process pH information an optimal control algorithm for the biosynthesis process of the alpha-amylase with *Bacillus subtilis* microorganism was implemented.

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