

OPTIMAL CONTROL OF BIOLOGICAL SBRs FOR THE TREATMENT OF DAIRY AND TOXIC WASTEWATERS

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Abstract: This paper presents two optimal control strategies developed for the control of two biological Sequencing Batch Reactors (SBR), the first one performing both organic carbon and nitrogen removal from dairy wastewaters while the second one treats toxic wastewaters. The proposed control laws are based on models that have been validated with real data acquired on two real biological SBR pilot plants. These models are presented in (Mazouni et al, 2005a). The validation results of these control strategies are presented and discussed.

Keywords: Sequencing Batch Reactors (SBR), optimal time control, optimization

1. INTRODUCTION

The objectives of the control module which was developed within the EOLI integrated system were twofold. First, develop an algorithm for the optimal control of the SBR in the presence of an inhibiting reaction scheme and second, develop a time optimal control strategy for the control of aerobic SBRs with carbon and nitrogen removal capacities.

These model-based control laws are directly derived from the models proposed in (Mazouni et al, 2005b). They also take into account the information about for direct measurement (via hardware sensors) presented in (Pauss et al, 2005) and, about the indirect measurement (via software sensors) proposed in (Fibrianto et al, 2006). Because of the type of operation (which is a batch), optimal control is the core of the control design in order to optimise: i) the feeding strategy by distributing the feed with time in order to avoid accumulation of toxics and/or inhibitory substances in the cases of toxic effluents and ii) the aerobic and anoxic phase time durations in order to minimise the total reaction time in the case of carbon and nitrogen removal.

2. CARBON AND NITROGEN REMOVAL FROM DAIRY WASTEWATERS

The process

The objective of the control is to compute the switching sequence (aerobic/anoxic) and the corresponding switching instants such that any initial point in the attainable set reaches the target set (defined as the set of concentrations such that $S_1 < S_{1N}$,

$S_2 < S_{2N}$ and $S_3 < S_{3N}$) where S_1 is the soluble COD, S_2 is the ammonium nitrogen concentration, S_3 the ammonium nitrite+nitrate concentration and S_{1N} , S_{2N} and S_{3N} are the normative rejection norms.

The minimal time optimal control is based on a simple model directly derived from those presented in . This model is briefly reported hereafter. A schematic view of the process available at the LBE, Narbonne, France, is given in figure 2.1.

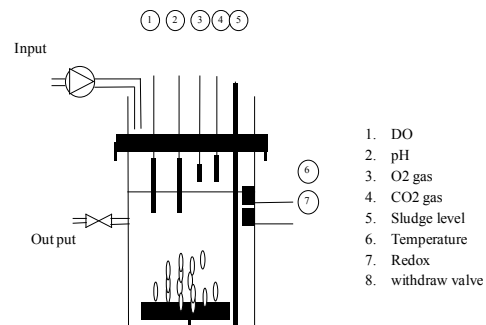


Figure 2.1 : Schematic view of the process

The tank of the reactor has a cylindrical form. Its dimensions are 50cm Ø and 130cm height with a total volume of 255L. It is equipped with a variable flow rate pump to fill the reactor and a controlled valve to withdraw the effluent and the sludge in excess. Air is used for aeration and mixing. Its flow is controlled by a flow meter.

The reactor is operated at an ambient lab temperature of 20°C. Each cycle duration is 24 hours. More

specifically, the reaction phases are divided into 2 periods. In each one, half of the total influent daily volume is added (25 liters). A schematic view of the operating modes is shown in figure 2.2.

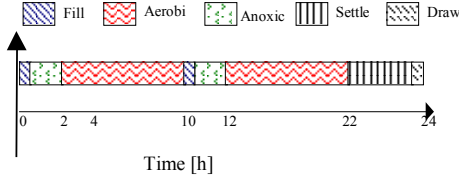


Figure 2.2 : Schematic view of the classical alternating aerated conditions

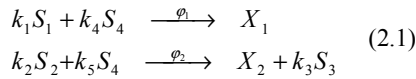
Because both the carbon and nitrogen are treated, two specific phases are needed : aerobic (presence of oxygen) and anoxic (no oxygen but nitrite and nitrate). During the anoxic phase, the nitrite+nitrate from the last cycle are transformed into gaseous nitrogen. This step is realized by heterotrophic bacteria who also need soluble organic carbon to grow ; cf. (Hu *et al.*, 2003) or (Jeppsson, 1996). When all the nitrite-nitrate has been removed, one can switch to aerobic mode where the ammonium nitrogen will be transformed into nitrite and nitrate while the remaining soluble carbon will be removed.

From now, we only concentrate on what happens during the aerobic phase and the following notations are used:

- X_1 : Heterotrophic microorganisms. (mg/l)
- X_2 : Autotrophic microorganisms (mg/l)
- S_1 : Organic carbon. (mg COD/l)
- S_2 : Ammonium nitrogen. (mg N-NH4/l)
- S_3 : Nitrates/Nitrites nitrogen (mg N-NO3/l+ mg N-NO2/l)
- S_4 : Dissolved oxygen (mg O2/l)

Modeling

The reaction scheme of the aerobic phase is as follows:



This synthetic scheme means that S_1 and S_2 are degraded by X_1 and X_2 respectively with the rates φ_1 and φ_2 in the presence of S_4 . In other words, the pollutant S_1 serves as a basis for the growth of X_1 while S_2 is transformed into S_3 by X_2 .

Considering the above reaction scheme, we can apply the mass balance principle to determine the state space model of the aerobic phase (Bastin *et al.* 1990):

$$\dot{X}_1 = \mu_1(S_1, S_4) X_1 \quad (2.2)$$

$$\dot{X}_2 = \mu_2(S_1, S_4) X_2 \quad (2.3)$$

$$\dot{S}_1 = -k_1 \mu_1(S_1, S_4) X_1 \quad (2.4)$$

$$\dot{S}_2 = -k_2 \mu_2(S_1, S_4) X_2 \quad (2.5)$$

$$\dot{S}_3 = k_3 \mu_2(S_1, S_4) X_2 \quad (2.6)$$

$$\dot{S}_4 = -k_4 \mu_1(S_1, S_4) X_1 - k_5 \mu_2(S_1, S_4) X_2 + K_L a (S_4^{\max} - S_4) \quad (2.7)$$

with

$$\begin{aligned} \mu_1 &= \mu_{1\max} \frac{S_1}{K_{S1} + S_1} S_4 \\ \mu_2 &= \mu_{2\max} \frac{S_2}{K_{S2} + S_2} S_4 \end{aligned} \quad (2.8)$$

As can be seen, the specific growth rates in aerobic phase, μ_1 and μ_2 , are proportional to the dissolved oxygen concentration, S_4 , in the reactor instead of the classical expression $\frac{S_4}{K_o + S_4}$ proposed in (Henze *et al.*, 1987). It is essentially because the available experiments were realized with a non-limiting oxygen concentration, S^* being the average of residual COD in the reactor (Mazouni *et al.*, 2005a). Furthermore, if it is assumed that the oxygen is not limiting, then the differential equation describing the time variation of the oxygen can be omitted. Using the mass balance conservation principle in a batch reactor, it is then possible to show that the above system can be reduced to the following third order dynamical system:

$$\begin{bmatrix} \dot{S}_1 \\ \dot{S}_2 \\ \dot{S}_3 \end{bmatrix} = \begin{bmatrix} f(S_1) \\ g(S_2) \\ -\alpha g(S_2) \end{bmatrix} u + \begin{bmatrix} f(S_1)h(S_3) \\ 0 \\ \beta f(S_1)h(S_3) \end{bmatrix} (1-u) \quad (2.9)$$

which can itself be put under the following compact form:

$$\begin{cases} \dot{Z} = F(Z) + G(Z)u \\ Z_0^T = [S_1(0) \quad S_2(0) \quad S_3(0)] \end{cases} \quad (2.10)$$

where $Z^T = [S_1, S_2, S_3]$ and where all functions and parameters depend on the original model (2.2) to (2.8).

The first task is to characterize the attainable set, that is characterizing the set of initial conditions for which there exists a control sequence, thus defining a trajectory, that drives the initial point towards the final target set defined as $\{S_1 < S_{1N}, S_2 < S_{2N}, S_3 < S_{3N}\}$. The details of this study are reported in (Mazouni *et al.*, 2005b).

The control design

From now onwards, it is supposed that $X_1(0) \neq 0$ and $X_2(0) \neq 0$. Defining

$\Omega_A = \{Z \in \mathfrak{R}^{3+} / S_2 < \alpha^{-1} S_{3N}, S_3 < \beta S_1 - \alpha S_2 + S_{3N}\}$,
 $\Omega_B = \{Z \in \mathfrak{R}^{3+} / S_2 > \alpha^{-1} S_{3N}, S_3 < S_1 - \alpha S_2 + \beta(S_3 - S_{3N})\}$
 with $\alpha = k_{32}/k_{22}$ and $\beta = k_{33}/k_{11}$, we now recall the following result:

Proposition 1: The attainable set is given by:

$$\Omega = \Omega_A \cup \Omega_B$$

Proof: cf. (Mazouni *et al.*, 2004).

Graphically, the attainable set is represented in figure 1.

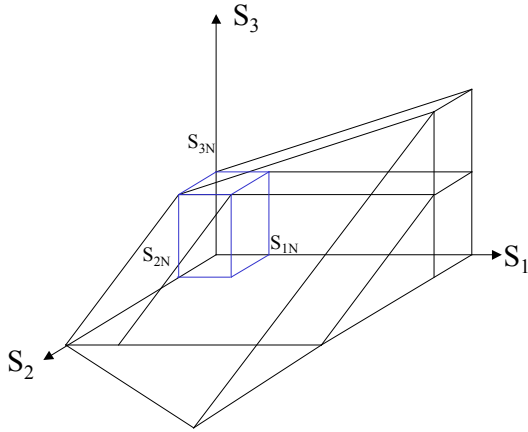


Figure 2.3: The attainable set

Once it has been verified that there exists a trajectory allowing us to drive the state toward the final set, it is of interest to compute the control actions (switching instants between aerobic and anoxic phases) in order to do so. Within the set of all possible switching policy and in order to keep the problem tractable (in practice, it is not possible to switch too often), it was decided to limit the computation to the search for control sequences comprising only 2 switches at most. In other words, the class of optimal control sequence to be applied can be schematically represented in the Figure 4.

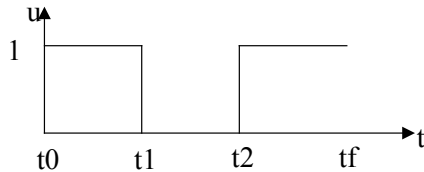


Figure 2.4: The class of admitted optimal control sequence to be applied

Indeed, it should be noticed here that any initial condition within the attainable set can be driven toward the final set in applying the specific sequence {aerobic, anoxic, aerobic}, cf. (Mazouni *et al.*, 2005b).

The problem to be solved can now be reformulated as the search for the two switching instants t_1 and t_2 such that any initial condition in the attainable set is driven towards the final set in a minimum time:

$$T = t_{aerob}^1 + t_{anox} + t_{aerob}^2$$

Unless the optimal solution be $u=0$ (it means that there is almost no ammonium nitrogen (S_2) in the effluent, that is when $S_2(t_0) < S_{2N}$), two distinct cases can arise: either the optimal trajectory first reaches the plane defined by $S_1 = S_{1N}$ or the one defined by $S_2 = S_{2N}$. Since both concentrations S_1 AND S_2 must verify $S_1(t_f) < S_{1N}$ AND $S_2(t_f) < S_{2N}$, the problem can be rewritten as the search for t_1 and t_2 such that:

$$t_{aerobic} = \int_{t_0}^{t_1} dt + \int_{t_2}^{t_f} dt = \max \left(\left(\int_{S_1(t_0)}^{S_1(t_1)} \frac{ds}{f(s)} + \int_{S_1(t_2)}^{S_{1N}} \frac{ds}{g(s)} \right), \left(\int_{S_2(t_0)}^{S_2(t_1)} \frac{ds}{f(s)} + \int_{S_2(t_2)}^{S_{2N}} \frac{ds}{g(s)} \right) \right)$$

be minimal.

To solve the general case (find the switching instants for t_1 and t_2 of the control sequence aerobic/anoxic/aerobic), the maximum principle is first used. Using this principle, it is possible to show that there exists a switching plane which defines the commutation instant t_2 . In order to compute t_1 , an optimisation problem is solved numerically: it corresponds to the search for t_1 that minimizes the anoxic phase time period. during anoxic phases, $u=0$. Thus S_2 is constant while $S_1(t)$ and $S_3(t)$ are linearly related referring to the relationships obtained from the

first integral $\frac{dS_3}{dt} = \beta \frac{dS_1}{dt}$. In order to parameterise the anoxic phase time period, we introduce the

following variable: $\theta = S_1(t_1) - S_1 = \frac{1}{\beta} (S_3(t_1) - S_3)$

such that $S_1 = S_1(t_1) - \theta$ and $S_3 = S_3(t_1) - \beta\theta$. Let δ be the variation of S_1 in the anoxic phase (it is proportional to the variation of S_3 over the same period). It is given

by $\delta = S_1(t_1) - S_1(t_2) = \frac{1}{\beta} (S_3(t_1) - S_3(t_2))$. The anoxic phase time period is then given by:

$$t_{anox}(\delta, S_1^1, S_3^1) = \int_0^\delta \frac{1}{f(S_1^1 - \theta)} \frac{1}{h(S_3^1 - \beta\theta)} d\theta \\ = \int L(\theta, S_1^1, S_3^1) d\theta$$

where (S_1^1, S_2^1, S_3^1) is the solution of the dynamical system (2.10) for $u=1$ at $t=t_1$.

The biological interpretation of the optimal solution is as follows. The nitrogen removal kinetics is very slow compared to the carbon removal. Thus, the required aerobic time corresponds essentially to the nitrogen removal. Since nitrogen is not eliminated in anoxic phase, the aerobic phase duration cannot be minimized. We can only reduce the total cycle time by reducing the anoxic phase time.

In standard cases the anoxic phase takes place at the beginning of the cycle. The anoxic reaction rate depends on the two substrate concentrations S_1 and S_3 . At the beginning, the maximum of carbon is available. In most cases (depending on the initial conditions), the optimal control strategy consists in starting with an aerobic phase in order to maximize the anoxic reaction rate. During the first aerobic phase, S_3 increases and S_1 decreases. The anoxic phase is applied when the maximal possible rate of the anoxic reaction is reached, so that the total time of this phase is reduced. Of course if the maximum anoxic rate is given at the initial time, the batch starts with the anoxic phase as in the classical approach the total time cannot be further reduced.

Hereafter, we present a comparison between the application of a classical control sequence based on a constant time period approach (anoxic/aerobic) and the above presented optimal control approach. Initial conditions are about $S_1(0)=700$ mg/l, $S_2(0)=50$ mg/l, $S_3(0)=30$ mg/l. The switching instants were computed off-line using the influent characterisation and the initial biomass concentrations.

Table 2 1: Phases duration comparison with real data

	Anoxic time (min)	Aerobic Time (min)	Total (min)
Classical cycles	32	390	422
	35	410	435
	30	400	430
Optimal control approach	28	10+380	418
	25	10+360	395
	26	10+380	416
	22	10+400	432
	24	10+390	414

Simulation results are presented hereafter:

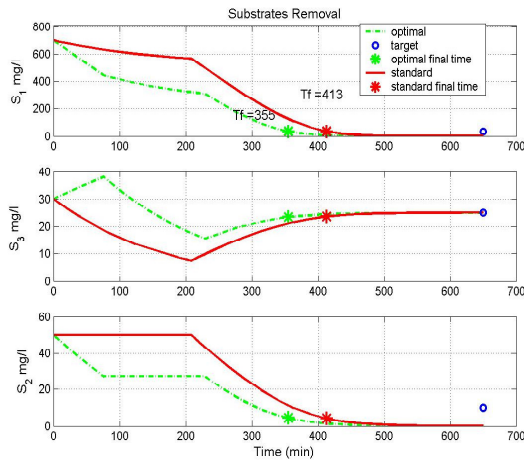


Figure 2 6: Phases duration comparison with real data

The optimal approach was applied with several replicates. Globally, The average of the anoxic phase duration in standard case was 32 ± 3 min and the aerobic phase 410 ± 15 min. with the optimal approach the average of the anoxic phase time was around 25 ± 5 min and the aerobic phase 390 ± 20 min. The time reduction for the anoxic phase is around 13% while the total reaction time was reduced at only 4%. This happen because the long aerobic phase depends essentially of the nitrogen removal which is not eliminated in the anoxic phase. The anoxic reaction time is reduced by increasing the anoxic reaction rate.

3. TREATMENT OF TOXIC WASTEWATERS

The process

For the toxic wastewater treatment the SBR sequence is similar to the one depicted in the Figure 2 in section 2, except that there exist no anoxic phase i.e. there is only one single aerobic phase. The classical batch operation mode of the SBR feeds the influent all at once at the beginning of the cycle. This causes an inhibition of the biomass, due to the excessive toxic concentration fed, that renders the reaction inefficient. The time optimal control (TOC) objective is chosen as to minimize such a reaction time by controlling the feeding rate i.e. by using a fed-batch mode. The problem for implementing the TOC is the lack of online measurements for the substrate and biomass concentrations both in the SBR tank and/or in the influent flow. Because of such a limitation, even having a good mathematical model for the process is not enough in order to optimally control it.

Modeling

The reaction scheme of the reaction phase is



which, assuming that the dissolved oxygen is not limiting, that the biomass decay is negligible and that no biomass nor oxygen are fed via the influent, leads to the mass balance based model:

$$\dot{X} = \mu(S)X - XQ/V \quad (3.2)$$

$$\dot{S} = -k_1 \mu(S)X + (S_{in} - S)Q/V \quad (3.3)$$

$$\dot{S}_4 = -(k_4 \mu(S) + b)X + k_L a (S_{4,sat} - S_4) - S_4 Q/V \quad (3.4)$$

$$\dot{V} = Q \quad (3.5)$$

where

- $0 < Q < Q_{max}$: Inflow volumetric flow (l/h)
- $V_0 \leq V \leq V_f$: Volume level of the liquid in the tank (l)
- S : Toxic concentration in the tank (mg COD/l)

S_{in} : Toxic concentration in the influent (mg COD/l)
 S_4 : Dissolved oxygen concentration (mg O2/l)
 $S_{A,sat}$: Saturation value of the dissolved oxygen concentration in the liquid medium (mg O2/l)
 $k_1 a$: Oxygen mass transfer coefficient (h^{-1})
 $b > 0$: Endogenous respiration coefficient (h^{-1})
 μ : Specific biomass growth rate (h^{-1})

The main characteristic of the model structure is the inhibitory effect that the toxic concentration does have on the biomass behavior, represented by μ in Fig. 3.1. Let us call S^* the toxic concentration at which it reaches its maximum value (μ^*). i.e. the point where inhibition just begins. S_{batch} represents the toxic substrate concentration value that is reached inside the SBR when the filling process finishes using the typical batch mode. Such a fast filling process is represented by the first arc of the Substrate-Volume (SV) trajectory projected in Fig. 3.2 i.e. to take the volume quickly from its initial value (V_0) to its final one (V_f) thus increasing the concentration inside the tank from its initial value (S_0) to its maximum value during the reaction (S). Relating Fig. 3.2 to Fig. 3.1 it is easy to see that the batch reaction gets inhibited soon after the beginning and will stay so until the substrate is degraded down to the S^* value, which usually is accomplished only at the final stage of the reaction i.e. a typical batch reaction spends most of its time inhibited.

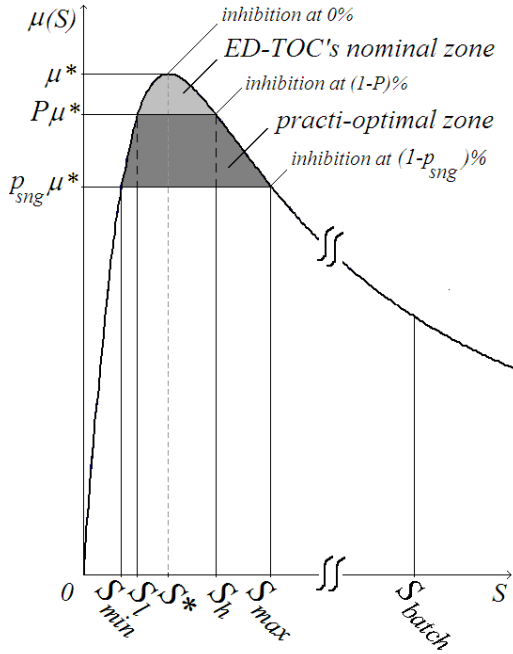


Figure 3.1 : Inhibitory specific biomass growth rate

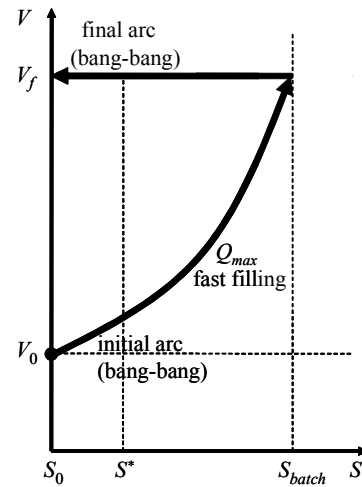


Figure 3.2 : Typical batch SV -trajectory

The control design

Results useful to optimize a batch process as the one producing the trajectory in Fig 3.2 are already available (Moreno, 1999; Sarkar and Modak, 2003; Smets et al., 2002). The exact minimum time trajectory is shown in Fig. 3.3. It does have 3 arcs. The initial and final arcs are of the **bang** type, i.e. either maximum or zero input flow is applied, while the intermediate one should live in the **singular** surface ($S = S^*$) i.e. the inflow should be controlled exactly as calculated by (Moreno, 1999):

$$Q_{sng} = \frac{k_1 \mu X V}{S_{in} - S}$$

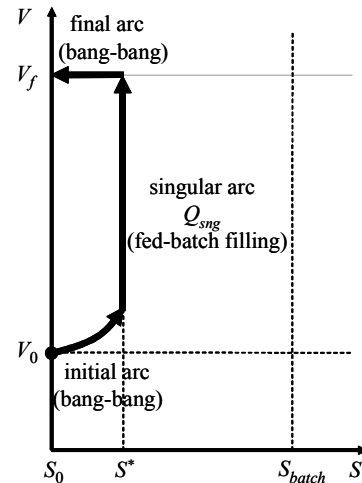


Figure 3.3 : Nominal (ideal) TOC SV -trajectory

The problem for calculating such a singular flow is that the values of S , S_{in} and X are not available online.

Assumption 3.1: $S_{in} \gg S^* > S_0$

Assumption 3.2: $Q_{max} > Q_{sng}$

Assumptions 3.1 and 3.2 are natural conditions for the problem. The first one guarantees that the initial bang

arc may be one of the “fill” type (i.e. $Q = Q_{\max}$) while the second one guarantees that $dS/dt > 0$ during such a fill arc if it started to the left of the singular surface. Note that On the other hand a bang “react” arc (i.e. $Q = 0$) will always comply that $dS/dt \leq 0$. Note that fill arcs generate trajectories that grow both in V and in S (e.g. the initial arc in Fig. 3.3) while react arcs generate horizontal trajectories of constant V and decreasing S e.g. the final arc.

Let us define as practically optimal (**practi-optimal**) a controller whose trajectory performs the initial and final arcs of the TOC exactly but only approximates the singular one. Fig. 3.4 shows a way to describe the acceptable approximations i.e. the ones which approximate (arbitrarily well) the singular arc inside a given tube defined by $S_{\min} < S < S_{\max}$ such that, inside such a tube, $\mu > p_{sng} \mu^*$, as depicted in Fig. 3.1.

Model based observers to estimate S using the volume level and the dissolved oxygen (V, S_4) have been used in a feedback control to implement a practi-optimal solution in a lab-scale SBR (Vargas et al., 2000). However, it required the (normally unavailable) values of X and S_{in} to operate properly, so its practical use in real wastewater treatment plants was not feasible. Next, a practical approximation to the TOC that uses also V and S_4 but that does not require the unavailable measurements will be presented.

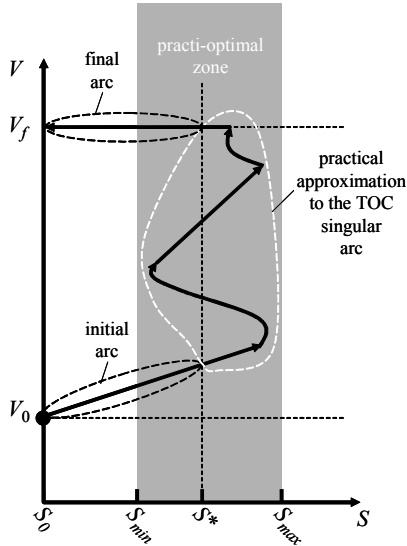


Figure 3.4 : Practical TOC SV-trajectory

Event Driven TOC (ED-TOC),

The idea to implement the ED-TOC is to perform the approximation of the singular arc by iteratively switching the influent flow (Q) on-off i.e. by generating a bang-bang trajectory shaped like a zigzag composed of fill (on) and react (off) arcs (Fig. 3.5). Note that each pair of consecutive fill-react arcs resembles a **mini-batch**. The resulting trajectory is practi-optimal if all mini-batch arcs reside inside the allowed practi-optimal zone. In order to guarantee that such is the case, even if there are bounded

perturbations in the measured variables, the ED-TOC targets an inner “nominal-zone” defined by a tuning parameter $p_{sng} < P < 1$ (Fig. 3.1) which allows to choose the nominal switching surfaces $S = S_l$ and $S = S_h$. Note that by choosing P (Fig. 3.1) arbitrarily close to one renders the practical approximation in Fig. 3.5 arbitrarily close to the exact optimal one in Fig. 3.3.

If S was available and S_l, S_h were well known, then detecting the **events** related to the crossing of the switching surfaces (Fig. 3.5), by using a set of comparators, would be straightforwardly easy. However that is not the case. Instead, the idea behind the ED-TOC is to use the knowledge about the model structure to perform an estimation of such events needed to **drive** the controller. Next, a simplified 3 steps explanation into the workings of the ED-TOC follows: 1) a way to compute the oxygen mass uptake rate (OMUR) using only the available data will be derived, 2) the use of an hypothetical variable (named γ) to detect the events needed to drive the ED-TOC will be explained and 3) a justification for using the OMUR instead of γ for performing a practi-optimal ED-TOC will be given.

1) The OMUR may be defined as the volume multiplied by the oxygen uptake rate (OUR) and then Eq. (3.4) maybe rearranged to compute it as

$$\begin{aligned} OMUR &:= k_4 \mu(S) B + bB \\ &= k_L a (S_{4,sat} - S_4) V - S_4 Q - \dot{S}_4 V \end{aligned} \quad (3.6)$$

where $B := XV$ is the total biomass, $k_4 \mu B$ is related to the exogenous respiration which in turn is directly proportional to the substrate reaction rate and bB is related to the endogenous respiration. Note that the right hand side of this equation is computable online as every term there is known or measurable.

2) Let us assume that the function

$$\gamma := k_4 \mu(S) B_0 \quad (3.7)$$

is available online, where $B_0 := X_0 V_0$ is a positive constant representing the initial total biomass. Then it is possible to relate the switching surfaces directly to γ by defining $\gamma^* = k_4 \mu^* B_0$ and $\gamma = P \gamma^*$ as the surface where either $S = S_l$ or $S = S_h$. In order to differentiate which one of such events is the one really happening it suffices to know the sign of the derivative of γ and the state of Q . If the arc being produced is of the react type then a decreasing γ means that the trajectory is on the left side of the singular surface, thus the switching occurs for $S = S_l$. On the other hand, if the arc is of the fill type then the same decreasing behaviour of γ means that the trajectory is on the right side of the singular surface, hence the switching occurs for $S = S_h$.

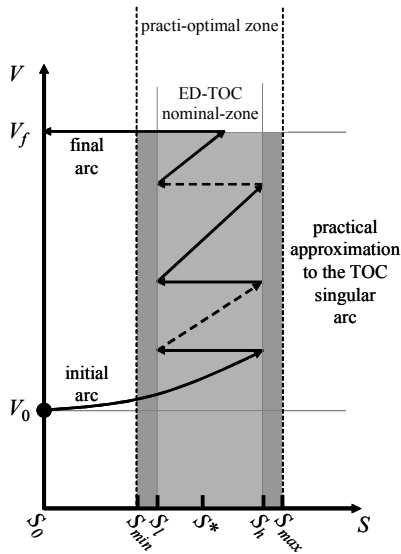


Figure 3.5 : ED-TOC SV-trajectory

Using such information is easy to implement the nominal ED-TOC, exactly as in Fig. 3.5, as follows: First (using assumption 3.1) apply $Q = Q_{\max}$ to produce a fill type arc. Once γ reaches a maximum and begins to decrease the singular surface was crossed from left to right. Such a maximum is γ^* . Keep filling until $\gamma = P\gamma^*$. At this point the event of crossing $S = S_h$ is detected and the filling is stopped. Then a react type of arc begins and the behaviour of gamma repeats itself i.e. it will increase again until a maximum (γ^*). At that point the controller knows the singular surface is being crossed, this time from right to left. Then when γ decreases down to $P\gamma^*$ the event of crossing the switching surface $S = S_i$ is detected and a new fill arc begins. Such a fill-react-fill cycle is repeated until the tank gets full.

3) The type of processes under study are of the substrate degrading type and not of the biomass producing ones. This means that the total biomass increase ($\Delta B = B_f - B_0$) is negligible ($\Delta B \ll B_0$) during a single batch. Additionally, in a properly designed toxic wastewater treatment system, the endogenous respiration is much less than the exogenous one when the process is taken near to the singular surface ($k_4\mu^*B \gg bB$). Using these conditions in the left hand side of Eq. (3.6) it is easy to see that, inside the practi-optimal zone (Fig. 3.5) the error in detecting the events of the crossing of the switching surfaces is low if the OMUR is used instead of the ideal γ in Eq. (3.7) for implementing the ED-TOC i.e.

$$OMUR \approx \gamma.$$

A complete explanation of the ED-TOC and a robustness analysis, including the effects of the biomass growth and the endogenous respiration when they are not negligible, is given in Betancur et al. (2005).

Experimental results

The ED-TOC, using the computation of the right hand side of the OMUR in Eq.(3-6) directly instead of the ideal γ in (3.7) was applied to the treatment of a synthetic wastewater containing 4-clorophenol (4CP) as a toxic model compound. A 7 litre lab-scale SBR was used with an exchange volume of 53%. The influent toxic concentration defined as the standard condition was $3.5 \text{ g}4\text{CP/l}$. Multiple ED-TOC fed-batch experiments were performed for both the standard condition and for load shocks i.e. the influent toxic concentration was increased up to 20 times the standard one as a perturbation of the standard operating condition. A comparative analysis was made versus the pure batch operation mode. It must be noted that the pure batch operation mode is not able to withstand unknown perturbations higher than 3 times the standard condition because the inhibition caused to the biomass is so high that it gets irreversible and the SBR gets disabled. Then, in order to be able to compare data, it was assumed that the perturbation was known (as if the influent concentration S_m was measurable) and a pre-dilution of the influent to the standard condition was allowed for the pure batch case (not for the ED-TOC case). This means that multiple pure batches were required to treat the same amount of influent that the ED-TOC was able to treat in a single fed-batch during the shock load perturbations.

The improvements of using the ED-TOC over the pure batch mode are reported in Moreno-Andrade et al. (2005). A summary follows:

- 1) A reduction in total batch time that allowed increasing the daily applicable load in a range from 63% up to 90%, both in standard and in shock load conditions.
- 2) Savings in energy between 25% and 39% represented in less aeration and stirring time required during the reaction phase.

CONCLUSIONS

In this paper, two optimal control strategies for two types of biological processes performed in sequencing batch reactors were derived. The first strategy aims at driving an initial condition to the target set in performing both carbon and nitrogen removal from dairy wastewater in minimal time. The problem that has been solved is to find the optimal switching instants of the predefined control sequence {aerobic-anoxic-aerobic}.

The second strategy aims at optimizing the aerobic treatment of a toxic substance in a fedbatch feeding operating mode using only the dissolved oxygen on-line measurement. Even if a good model for the toxic wastewater treatment is available, the state of the art of the sensor technology does not yet allows measuring key process variables as substrate and biomass concentrations. Thus it is not feasible to

implement an optimal control directly for such a kind of processes.

It was shown how to take advantage of the structure of the model and of the robustness given by the mass balance approach in order to perform the estimation of events related to the closeness of the system to the singular surface of the minimum time optimal solution. Relating these events to an online computable variable, the oxygen mass uptake rate, it was possible to implement a practical approximation to the optimal control, the event driven time optimal control (ED-TOC).

Experimental results treating 4-chlorophenol as a model for the toxic compound in a lab-scale SBR validate the ED-TOC proposal.

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REFERENCES

- Betancur MJ, Moreno JA, Moreno-Andrade I, Buitrón G. 2005. (accepted). Practical optimal control of fed-batch bioreactors for the wastewater treatment. *International Journal of Robust and Nonlinear Control*, Special Issue on "Control of (Bio)Chemical Reacting Systems".
- Fibrianto H., D. Mazouni, M. Ignatova, M. Herveau, J. Harmand and D. Dochain 2006. "Dynamical modelling, identification and software sensors for SBR's", *5th MATHMOD VIENNA, IMACS Symposium on Mathematical Modelling*, Vienna, 8-10 février 2006.
- Mazouni, D., M. Ignatova et J. Harmand 2005. "A Multi-Model approach for the monitoring of carbon and nitrogen concentration during the aerobic phase of a biological sequencing batch reactor", 16th IFAC World Congress, 5-8 juillet, Prague, République Tchèque.
- Mazouni, D., J. Harmand, A. Rapaport 2005. "Attainability and Suboptimal minimal time Control of a class of biological sequencing batch reactors ", IFAC 2005 World Congress, July, 4-8 2005, Prague, Czech republic.
- Mazouni, D., J. Harmand, A. Rapaport and H. Hammouri 2004. "Modelling and controlability analysis of an aerobic SBR", 7th African Conference on Research in Computer Science, CARI, November 22-25, 2004, Hammamet, Tunisia.
- Moreno J. 1999. Optimal time control of bioreactors for the wastewater treatment. *Optim Contr Appl Met* 20:145-164.
- Moreno-Andrade I, Buitrón G, Betancur MJ, Moreno JA. 2005 (accepted). Optimal Degradation of Inhibitory Wastewaters in a Fed-batch Reactor. *J Chem Tech Biotech*.
- Pauss A., Schoefs O., Bekri, M. Bouvier J.C., Canziani R., Ficara E., Fiocchi N. Luccarini L., Ciappelloni F., Ratini P., Pirani M. and Mariani S. 2006. "Development of hardware sensors for the on-line monitoring of SBR used for the treatment of industrial wastewaters" *5th MATHMOD VIENNA, IMACS Symposium on Mathematical Modelling*, Vienna, 8-10 February 2006.
- Sarkar D, Modak JM. 2003. Optimisation of fed-batch bioreactors using genetic algorithms. *Chem Eng Sci* 58:2283-2296.
- Smets IYM, Versyck KJE, Van Impe JFM. 2002. Optimal control theory: a generic tool for identification and control of (bio)chemical reactors. *Annual Reviews in Control* 26:57-73.
- Vargas A, Soto G, Moreno J, Buitrón G. 2000. Observer based time-optimal control of an aerobic SBR for chemical and petrochemical wastewater treatment. *Water Sci Technol* 42(5-6):163-170.