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ON LINEARIZING CONTROL OF AN ACTIVATED SLUDGE PROCESS

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Abstract: In this paper, a linearizing control law of an activated sludge process is proposed. The objective to be reached consists of controlling the concentration of nitrogen products at the outlet of the settler. The oxygen concentration is supposed to be constant during aerobic phases. The control variable is the external carbon supplying during anoxic phases. The open loop model of the process is a simplified version of the nonlinear International Association for Water Quality model. A nonlinear control law is derived such that the closed loop system behaves like a linear system whose dynamics can be fixed a priori. *Copyright © 1999 IFAC*

Keywords: Bio control, Lumped-parameter systems, Nonlinear control, Process control, Water pollution.

1. INTRODUCTION

Biological treatment of urban wastewater is often carried out in activated sludge processes. Organic carbon products removal is not anymore the only limiting element of the water quality. As a set-off, improving this quality can be obtained by enhancing the struggle against the nitrogen pollution. New more drastic standards on a two-hours sample are imposed nowadays. In order to control the process, two main control variables can be chosen :

- the air flowrate during aerobic phases (nitrification) when the oxygen concentration is not regulated,
- the external carbon supplying during anoxic phases (denitrification).

The aim of this paper is to present some results about linearizing control of a sequential activated sludge process when the oxygen concentration is regulated during aerobic phases. So, the control variable is the external carbon concentration supplied during anoxic phases. It is assumed that nitrate concentration can be measured on-line and ammonia concentration can be reconstructed by implementing a state observer.

2. DESCRIPTION OF THE PROCESS

The studied continuous flow activated sludge process (low organic load) comprises a mixer, an aeration tank and a settler (Figure 1). Biomass is recycled from the settler to the aeration tank, excess sludge is wasted from the latter and oxygen is supplied intermittently in the reactor to create nitrification and denitrification conditions. Carbon and nitrogen are removed via this process.

Switching between aerobic phase and anoxic phase occurs when the ammonia concentration is less

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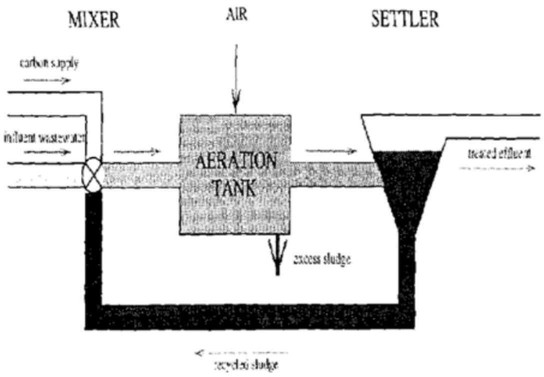

Fig. 1. Activated sludge process.

than the ammonia saturation coefficient for the autotrophic biomass (K_{NH4AUT}). Switching between anoxic phase and aerobic phase occurs when the nitrate concentration is less than the nitrate saturation coefficient (K_{NO3}).

Two control variables can be considered :

(a) the addition of an external carbon source during the denitrification phase,

(b) the aeration flowrate to optimize the cycle lengths (nitrification/denitrification) to meet the required effluent criteria and minimize eventually the energy consumption.

On-line measurements available for these controls are oxygen and nitrate concentrations. Off-line measurements of ammonia concentration are also available and necessary for off-line identification of model parameters.

3. MATHEMATICAL MODELLING

The reference model which describes the elimination of nitrogen and carbon is the I.A.W.Q. model n°1 (Henze *et al*, 1987a; Henze *et al*, 1987b) in which some modifications have been made (Julien *et al*, 1998a). It contains eleven state variables and twenty parameters. The considered reactor being a low organic loading activated sludge process, the removing of carbon does not state a problem ; so, it may be interesting for control study, to get a simplified state model characterized by three state variables S_{NO3}, S_{NH4} and S_{O2} denoting concentrations of nitrate, ammonia and oxygen respectively.

In order to get a reduced order model, a certain number of approximations has to be done from biochemical and mathematical considerations. This can be achieved by observing the evolution of state variables in different experimental conditions and by simplifying the reaction kinetics.

The final reduced order model fulfils the observability property in both conditions (aerobic and anoxic) and the controllability property in aerobic conditions (Julien *et al*, 1998b). It is described by two differential equation systems :

- aerobic submodel ($S_{O2} > 0$)

$$\begin{aligned}
\dot{S}_{NO3} &= -(D+D_c)\ S_{NO3} - \frac{1}{2.86}\rho_{2ae} + \rho_{3ae} \\
\dot{S}_{NH4} &= D\ S_{NH4in} - (D+D_c)\ S_{NH4} \\
&\quad -b\ (\rho_{1ae} + \rho_{2ae}) - \rho_{3ae} + \rho_{4ae} \\
\dot{S}_{O2} &= -(D+D_c)\ S_{O2} - \rho_{1ae} - 4.57\rho_{3ae} \\
&\quad +kla\ (S_{O2sat} - S_{O2})
\end{aligned} \tag{1}$$

with

$$\rho_{1ae} = k_{12}\ (S_{Sin} + \frac{k_5}{D})\frac{S_{O2}}{S_{O2}+K_{O2H}}$$

$$\rho_{2ae} = k_{22}\ (S_{Sin} + \frac{k_5}{D})\frac{K_{O2H}}{S_{O2}+K_{O2H}}\frac{S_{NO3}}{S_{NO3}+K_{NO3}}$$

$$\rho_{3ae} = k_3\ \frac{S_{O2}}{S_{O2}+K_{O2AUT}}\frac{S_{NH4}}{S_{NH4}+K_{NH4AUT}}$$

$$\rho_{4ae} = k_4$$

- anoxic submodel ($S_{O2} = 0$)

$$\begin{aligned}
\dot{S}_{NO3} &= -(D+D_c)\ S_{NO3} - \frac{1}{2.86}\ \rho_{1an} \\
\dot{S}_{NH4} &= D\ S_{NH4in} - (D+D_c)\ S_{NH4} \\
&\quad -b\ \rho_{1an} + \rho_{2an} \\
\dot{S}_{O2} &= 0
\end{aligned} \tag{2}$$

with

$$\rho_{1an} = k_{22}\frac{S_{NO3}}{S_{NO3}+K_{NO3}}\frac{S_{NH4}}{S_{NH4}+K_{NH4H}} *$$
$$(S_{Sin} + \frac{D_c}{D}\ S_{Sc} + \frac{k_5}{D}\eta_{NO3h}\frac{S_{NO3}}{S_{NO3}+K_{NO3}})$$

$$\rho_{2an} = k_4$$

where

- $D = \frac{Q_S}{V}$ and $D_c = \frac{Q_c}{V}$ with Q_S the input flowrate, Q_c the external carbon flowrate and V the volume of the reactor,
- S_{Sc} is the concentration of the supplied external carbon,
- kla and S_{O2sat} are the coefficient of oxygen transfer and the saturation concentration of oxygen, respectively,
- S_{NH4in} and S_{Sin} are the concentrations of ammonia and soluble carbon in the input wastewater,

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- (k_{12}, k_{22}, k_3, k_4, k_5, K_{O2H}, K_{O2AUT}, K_{NH4AUT}, K_{NO3}, b) and (k_{22}, k_4, k_5, K_{NO3}, K_{NH4H}, η_{NO3h}, b) are the model parameters to be identified (Julien et al, 1998b) respectively in aerobic and anoxic conditions.

  (K_{O2H}, K_{O2AUT}, K_{NH4AUT}, K_{NH4H}, K_{NO3}, η_{NO3h}) are common parameters with the I.A.W.Q. model n°1 (Henze et al, 1987a; Henze et al, 1987b), whereas (k_{12}, k_{22}, k_3, k_4, k_5, b) are specific to the reduced order model.

4. FORMULATION OF THE CONTROL PROBLEM

4.1 *Objective*

According to the new European standards of the water quality, the global nitrogen concentration must be lower than 10 g/m^3 at the outlet of the settler, for mean samples over two hours (NGL_2 standard).

But, at the outlet of the settler, the organic nitrogen concentration is practically constant, about 2 g/m^3. So, the NGL_2 standard can be replaced by a standard on the sum of ammonia and nitrate concentrations equal or less than 8 g/m^3.

Assuming that the oxygen concentration is regulated at 2 g/m^3, the only possible control variable is the external carbon concentration during anoxic phases.

4.2 *Linearizing control*

Because of the sequential behaviour of the process, the latter is always in transient state. So, it can be interesting to control the process dynamics during anoxic phases, in order to get the nitrogen concentration at the outlet of the settler at the nearest possible value of the standard. To solve this problem of control, the linearizing control method (Bastin and Dochain, 1990) can be used. Two types of output variable can be considered :

- the nitrogen concentration S_N at the outlet of the settler ("First case") :

$$y(t) = S_N(t) \quad (3)$$

- the integral over a period T (e.g. $T = 2\ h$) of the nitrogen concentration at the outlet of the settler ("Second case") :

$$y(t) = \frac{1}{T}\int_{t_1}^{t_1+T} S_N(t)dt \quad (4)$$

In both cases, a mathematical model of the settler is needed. A simplified model consists of writing down a first-order filter equation :

$$\frac{dS_N}{dt} = \frac{Q_S + Q_c}{V_d}(S_{NO_3} + S_{NH_4} - S_N) \quad (5)$$

where V_d is the volume of the settler.

The principle of linearizing control is to find a control law $S_{S_c}(t)$ such that the tracking error $(y^* - y)$ between the model output y and the desired output y^*, is governed by a prespecified stable linear differential equation selected as follows :

$$\sum_{j=0}^{\delta} \lambda_{\delta-j}\frac{d^j}{dt^j}[y^*(t) - y(t)] = 0, \qquad \lambda_0 = 1 \quad (6)$$

where δ is the relative degree of the system. The control design consists of calculating the terms $\frac{d^j y(t)}{dt^j}|_{j=1,\dots,\delta}$ and of replacing them in (6).

5. CONTROL ALGORITHMS AND SIMULATION

In this section two control algorithms are established according to the two types of output variable defined in the preceding section. The input variables (input flowrate, input ammonia concentration, input carbon concentration) are depicted on Figure 2 :

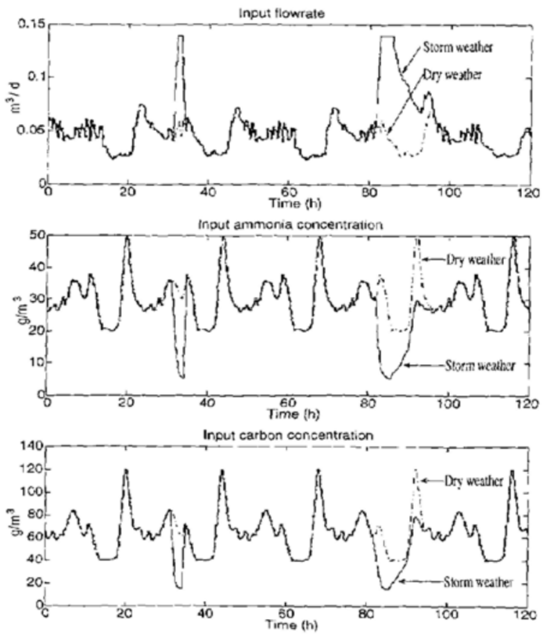

Fig. 2. Input variables.

Simulations are carried out for two types of weather (dry and storm) scaled for a pilot unit.

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5.1 *First case*

The considered output variable is the nitrogen concentration at the outlet of the settler. In this case, the relative degree of the system is equal to 2. It means that, the output equation (5) has to be differentiated twice. The control algorithm is as follows :

$$
\begin{aligned}
S_{Sc} = \frac{1}{Den} \Big[& -D\ S_{NH4in} - \lambda_2 \frac{V_d}{Q_S + Q_c}(y^* - y) \\
& -(\frac{Q_S + Q_c}{V_d} - \lambda_1)(S_{NO3} + S_{NH4} - S_N) \\
& -k_4 + (D + Dc)(S_{NO3} + S_{NH4}) \qquad (7) \\
& +k_{22} \frac{S_{NO3}}{S_{NO3} + K_{NO3}} \frac{S_{NH4}}{S_{NH4} + K_{NH4H}}(b \\
& + \frac{1}{2.86})(S_{Sin} + \frac{k_5}{D}\eta_{NO3h} \frac{S_{NO3}}{S_{NO3} + K_{NO3}}) \Big]
\end{aligned}
$$

where
$Den = k_{22} \frac{Dc}{D} \frac{S_{NO3}}{S_{NO3}+K_{NO3}} \frac{S_{NH4}}{S_{NH4}+K_{NH4H}} (b + \frac{1}{2.86})$

Simulation results : the performances of the above controller are shown on Figures 3 (dry weather) and 4 (storm weather).

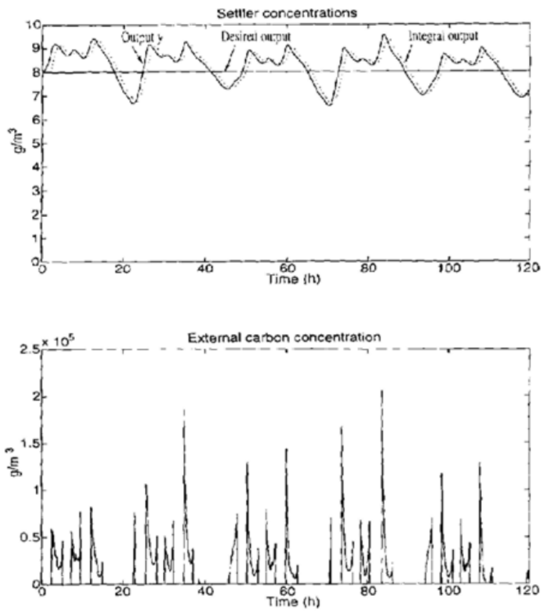

Fig. 3. First case - dry weather.

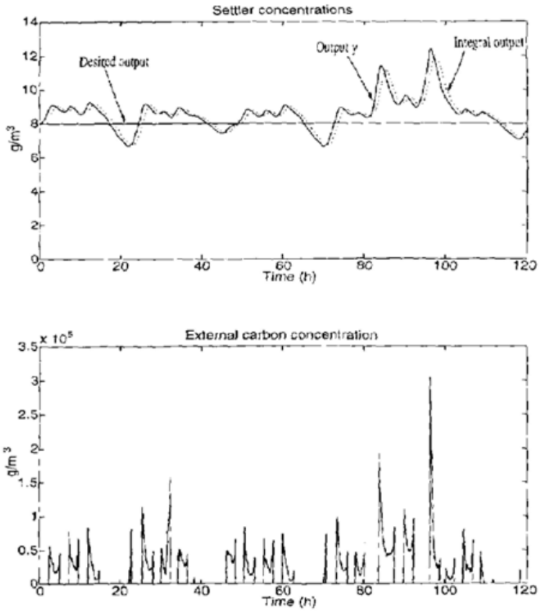

Fig. 4. First case - storm weather.

5.2 *Second case*

The considered output variable is the integral over two hours of the nitrogen concentration at the outlet of the settler. In this case, the relative degree of the system is equal to 3. It means that, the output equation (5) has to be differentiated three times. The control algorithm is as follows :

$$
\begin{aligned}
S_{Sc} = \frac{1}{Den} \Big[& -D\ S_{NH4in} - \lambda_3 \frac{V_d.T}{Q_S + Q_c}(y^* - y) \\
& -(\frac{Q_S + Q_c}{V_d} - \lambda_1)(S_{NO3} + S_{NH4} - S_N) \\
& -\lambda_2 \frac{V_d}{Q_S + Q_c} S_N - k_4 \qquad (8) \\
& +(D + Dc)(S_{NO3} + S_{NH4}) \\
& +k_{22} \frac{S_{NO3}}{S_{NO3} + K_{NO3}} \frac{S_{NH4}}{S_{NH4} + K_{NH4H}}(b \\
& + \frac{1}{2.86})(S_{Sin} + \frac{k_5}{D}\eta_{NO3h} \frac{S_{NO3}}{S_{NO3} + K_{NO3}}) \Big]
\end{aligned}
$$

where Den is the same as in the first case.

Simulation results : the performances of the above controller are shown on Figures 5 (dry weather) and 6 (storm weather).

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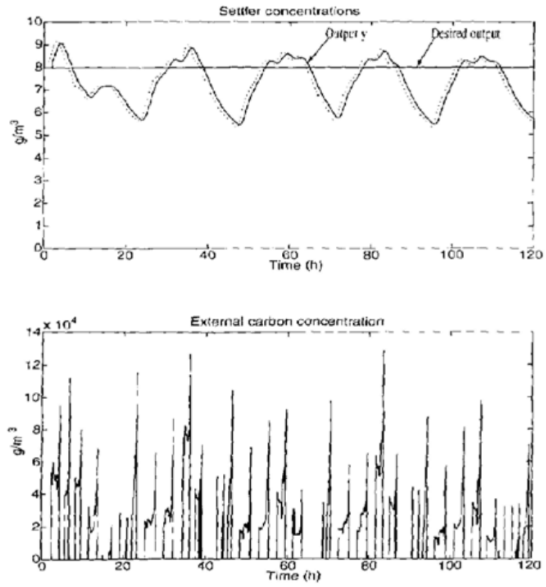

Fig. 5. Second case - dry weather.

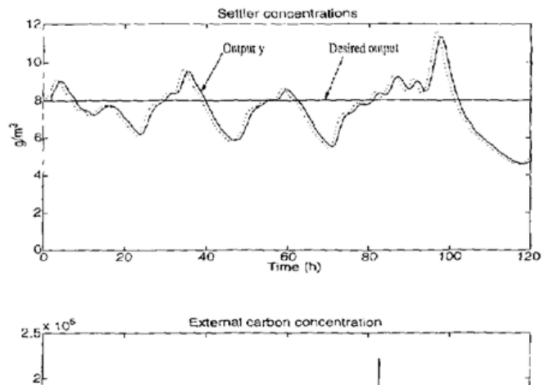

Fig. 6. Second case - storm weather.

5.3 *Comments on simulation results*

The performance of the control law must be characterised by considering two aspects : the quality of the standard respect and the cost of the control action (the air supplied during aerobic phases and the external carbon supplied during anoxic phases).

By considering the preceding figures, the following comments can be stated :

- the lengths of aerobic and anoxic phases can be obtained by considering the control variable (carbon concentration) evolution ; aerobic phases correspond to zero concentration ;
- in the "second case", the standard is better respected than in the "first case" ;
- the overshoots at the output are lower in the "second case" ;
- the quantity of needed carbon is lower in the "first case" ;
- in both cases, the quantity of air supplied is the same.

Quantitatively speaking, the main numerical results are given in the following table :

Table 1. Comparative results for both cases

Description	**First case output**		**Second case output**	
Type of weather	dry	storm	dry	storm
Carbon mass (g)	29.49	37.09	31.46	47.24
Overshoot integral ($g/m^3.d$)	1.74	3.21	0.92	1.00

The "first case" is preferable if the cost viewpoint is the most important, whereas the "second case" allows a better quality of standard respect.

6. CONCLUSION

In this paper, the problem of controlling the concentration of nitrogen products at the outlet of the settler has been solved by applying a linearizing control method well known in the field of biotechnological processes. Simulation results are globally satisfactory. Nevertheless, on the applicability viewpoint, the theoretical control law must be slightly modified in order to take into account the real constraints of the action modes.

The peaks observed on the figures of the external carbon concentration evolution must be avoided. For that purpose, a mean control value over an anoxic phase can be applied instead of the theoretical control law.

The simulation results do show that there does not exist an optimal solution : a good solution is derived from a compromise between the cost of the control action and the respect of the standard.

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