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Feedback-feedforward control of a sewer

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Abstract

This paper deals with the design of a feedback-feedforward controller for a sewer. The objective is to reduce the concentration of macromolecules (typically proteins, lipids and polysaccharides) entering the wastewater plant via the addition of a consortium of enzymes and bacteria in the sewer connecting houses to the plant. The hydrodynamics of the sewer are basically plug flow ones. An experimental set-up has been built in order to simulate the behaviour of the sewer at laboratory scale. The design of the controller is based on a simplified model of the sewer consisting of a CSTR model plus a time delay. The controller includes feedforward action in order to reduce the influence of the periodical variation of the influent pollutants. The controller performance is illustrated in numerical simulation.

1 Introduction

The control of biological wastewater treatment processes has been an active research area for more than three decades. So far the activity has concentrated directly on the control of wastewater treatment plants and of the processes (activated sludge, anaerobic digestion) that are operated in these plants. Little concern has been given so far to the wastewater coming into the plants. However one of the main challenges that wastewater treatment processes and their control have presently to face is to operate these plants in such a way that the water in the outlet is as clean as possible with respect to the legal standards while the influent wastewater is largely time-varying not only in terms of flow rates but also in terms of content. Over the past years, a research activity has been pursued with the objective to reduce the content of macromolecules (typically proteins, lipids and polysaccharides) of the wastewater treatment plant inlet via the injection of consortia of enzymes and bacteria in the sewer system linked to the plant (e.g. [9]). It is in this context that the present paper has to be considered. The objective of the present work has been to develop, analyze and implement control algorithms that can help to reduce the content in macromolecules in the influent wastewater. This work is carried out in collaboration with the Unit of Bioengineering (UCL) where a laboratory plant has been built in order to experimentally simulate at the laboratory level a typical sewer system. The experimental set-up is composed of a cascade of five reactors that is capable of reproducing the plug flow behaviour of a sewer. In this paper, we shall present the results of the control design and the illustration of its performance via numerical simulations. The control design is based on a dynamical model of the cascade reactors, more precisely on a reduced-order version of the process composed of mass balances for a CSTR (continuous stirred tank reactor) plus a time delay. The controller also includes a feedforward action in order to reduce the effect of the inlet flow rate and concentration variability on the wastewater at the sewer outlet, and an adaptation mechanism to handle the uncertainty related to model parameters. The paper is organized as follows. We shall first (section 2) introduce the process and the dynamical model of the sewer. Then, in section 3, we shall introduce the basic ideas of the control design and develop the control algorithm. Section 4 will present numerical simulations in order to illustrate the performance of the control system.

2 Dynamical model of the sewer

An experimental set-up has been built to experimentally simulate a typical sewer. It is composed of a cascade of five reactors with a volume of 0.5 l each. The choice of five reactors corresponds to the minimal number required to approximate plug flow conditions (see e.g. [6]. Hydrodynamical tests have been performed in order to check the validity of plug flow conditions in the cascade (see [1]). The dynamics of the process are given by mass balances for the substrate concentration S (macromolecules) and for the biomass concentration X (biomass in the wastewater + consortium of enzymes and bacteria), i.e. :

$$\frac{dS_1}{dt} = \bar{D}_1 S_{in} - \bar{D}_2 S_1 - k_1 \mu_1 X_1 \quad (1)$$

$$\frac{dX_1}{dt} = \bar{D}_1 X_{in} + \bar{D}_r X_{inr} - \bar{D}_2 X_1 + \mu_1 X_1 \quad (2)$$

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$$\frac{dS_i}{dt} = \bar{D}_2 S_{i-1} - \bar{D}_2 S_i - k_1 \mu_i X_i,\ i = 2, ..., 5 \quad (3)$$

$$\frac{dX_i}{dt} = \bar{D}_2 X_{i-1} - \bar{D}_2 X_i + \mu_i X_i,\ i = 2, ..., 5 \quad (4)$$

In the above equations, the index i holds for the reactor number, μ is the specific growth rate (h^{-1}), k_1 is the yield coefficient between the biomass and the substrate, S_{in} and X_{in} are the influent concentration of substrate and biomass, respectively, X_{inr} is the concentration of biomass introduced to reduce the content of macromolecules, $\bar{D}_1$ is the ratio of the influent flow rate over each reactor volume, $\bar{D}_r$ is the ratio of the flow rate of the biomass used for control over each reactor volume, and $\bar{D}_2$ is the dilution rate of each reactor. We have the following relationship between $\bar{D}_1$, $\bar{D}_2$ and $\bar{D}_r$: $\bar{D}_1 + \bar{D}_r = \bar{D}_2$. In line with other works in wastewater treatment, we have considered a Monod model for the specific growth rate :

$$\mu_i = \frac{\mu_{max} S_i}{K_S + S_i},\ i = 1, ..., 5 \quad (5)$$

The parameters of the model have been set to the following values according to available experimental data : $k_1 = 2.5$, $\mu_{max} = 0.62$ d^{-1}, $K_S = 100$ mg/l

3 Control design preliminaries

3.1 Control objectives

The control objective is here to maintain the concentration of macromolecules at the output of the sewer at a desired level in spite of the variations of the influent wastewater concentrations and flow rate by introducing a consortium of enzymes and biomass at the sewer input.

3.2 Reduced-order model

The dynamical model of the sewer is rather complex. The order of the system is equal to 10. Its relative degree (i.e. the number of time derivation of the output variable necessary before obtaining an equation that includes the control input) is either 1 (if we choose the influent flow rate of biomass $F_{in,r}$) or 6 (if we select X_{inr} as the control variable). Especially in the second case, it is more convenient to use a less complex model for control design. Moreover, the use of a complex model may easily lead to disastrous control results due to the large uncertainty concerning the values of the model parameters. We have therefore considered a reduced order model of the process. This model has been obtained by considering the usual approximation of plug flow reactor model by a CSTR model plus a time delay t_m (corresponding to the transport delay between the input and output of the sewer, i.e. $t_m = 5/\bar{D}_2$) (see e.g. [4] for a mathematical justification of the approximation). The reduced-order model takes the following form :

$$\frac{dS_c}{dt} = D_1 S_{in} - D_2 S_c - k_1 \mu_{c,max} \frac{S_c X_c}{K_S + S_c} \quad (6)$$

$$\frac{dX_c}{dt} = D_1 X_{in} + D_r X_{inr} - D_2 X_c + \mu_{c,max} \frac{S_c X_c}{K_S + S_c} \quad (7)$$

$$S_m(t) = S_c(t - t_m),\ X_m(t) = X_c(t - t_m) \quad (8)$$

where the indices c and m hold for the values in the equivalent CSTR and the values at the sewer output, respectively. Since we consider an unique tank for the five cascade reactors, D_1, D_2 and D_r are equal to : $D_i = \bar{D}_i/5$, i = 1, 2, r. An important constraint for the reduced-order is that it must obviously give the same steady-state values, at least for the controlled output, than the full order model. That's why we have selected a value of $\mu_{c,max}$ such that $\bar{S}_5 = \bar{S}_m$. This gives the following relationship :

$$\mu_{c,max} = \frac{(K_S + \bar{S}_5)(D_1 S_{in} - D_2 \bar{S}_5)}{k_1 \bar{S}_5 \bar{X}_5} \quad (9)$$

3.3 Control design : basics

In line with many other works in the control of bioprocesses, we have decided to use an adaptive linearizing control law, which presents the advantages of combining the well-known part of the structure of the process dynamics (based on mass balances and the reaction network structure) while handling the model uncertainty (typically the kinetics) via the use of an adaptation mechanism (see e.g. [2]). In the present situation, the basic adaptive linearizing control scheme has to be modified to handle the delay. This has been done by considering an adaptation of the Smith predictor to nonlinear systems (as derived in [5]).

We have now two possible control variables. Formally, the introduction of the consortium of enzymes and biomass in the sewer can be done under two different forms : either via the variable action of the flow rate $F_{in,r}$ (with a constant concentration X_{inr}), or via the variable action of the inlet concentration X_{inr} (with a constant flow rate $F_{in,r}$). Let us examine the design of the controller in both situations.

3.4 Control design : $F_{in,r}$ as the control input

This option is a priori the most attractive because it is the simplest one. Looking at the dynamical model (1)-(4), we note that the relative order is equal to one since the input $F_{in,r}$ appears explicitely (via $\bar{D}_r$) in the mass balance equation of the controlled output S_5. However this choice will eventually lead to an unstable control law due to the non-minimum phase behaviour (or inverse response) of the system with such a choice. This is due to the fact that linearizing control basically inverts the process model, and therefore "unstable" positive zeros of the system becomes unstable poles of the controller.

The non minimum phase behaviour has been confirmed both in simulation (step responses with $F_{in,r}$ of the dynamical model exhibits an inverse response for S_5) and via the computation of the transfer function of the linearized tangent model of (1)-(4). The computation of the zeros of the transfer function for different steady states shows that one of the zero is always positive [1]. This result is in line with the conclusions drawn in [3]. We have therefore decided not to consider $F_{in,r}$ as a control input.

4 Control design : X_{inr} as the control input

4.1 Control design without the delay

As we have already mentioned, since the relative degree is high (equal to 6), it may be better to design the controller on a reduced-order model. Let us first consider the model without delay. Then the controlled output is the substrate concentration S_c. With the reduced-order model (6)(7), the relative degree is now equal to 2. Indeed we have to derive the output S_c twice before the input X_{inr} appears explicitly :

$$\begin{aligned}\frac{d^2S_c}{dt^2} &= -\tfrac{k_1\mu_{c,max}}{(K_S+S_c)}\left[\tfrac{K_S}{(K_S+S_c)}\tfrac{dS_c}{dt}X_c\right.\\ &\quad +S_c(D_1X_{in}+D_rX_{inr}-D_2X_c]\\ &\quad -k_1\tfrac{\mu_{c,max}^2S_c^2}{(K_S+S_c)^2}X_c-D_2\tfrac{dS_c}{dt}+D_1\tfrac{dS_{in}}{dt}\end{aligned} \tag{10}$$

The above equation will serve as a basis for the control design. Assume that the objective is to have the following closed loop stable dynamics :

$$\frac{d^2S_c}{dt^2}=-r_1\frac{dS_c}{dt}+r_2(S^*-S_c),\ r_1,r_2>0 \tag{11}$$

with S^* the desired value of S at the output of the sewer. The choice of a second order equation for the closed loop dynamics is dictated by the relative degree of the system. By combining the above equations (10) and (11) and eliminating the second order derivative $\frac{d^2S_c}{dt^2}$, we obtain the following linearizing control law :

$$\begin{aligned}X_{inr} &= \frac{D_2}{D_r}X_c-\frac{D_1}{D_r}X_{in}-\frac{\mu_{c,max}S_c}{D_r(K_S+S_c)}X_c\\ &\quad +\frac{(K_S+S_c)}{k_1\mu_{c,max}S_cD_r}[-r_2(S^*-S_c)+D_1\frac{dS_{in}}{dt}\\ &\quad +(r_1-D_2-\frac{k_1\mu_{c,max}K_S}{(K_S+S_c)^2}X_c)]\end{aligned} \tag{12}$$

The above control structure deserves some comments. First of all, it requires the knowledge of several parameters, in particular the kinetics parameters $\mu_{c,max}$ and K_S, and the biomass concentration. We shall develop algorithms for estimating the biomass concentration and one kinetic parameter in the following sections. But before that, let us introduce some comments about the structure of the control law (12).

An important feature of the control law is that it includes a feedforward action for the influent flow rate D_1 (via the terms in D_1 and also in D_2 which is directly linked to D_1) and the influent concentrations of S_{in} (via its value and its time derivative $\frac{dS_{in}}{dt}$) and X_{in}. This is an essential feature of the controller. Indeed the major issue of the control design is to compensate the time-varying load of the plant. This time variation is due to periodical (diurnal and weekly : the wastewater load is different in the day and in the night, and in the weekend from the rest of the week) variations and accidental variations (e.g. storms, presence of detergents or other toxics,...). Any information about the influent wastewater will be directly handled by the controller in order to reduce its effect on the controlled output, i.e. the concentration of S at the outlet of the sewer. In the numerical simulations, we shall consider realistic wastewater influent profiles in order to analyze properly the performance of the controller.

4.2 Delay compensation

Before dealing with the adaptive part of the control algorithm, let us first concentrate on the delay compensation. We have basically considered a Smith predictor (e.g. [8]) modified by Francoisse [5] to be included in an adaptive linearizing control loop. The relative degree of the process dynamics was then equal to one. Here we present the extension of the delay compensation to the relative degree two.

In the preceding section, we have considered as the controlled output the undelayed value of the substrate concentration in the reduced order model S_c, but indeed the controlled variable is S_5. So basically S_c should be replaced by S_5 in the control law (12). But in order to compensate the delay between both variables, we proceed as follows. We replace the proportional error term in (12), $r_2(S^*-S_5)$, by the following expression : $r_2[(S^*-S_5)+(S_m-S_c)]$, i.e. the same expression as before to which we have added the difference between the value of the substrate of the reduced model (CSTR + time delay) and that at the output of the equivalent CSTR. Note that the second term is equal to zero in steady state. The above expression can also be written as follows :

$$r_2[(S^*-S_c)-(S_5-S_m)]=r_2[\tilde{S}_c-\tilde{S}_5] \tag{13}$$

This writing illustrates more explicitly the delay compensation, since the set point is now compared to the undelayed response of the CSTR, S_c, corrected by the term (S_5-S_m) related to the delay, i.e. the difference between the output of the process and the output of the reduced order model (with delay). Following the same line of argument, S_c and X_c are replaced by $S_r=S_c+(S_5-S_m)$ and $X_r=X_c+(X_5-X_m)$, respectively. This last modification is new with respect to the delay compensation in [5]. With these modifications, the linearizing control law (12) becomes :

$$X_{inr} = \frac{D_2}{D_r}X_r-\frac{D_1}{D_r}X_{in}-\frac{\mu_{c,max}S_r}{D_r(K_S+S_r)}X_r$$

$$+\frac{(K_S+S_r)}{k_1\mu_{c,max}S_rD_r}[-r_2(\tilde{S}_c-\tilde{S}_5)+D_1\frac{dS_{in}}{dt}$$
$$+(r_1-D_2-\frac{k_1\mu_{c,max}K_S}{(K_S+S_r)^2}X_r)] \qquad (14)$$

A schematic view of the linearizing controller with the delay compensation is given in Figure 1.

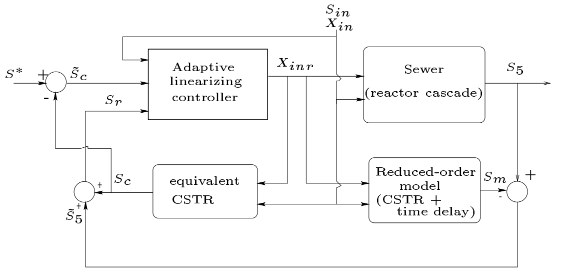

Figure 1: Schematic view of the closed loop system with delay compensation

4.3 On-line estimation of the biomass concentration

Since the value of the biomass concentration is not available for on-line measurement, we have considered an estimate of X_5 provided by an asymptotic observer [2]. The design of the asymptotic observer is based on the reduced-order model (6)-(8). For the CSTR model (6)(7), we define the auxiliary variable Z_c :

$$Z_c = k_1X_c + S_c \qquad (15)$$

whose dynamics is equal to :

$$\frac{dZ_c}{dt} = -D_2Z_c + k_1(D_1X_{in} + D_rX_{inr}) + D_1S_{in} \qquad (16)$$

If we consider the delayed value $Z_m(t) = Z_c(t-t_m)$, which can also be defined as in (15) with the delayed values of S_c and X_c : $Z_m = k_1X_m + S_m$ and the measured value at the sewer outlet for S_m, we obtain the following estimate for the biomass concentration of biomass X_5 at the sewer outlet :

$$\hat{X}_5 = \frac{Z_m - S_5}{k_1} \qquad (17)$$

4.4 On-line estimation of the maximum specific growth rate

We have considered an observer-based estimator ([2], [7]) for the estimation of $\mu_{c,max}$. This estimator plays indeed a double role : it provides an on-line estimate of a process parameter while incorporating an integral action in the control action. It is also based on the reduced-order model (6)-(8). For the equivalent CSTR (without delay), and in order to account for the time delay compensation and the fact that the value of X is given by the asymptotic observer, it is written as follows :

$$\begin{aligned}\frac{d\hat{S}_r}{dt} &= D_1S_{in} - D_2S_r - k_1\mu_{c,max}\frac{S_r\hat{X}_r}{K_S+S_r} \\ &\quad +\omega(S_r-\hat{S}_r), \qquad \omega > 0 \qquad (18)\\ \frac{d\hat{\mu}_{c,max}}{dt} &= -\gamma\frac{K_S+S_r}{k_1S_r\hat{X}_r}(S_r-\hat{S}_r), \;\; \gamma>0 \qquad (19)\end{aligned}$$

with $\hat{X}_r = X_c + \hat{X}_5 - X_m$. Note that, in line with [7], the gain of the estimation of $\mu_{c.max}$ is divided by the regressor $k_1S_r\hat{X}_r/(K_S+S_r)$ (in order to have estimator dynamics independent of the process variables).

4.5 The adaptive linearizing controller

If we include the estimation of the biomass concentration and of the maximum specific growth rate, the control algorithm (14) becomes :

$$\begin{aligned}X_{inr} &= \frac{D_2}{D_r}\hat{X}_r - \frac{D_1}{D_r}X_{in} - \frac{\hat{\mu}_{c,max}S_r}{D_r(K_S+S_r)}\hat{X}_r \\ &\quad +\frac{(K_S+S_r)}{k_1\hat{\mu}_{c,max}S_rD_r}[-r_2(\tilde{S}_c-\tilde{S}_5)+D_1\frac{dS_{in}}{dt} \\ &\quad +(r_1-D_2-\frac{k_1\hat{\mu}_{c,max}K_S}{(K_S+S_r)^2}\hat{X}_r)] \qquad (20)\end{aligned}$$

Equations (16) (17) (18) (19) and (20) are the adaptive linearizing controller of the sewer.

5 Numerical simulations

The performance of the controller have been tested in numerical simulations on the basis of realistic influent profiles. These profiles have been drawn from an European COST action (682, "Integrated Wastewater Management", web page : http://www.ensic.u-nancy.fr/COSTWWTP/). This action has in particular defined a WWTP benchmark for testing control strategies, that includes influent profiles in dry, stormy and rainy weather conditions. These profiles are shown in Figures 2, 3 and 4.

As already mentioned, an important feature of the controller is its feedforward action. As we see in the controller equation (20), it uses measured values of the influent flow rate F_{in} and concentrations S_{in} and X_{in}, and of the time derivative of the influent substrate concentration dS_{in}/dt. It is however unrealistic to consider that in practice these flow rate and concentrations will be available for on-line measurement in a sewer. Besides, these signals appears to be very noisy (as suggested in Figures 2, 3 and 4). Yet it is fair to assume that a rather good idea of the type of influent profile (standard reference profile) can be deduced from a measurement campaign performed over a few weeks. The simplest way to introduce this type of information here is to consider filtered values of the influent

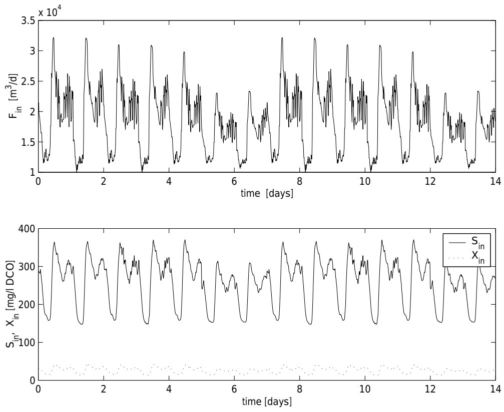

Figure 2: Influent profiles : dry weather

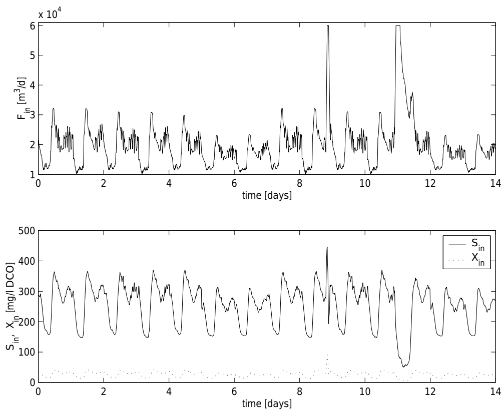

Figure 3: Influent profiles : stormy weather

profiles 2, 3 and 4 (with the idea that these profiles would have been reconstructed from the experimental data of the measurement campaign). The numerical simulations have been performed under the following conditions :

$$\begin{aligned}
X_1(0) &= 93.84\,mg/l,\ S_1(0) = 337.09\,mg/l \\
X_2(0) &= 115.95\,mg/l,\ S_2(0) = 281.82\,mg/l \\
X_1(0) &= 140.96\,mg/l,\ S_1(0) = 219.29\,mg/l \\
X_1(0) &= 167.13\,mg/l,\ S_1(0) = 153.87\,mg/l \\
X_1(0) &= 191.05\,mg/l,\ S_1(0) = 94.06\,mg/l \\
r_1 &= 6\,d^{-1},\ r_2 = 2.25\,d^{-2},\ S^* = 110\,mg/l \\
\gamma &= 50\,d^{-2},\ \omega = 14.14d^{-1},\ \hat{S}_r(0) = S_5(0) \\
Z_c(0) &= Z_m(0) = 500\,mg/l,\ \hat{\mu}_{c,max}(0) = 50\,d^{-1}
\end{aligned}$$

Figures 5 and 6 show the simulation results of the controller in the first two types of weather conditions : dry and stormy,respectively (the results with rainy weather data are similar). Note the ability of the controller to maintain the controlled variable, S_5, close to the desired value S^* in spite of the large variations of the influent variables and of the time delay. Note in particular the ability of the controller to maintain good control performance in presence of stormy and rainy periods.

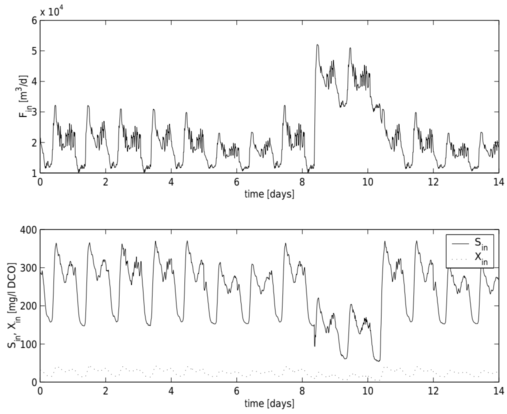

Figure 4: Influent profiles : rainy weather

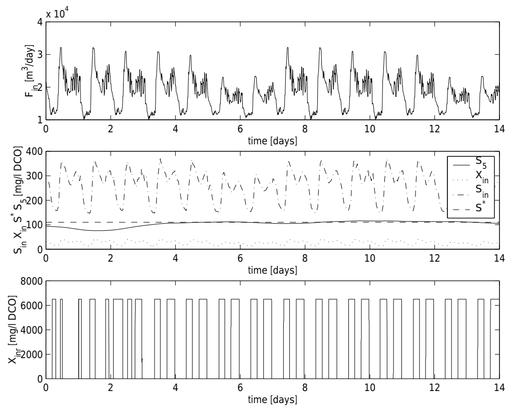

Figure 5: Adaptive linearizing control of the sewer : dry weather

Note also the improvement of the control performance between the beginning and the end of the simulation run. This is due to the adaptive part that starts with wrong initial values. This effect disappears once the initial estimation phases, both of the biomass concentration and of the maximum specific growth rate, have come to an end. The estimated values of the biomass concentration $\hat{X}_5$ and of the maximum specific growth rate $\mu_{c,max}$ are presented in Figure 7 for one set of influent profile (dry weather), the behaviour of the estimation being basically similar in the other two situations. Note that here the initial transient for the estimation of $\mu_{c,max}$ is very large but does not degrade the control performance very much. Note also the good estimation of the biomass although it is based on the reduced-order model.

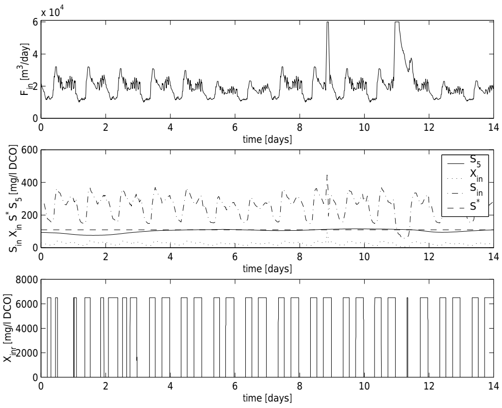

Figure 6: Adaptive linearizing control of the sewer : stormy weather

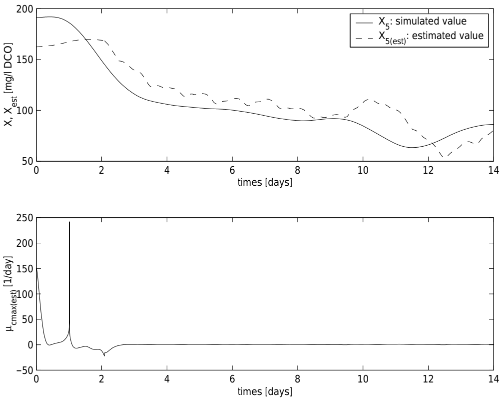

Figure 7: Estimation results of $\hat{X}_5$ and $\mu_{c,max}$ (dry weather)

6 Conclusions

In this paper, we have considered the problem of controlling a sewer by introducing consortia of enzymes and bacteria in order to reduce the content of macromolecules entering the wastewater treatment plant. The design of the controller was based on a reduced-order model that approximates the plug flow model of a sewer. The controller is feedback-feedforward controller that also includes state and parameter estimation as well as time delay compensation. The performance of the controller has been tested on the basis of realistic influent profiles.

The future perspective of the control design consists of looking at designing a control strategy that separates the feedback action from the feedforward action. The feedforward would be based on an addition of the consortium at the input of the sewer on the basis of the knowledge of the time-varying influent profile. The feedback loop would then consist of an addition of the enzyme-bacteria consortium closer to the sewer output (in order to reduce the negative effect of the time delay on the control performance). An optimal actuator location study, based on the conditioning number of the controllability matrix of the linearized tangent model of the process has been carried out in [1] and shows that the addition for the feedback loop could be advantageously located in the last sections of the sewer.

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