

State Estimation for an Anaerobic Bioprocess using an Interval Observer

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Abstract. This paper deals with the design of interval observers for estimation of some state variables in an uncertain biotechnological process. In other words, using some interval observers, two biomass concentrations and the synthesis product in an anaerobic bioprocess are estimated. Since the modelling of these processes is uncertain only the bounds of the two biomass concentrations and the synthesis product can be estimated by using appropriately interval observers. These limits depend on the known limits of the influent substrate concentration implied in process. These observers are used in an adaptive controlling problem of a substrate inside of a reactor. The effectiveness and performance of these interval observers as well as of the adaptive control strategy are illustrated by numerical simulations applied in the case of a wastewater treatment bioprocess.

Keywords-interval observer, wastewater treatment bioprocess, biomass estimation

1. Introduction

In recent years the main concern for the engineers in controlling the bioprocesses was to improve production efficiency and operational stability [1].

Applications of biotechnology can be found in many domains, but especially in food industry, pharmaceutical production, wastewater treatment and depollution processes [2].

Due to the fact that biotechnological systems are dealing with living organisms, these are not perfectly described by the physical laws. This is one strong motive for using robust methods for the control of this type of systems and for the estimation of the variables that are not measured [3].

In the case of biotechnological processes, a very important problem is the fact that we deal with an acute lack of accurate information. This can be proved using the information about system inputs that can be uncertain, because the measurements are often influenced and it is available only the rough approximate model of the system dynamics [3].

In practice, the bioprocesses control is limited to regulation of some parameter at optimal values for microbial growth. The bioprocess performances can be visibly improved by controlling biological performances. For doing this it is necessary to obtain a good dynamical model [8].

A mathematical model for a biotechnological system can be constructed for various objectives like the need to predict the behaviour of this biotechnological system, or to estimate key parameters, or to develop and test a control strategy or to estimate variables through observers [4]. Online monitoring of these kinds of processes is a rather complicated task. This has happened because one of the main limitations for improving monitoring and optimization of bioreactors is to measure chemical and biological variables [5].

Interval observers were introduced in a general context by using the concept of framer, which is defined as a unique pair of estimates able to provide uncertain state limits, without taking into consideration any stability constraint [4].

Interval observers work under the formulation of two observers: an upper observer, which produces an upper bound of the state vector, and a lower observer producing a lower bound, providing by this way a bounded interval in which the state vector is guaranteed to lie [4]. For the formulation of the interval observer, it is necessary to know the bounds of the uncertainties in the model (i.e. uncertainties in model parameters, input variables, etc.) [2].

In this paper the design and the analysis of some interval observers for estimation of some state variables in a strongly nonlinear and uncertain biotechnological process is presented.

The paper is organized as follows: in Section 2 the mathematical model of a wastewater treatment bioprocess is presented, the problem of estimation of some immeasurable states of a process is presented in Section 3 and in Section 4 the process is simulated and analyzed. Concluding remarks in Section 5 finish the paper.

2. Mathematical Model for the Bioprocess

In [6] the anaerobic digestion is a multi-stage biological wastewater treatment process where bacteria decompose the organic matter to carbon dioxide, methane and water.

The digestion process consists of hydrolysing the input materials with the purpose of obtaining polymers such as carbohydrates to feed them to other bacteria. The process follows on with converting the sugars and amino acids into carbon dioxide, hydrogen, ammonia and organic acids. The bacteria responsible for this process then take the resulting acid substances and turn them to acetic acid, ammonia, carbon dioxide and hydrogen. The last step is to turn these products into carbon dioxide and methane [7].

The model that we want to consider in this paper is described by the following reactions [8]:



The first reaction describes acidogenesis, and the second reaction describes methanogenesis [8].

This model is a very simple one, because only two main bacterial populations are considered: acidogenic and methanogenic bacteria population [8].

From the simplified reaction scheme represented in equation (1) can be extracted the following symbols:

- X_1 – biomass concentration of acidogenic bacteria [g/l]
- S_1 – glucose substrate concentration [g/l]
- X_2 – biomass concentration of acidoclastic methanogenic bacteria [g/l]
- S_2 – acetate substrate concentration [g/l]
- P_1 – synthesis product concentration [g/l]
- μ_1, μ_2 – growth rate for acidogenic bacteria and methanogenic bacteria [h^{-1}]
- k_j – yield coefficients [g/g], $j = \overline{1,4}$

The specific reaction rates are strongly nonlinear and are described as follows [8, 9]:

$$\begin{aligned} \mu_1 &= \mu_1^* \frac{S_1}{S_1 + k_{s1}} \\ \mu_2 &= \mu_2^* \frac{S_2}{S_2 + k_{s2} + S_2^2/k_i} \end{aligned} \quad (2)$$

The maximum specific growth rate for each bacteria is noted with μ_1^*, μ_2^* ; k_{s1}, k_{s2} is a notation for half the saturation constant associated with S_1, S_2 , and with k_i the inhibition constant is noted [8, 9].

The dynamic model for the anaerobic digestion bioprocess is presented in equations (3) [8]:

$$\frac{dX_1}{dt} = \mu_1(S_1)X_1 - DX_1 \quad (3a)$$

$$\frac{dS_1}{dt} = -k_1\mu_1(S_1)X_1 - D(S_1 - S_{1in}) \quad (3b)$$

$$\frac{dX_2}{dt} = \mu_2(S_2)X_2 - DX_2 \quad (3c)$$

$$\frac{dS_2}{dt} = -k_3\mu_2(S_2)X_2 + k_2\mu_1(S_1)X_1 - DS_2 \quad (3d)$$

$$\frac{dP_1}{dt} = k_4\mu_2(S_2)X_2 - DP_1 - Q_1 \quad (3e)$$

In equations (3) the following symbols appear:

D – dilution rate [h^{-1}]

S_{1in} – concentration of influent organic substrate [g/l]

Q_1 – basis output flow

3. Estimation Procedure

As it is mentioned in section one, the lack of reliable and cheap sensors makes controlling the system very difficult.

This difficulty is due to the fact that this lack of sensors has two important consequences: the modelling of the growth rate expressions and the identification of their parameters is extremely hard to do and the observation and control techniques cannot be used without additional assumption because this lack of sensors is leading to non-detectable systems [4].

These disadvantages can be ignored, if it is possible to admit that the lower and upper limit are known for the unknown inputs and there exists the possibility to design a system comprised of two observers, with the objective of guaranteeing the limits of the unmeasured variables. This kind of observers is called "interval observers" [4]. This type of observers was used for the first time for a class of nonlinear systems with the proposed robust observation and control of these kinds of systems [4].

Note that in this process the influent substrate concentration S_{1in} can be considered a disturbance whose exact values are not compulsory to be known, but in the same time the values of S_{1in} can vary between two known limits (an upper limit denoted by S_{1in}^+ and a lower limit denoted by S_{1in}^-). Knowing these two limits we attempt to estimate all the others immeasurable state variables in model (3) by using of course all available information.

Therefore in the following we consider that the condition $S_{1in}^- \leq S_{1in} \leq S_{1in}^+$ is fulfilled.

To estimate the values of the biomass concentrations X_1 and X_2 as well as the value of the synthesis product P , first we introduce the following three additional variables:

$$z_1 = k_1X_1 + S_1 \quad (4a)$$

$$z_2 = k_1k_3X_2 + k_1S_2 + k_2S_1 \quad (4b)$$

$$z_3 = P_1 + \frac{k_2k_4}{k_1}S_1 \quad (4c)$$

The dynamics of z_i , $i=1, 2, 3$ deduced from model (3) are expressed by the following linear stable equations:

$$\begin{aligned}\frac{d\hat{z}_1^+}{dt} &= -D(\hat{z}_1^+ - S_{1in}^+) \\ \frac{d\hat{z}_1^-}{dt} &= -D(\hat{z}_1^- - S_{1in}^-)\end{aligned}\tag{5}$$

$$\begin{aligned}\frac{d\hat{z}_2^+}{dt} &= -D(\hat{z}_2^+ - k_2 S_{1in}^+) \\ \frac{d\hat{z}_2^-}{dt} &= -D(\hat{z}_2^- - k_2 S_{1in}^-)\end{aligned}\tag{6}$$

$$\begin{aligned}\frac{d\hat{z}_3^+}{dt} &= -D\left(\hat{z}_3^+ - \frac{k_2 k_4}{k_1} S_{1in}^+\right) \\ \frac{d\hat{z}_3^-}{dt} &= -D\left(\hat{z}_3^- - \frac{k_2 k_4}{k_1} S_{1in}^-\right)\end{aligned}\tag{7}$$

that are independent of the process kinetics that could be completely unknown.

Because of S_{1in} is known only by its upper and lower limits, we can observe that in equations (5) - (7), that z_1 , z_2 and z_3 , can only be determined by their upper and lower limits values. For this reason, the real values of X_1 , X_2 and P are located in an interval that is bounded by these parameters' limits.

Then, from (4), the on-line estimation of X_1 , X_2 and P are given by the following relations:

$$\begin{aligned}\hat{X}_1^+ &= \frac{1}{k_1}(\hat{z}_1^+ - S_1) \\ \hat{X}_1^- &= \frac{1}{k_1}(\hat{z}_1^- - S_1)\end{aligned}\tag{8}$$

$$\begin{aligned}\hat{X}_2^+ &= \frac{1}{k_1 k_3}(\hat{z}_2^+ - k_2 S_1 - k_1 S_2) \\ \hat{X}_2^- &= \frac{1}{k_1 k_3}(\hat{z}_2^- - k_2 S_1 - k_1 S_2)\end{aligned}\tag{9}$$

$$\begin{aligned}\hat{P}_1^+ &= \hat{z}_3^+ - \frac{k_2 k_4}{k_1} S_1 \\ \hat{P}_1^- &= \hat{z}_3^- - \frac{k_2 k_4}{k_1} S_1\end{aligned}\tag{10}$$

where \hat{z}_i , $i=1, 2, 3$ are given by (5)-(7).

In equations (8)-(10) \hat{X}_1 , \hat{X}_2 and \hat{P} represent the estimations of the two biomasses X_1 and X_2 and of the synthesis product P , and the symbols "+" and "-" denoted respectively the upper and lower limits.

4. Simulation Results

In this section we chose as input control the dilution rate for controlling the output that is the pollution level [8].

The interval observer presented in Section 3 is used to estimate the upper and lower bounds of two cell populations in the case of an anaerobic digestion process (3). The influent substrate shape for S_{1in} is not known for this process, but the upper and lower limits are. Therefore, we can estimate the values of the two bacterial populations only by using an interval observer given by (8), (9) and (10).

The simulations have been made using the model composed by the equation (3) with the parameter values from [7], considering that the process is done in 70 hours and that the input concentrations are in a guaranteed interval.

The values of the kinetic parameters used in simulations are [11]: $\mu_1^* = 0.2$, $\mu_2^* = 0.35$, $k_{s1} = 0.5$, $k_{s2} = 4$, $k_i = 21$, $X_1(0) = 0.7$, $S_1(0) = 0.1$, $X_2(0) = 0.2$, $S_2(0) = 1$.

The yield coefficients for the proposed model are [11]: $k_1 = 3.2$, $k_2 = 1.035$, $k_3 = 16.7$, $k_4 = 1.1935$.

Using an interval observer we have only the upper and lower limit for the influent substrate.

For the limits of influent substrate concentration we consider two sinusoidal waves. The real form must be between the two limits in every moment.

The graphics resulted from the simulation are:

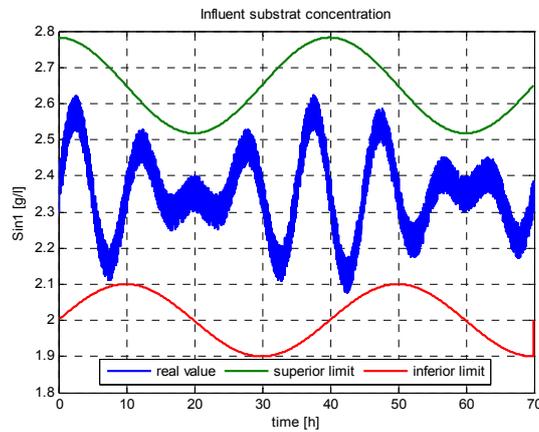


Figure 1. Evolution of influent substrate concentration S_{1in}

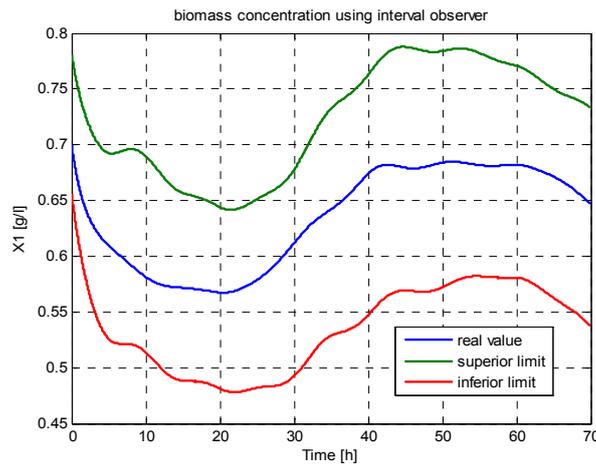


Figure 2. Profile of estimates of unknown concentration acetogenic bacteria (Biomass X_1) versus its real value.

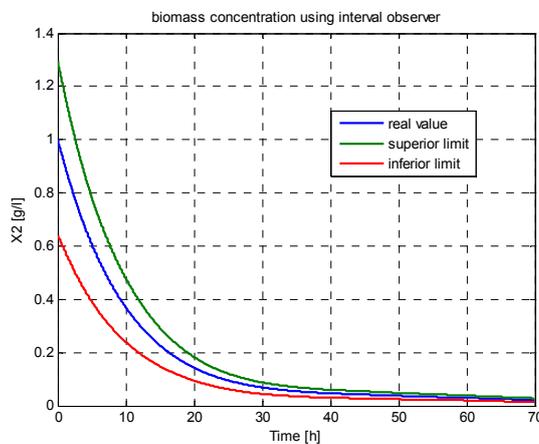


Figure 3. Profile of estimates of unknown concentration methanogenic bacteria (Biomass X_2) versus its real value.

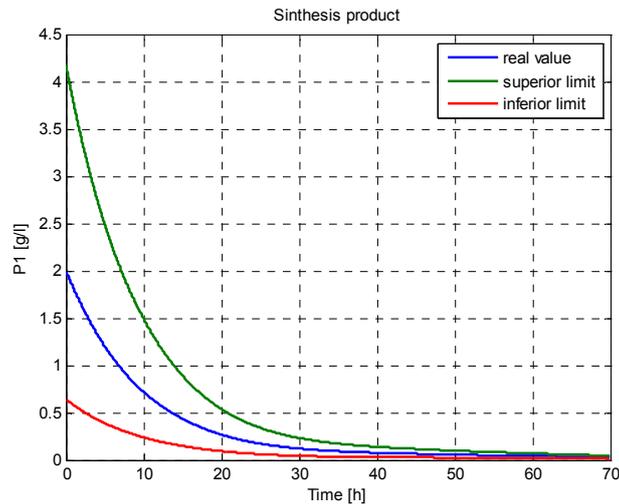


Figure 4. Profile of estimates of unknown concentration of the synthesis product concentration P versus its real value.

In Figures 2-4 the lines marked with blue correspond to the values of the real concentration of S_{lin} , as it should be known while the lines marked green and red correspond respectively to known upper and lower limits of S_{lin} .

Using a rather complicated shape for the influent substrate concentration, shape included between the two known limits, that are rendered as sinus waves, it can be seen that the behaviour of the proposed interval observers is good, the values of the estimated biomasses X_1 , X_2 and of the synthesis product P remaining between the limits.

5. Conclusion

In this paper the design and the analysis of some interval observers for estimation of state variables in a strongly nonlinear and uncertain biotechnological process was presented.

These limits depend on the known limits of the influent substrate concentration implied in process. These observers were used in a controlling problem of the substrate inside of the reactor. The effectiveness and performance of the presented interval observers as well as of the adaptive control algorithm were illustrated by numerical simulations applied in the case of the above mentioned bioprocess.

The method can be applied to a large class of bioprocesses.

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7. References

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