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Abstract : This paper aims at studying the robustness of an adaptive optimal control approach initially proposed for optimizing membrane systems and limit energy requirements due to membrane fouling. It is shown that the proposed adaptive optimal controller may be designed for a large set of membrane filtration systems, notably micro and ultra filtration processes and that it is robust against model parameters as well as model structure uncertainties.

Keywords: membrane fouling; model-based control; energy minimization

1. INTRODUCTION

The modeling and control of membrane filtration systems to limit membrane fouling has attracted lot of attention since fouling remains the main problem to be faced when working with membrane systems. Depending on the kind of membrane, on the fluid to be treated and on the technology used, different methods were proposed and tested (cf. for instance (Yusuf *et al*., 2014) and related references). However, most approaches are based on holistic rather than model-based methods. By holistic, we mean methods based either on data, knowledge or any kind of procedures that do not need any mathematical model describing the dynamics of the fouling phenomena, cf. for instance (Chen *et al*., 2003) who used a statistical method to optimally manage the reactor. Such methods precisely present the advantage of not necessiting a precise model of the process – that can take time to obtain – but by nature, do not allow to determine the real optimal way of driving the process. Indeed, optimal fouling control means using the available levers of actions (instants at which relaxation or backwash occur, time periods between filtration and relaxation/backwash sequence, backwash pressure or air/gas sparging flow rates,…) to minimize a given optimization objective (minimizing time to attain a given target or filtration/backwash energy, maximizing volume treated over a given period of time under performance constraints, cf. for instance Kalboussi *et al*., 2017). However, in fact it is difficult to claim that a fouling control strategy is optimal without considering a model of the process. Indeed, one of the main advantages of having a validated model of fouling mechanisms in addition to the possibility to design optimal fouling control laws is that, in the presence of disturbances it is usually possible to evaluate how far from the optimal is the actual functioning. Model-based methods were more particularly proposed in fields where the treatment does not allow the production or the recovering of high-value products such as the treatment of wastewater. In this field MicroFiltration (MF), UltraFiltration (UF) and NanoFiltration (NF) are now commonly used. In this paper, we more precisely deal with membrane systems where fouling is controlled using relaxation or backwash. Because real plants are subject to disturbances typically due to the continuous variation of the quality of the fluid to be treated, it is important to continuously adapt the fouling control strategy and notably the length and the frequency of relaxation/backwash periods. In this case, it is important to adapt the control strategy on-line. For systems functioning at constant flux flow which the objective is to minimize the total energy to treat a given volume of water, (Chaaben *et al*., 2024) proposed an adaptive optimal control able to deal with the presence of uncertainty and disturbances. In particular, it was shown that such a strategy is able to cope with unknown input disturbances – intrinsic characteristics of the fluid to be treated, such as the concentrations of Total Suspended Solids (TSS) or in Soluble Microbial Products (SMP). However, the process functioning parameters such as the characteristics of the membrane or the functioning conditions of the process (as the working temperature) can also vary with time: in such a case, we must also deal with such uncertainties and disturbances. In this paper, we show that the proposed adaptive optimal control approach is also robust to these uncertainty and disturbances and that it may be applied to a wide class of membrane filtration systems.

The paper is organized as follows. In the section materials and methods, both the models used to evaluate the performances of controls and the adaptive optimal control are recalled. In the section results and discussion, preliminary results demonstrating the interest of the proposed approach to deal with a large class of process uncertainty and disturbances are presented. Finally, some conclusions and perspectives are drawn.

2. MATERIALS AND METHODS

The adaptive approach proposed in this paper consists in iteratively applying the optimal control approach initially proposed in (Aichouche *et al*., 2020). To be evaluated, a control model of the filtration dynamics is needed: it is a simple model used for the control synthesis, hereafter called “control model”. In addition, either a completely instrumented real process or a virtual model of the process is also needed: hereafter the latter is called “simulation model”. In this section, both models are described and the optimal control is explained.

2.1 The simulation model: a virtual process to evaluate the approach

To simulate the functioning of a biological system, we chose to couple a biokinetic model of the anaerobic digestion including the dynamics of the SMPs (*cf*. (Benyahia *et al*., 2013)) to a fouling model initially proposed in (Benyahia *et al*., 2016 and Benyahia *et al*., 2024). This model describes the dynamics of a well known two step model of the anaerobic digestion that has been validated several times on real data, including the dynamics of the so-called Soluble Microbial Products model named "AM2b", *cf*. (Charfi *et al*., 2017). As underlined in (Chaaben *et al*., 2024), an interesting point is that this last model potentially allows us to take into account the influence of both the Total Suspended Solids that attach onto the membrane (the "cake") and the SMP (that are smaller components) that can block the pores of the membrane or reduce the porosity of the cake layer. This model is used both for generating data necessary to identify the parameters of the control model and for evaluating the different control strategies.

2.2 Modeling fouling dynamics

To design the optimal control, a model of the fouling dynamics is needed. It consists in the modeling of the dependence of the TransMembrane Pressure (TMP), the flux (J_{out}) and a "hidden variable *x*" – that was interpreted in (Chaaben *et al*., 2024) as the quantity of mass attached onto the membrane. By convention, the control, denoted *u* allows to use the system under filtration (*u*=1) or backwash/relaxation mode (*u*=0). Under these assumptions, the dynamic of the hidden variable can be written as:

$$\dot{x} = \frac{1+u}{2} f_p(x) - \frac{1-u}{2} f_r(x) \tag{1}$$

The dynamic of the water produced over time is given by:

$$\dot{p} = \frac{1+u}{2} J_p - \frac{1-u}{2} J_r \tag{2}$$

where J_p and J_r are the fluxes during filtration and backwash respectively.

It was further assumed that the total energy demand is the sum of the energy needed during the filtration phase and the one required during the backwash phase: this energy, denoted E_T depends on $x(t)$ and is expressed by (3):

$$E_T(x_0, u(.)) = \int_0^{t_f} \left(\frac{1+u}{2} l_p(x(t)) + \frac{1-u}{2} l_r(x(t)) \right) dt \quad (3)$$

where x_0 is the initial state while l_p and l_r are functions modeling the required energy during the filtration and the backwash phases, respectively.

This model is identified using the data generated with the simulation model presented in the previous section.

2.3 An optimal control approach

Under appropriate general hypotheses and using the Pontryagin Maximum Principle, (Aichouche *et al.* 2020) solved analytically the problem of minimizing the total energy E_T to attain a given quantity of water treated at the free final time t_f in computing the best sequence of filtration and backwash phases, and their optimal lengths for the specific functions f_p and f_r. In particular, depending on the initial conditions, they demonstrated that the optimal control consists in alternating filtration-backwash/relaxation sequences of specific time lengths which only depend on parameters of the model and of the objective function chosen, *cf*. Figure 1. In practice, the control model previously identified with data generated with the simulation model was used.

2.3 An adaptive optimal control approach

The control design recalled in the previous section yields a control that can be applied in open loop: given a model of the process, the ratio of filtration-backwash/relaxation time length is computed once and for all and applied independently of the actual state of the system to the simulation model.

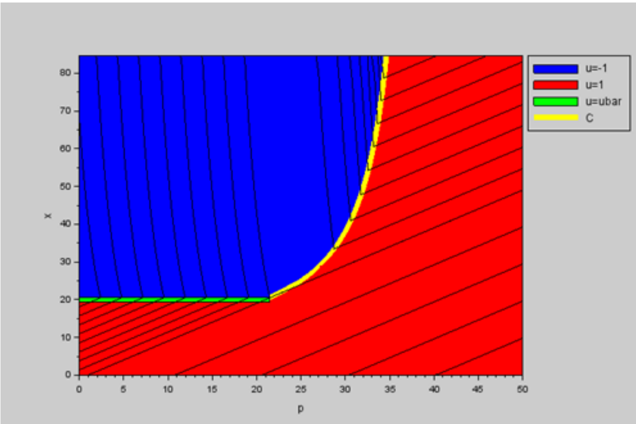

Figure 1. Optimal synthesis for the considered parameters in the (p; x) plane. The singular arc is in green and the switching curve in yellow, from (Aichouche *et al*., 2020)

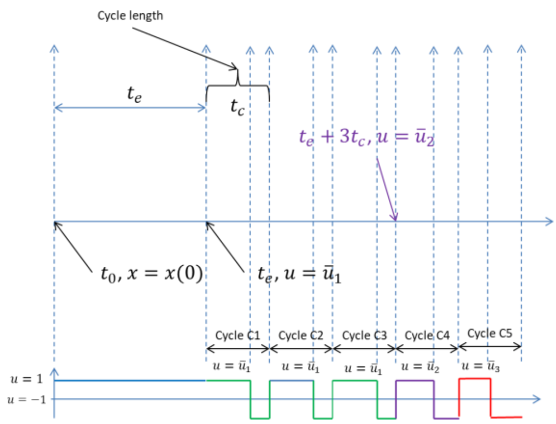

Figure 2. An adaptive optimal control of the filtration membrane system to adapt the optimal control in the presence of input variations, adapted from (Chaaben *et al*., 2024)

The algorithm of the proposed adaptive optimal control is schematically represented in Figure 2, from (Chaaben *et al.,* 2024):

- The initialization of the control is the same as in (Aichouche *et al*., 2020): a first identification of the control model is realized using data available during one (or more) filtration/backwash sequence(s), in blue in the Figure 2. Then, based on the identified dynamics, the computation of the optimal control parameters is realized;
- At a given time t_e (chosen by the user), using the last available data generated with the simulation model, we identify again the control model dynamics and, based on this latter, compute a new optimal control u_1. To allow for the system to attain a pseudo steady state, the new computed control is applied for a number of cycles, typically 3 (and we denote t_c one cycle length), in green in the Figure 2;
- From that time (t_e+3t_c) until the time at which the objective will be attained (when a given quantity of treated water has been produced), we i) re-identify the dynamics of the control model system, ii) re-compute optimal control parameters and iii) apply it to the simulation

model after each cycle period. Two such cycles are represented in violet and in red in the Figure 2.

3. RESULTS AND DISCUSSION

In (Chaaben et al., 2024), it was shown that the adaptive optimal control law was able to adapt the fouling control strategy to unknown disturbance. In particular, this new control allowed to minimize the process energy requirements while accounting for unknown input substrate concentrations. Using simulations, it was shown that this new control is indeed able to minimize energy requirements while maximizing the volume of treated water over a given period of time in adapting the ratio of the filtration and the backwash phase lengths. In the present paper, we extend this study in considering conditions under which the control exhibit an interesting robustness. In particular, using different simulation model parameters identified with data from the literature, we highlight its high genericity in the sense it can be used to control fouling of different kinds of filtration systems such as MF, UF or even NF. In addition, we show it is possible to not only deal with unknown input concentrations changes but also with both model parameters and model structure uncertainties.

In order to evaluate the performance of the new adaptive control, in the presence of all kinds of input disturbances, model parameter and model structure uncertainties, we compared three different strategies:

- The first strategy consists in applying to the different simulation models a constant filtration/backwash ratio as if inputs were not varying with time: it is a kind of industrial reference control. It is the “temporized mode”;
- The second tested strategy consists in applying to the different simulation models the original optimal control proposed in (Aichouche et al., 2020) without updating model parameters over the entire operation time. Said otherwise, the optimal control is applied in open loop;
- The third control strategy consists in applying to the different simulation models the actual adaptive optimal control approach in” closing the loop” as proposed and explained in the section 2.3.

Preliminary results show that in all simulations, for all simulation models considered, and whatever the kinds of disturbances or uncertainties considered the adaptive optimal strategy does better than the others.

CONCLUSIONS

In the presence of disturbances and uncertainties, the adaptive optimal control continuously adapts control parameters to the actual fouling dynamic. It is an important step forward since instead of an open-loop control, the optimal control works now in closed-loop. In addition, it is a generic control in the sense it can be applied to a large class of filtration systems, such as MF, UF or even some NF processes. In the future, we will investigate the robustness of the proposed adaptive controller with respect to different kinds of fouling mechanisms and try to develop new optimal controllers for more detailed membrane fouling models, for instance in explicitly taking into account the pore blocking dynamics.

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