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EVALUATION OF CONTROL TECHNIQUES APPLIED ON A WASTEWATER TREATMENT PROCESS WITH ACTIVATED SLUDGE

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Abstract

Wastewater treatment processes with activated sludge are described in the specialized literature by complex models with nonlinear parameterization, such as for example Activated Sludge Model ASM1, ASM2 or ASM3. Under these conditions, the design of control structures using the state space representation is very difficult. Suitable techniques to approach the control of these processes are using control structures based on an input-output model or using control structures obtained without even knowing the process model. In this paper two techniques of this type are analyzed: a data driven technique, Virtual Reference Feedback Tuning (VRFT), and a robust control technique, Quantitative Feedback Theory (QFT). The control structures designed by the two methods are implemented using a wastewater treatment plant implemented in the simulation software SIMBA for which a complex influent was considered. The influent includes information on water temperature and gives data for a period of one year. The analysis of the two methods considers the quality of the obtained control results but, at the same time, the difficulty of implementing the two methods.

Key words: data driven control, robust control, wastewater treatment plant

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1. Introduction

Wastewater treatment plants are subjected to increasingly strict environmental regulations. Under these circumstances, one of the solutions to increase the efficiency of their operation is to apply automatic control techniques in different stages of their operation.

This paper considers the most applied technology for wastewater treatment: the activated sludge process. This technology allows the use of automatic control techniques for improving the wastewater treatment efficiency in different stages of the plant. Thus, in the specialized literature numerous automatic control problems concerning the removal of nutrients, organic substrate were defined minimizing the sludge production, minimizing costs (mainly due to aeration) and so on (Ostace et al., 2012). Moreover, in the last years the following benchmark systems have been defined: Benchmark Simulation Models (BSM1 and BSM2), which allow the evaluation of different control strategies based on a unified platform in terms of influent, operational costs etc. (Copp, 2002).

Currently, there is a variety of approaches in designing the WWTP control structures. The most commonly used are the conventional controllers (PI or PID) (Stare et al., 2007; Zhang et al., 2008), in classical or multivariable control loops (Rojas et al., 2012). There are many papers that use Model Predictive Control (MPC) strategy (Caraman et al., 2007; O'Brien et al., 2011). Robust control solutions applied to WWTP are also proposed (Barbu and Caraman, 2007), or adaptive control (Nejjari et al.,

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1999), data-driven control techniques (Rojas et al., 2012) and solutions based on the use of artificial intelligence techniques (Gholikandi et al., 2014; King and Stathaki, 2004). Particular attention is given to the problem of the oxygen concentration control in wastewater treatment plants for which specific solutions are developed (Amand et al., 2013; Barbu et al., 2010).

2. Material and methods

2.1. Virtual Reference Feedback Tuning (VRFT) method

Given a process described by the transfer function *P(z)*, it is assumed that this transfer function is not known; however, a set of input-output experimental data from the open loop operation of the process is known. The VRFT method, proposed by Campi et al. (2002), presupposes to establish some performance specifications of the closed loop system, through the reference model, $M(z)$, and determining a dynamic compensator, $C(z;\theta)$, where θ represents its parameters. The problem of obtaining the controller parameters vector is based on the minimization of the following performance criterion (Eq. 1):

$$J_{MR}(\theta) = \left\| \left(\frac{P(z)C(z;\theta)}{1+P(z)C(z;\theta)} - M(z) \right) W(z) \right\|_2^2 \tag{1}$$

where $W(z)$ is a weighting function chosen by the user.

The VRFT method has the structure presented in Fig. 1, where p is the disturbance acting on the process output. It is assumed that the input-output process data are known over a given time horizon $\{u(t), y(t)\}_{t=\overline{1,N}}$. Based on the reference model, the inverse model is computed which gives as output the virtual reference, $\bar{r}(t)$, (Eq. 2):

$$\bar{r}(t) = M^{-1}(z) \cdot y(t) \tag{2}$$

Based on the virtual reference the virtual tracking error is computed, $\bar{\varepsilon}(t) = \bar{r}(t) - y(t)$, which is applied to the controller $C(z;\theta)$, where the vector of parameters, θ, must be determined. According to (Campi et al., 2002), the virtual tracking error, $\bar{\varepsilon}(t)$, and process control variable, $u(t)$, are transferred through filters with the transfer function $L(z)$, resulting the signals $\overline{\varepsilon_L}(t)$ and, respectively, $u_L(t)$. Knowing the data set $\{\overline{\varepsilon_L}(t), u_L(t)\}_{t=\overline{1,N}}$, the parameter vector θ is obtained through an identification procedure of the controller.

2.2. Quantitative Feedback Theory (QFT) method

QFT is a robust control method proposed by Horowitz (1973) and uses Nichols frequency characteristics aiming to ensure a robust design over a specified uncertainty area of the process. The QFT method was designed for the control of the processes described by linear models with variable parameters (Eq. 3):

$$P(s) = \frac{Ka}{s(s+a)} \tag{3}$$

where parameters K and a are varying in the domain: $K \in [K_{\min}, K_{\max}]$ and $a \in [a_{\min}, a_{\max}]$.

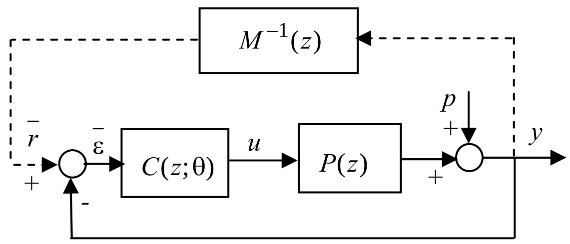

Fig. 1. Control loop structure in the VRFT method (Campi et al., 2002)

The QFT method considers for the process $P(s)$ the design of a controller, $G(s)$, and a prefilter, $F(s)$, so that the behavior of the closed loop system is within the imposed margins. The imposed margins are actually the lower and upper bounds on which the output, $y(t)$, of the closed loop in the case of a unit step input. These margins are defining the acceptable performance zone for the closed loop system, as shown graphically in Fig. 2. In this way, some performances such as time response or the overshoot are imposed for the closed loop system.

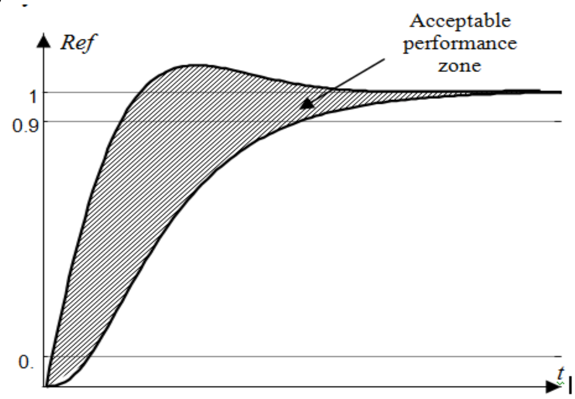

Fig. 2. Upper and lower bounds of the system output (Horowitz, 1973)

The method can be also applied for nonlinear processes through their linearization around several operating points. A linear model will result, with variable parameters describing the nonlinear process behavior in every point in the operating area.

The limits of variation of the linear model parameters obtained through linearization can be extended to incorporate the effect of the parametric uncertainties that affect the nonlinear process. For this linear model a robust controller using QFT method is then designed.

3. Experimental

The process considered in the paper was implemented in SIMBA and consists of two tanks, one anoxic and one aerobic, and a secondary clarifier and it is shown in Fig. 3 (Carp et al., 2013). The model implemented is the ASM1 model which is a complex model that includes 13 state variables and 8 processes. The use of this model in automatic control problems is very difficult.

In these conditions one option is to use input-output models for which control algorithms are easier to be designed and implemented. The simplified models are used in the control algorithms design but the controllers' validation was made using the full ASM1 model.

For this system, it was considered the influent proposed by Gernaey et al. (2011), in which a phenomenological modelling approach is proposed to generate dynamic influent pollutant disturbance scenarios. The influent model contains information regarding all the state variables of the ASM1 model and information on the water temperature variation over a year period.

Thus, the simulation is done as close to the real conditions of the wastewater treatment processes as possible. The evolution of key variables from the considered influent model is shown in Fig. 4.

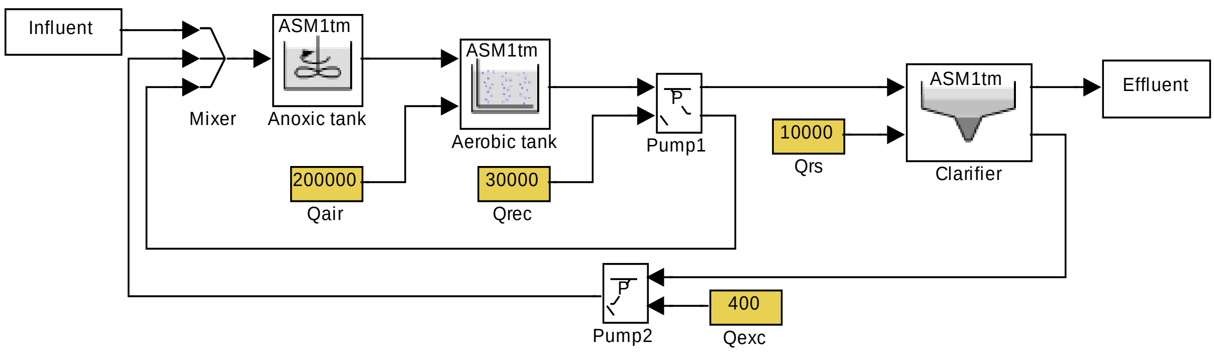

Fig. 3. The scheme of the wastewater treatment process (Carp et al., 2013)

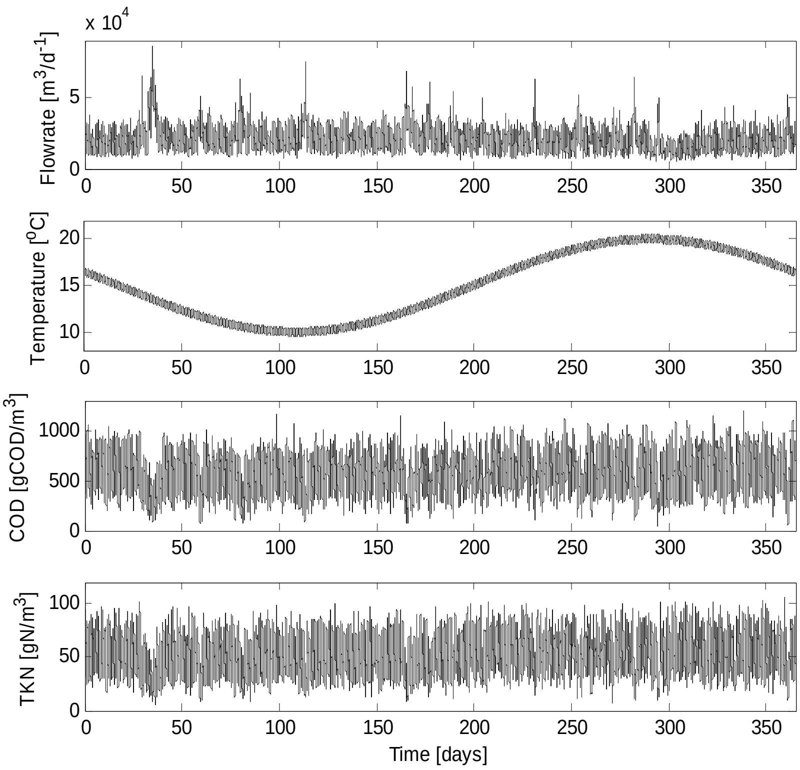

Fig. 4. The considered influent evolution over a year

In this paper the following control strategy has been adopted:
- control of the dissolved oxygen concentration (S_{O2}) in the aerobic reactor using its air flow rate (*Qair*);
- control of the nitrate concentration (S_{NO}) in the anoxic tank using the internal recycle flow rate (*Qrec*).

Due to the fact that the coupling between the two loops is weak, a decentralized approach was used.

To evaluate the wastewater operation in terms of water quality, two parameters must be calculated: the chemical oxygen demand (COD) and the total nitrogen (Eqs 4-6) (Copp, 2002):

$$COD = S_I + S_S + X_I + X_S + X_{B,H} + X_{B,A} + X_P \quad (4)$$

$$TKN = S_{NH} + S_{ND} + X_{ND} + 0.04S_I + 0.02X_I + \\ + i_{XB}\left(X_{B,H} + X_{B,A}\right) + i_{XP}X_P \quad (5)$$

$$N_{total} = TKN + S_{NO} \quad (6)$$

3. Results and discussion

First the control structured was obtained using the VRFT method (Carp, 2014). For this the reference model for the control channel $Q_{air} - S_{O2}$ was imposed as a first order system (Eq. 7):

$$H_{MR,Q_{air}-S_{O2}}(s) = \frac{1}{Ts+1} \quad (7)$$

with: $T = 0.002$ days.

The reference model was then discretized (Eq. 8).

$$H_{MR,Q_{air}-S_{O2}}(z^{-1}) = \frac{0.2953z^{-1}}{1-0.7047z^{-1}} \quad (8)$$

with the sampling time of 0.0007 days.

The used filter has the transfer function expressed by Eq. (9):

$$L_{Q_{air}-S_{O2}}(z^{-1}) = \frac{0.2953z^{-1} - 0.2953z^{-2}}{1-1.409z^{-1}+0.4966z^{-2}} \quad (9)$$

Using the identification procedure, considering *m* = 5, the following dynamic compensator results:

$$C_{Q_{air}-S_{O2}}\left(z^{-1}\right) = 0.072 - 0.5z^{-1} + 2.06z^{-2} - \\ - 1.88z^{-3} + 0.31z^{-4} + 0.008z^{-5} \quad (10)$$

The same steps are used for the control channel $Q_{rec} - S_{NO}$. The reference model is again a first order system (Eq. 11):

$$H_{MR,Q_{rec}-S_{NO}}(s) = \frac{1}{Ts+1} \quad (11)$$

with: $T = 0.08$ days.

This reference model is discretized in the form of Eq. (12):

$$H_{MR,Q_{rec}-S_{NO}}(z^{-1}) = \frac{0.08378z^{-1}}{1-0.9162z^{-1}} \quad (12)$$

with the sampling time of 0.007 days.

The used filter has the transfer function given by Eq. (13):

$$L_{Q_{rec}-S_{NO}}(z^{-1}) = \frac{0.08378z^{-1} - 0.8378z^{-2}}{1-1.832z^{-1}+0.8395z^{-2}} \quad (13)$$

Finally, the identification procedure is applied, considering *m* = 5, and the following dynamic compensator results:

$$C_{Q_{rec}-S_{NO}}\left(z^{-1}\right) = 0.219 - 0.213z^{-1} + 0.249z^{-2} - \\ - 0.083z^{-3} - 0.47z^{-4} + 0.087z^{-5} \quad (14)$$

Based on the designed control structure, the wastewater treatment plant was simulated in closed loop. The results obtained are depicted in Fig. 5. The figure shows very good results regarding the control of the dissolved oxygen from the aerobic tank and an acceptable result on the control of the nitrate in the anoxic tank (in the first and second graphics the dotted lines are the imposed setpoints).

The evaluation of the control performances for the two control loops must take into account the strong variation of the influent, as it was presented in Fig. 4. In Fig. 5 it was also plotted the evolution of COD and total nitrogen in the effluent (with the red line are given the maximum allowable limits). One can notice that, in general, the effluent quality is meeting the imposed requirements, the overruns that appear being caused by different rainfall events included in the influent.

In the case of the wastewater treatment plant considered in this paper, for the QFT method, various input steps were applied for the identification of the two processes: $Q_{air} - S_{O2}$ and $Q_{rec} - S_{NO}$. The identified models for the both channels are corresponding to first order systems (Carp et al., 2013).

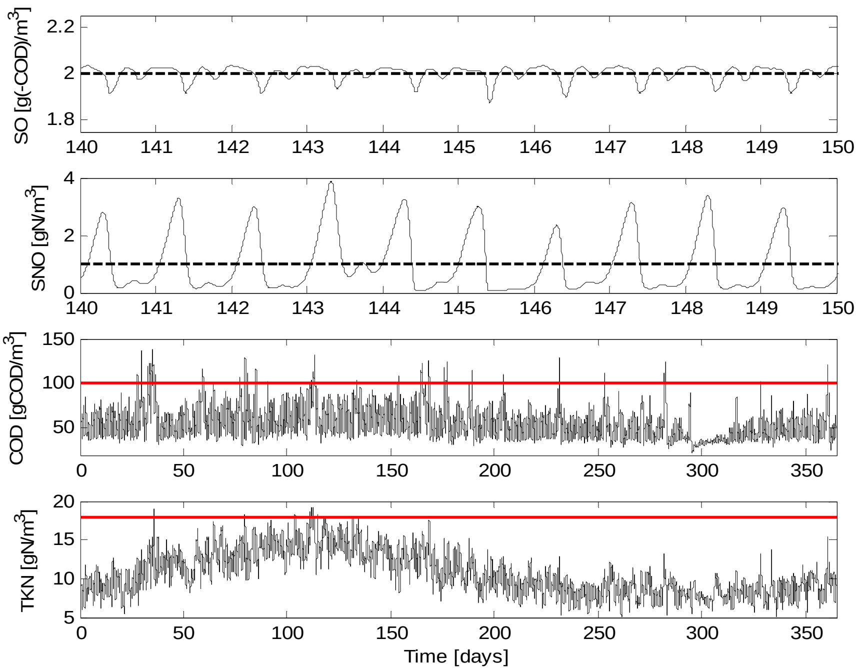

Fig. 5. The obtained results by applying the control structure resulted from the VRFT method

Thus, the obtained transfer functions are expressed by Eqs. (15, 16):

$$P_{Q_{air}-S_{O2}}(s)=\frac{K_1}{T_1 s+1} \tag{15}$$

with $K_1 \in [1.5 \quad 3]\cdot 10^{-5}$ and $T_1 \in [0.01 \quad 0.015]$.

$$P_{Q_{rec}-S_{NO}}(s)=\frac{K_2}{T_2 s+1} \tag{16}$$

with $K_2 \in [1.1 \quad 1.9]\cdot 10^{-4}$ and $T_2 \in [0.29 \quad 0.36]$.

By applying the algorithm previously presented for the QFT method and using the QFT Control Toolbox (Garcia-Sanz and Houpis, 2012), the transfer functions for the controller and prefilter are obtained (Eqs. 17-20):

$$G_{Q_{air}-S_{O2}}(s)=\frac{3.7\cdot 10^{7}\cdot(0.01s+1)}{s(0.00083s+1)} \tag{17}$$

$$F_{Q_{air}-S_{O2}}(s)=\frac{0.00067s+1}{0.004s+1} \tag{18}$$

and

$$G_{Q_{rec}-S_{NO}}(s)=\frac{9\cdot 10^{4}\cdot(0.25s+1)}{s(0.055s+1)} \tag{19}$$

$$F_{Q_{rec}-S_{NO}}(s)=\frac{0.126s+1}{0.222s+1} \tag{20}$$

Fig. 6 presents the simulation results for the QFT based control structure. It shows a significant improvement of the performances as compared to the results obtained with the VRFT method. This evaluation takes into account both the result of the control loops and the evolution of COD and total nitrogen in the effluent. Thus, the total nitrogen overruns to the maximum limits are fewer and for a shorter duration. For a more precise evaluation of the two control strategies and for the two loops, the integral of squared error has been calculated. The results are presented in Table 1, where one can notice that indeed the QFT method allows obtaining better results.

Table 1. The integral of squared error for the two considered loops and tuning methods

	SO control loop	*SNO control loop*
VRFT	0.0112	0.6441
QFT	0.0019	0.5406

The evaluation of these controllers led to the conclusion that the system performance is better in the case of the QFT robust algorithm. This is justified mainly by the fact that in the simulation of treatment plant the information on water temperature was introduced, the robust controller managing to better reject the parametric uncertainties that results.

In evaluating the two methods of tuning the control loops, one should also take into consideration the difficulty of implementing the method.

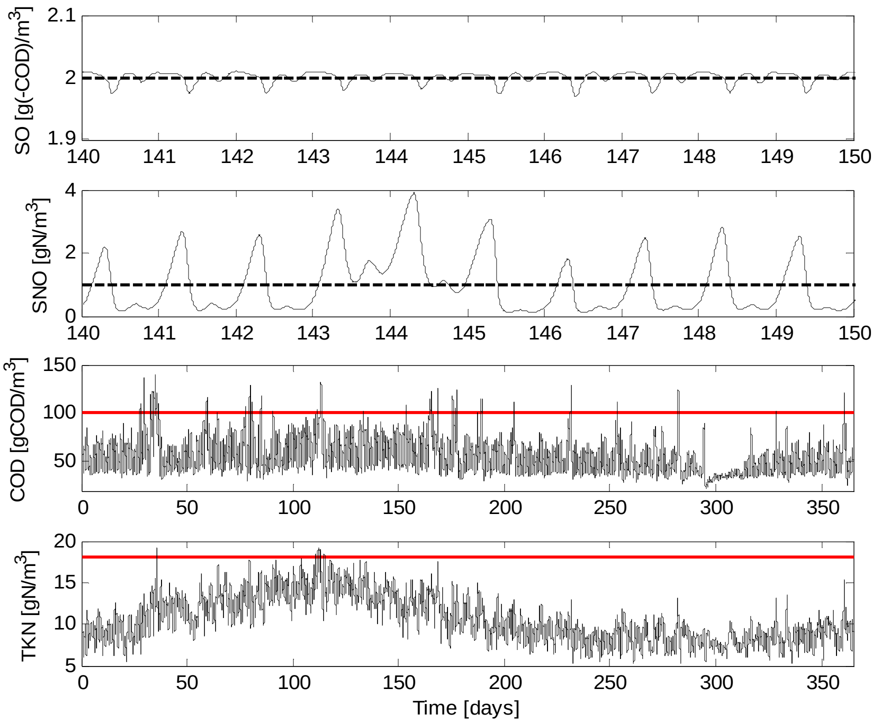

Fig. 6. The obtained results by applying the control structure resulted from the QFT method

Thus, although the QFT method is difficult to implement in the absence of a specialized design software, the use of a toolbox such as QFT Control Toolbox enables the user to easily design the controller and the prefilter. However, the VRFT method has the advantage that it does not require the knowledge of a mathematical model of the process, requiring only input-output signals from the open loop process.

This advantage is particularly useful for the treatment processes, where the mathematical model is complex and has nonlinear parameterizations.

4. Conclusion

In this paper, two methods for designing control structures were evaluated in the case of wastewater treatment processes. As shown in the paper, although both methods are linear methods, they can be successfully used in the design of high performance controllers.

The results showed that in the presence of parametric uncertainties arising from the use of influent that includes temperature data for a period of one year, QFT robust method leads to the better results. This evaluation took into account the performances of the control loops, expressed by the integral of squared error for the two considered loops, but, at the same time, the quality of the resulted effluent.

In evaluating the difficulty to design the control structure in the two methods, the VRFT method is easier to use, especially since it does not require knowledge of a process model, which makes it very attractive in the case of wastewater treatment processes. The QFT method presents the advantage of using a specialized design software, which provides a user-aided design, with multiple intermediate checks, both in terms of loop stability and dynamic performances on all the considered functioning points.

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