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QFT Robust Control of Wastewater Treatment Processes

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1. Introduction

Wastewater treatment issues are extremely important for humanity. Their consideration becomes more than a necessity, a responsibility and every producer must improve their treatment processes. The efficiency increasing of these processes has been done in two ways:

1. by technological way - various types of treatment were developed during the past years and this domain has almost no technological secrets;
2. by using control methods – which currently represent a real challenge for researchers.

Wastewater treatment processes consist of a series of physical, chemical or biological processes that allow the separation between some particles (solid or dissolved, organic compounds, minerals etc.) and water, aiming to obtain a "clean" water able to meet certain standards for discharge or domestic/ industrial consumption. In Europe, the water purity standards are established by the Directive no. 2000/ 60/ EC. In the same time, the standards that are currently in use, defined by *water law* from February 3th, 1992, modified by the ordinance from February 2nd, 1998, are added to this directive. These rules define the maximum concentrations for each harmful compound from the wastewater. Generally the admissible concentrations are functions of the daily effluent flow.

Currently, new rules are applied regularly to the wastewater treatment. Global indicators for treatment efficiency, such as COD (*Chemical Oxygen Demand*), BOD (*Biochemical Oxygen Demand*), TOC (*Total Organic Carbon*) and for nutrients removal (phosphorus, ammonia nitrogen, total nitrogen etc.), whose normative are increasingly stringent, are taken into account. New compounds such as pigments, heavy metals, organic compounds, chlorinated solvents etc. are also considered for removal. For the waters coming from different industries and to be discharged into nature, the treatment rules are not the same. They depend on the receiving water and the type of the industry from which the wastewater results. For example, in metallurgical industry the wastewater containing heavy metals dominates, unlike the food industry, where the water containing organic compounds prevails.

Biological treatment processes are characterized by a number of specific features that make these processes real challenges for the specialists in control (Olsson & Newell, 1999):

- the daily volume of wastewater treated can be huge;
- the disturbances in the influent are enormous compared to most industries;
- the influent must be accepted and treated, there is no returning it to the supplier;
- the concentrations of nutrients (pollutants) are very small, even challenging sensors;

- the process depends on microorganisms, which have a definite mind of their own;
- wastewater treatment processes are very complex, strongly non-linear and characterized by uncertainties regarding its parameters (Goodman & Englande, 1974).

In the literature there are many models that try to capture as closely as possible the evolution of the wastewater treatment processes with activated sludge (Henze et al., 1987, 1995, 2000). The modelling of these processes is made globally, considering the nonlinear dynamics, but trying in the same time to simplify the models for their use in control (Barbu, 2009). One can state that the problem of wastewater treatment process control is difficult due to the factors mentioned before. The low repeatability rate, slow responses and the lack or high cost of the measuring instruments for the state variables of bioprocesses (biomass concentration, COD concentration etc.) also contribute to the difficulty of wastewater treatment process control. Therefore advanced and robust control algorithms that usually include in their structure state and parameter observers are currently used to control these processes.

Accordingly to (Larsson & Skogestad, 2000) two approaches in choosing the process control structure are taken into consideration: the approach oriented to the process and the one based on mathematical model. The first approach assumes the separated control of the main interest variables: dissolved oxygen concentration, nitrate and phosphate. One of the major and oldest problems encountered in wastewater treatment processes with direct impact on performance requirements is the dissolved oxygen concentration control. One can state that a satisfactory level of the dissolved oxygen concentration allows the developing of the microorganism' populations (the sludge) used in the process (Olsson, 1985), (Ingildsen, 2002). Taking into account the importance of this problem, there are many approaches regarding the dissolved oxygen control in the literature: PI and PID-control, fuzzy logic, robust control, model based control etc. (Garcia-Sanz et al., 2008), (Olsson & Newell, 1999). Recently the control problem of nitrate and phosphate level also became a priority. The control based on mathematical model of the wastewater treatment process has known many developing, depending on the type of the mathematical model used in the control algorithm design, as in the case of state estimators. So, the model described in (Olsson & Chapman, 1985) allowed the use of classic and modern techniques. It can be mentioned the classic structures of PI and PID type (Katebi et al., 1999) where the non-linear model linearized around an operating point is used for controller design, up to exact linearizing control, multivariable or in an adaptive version together with a state and parameter estimator (Nejjari et al., 1999). The use of this model leads to the design of an indirect control structure of the process. It can be concluded that the control of the dissolved oxygen concentration in the aerated tank practically assures a satisfactory level for the organic substrate. This problem - the control of the dissolved oxygen concentration - has been approached with good results in the control of a non-linear organic substrate removal process using multi-model techniques (Barbu et al., 2004).

The use of ASM1 model (*Activated Sludge Model 1*) determined by a work group belonging to IAWQ (*International Association of Water Quality*) makes the control problem more difficult and the results are less numerous. Based on ASM1 model in (Brdys et al., 2001a) a non-linear predictive control technique for the indirect control of organic substrate through the control of dissolved oxygen concentration has been used. For the same model (Brdys et al., 2001b) proposes a hierarchic control structure. This structure contains three levels: a higher level where a stable trajectory for the process on a time horizon is calculated, a mean level where the optimization of the trajectories for dissolved oxygen concentration, the recycled

activated sludge flow and the recycled nitrate flow takes place and the lower level where the control of dissolved oxygen concentration based on the setpoint imposed by the mean level is done. Another approach that now is very appropriated is artificial intelligence based control. It uses the knowledge and the expertise of the specialists about the process management. Expert systems, fuzzy and neuro-fuzzy systems have been used for the wastewater treatment processes control (Manesis et al., 1998), (Yagi et al., 2002).

In the present chapter the authors propose the use of a robust control method (QFT – *Quantitative Feedback Theory*) for wastewater treatment processes control. Generally, wastewater treatment processes, as well as biotechnological processes, are characterized by parametric uncertainties that are determined by the operating conditions and the biomass growth. QFT method is a linear method frequently used for the processes described by variable parameter models. In this case, the transfer function with variable parameters will include both modifications caused by changing the operating point and parametric uncertainties that affect the process.

The chapter is structured as follows: the second section presents a few aspects regarding wastewater treatment process modelling (subsection 2.1 describes the wastewater treatment pilot plant with which some experiments were carried out in different operating conditions: different types of wastewaters, different concentrations of the influent and biomass etc. aiming to control the dissolved oxygen concentration in the aerated tank despite the variability of the operating conditions; in subsection 2.2 the simplified version of ASM1 model for ammonium removal is presented); the third section deals with the theoretical aspects regarding QFT robust control method; the fourth section shows the results obtained in the case of two control applications: the first is the control of dissolved oxygen concentration (experimentally validated) and the second is the control of ammonium concentration in the wastewater (validated through numerical simulations). In both control applications the robust control method QFT was used. The last section is dedicated to the conclusions.

2. A few aspects regarding wastewater treatment process modelling

This section deals with the wastewater treatment pilot plant used for carrying out the experiments for the design of dissolved oxygen robust control loop (subsection 2.1) and with simplified version of ASM1 model used for the ammonium removal (subsection 2.2).

2.1 Wastewater treatment pilot plant

A wastewater treatment pilot plant which is completely controlled by the computer (Figure 1) was conceived for studying and implementing various control algorithms in a national research project managed by “Dunarea de Jos” University of Galati.

The objective of the pilot plant was the efficiency improvement of the biological treatment processes of various types of wastewaters in aerobic conditions using control methods. This concept leads to a flexible design which allows us to interchange easily the treatment profiles (Barbu et al., 2010).

The feeding tank [1] has the capacity of 100 L and the ability to maintain the wastewater inside at almost constant characteristics due to its refrigeration equipment (1 – 6°C). The feeding flow can be strictly controlled through a peristaltic pump with a 12 Lph maximum flow. Before being pumped into the tanks the wastewater can be heated in a small expansion

tank. The aeration tank [2] is the heart of the biological treatment process. Here the wastewater is mixed with the activated sludge and to fulfil the process it is also mixed with air. The air is bubbled into the aeration tank through a set of air ejectors which have also a mixing role. To be able to control the medium homogeneity the aeration tank is also equipped with a mechanical paddle mixer with three working regimes: 60rpm, 180rpm and 300rpm. The aeration tank working volume is 35L. The treatment temperature can be on-line monitored and controlled through a temperature probe and an electric heating resistance both mounted inside the tank. The pH can also be on-line monitored and controlled through a pH electrode connected to a pH controller and two peristaltic pumps, one for acid and the other for base (acid tank [3] and base tank [4]). The turbidity can be on-line monitored with a dedicated optical electrode. The evolution of biomass can be indirectly estimated through the turbidity values; the correlation between the two variables is usually made off-line by measuring the sludge dry matter. The aeration tank is also provided with an ORP (oxide-reduction potential) transducer. ORP potential can be correlated, in some cases, with the COD of the wastewater. The anoxic tank [5] can be used in the advanced nitrification – denitrification processes or it can be used in a sludge stabilization stage. In our experiments this tank remained unused. The sludge flocks formed in the aeration tank are allowed to settle in the clarifier [6]. This tank is provided with an ultrasonic level transducer which gives the flexibility to work at different retention times according to the chosen treatment scheme. From the bottom of the clarifier the settled sludge is recycled with a peristaltic pump back into the aeration tank.



Fig. 1. Wastewater treatment pilot plant

One of the most important variables in an aerobic treatment process is the DO (dissolved oxygen) concentration which is controlled by a cascade control structure. The cascade control system contains an inner loop (air flow control loop) that has a fast dynamics and an outer loop (the DO control loop) that has a slower dynamics. The air flow is on-line measured with a flow meter and it is controlled with an electric continuous valve. The DO concentration is on-line measured with an electrochemical electrode mounted in the aeration tank and it is controlled using the aeration rate as a control variable. The transducer signals are captured by a PCI data acquisition board. A HMI (*Human-Machine Interface*) facilitates the process control and monitoring. The data can be stored in a data base and processed thereafter.

2.2 Mathematical model of the wastewater treatment processes that include the nitrogen removal

The most popular model in literature of the wastewater treatment processes that includes the carbon and nitrogen removal is ASM1, proposed in 1987 (Henze et al., 1987). The model is extremely complex, it captures eight phenomena occurring in the anoxic and aerated reactors:

P ₁	Aerobic growth of heterotrophic biomass - the process converts readily biodegradable substrate, dissolved oxygen and ammonium in the heterotrophic biomass;
P ₂	Anoxic growth of heterotrophic biomass – the process converts readily biodegradable substrate, nitrate and ammonium in heterotrophic biomass;
P ₃	Aerobic growth of autotrophic biomass – the process converts the dissolved oxygen, and ammonium in autotrophic biomass;
P ₄	Heterotrophic decomposition - heterotrophic biomass is decomposed into slowly biodegradable substrate and other particles;
P ₅	Autotrophic decomposition - autotrophic biomass is decomposed into slowly biodegradable substrate and other particles;
P ₆	Ammonification - biodegradable organic nitrogen is converted to ammonium;
P ₇	Hydrolysis of the organic matter - slowly biodegradable substrate is converted into readily biodegradable substrate;
P ₈	Hydrolysis of organic nitrogen - solid biodegradable organic nitrogen is converted into soluble biodegradable organic nitrogen.

Table 1. The eight phenomena occurring in the anoxic and aerated reactor

The main deficiency of the model ASM1 is its complexity, making it virtually useless in control issues. A simplified version of the model ASM1 is proposed in (Jeppsson, 1996). Thus, in this version, only the significant variables for an average time scale (several hours to several days) are considered. Therefore, variables with a slow variation in time are considered constant, while those with a fast variation will be neglected. Based on these considerations, the processes of autotrophic and heterotrophic growth could be seen as slow events, so the processes denoted by P₄ and P₅ can be neglected within the model. The ammonification and hydrolysis processes (P₆, P₇ and P₈) will also be neglected, because under normal operating conditions these processes have a constant evolution.

The model ASM1 contains 13 state variables, as follows:

S_I	Soluble inert organic matter;
S_S	Readily biodegradable soluble substrate;
X_I	Various independent particles of inert organic matter and other particles;
X_S	Readily biodegradable soluble substrate;
$X_{B,H}$	Activated heterotrophic biomass;
$X_{B,A}$	Activated autotrophic biomass;
X_P	Different particles resulting from the biomass decomposition;
S_O	Dissolved oxygen concentration
S_{NO}	Soluble nitrate;
S_{NH}	Soluble ammonium;
S_{ND}	Soluble biodegradable organic nitrogen;
X_{ND}	Various particulate of biodegradable organic nitrogen;
S_{ALK}	Alkalinity

Table 2. State variables of ASM1 model

As a consequence, from the eight processes initially modelled by ASM1, only three of them will be used in the simplified model. The treatment process will be modelled as a system with two tanks, an anoxic one and an aerated one. The assumption that the amount of dissolved oxygen concentration in the anoxic tank is equal to zero is done: $S_O(1)=0$. In these circumstances, the simplified ASM1 model is described by the following equations:

$$\frac{dS_{NH}(1)}{dt} = \frac{Q}{V_1} S_{NH,in} - \frac{Q+Q_i}{V_1} S_{NH}(1) + \frac{Q_i}{V_1} S_{NH}(2) - i_{XB} P_2(1) \quad (1)$$

$$\frac{dS_{NH}(2)}{dt} = \frac{Q+Q_i}{V_2} S_{NH}(1) - \frac{Q+Q_i}{V_2} S_{NH}(2) - i_{XB} P_1(2) - \left(i_{XB} + \frac{1}{Y_A} \right) P_3(2) \quad (2)$$

$$\frac{dS_{NO}(1)}{dt} = -\frac{Q+Q_i}{V_1} S_{NO}(1) + \frac{Q_i}{V_1} S_{NO}(2) - \frac{1-Y_H}{2.86Y_H} P_2(1) \quad (3)$$

$$\frac{dS_{NO}(2)}{dt} = \frac{Q+Q_i}{V_2} S_{NO}(1) - \frac{Q+Q_i}{V_2} S_{NO}(2) + \frac{1}{Y_A} P_3(2) \quad (4)$$

$$\frac{dS_S(1)}{dt} = \frac{Q}{V_1} S_{S,in} - \frac{Q+Q_i}{V_1} S_S(1) + \frac{Q_i}{V_1} S_S(2) - \frac{1}{Y_H} P_2(1) \quad (5)$$

$$\frac{dS_S(2)}{dt} = \frac{Q+Q_i}{V_2} S_S(1) - \frac{Q+Q_i}{V_2} S_S(2) - \frac{1}{Y_H} P_1(2) \quad (6)$$

$$P_1(1) = \mu_H \frac{S_S(1)}{K_S + S_S(1)} \frac{S_O(1)}{K_{O,H} + S_O(1)} X_{B,H} \quad (7)$$

$$P_1(2) = \mu_H \frac{S_S(2)}{K_S + S_S(2)} \frac{S_O(2)}{K_{O,H} + S_O(2)} X_{B,H} \quad (8)$$

$$P_2(1) = \mu_H \frac{S_S(1)}{K_S + S_S(1)} \frac{K_{O,H}}{K_{O,H} + S_O(1)} \frac{S_{NO}(1)}{K_{NO} + S_{NO}(1)} \eta_g X_{B,H} \quad (9)$$

$$P_2(2) = \mu_H \frac{S_S(2)}{K_S + S_S(2)} \frac{K_{O,H}}{K_{O,H} + S_O(2)} \frac{S_{NO}(2)}{K_{NO} + S_{NO}(2)} \eta_g X_{B,H} \quad (10)$$

$$P_3(1) = \mu_A \frac{S_{NH}(1)}{K_{NH} + S_{NH}(1)} \frac{S_O(1)}{K_{O,A} + S_O(1)} X_{B,A} \quad (11)$$

$$P_3(2) = \mu_A \frac{S_{NH}(2)}{K_{NH} + S_{NH}(2)} \frac{S_O(2)}{K_{O,A} + S_O(2)} X_{B,A} \quad (12)$$

Observation: index 1 refers to the anoxic tank and index 2 – to the aerated tank.

Further on the input and output process variables are presented:

- input variables: internal recirculating flow, Q_i , dissolved oxygen concentration in the aerated tank, $S_O(2)$, and external carbon dosage, $S_{Sdosage}$.
- output variables (measurable variables): ammonium concentration at the output, $S_{NH}(2)$, (equal to ammonium concentration from the aerated tank) and nitrate concentration at the output, $S_{NO}(2)$, (equal to nitrate concentration from the aerated tank).

The two process output variables are quality variables too. Thus the purpose of the control structure will be the obtaining of an effluent having an output ammonium concentration less than 1 gN/ m³ and an output nitrate concentration less than 6 gN/ m³.

For the model described by equations (1) – (12) the following parameters were taken into consideration:

$V_1=2000$ m³, $V_2=3999$ m³, $Q=18446$ m³/ day, $S_{NH,in}=30$ gN/ m³, $\eta_g=0.8$, $i_{XB}=0.08$, $S_{S,in}=115+S_{Sdosage}$ gCOD/ m³, $K_{NH}=1$ gNH₃-N/ m³, $K_{NO}=0.5$ gNO₃-N/ m³, $Y_A=0.24$, $Y_H=0.67$, $K_{O,H}=0.2$ gO₂/ m³, $K_{O,A}=0.4$ O₂/ m³, $K_S=10$ gCOD/ m³, $\mu_A=0.6$ day⁻¹, $\mu_H=5$ day⁻¹, $X_{B,A}=110$ gCOD/ m³, $X_{B,H}=2200$ gCOD/ m³.

Figure 2 presents the simulation results regarding the free dynamics of the simplified ASM1 model. The simulation was done considering the following initial conditions: $S_{NH}(1)(0)=10$ gN/ m³, $S_{NH}(2)(0)=9.7$ gN/ m³, $S_{NO}(1)(0)=0.9$ gN/ m³, $S_{NO}(2)(0)=2.15$ gN/ m³, $S_S(1)(0)=2.8$ gCOD/ m³, $S_S(2)(0)=0.9$ gCOD/ m³.

The following values of the input variables were also taken into consideration: $S_O(2)=1.5$ mg/ l, $Q_i=40000$ m³/ day, $S_{Sdosage}=40$ gCOD/ m³.

3. Robust control of monovariable processes using QFT method

QFT is a robust control method proposed by Horowitz in 1973 and it was designed for the control of the processes described by linear models with variable parameters (Horowitz, 1973). QFT is a technique that uses Nichols frequency characteristics aiming to ensure a robust design over a specified uncertainty area of the process. The method can be also

applied for nonlinear processes through their linearization around several operating points. It results a linear model with variable parameters describing the nonlinear process behaviour in every point of 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.

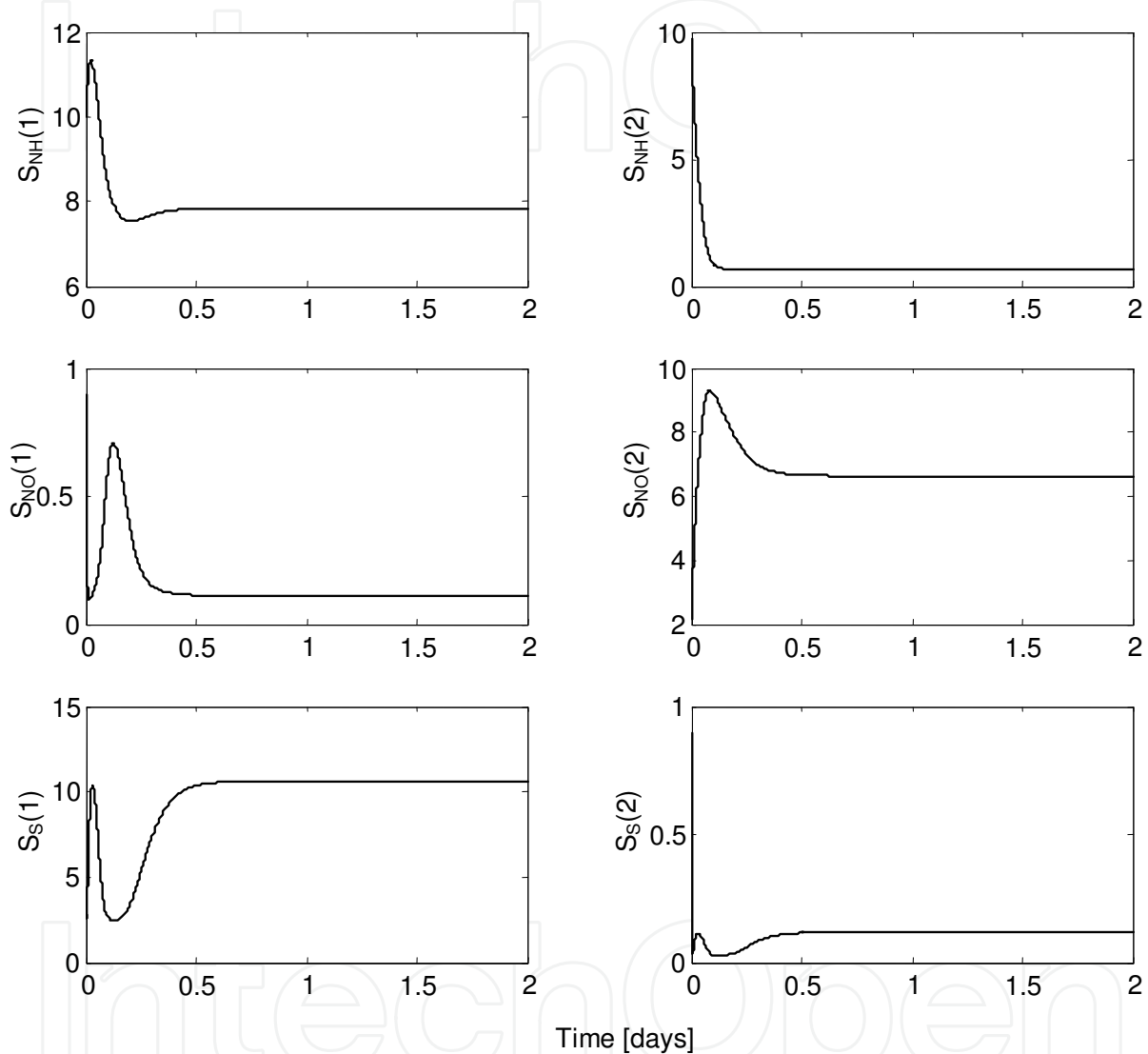


Fig. 2. Simulation results of the simplified ASM1 model

In most control cases, the evolution of the output variable, $y(t)$, of the closed-loop system must be bounded by an upper and a lower limit, as presented in Figure 3, where both limits of the response to a step signal were shown. QFT method ensures the operation of a linear system with variable parameters within the imposed domain of evolution.

It is considered a process described by a variable parameter transfer function of the following type:

$$P(s) = \frac{Ka}{s(s+a)} \quad (13)$$

where parameters K and a varies due to the operating conditions, so $K \in [K_{\min}, K_{\max}]$ and $a \in [a_{\min}, a_{\max}]$.

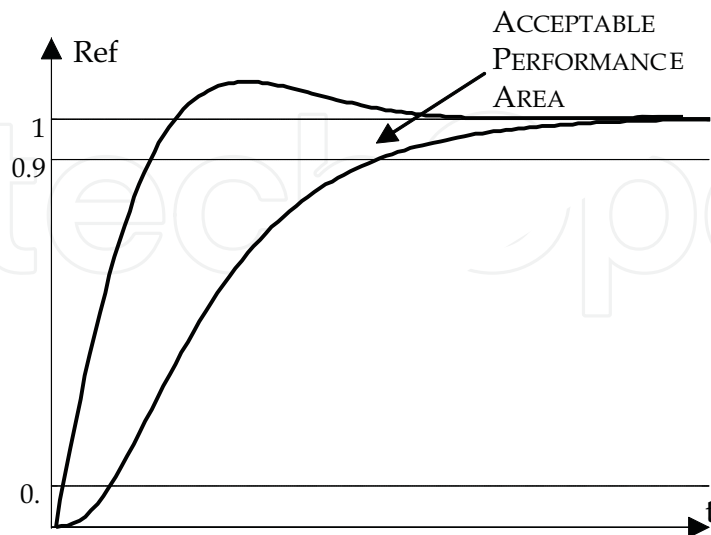


Fig. 3. Upper and lower bounds of the system output

QFT method consists in the synthesis of a compensator $G(s)$ and a prefilter $F(s)$ so that the behaviour of the closed-loop system is between the bounds imposed to the system. Figure 4 presents the control structure:

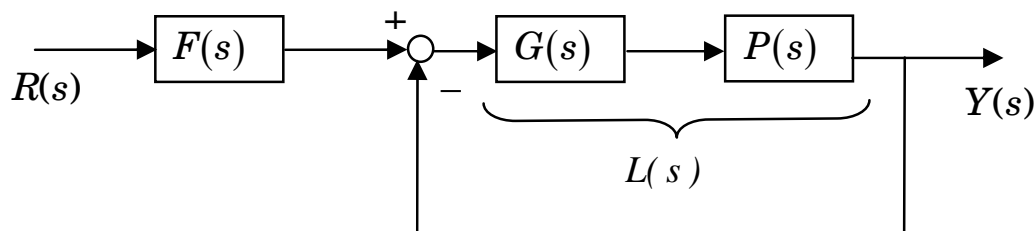


Fig. 4. Compensated linear system

The steps of robust design using QFT method for a tracking problem are the following (Houpis & Rasmussen, 1999):

Step 1. The synthesis of the desired tracking model.

The synthesis of the tracking model consists in defining the performance specifications through two invariant linear transfer functions, which set upper and lower design limits. In this way a series of closed-loop system performances which will result from the design are imposed. The considered performances are the rising time, the response time and the overshoot. The tracking specifications are referring to the tracking system which, in closed-loop, has the following transfer function:

$$H_u(s) = \frac{F(s)G(s)P(s)}{1 + G(s)P(s)} = \frac{F(s)L(s)}{1 + L(s)} \quad (14)$$

Since the linear model parameters change depending on the operating regime, the closed-loop system characteristics will have some variations. One imposes that these changes be within certain limits defined by an „upper“ and „lower“ gain characteristic:

$$|H_{ri}(j\omega)| \leq |H_u(j\omega)| \leq |H_{rs}(j\omega)| \quad (15)$$

in which, usually, the upper tracking model corresponds to the response of a second order system with overshoot, while the lower tracking model corresponds to a first order step response. Thus $H_{ri}(s)$ and $H_{rs}(s)$ have the expressions (Houpis & Rasmussen, 1999):

$$H_{rs}(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (16)$$

$$H_{ri}(s) = \frac{a_1 a_2}{(s + a_1)(s + a_2)} \quad (17)$$

In (16) and (17) it has to take into account the constraint regarding the steady transfer coefficient, that always must be equal to 1. Thus, at each frequency ω_i a bandwidth $\delta_u(j\omega_i)$ is provided, as shown in Figure 5.

In the transfer function of the upper limit a zero close to the origin could be introduced, with an effect as low as possible on the response time. This zero produces the increasing of the bandwidth $\delta_u(j\omega_i)$ at high frequencies. The bandwidth can be increased further by adding a pole near the origin. This pole does not significantly modify the response time of the lower limit transfer function. By introducing these additional elements one seeks for an easier fitting of the parametric uncertainties into the higher frequencies domain and thus the problem of prefilter synthesis $F(s)$ is simplified.

Step 2. Description of the linearized process through a set of N invariant linear models, which define the parametric uncertainty of the model.

The linearized process is described through a set of N invariant linear models which define the parametric uncertainty of the model. The parametric uncertainties of the linear model are determined by the range of operating and parametric uncertainties of the nonlinear model.

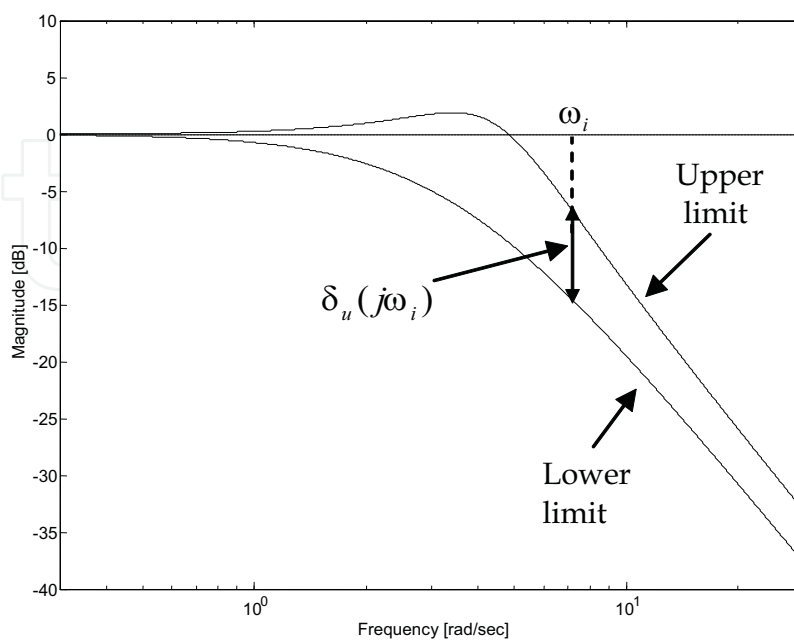


Fig. 5. Bode characteristics of upper and lower limits

Step 3. The obtaining of the templates at specified frequencies which graphically describe the parametric uncertainty area of the process on Nichols characteristic.

The N characteristics (gain and phase) of the considered models are represented on Nichols diagram for every frequency value. These N points define a closed contour, named template, which limits the variation range of parametric uncertainty.

Step 4. Selection of the nominal process, $P_0(s)$.

Although any process can be chosen, in practice the process whose point on the Nichols characteristic represents the bottom left corner of the templates for all frequencies used in the design procedure is chosen.

Step 5. Determination of the stability contour – the contour U – on Nichols characteristic.

The performance specifications referring to stability and robust tracking define the limits within which the transfer function of the tracking system can vary, when the linear model varies in the uncertainty area. The stability of the feedback loop, regardless of how the model parameters vary in the uncertainty region is ensured by the stability specifications. The transfer function of the closed-loop system is:

$$H_0(s) = \frac{G(s)P(s)}{1 + G(s)P(s)} = \frac{L(s)}{1 + L(s)} \quad (18)$$

One imposes that in the considered bandwidth, the gain characteristics associated to the closed-loop transfer function to not exceed a value of the upper limit (Horowitz, 1991):

$$|H_0| = \left| \frac{GP}{1 + GP} \right| \leq M_L \quad (19)$$

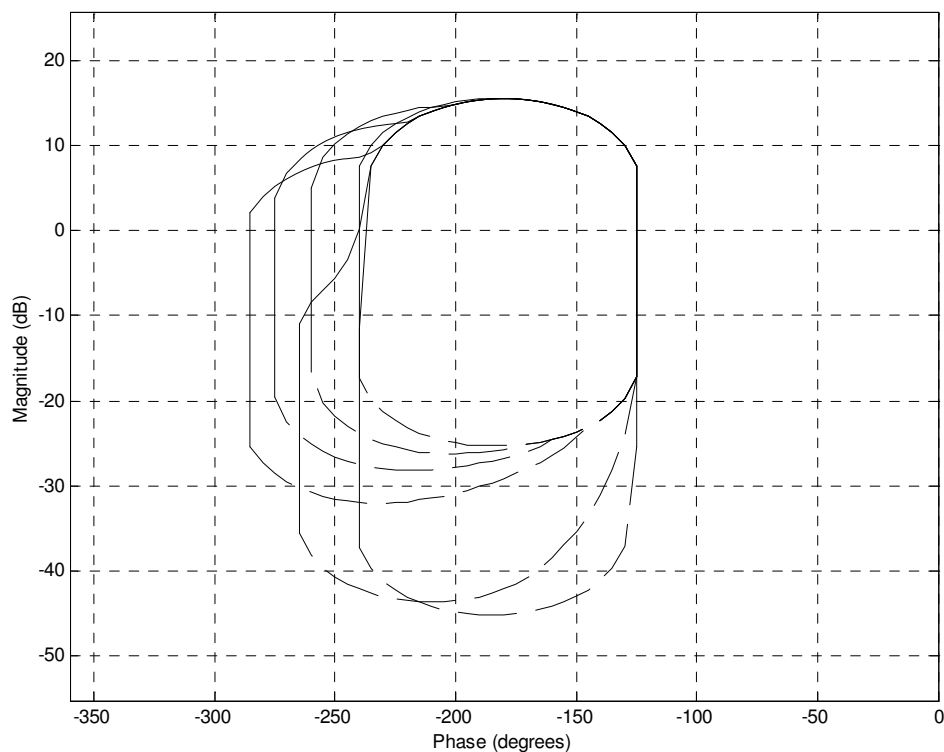


Fig. 6. Stability contours corresponding to the model given by equation (13)

In these conditions, a region that cannot be penetrated by the templates and the transmission functions $L(j\omega)$ for all frequencies ω is established on Nichols characteristic. This region is bounded by the contour M_L . The stability margins are determined using a frequency vector covering the area of interest. These margins differ from one frequency to another. Figure 6 presents the stability margins of the linear model given by equation (13).

Step 6. Determination of the robust tracking margins on Nichols characteristic.

The robust tracking margins must be chosen such that the placing of the loop transmission on this margin or above it ensures the robust tracking condition imposed by equation (15) to be met at every chosen frequency. This practically means that for each frequency the difference between the gain of the extreme points from the process template must be less than or equal to the maximum bandwidth $\delta_u(j\omega_i)$. Figure 7 illustrates the robust tracking margins of the linear model given by equation (13) with the tracking models (16) and (17).

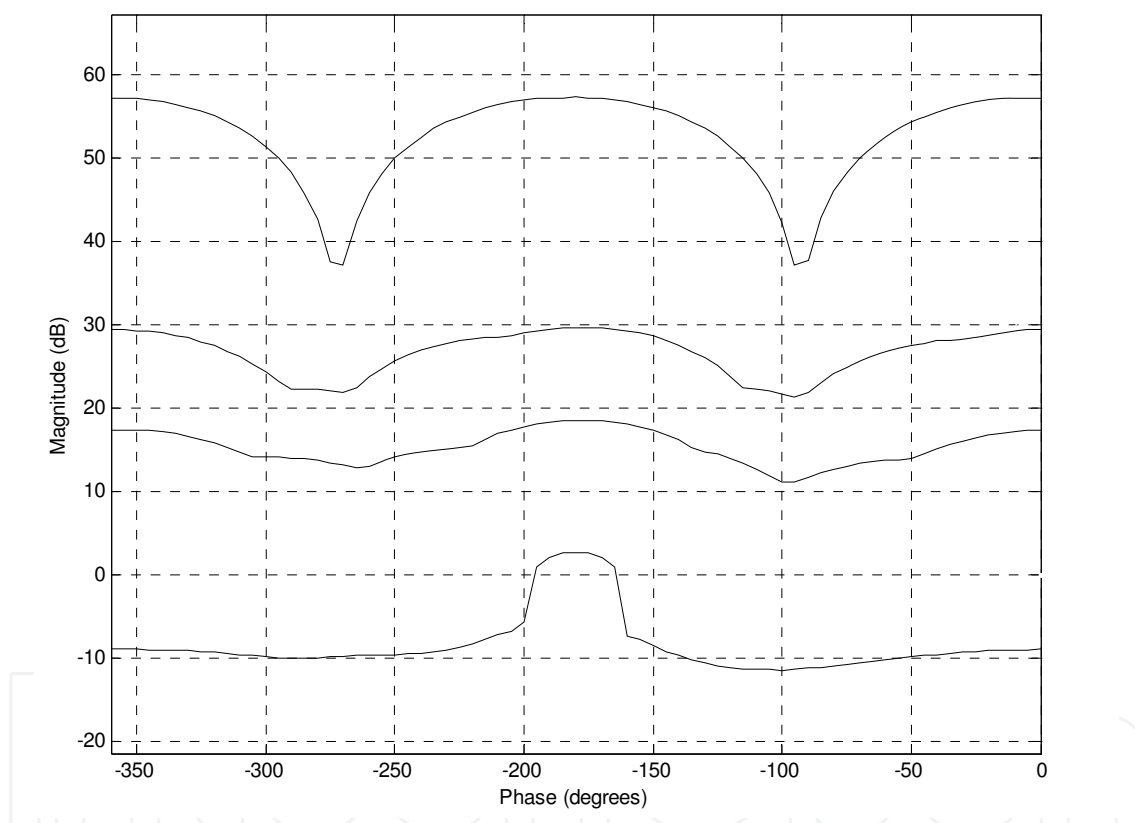


Fig. 7. Robust tracking margins corresponding to the model given by equation (13)

Step 7. Determination of the optimal margins on Nichols characteristics.

The optimal tracking margins are obtained from the intersection between the stability contours and the robust tracking margins for the frequencies considered of interest, taking into account the constraints that are imposed to the loop transmission. Thus the stability contour resulted at a certain frequency cannot be violated, so only the domains from the tracking margin that are not within the stability boundaries (18) will be taken into consideration. Figure 8 illustrates the optimal margins of the linear model given by equation (13).

Step 8. Synthesis of the nominal loop transmission, $L_0(s) = G(s)P_0(s)$, that satisfies the stability contour and the tracking margins.

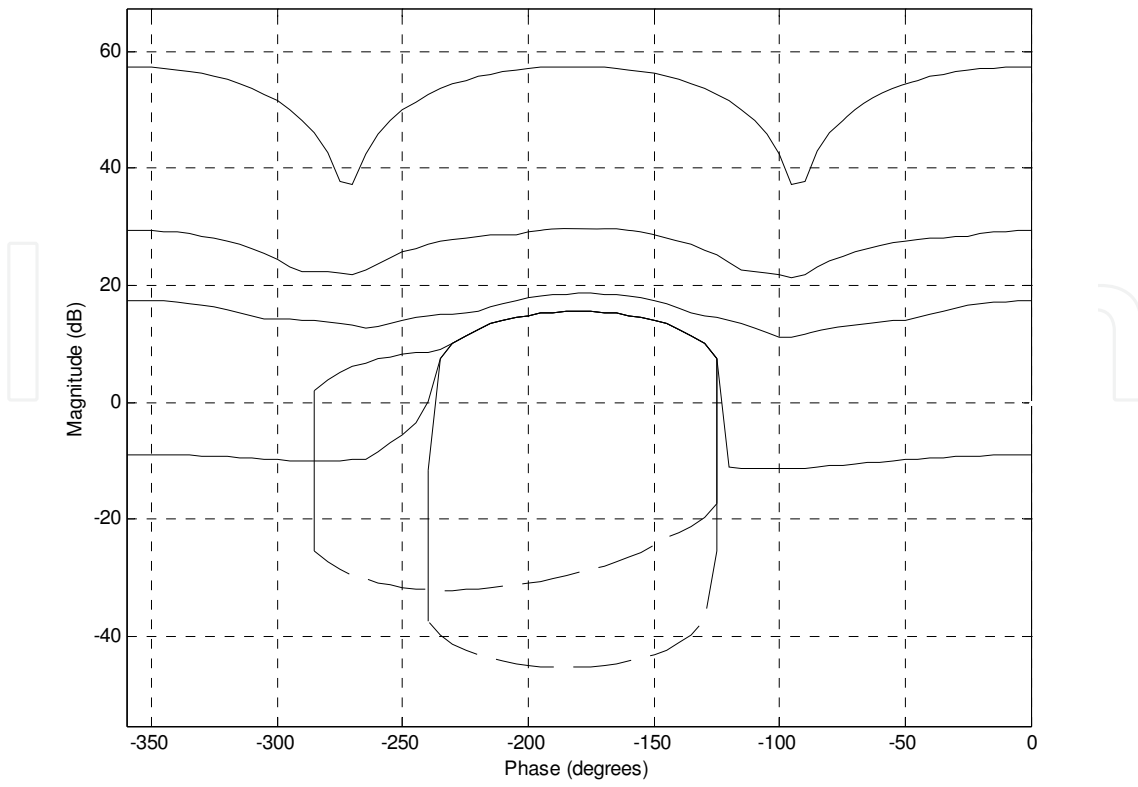


Fig. 8. Optimal tracking margins

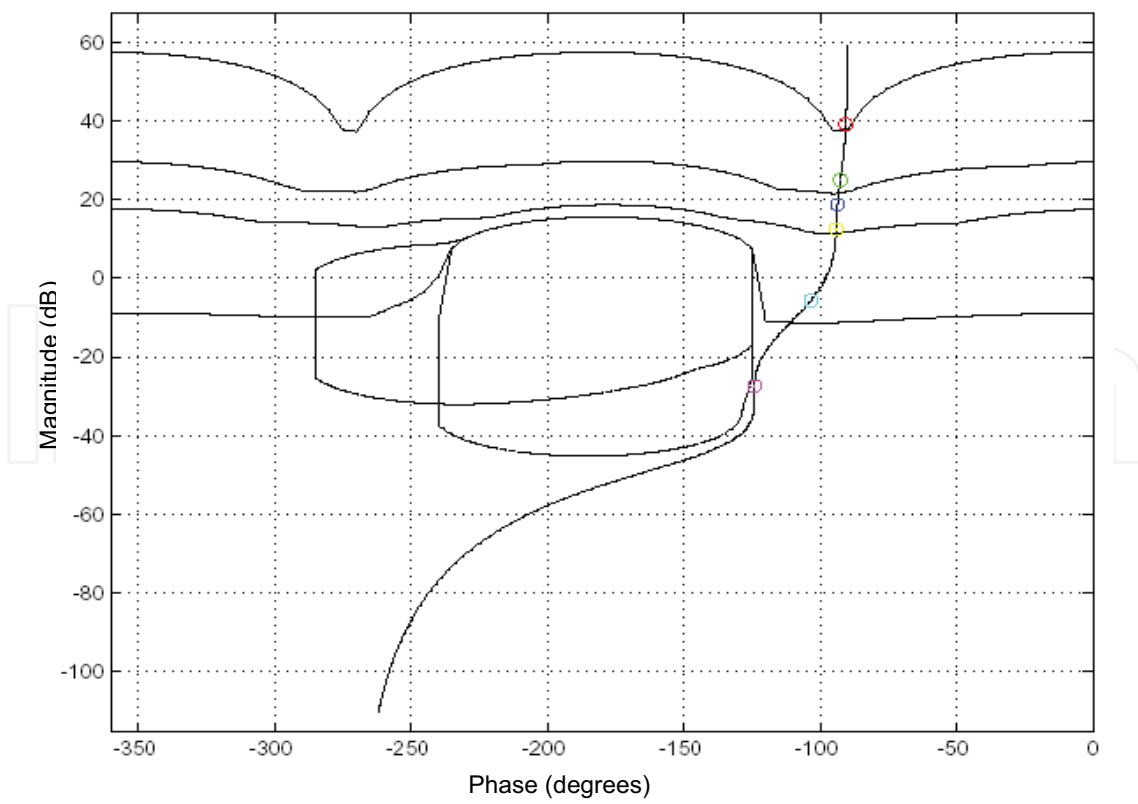


Fig. 9. Synthesis of the controller $G(s)$

Starting from the optimal tracking margins, the transmission of the nominal loop is also represented on Nichols diagram, corresponding to the nominal model, $P_0(s)$, considering initial expression of the controller $G(s)$. The transmission loop is designed such as not to penetrate the stability contours and the gain values must be kept on or above the robust tracking margins corresponding to the considered frequency. Figure 9 presents the optimal margins and the transmission on the nominal loop which has been obtained in its final form. It can be noticed that the transmission values within the loop, for the six considered frequencies, are distinctly marked, with respect to the condition that the first four values must be placed above the corresponding tracking margins.

Step 9. Synthesis of the prefilter $F(s)$.

Figure 10 presents Bode characteristic of the closed-loop system without filter. It can be noticed that the band defined by the tracking limits of the closed-loop system (solid lines) is smaller than the band defined by performance specification limits (dotted lines) but Bode characteristic also evolves outside limits imposed by the performance specifications. In order to bring the system within the envelope defined by the performance specification limits, the filter $F(s)$ is used. Figure 11 presents Bode characteristic of the closed-loop system with compensator and prefilter. It can be seen that the system respects the performance specifications of robust tracking (the envelope defined by solid lines is inside the envelope defined by dotted lines). Thus the robust closed-loop system respects the stability and robust specifications in range of variation of the model parametric uncertainties.

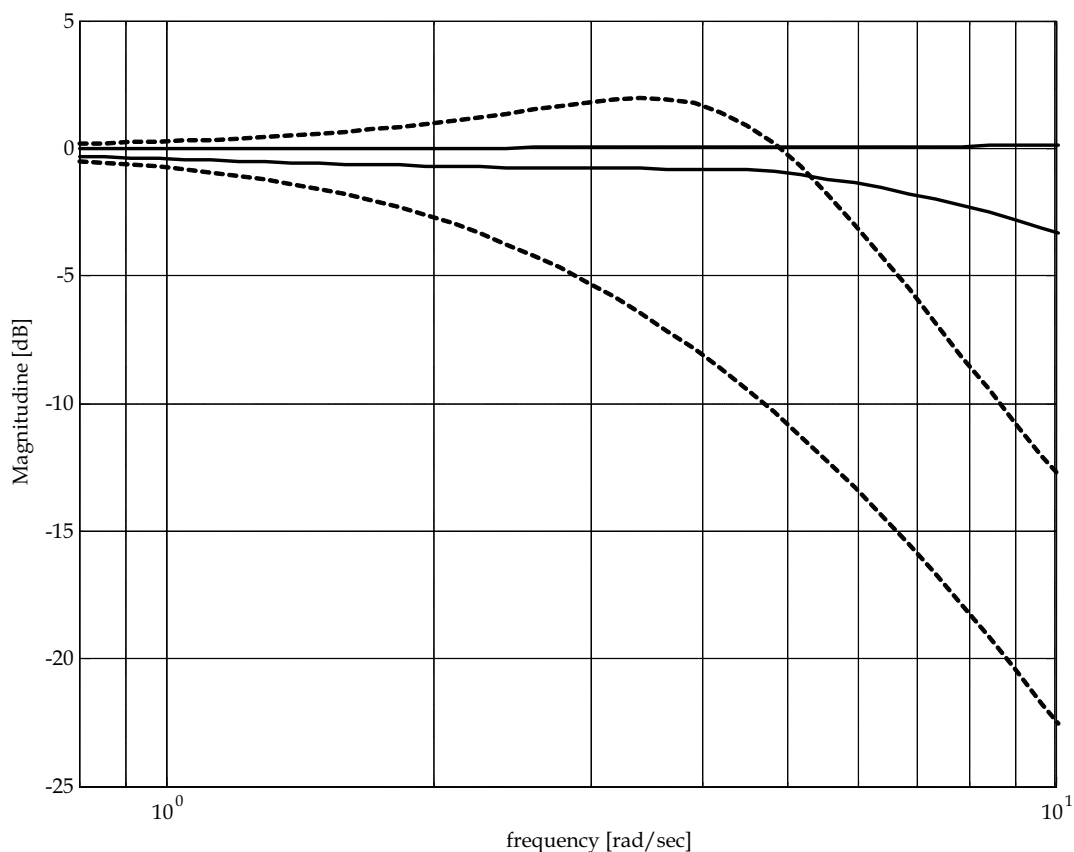


Fig. 10. Closed-loop system response with compensator

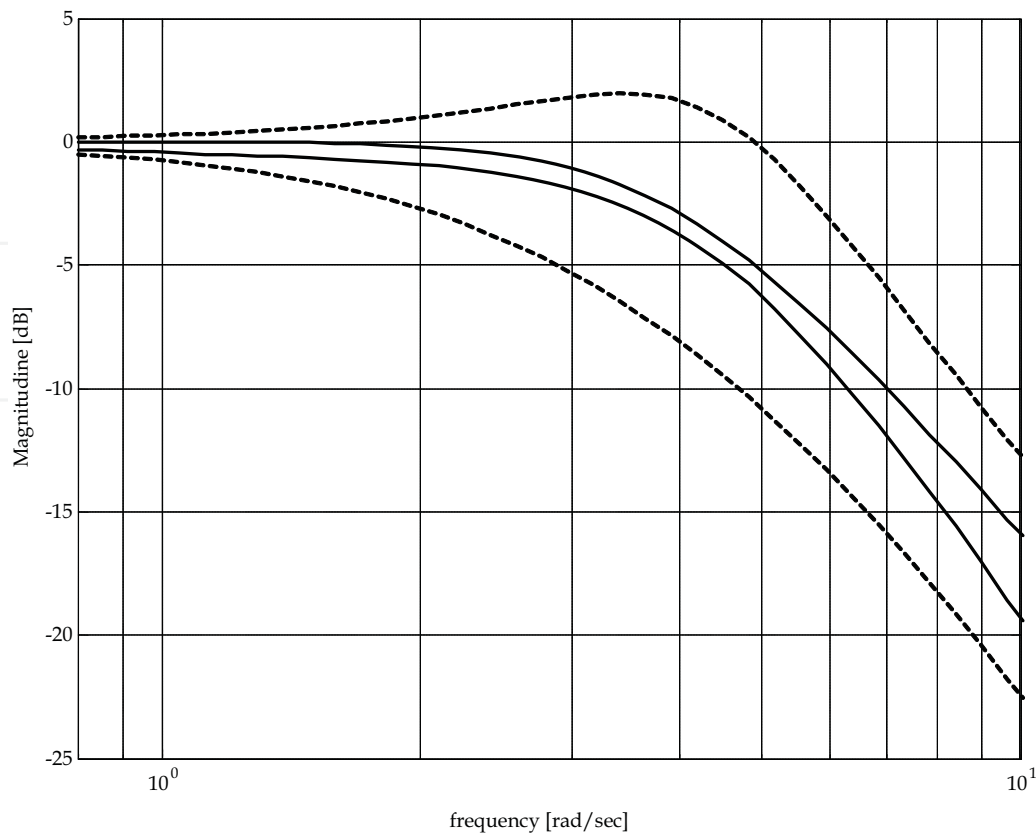


Fig. 11. Closed-loop system response with compensator and prefilter

4. Robust control of the wastewater treatment processes using QFT method

The control structure of a wastewater treatment process contains a first level with local control loops (temperature, pH, dissolved oxygen concentration etc.), which is intended to establish the nominal operating point, over which is superposed a second control level (global) for the removal of various pollutants such as organic substances, ammonium etc. For this reason the models used for developing control structures range from the simplest models for local control loops, up to very complicated models such as ASM models, as it is mentioned in section 1. Thus, subsection 4.1 will present the identification of dissolved oxygen concentration control loop and subsection 4.2 will present the control of ammonium concentration using the simplified version of ASM1 model. All the design steps of QFT algorithm were implemented using QFT Matlab® toolbox.

4.1 Dissolved oxygen concentration control in a wastewater treatment plant with activated sludge

To identify the dissolved oxygen concentration control loop a sequence of steps of various amplitudes was applied to the control variable that is the aeration rate. Figure 12 presents the sequence of steps applied to the dissolved oxygen concentration control system, while Figure 13 shows the evolution of the dissolved oxygen concentration. Analyzing the results presented in Figure 13 it can be concluded that the evolution of the dissolved oxygen concentration corresponds to the evolution of a first order system. At the same time, it can be seen in the same figure that the evolution of the dissolved oxygen concentration is strongly influenced by biomass and organic substrate evolutions. Thus, depending on

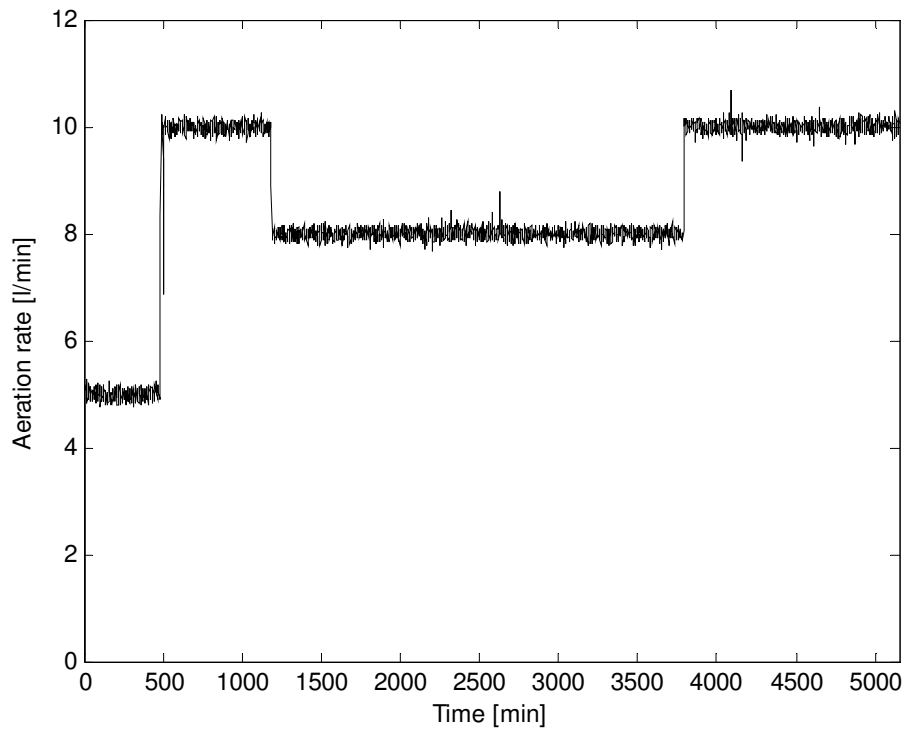


Fig. 12. Step sequence of the control variable: aeration rate

the oxygen consumption of microorganisms, the dissolved oxygen concentration from the aerated tank has different dynamics, each corresponding to different parameters of a first-order system.

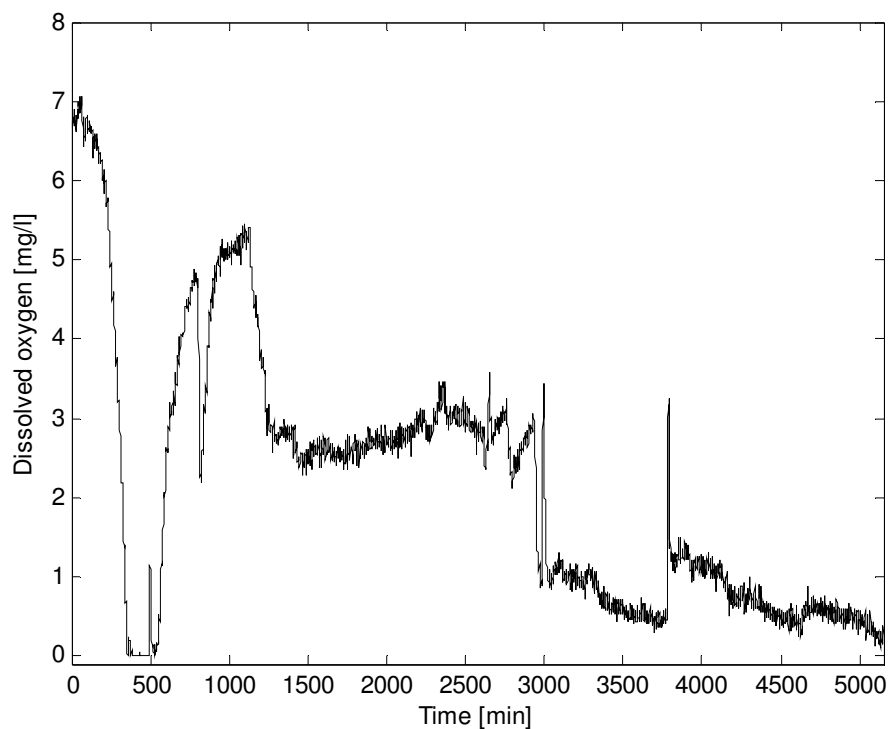


Fig. 13. Evolution of the dissolved oxygen concentration in the case when the aeration rate evolves according to Figure 12

In addition, considering that the microbial activity from the wastewater treatment process is influenced by the environmental conditions under which the process unfolds (temperature, pH etc.) and the type of substrate used in the process (in the pilot plant will be used organic substrates derived from milk and beer industries, substrates having different biochemical composition) it results that more transfer functions are necessary, aiming to model the evolution of the dissolved oxygen concentration in the aerated tank depending on the aeration rate. One possibility to model the dissolved oxygen concentration depending on the aeration rate is to take into consideration a first order transfer function with variable parameters (Barbu et al., 2010):

$$H(s) = \frac{K}{Ts + 1} \quad (20)$$

where, as a result of the identification experiments performed on data collected from different experiments carried out with the pilot plant, it was taken into consideration that the gain factor K varies in the range $K \in [0.8 \ 1.4]$ and the time constant of the first-order element varies in the range $T \in [1700 \ 2500]$.

The closed-loop system should have a behaviour between the two imposed limits, that give the accepted performance area. Taking into account the variation limits of the linear model parameters considered before, the two tracking models (the lower and upper bounds) were established:

$$H_{rs}(s) = \frac{10(s + 0.1)}{(s + 0.007 \pm j \cdot 0.007)} \quad (21)$$

$$H_{ri}(s) = \frac{1}{(300s + 1)(310s + 1)(30s + 1)} \quad (22)$$

Based on the linear model with variable parameters, given by equation (20), and on the tracking models, given by equations (21) and (22), all the steps provided in the design methodology using QFT robust method for a setpoint tracking problem has been completed. The transfer functions of the controller and prefilter are:

$$G(s) = \frac{0.22143 (s + 0.00039)}{s (s + 0.01217)} \quad (23)$$

$$F(s) = \frac{0.0068}{(s + 0.0068)} \quad (24)$$

Analyzing the controller transfer function $G(s)$, given by equation (23), it can be noticed that it also includes an integral component. Since the control variable is limited to a higher value given by the air generator used to provide the aeration - in the case of this pilot plant: 25 l/ min - and the controller includes an integral component, it was necessary to introduce an antiwind-up structure. This structure prevents the saturation of the control variable (the achievement of some unacceptable values for the integrator), helping to improve the dynamic regime of the controller.

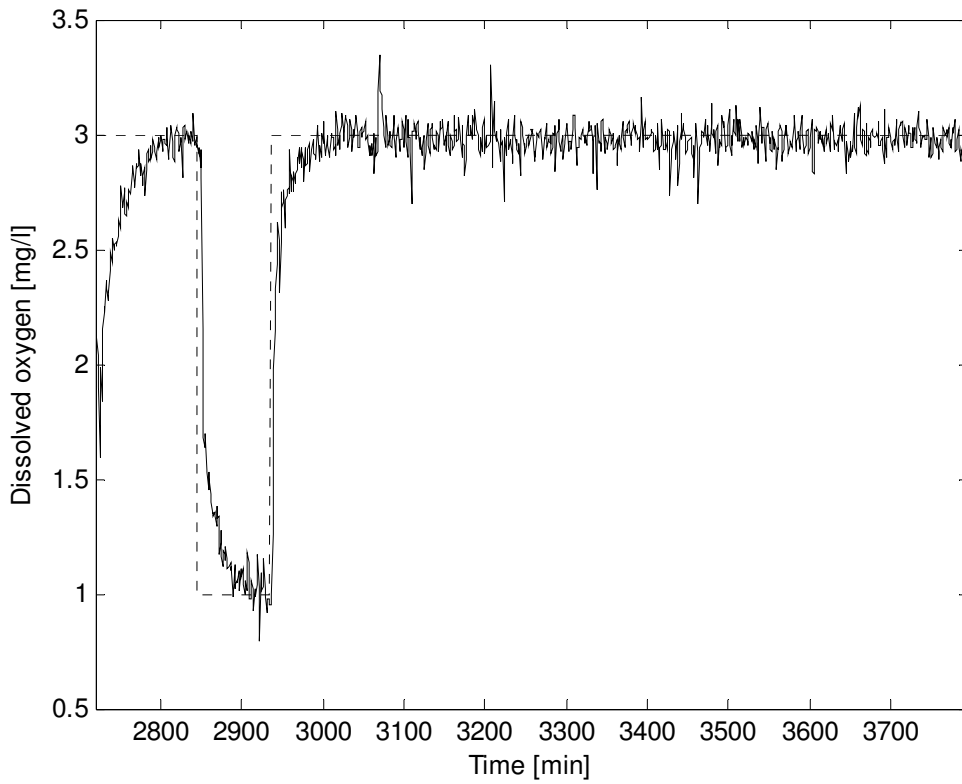


Fig. 14. Evolution of the dissolved oxygen concentration: solid line – pilot plant, dotted line – setpoint

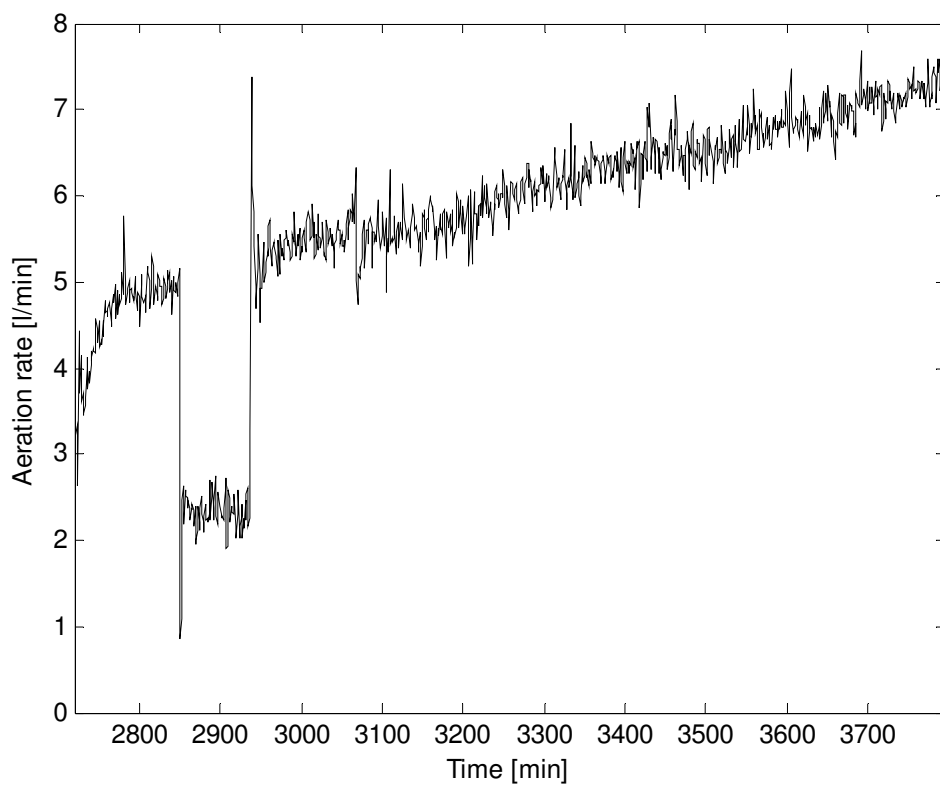


Fig. 15. Evolution of the control variable

The QFT proposed control structure was tested in the case of two experiments. The purpose was to observe the behaviour of the QFT controller in the case of two types of different wastewaters and when the process is in different stages of evolution from the biomass developing point of view. The first experiment was made considering the wastewater from the milk industry. Within this experiment, values of the dissolved oxygen setpoint ranging between 1mg/ l and 3mg/ l were taken into consideration. Figure 14 presents the evolution of the output variable (the DO concentration) and Figure 15 presents the evolution of the control variable (the air flow). The second experiment was made considering wastewater from the beer industry and in this experiment the biomass concentration developed in the aerated tank was monitored too. The results obtained in this experiment are shown in Figures 16, 17 and 18.

As a conclusion, the results obtained in the present chapter are very good in both cases, the QFT robust control structure succeeding to keep the dissolved oxygen setpoint imposed in the case of both types of wastewater considered in the experiments, from beer and milk industry, without being affected by the modification of the microorganism's concentration developed in the aerated tank during the experiments. This justifies the choice to use a robust controller as is the one designed by QFT method. At the same time, from the analysis of the evolution diagrams of the aeration rate and the dissolved oxygen concentration, it can be noticed that for maintaining a constant setpoint of the dissolved oxygen concentration in the aerated tank, the aeration rate will be directly influenced by the concentration of microorganisms that consume oxygen in the aerated tank.

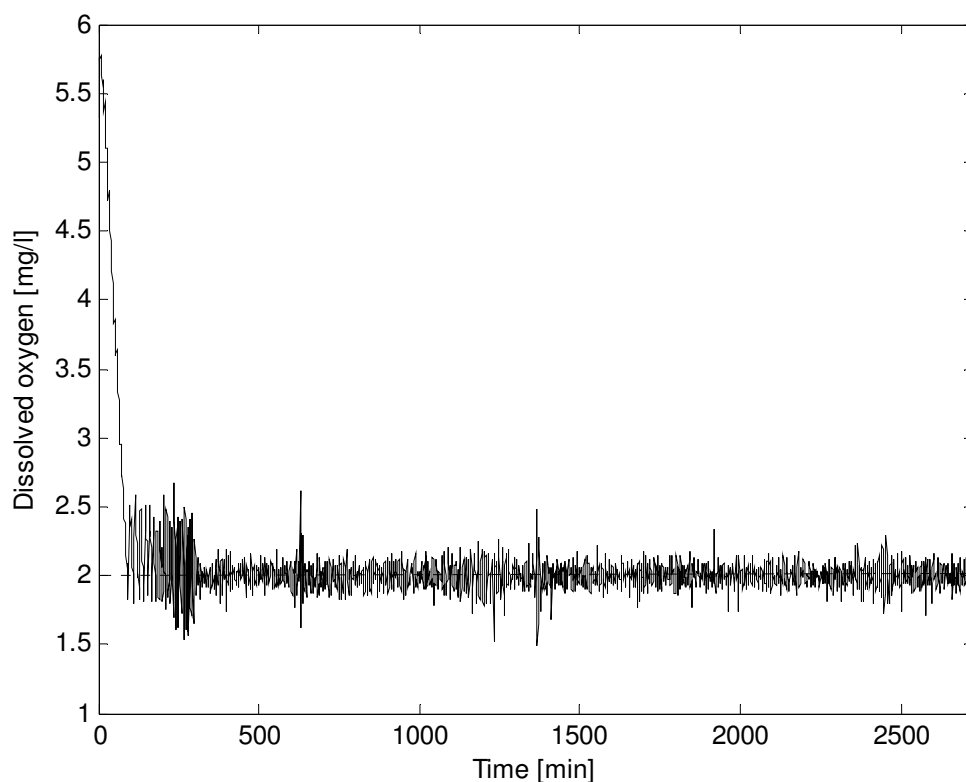


Fig. 16. Evolution of the dissolved oxygen concentration: solid line – pilot plant, dotted line – setpoint

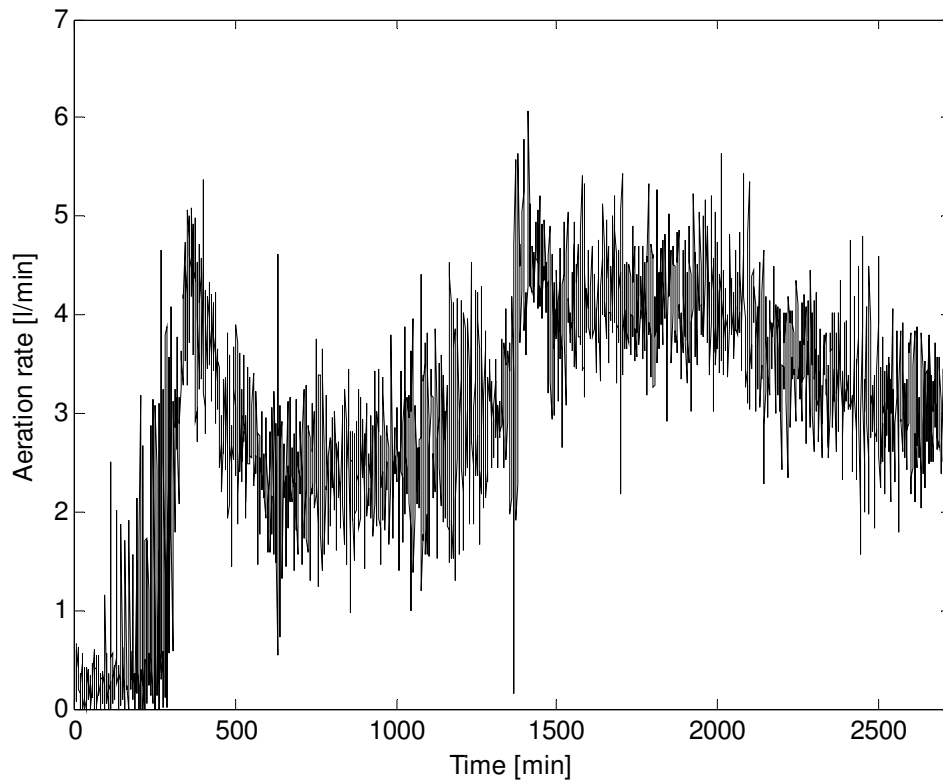


Fig. 17. Evolution of the control variable

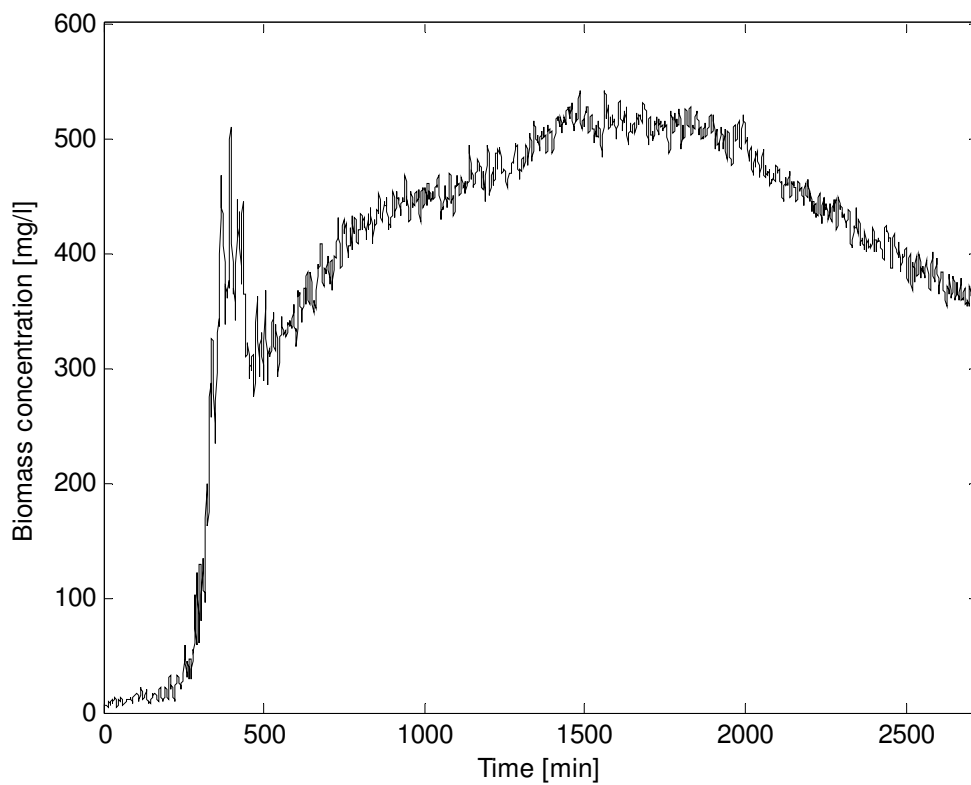


Fig. 18. Evolution of the biomass concentration

4.2 QFT multivariable control of a biological wastewater treatment process using ASM1 model

Within this section the robust linear control method QFT is used for the control of a nonlinear wastewater treatment process with activated sludge. The considered model for the wastewater treatment process is a simplified version of ASM1 model which has been presented in subsection 2.2. For this purpose the non-linear model was linearized in different operating points, resulting a linear model with variable parameters that approximates the behaviour of the non-linear process in all its operating points. The control variables of the multivariable process are: internal recycled flow, Q_i , and dissolved oxygen concentration from the aerated tank, $S_O(2)$. The output variables are the following: ammonium concentration at the output, $S_{NH}(2)$, equal to ammonium concentration from the aerated tank and nitrate concentration at the output, $S_{NO}(2)$, equal to nitrate concentration from the aerated tank. The purpose of the control structure is to obtain an effluent having an ammonium concentration at the output under 1 gN/ m^3 and a nitrate concentration at the output under 6 gN/ m^3 .

In (Barbu & Caraman, 2007) an analysis of the channel interaction, using RGA (Relative Gain Array) method was performed. This analysis indicates the fact that a control structure based on decentralized loops, considering as main channels – the control channels and as secondary channels – the disturbance channels, could be adopted. From the same analysis it results the following control channels: the dissolved oxygen concentration from the aerated tank – the ammonium concentration at the output ($S_O(2) - NH(2)$) and the recycle rate – the nitrate concentration at the output ($Q_i - NO(2)$). The secondary channels with a very weak interaction between them are: the recycle rate – the nitrate concentration at the output ($Q_i - NH(2)$) and the dissolved oxygen concentration from the aerated tank – the nitrate concentration at the output ($S_O(2) - NO(2)$).

The non-linear wastewater treatment process can be linearized taking into consideration three main functioning points (Barbu & Caraman, 2007):

1. rain - $S_{NH,in} = 25 \text{ gN/ m}^3$, $S_O(2) = 1.5 \text{ mg/ l}$, $Q_i = 30000 \text{ m}^3/ \text{ day}$;
2. normal - $S_{NH,in} = 30 \text{ gN/ m}^3$, $S_O(2) = 1.5 \text{ mg/ l}$, $Q_i = 40000 \text{ m}^3/ \text{ day}$;
3. drought - $S_{NH,in} = 35 \text{ gN/ m}^3$, $S_O(2) = 2 \text{ mg/ l}$, $Q_i = 50000 \text{ m}^3/ \text{ day}$.

The transfer functions obtained in the case of the three operating regimes were simplified through a frequency analysis and they have the following expressions:

1. Rain:

$$P_{S_O(2)-NH(2)}(s) = \frac{23.664}{s + 115} \quad (25)$$

$$P_{Q_i-NO(2)}(s) = \frac{0.00149(s^2 + 36.03s + 2596)}{(s + 115)(s + 11.82)(s + 22.56)} \quad (26)$$

2. Normal:

$$P_{S_O(2)-NH(2)}(s) = \frac{15.036}{s + 115.4} \quad (27)$$

$$P_{Q_i-NO(2)}(s) = \frac{0.00156(s^2 + 41.81s + 2924)}{(s + 115.4)(s + 13.75)(s + 26.92)} \quad (28)$$

3. Drought:

$$P_{S_o(2)-NH(2)}(s) = \frac{11.32}{s + 109.6} \quad (29)$$

$$P_{Q_i-NO(2)}(s) = \frac{0.00149(s^2 + 42.66s + 2584)}{(s + 109.6)(s + 13.68)(s + 29.13)} \quad (30)$$

Taking into account the transfer functions obtained for the three operating regimes, it can be seen that the main channel, the dissolved oxygen concentration from the aerated tank – the ammonium concentration at the output ($S_o(2) - NH(2)$) can be described by the following transfer function with variable parameters:

$$P_{S_o(2)-NH(2)}(s) = \frac{K_1}{s + a_1} \quad (31)$$

where: $K_1 \in [10 \ 20]$, $a_1 \in [109 \ 116]$.

The tracking models imposed for this control channel are given by the following transfer functions:

$$H_{rs} = \frac{20 \cdot (s + 100)}{(s + 20 \pm j \cdot 40)} \quad (32)$$

$$H_{ri} = \frac{73500}{(s + 30)(s + 35)(s + 70)} \quad (33)$$

As a result of applying the QFT algorithm, the following robust controller results:

$$G_{S_o(2)-NH(2)}(s) = \frac{270.2621}{s + 0.063} \quad (34)$$

and the prefilter:

$$F_{S_o(2)-NH(2)}(s) = \frac{45.205}{s + 45.205} \quad (35)$$

The control channel, the recycled rate – the nitrate concentration at the output ($Q_i - NO(2)$), is described by the following transfer function with variable parameters:

$$P_{Q_i-NO(2)}(s) = \frac{K_2(s^2 + a_2s + b_2)}{(s + c_2)(s + d_2)(s + e_2)} \quad (36)$$

with:

$$K_2 \in [0.0014 \ 0.0016], a_2 \in [36 \ 43], b_2 \in [2580 \ 930], c_2 \in [109 \ 116], d_2 \in [11.5 \ 14], e_2 \in [22 \ 29.5]$$

The tracking models imposed for this control channel are given by the following transfer functions:

$$H_{rs} = \frac{10 \cdot (s + 50)}{(s + 10 \pm j \cdot 20)} \quad (37)$$

$$H_{ri} = \frac{12000}{(s + 15)(s + 20)(s + 40)} \quad (38)$$

As a result of applying the QFT algorithm, the following robust controller results:

$$G_{Q_i-NO(2)}(s) = \frac{10000(0.965s + 13.255)}{s + 0.0067} \quad (39)$$

and the prefilter:

$$F_{Q_i-NO(2)}(s) = \frac{1.07s + 25.194}{s + 25.194} \quad (40)$$

The robust control structure proposed in this chapter has been tested through numerical simulation in the case of each of the three operating regimes. In Figures 19 and 20 the simulation results for the two extreme operating regimes (rain and drought) are presented. It was also tested an operating sequence when the three operating regimes alternate, as is presented in Figure 21. All these figures show that the robust multivariable control structure is able to track the setpoints imposed for the output variables and the biodegradable substrate is efficiently treated. This is achieved despite the fact that the multivariable nonlinear process modifies its operating point, both in terms of the inflow and the organic matter load.

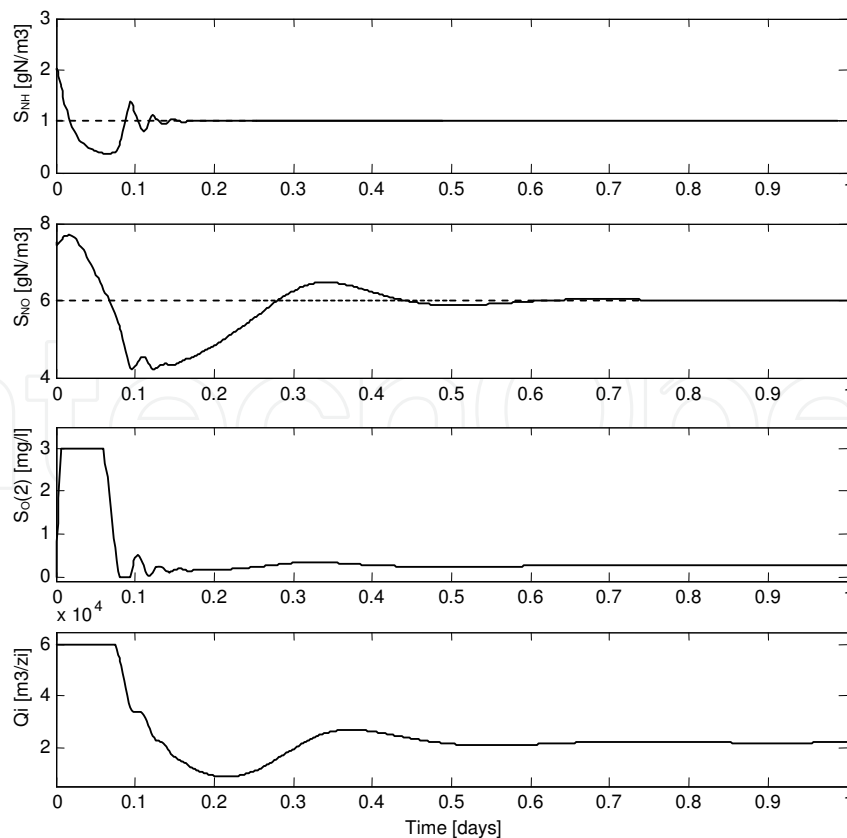


Fig. 19. QFT robust control applied in the case of “rain” regime

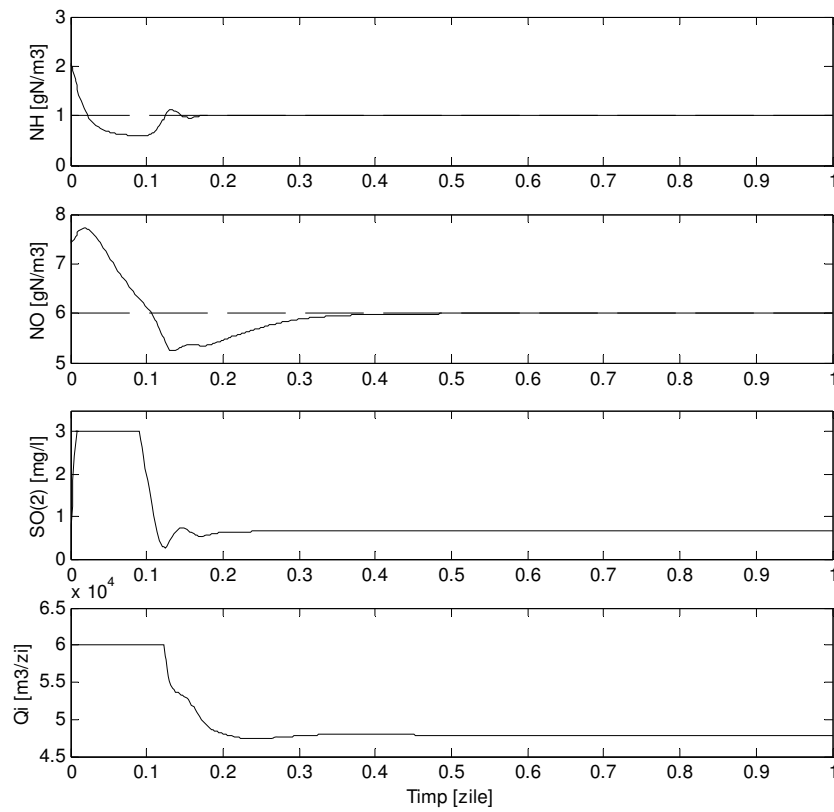


Fig. 20. QFT robust control applied in the case of “drought” regime

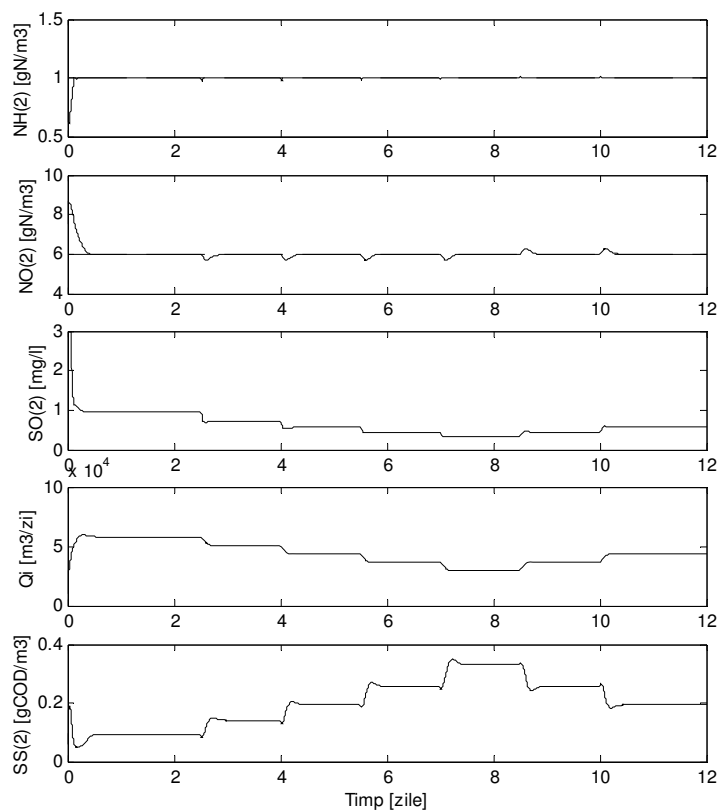


Fig. 21. QFT robust control of the wastewater treatment process

5. Conclusions

The present chapter deals with the robust control of wastewater treatment processes with activated sludge using QFT method aiming to increase their efficiency. The paper shows that QFT method is suitable for the control of these processes, taking into account the complexity, nonlinearity and the high degree of uncertainty that characterize biological wastewater treatment processes. QFT robust control method proved its effectiveness to be applied with good results both in local control loops, such as dissolved oxygen concentration control loop, as well as in the overall biological treatment algorithm, such as the control of ammonium concentration from the wastewater.

In order to design the QFT control law in the case of dissolved oxygen concentration control an analysis of the control loop dynamics was performed. It was concluded that the process can be approximated by linear models in different operating points. The testing of QFT control structure was done on a pilot plant for biological wastewater treatment, also presented in the paper.

In order to design the QFT control law in the case of the control of ammonium concentration in the effluent a simplified version of the ASM1 model was used. This model was linearized in three relevant operating points (rain, drought and normal). For each linear model the corresponding control structure has been designed. The results were validated through numerical simulation.

In both applications developed in this work it can be seen that QFT control structures offers good results, that is the output variables are tracking the imposed setpoints despite the fact that the nonlinear process modifies its operating point, both in terms of the inflow and the organic matter load.

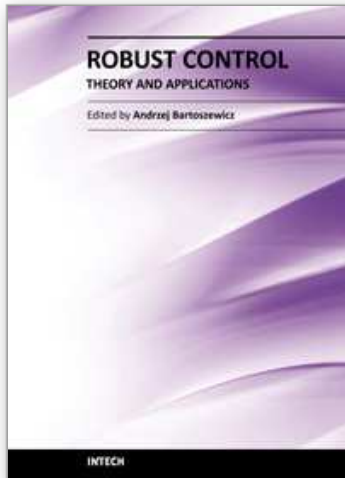
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The main objective of this monograph is to present a broad range of well worked out, recent theoretical and application studies in the field of robust control system analysis and design. The contributions presented here include but are not limited to robust PID, H-infinity, sliding mode, fault tolerant, fuzzy and QFT based control systems. They advance the current progress in the field, and motivate and encourage new ideas and solutions in the robust control area.

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