

# Gain Scheduling Control of Dissolved Oxygen Concentration in a Wastewater Treatment Process

Ciprian Vlad, Sergiu Caraman, Daniela Carp, Viorel Mînză, Marian Barbu

**Abstract**— The paper deals with the robust control of the dissolved oxygen concentration in the case of wastewater treatment processes. The Gain Scheduling control method has been chosen for the dissolved oxygen concentration control. Firstly the dissolved oxygen control loop was experimentally identified in various operating points. The Gain Scheduling strategy was designed so that the behaviour of the closed loop system to be the same around the mentioned operating points. The Gain Scheduling control strategy of the dissolved oxygen concentration was tested by simulation and using an experimentally pilot plant that is also presented in the paper.

## I. INTRODUCTION

The 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. 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.

The biological wastewater treatment process takes place in treatment plants. It is very important and gives us the certainty that human impact on the use of the water is highly reduced. The aim of the wastewater treatment is to reduce the quantities of nitrogen, phosphorus, organic matter and solid matters in suspension. Then, systematic approach has been performed in order to improve their operation efficiency, using modelling and control techniques.

One of the approaches in the modeling and control of wastewater treatment processes assumes the separated control of the main interest variable: the dissolved oxygen [1]. The oldest problem regarding the control of the wastewater treatment processes and in the same time one of the most important is the control of the dissolved oxygen level. 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 [2], [3]. 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. [4] - [7].

Gain Scheduling method is one of the most popular nonlinear control approach, which was successfully applied widely in different domains. This method uses a nonlinear controller with specific required dynamic properties, obtained by combining the members of an invariant linear controller family [8]. Each of these linear controllers provides satisfactory control around an operating point of the nonlinear system, thus being able to cover the entire operating domain.

In essence, this paper is focused on one of the major problems encountered in wastewater treatment processes: the dissolved oxygen concentration control. The objective of this work is to investigate how can be applied the Gain Scheduling control strategy to this type of processes.

The paper structure is as following: section 2 briefly presents the experimental wastewater treatment pilot plant, section 3 is referring to the experimental identification of the dissolved oxygen concentration control loop, section 4 presents the Gain Scheduling control algorithm, section 5 shows the simulation and experimental results and last section is dedicated to the conclusions.

## II. 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 during a research national project managed by "Dunărea de Jos" University of Galati. The objective of the pilot plant is to improve the efficiency of the biological treatment processes in case of various types of wastewaters from food industry in aerobic conditions [4].

The feeding tank has the capacity of 0.1 m<sup>3</sup> 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 0.288 m<sup>3</sup>/day maximum flow. Before being pumped into the tanks the wastewater can be heated in a small expansion tank. The aerobic tank is the heart of the biological treatment process. Here the wastewater is mixed with the activated sludge and to fulfill the process it is also mixed with air. The air is bubbled into

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the aerobic tank through a set of air ejectors which have also a mixing role. To be able to control the medium homogeneity the aerobic tank is also equipped with a mechanical paddle mixer with three working regimes: 60 rpm, 180 rpm and 300 rpm. The aerobic tank working volume is 0.04 m<sup>3</sup>. The treatment temperature can be online monitored and controlled through a temperature probe and an electric heating resistance both mounted inside the tank. The pH can also be online 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 and base tank). The turbidity can be online monitored with a dedicated optical electrode. The evolution of the biomass can be indirectly estimated through the turbidity values; the correlation between the two variables is usually made offline by measuring the sludge dry matter. The aerobic tank is also provided with an ORP (Oxide-Reduction Potential) transducer. The ORP potential can be correlated, in some cases, with the COD (Chemical Oxygen demand) of the wastewater. The anoxic tank 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. 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 aerobic tank.



Fig. 1. Wastewater treatment pilot plant from “Dunarea de Jos” University of Galati

The transducer signals are captured by a PCI data acquisition board. A HMI (*Human-Machine Interface*) facilitates the process control and monitoring (Figure 2). The data can be stored in a data base and processed thereafter.

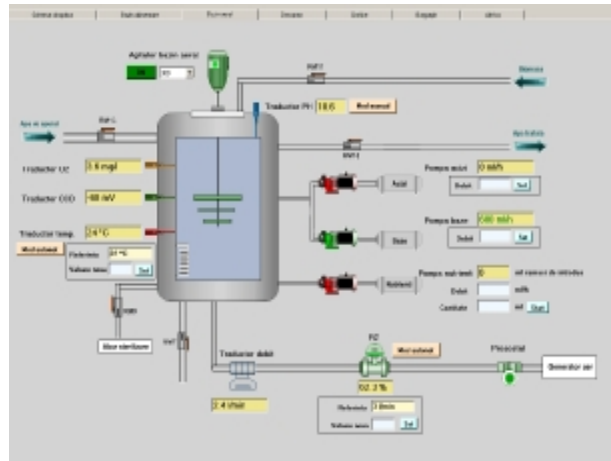


Fig. 2. HMI for monitoring and control the wastewater treatment pilot plant

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 slower dynamics. The air flow is on-line measured with a flow meter and it is controlled with an electric continuous valve. The maximum air flow rate is 43.23 m<sup>3</sup>/day. The DO concentration is on-line measured with an electrochemical electrode mounted in the aerobic tank and it is controlled using the aeration rate as a control variable.

### III. EXPERIMENTAL IDENTIFICATION OF THE DISSOLVED OXYGEN LOOP

In order to determine the control structure of the dissolved oxygen loop consecutive step inputs were applied on the aeration rate at different values of the influent flow rate. This experiment in which the main variables were monitored lasted approximately 11 days. The variation of the influent flow rate is expressed through the dilution rate variable. The dilution rate is the ratio between the influent flow rate and the volume of the aerobic tank. The dilution rate varies proportionally with the influent flow rate due to the fact that the water volume remains constant in the aerobic tank during the experiments.

Based on this experiment the aeration process of the aerobic tank was experimental identified on several operating points. The aeration process has as input the aeration rate ( $W$ ) which represents the air flow introduced in the wastewater from the aerobic tank. The output of the aeration process is the dissolved oxygen concentration in the wastewater from the aerobic tank. In Figure 3 are presented the main variables that affect the process evolution: aeration rate, dissolved oxygen concentration and dilution rate. Based on the experiment data seven representative operating points were identified (circled in

the Figure 3). In all these operating points the transfer function of the aeration process has a dynamic corresponding to a first order system. It results that each operating regime can be described by the two parameters:  $K$  (steady state gain factor) and  $T$  (time constant) from the well-known transfer function:

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

Practically the process is described by a first order system with variable parameters. The results of the process experimental identification in the seven considered operating points are presented in Table 1. From the analysis of the parameter values,  $K$  and  $T$ , one can see that the process is affected both by variations in the aeration rate and dilution rate (the two variables are defining the operating point of the considered process). The difficulty of the control problem stands on controlling the real process (due to its variability and nonlinearity) and not on controlling the simplified model.

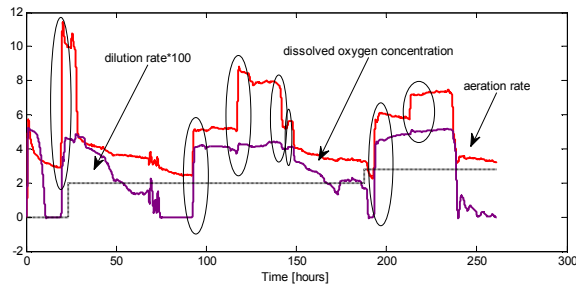


Fig. 3. The representation of the chosen operating points for process identification

TABLE I  
THE IDENTIFIED TRANSFER FUNCTIONS WITH GRAPHICAL METHOD

Operating point	Static gain $K$	Time constant $T$	Transfer function $W$ -DO
OP1	0.647	0.66185	$\frac{0.647}{0.6618s + 1}$
OP2	1.585	0.874	$\frac{1.585}{0.874s + 1}$
OP3	0.15	0.304	$\frac{0.15}{0.304s + 1}$
OP4	0.148	1.435	$\frac{0.148}{1.435s + 1}$
OP5	0.4318	0.535	$\frac{0.4318}{0.535s + 1}$
OP6	1.377	0.7468	$\frac{1.377}{0.7468s + 1}$
OP7	0.207	2.92	$\frac{0.207}{2.92s + 1}$

#### IV. GAIN SCHEDULING CONTROL ALGORITHM

Gain Scheduling approach in case of nonlinear systems uses the linearization of the system around several operating points. The basic idea is to divide the design into two steps. The first step is to design linear controllers using the nonlinear system linearization around different operating points. The second step is to obtain a nonlinear controller for the nonlinear system by interpolating (scheduling) the local linear controllers for various operating points.

One or more observable variables, called scheduling variables, are used to determine which operating region of the system is active and to allow changing the corresponding linear controller. Some controllers have the ability to adapt to changes in the dynamics of the process. Gain Scheduling is one of these controllers, with parameters changing while the process dynamics modifies. If the process dynamics can be deduced from measured variables, then the controller parameters can be calculated according to the values of these variables (Figure 4).

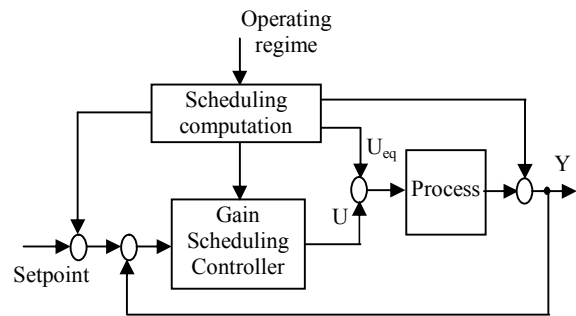


Fig. 4. Control scheme with Gain Scheduling controller type

For the calculus of the seven controllers corresponding to the seven operating points the pole-zero allocation method was used. To determine the controller parameters the closed loop system is assumed to be a second order system and the loop performances are imposed (time response and overshoot). In this paper a PI controller was considered and the controller parameters ( $K_p$  - proportional gain and  $T_i$  - integral time constant) are determined from the closed loop system and process transfer functions.

The transfer function of the closed loop system designed in the paper has the following form:

$$H_o(s) = \frac{K \cdot K_p (T_i \cdot s + 1)}{T_i \cdot T \cdot s^2 + (K \cdot K_p \cdot T_i + T_i) \cdot s + K \cdot K_p} \quad (2)$$

where  $K_p$  and  $T_i$  are the parameters of the adopted PI controller.

By imposing the system time response,  $t_r$ , and the system overshoot, (%OS), and based on the equations:

$$\xi = \frac{-\ln(\%OS)}{\sqrt{\pi^2 + \ln^2(\%OS)}}; \omega_n = \frac{4}{t_r \cdot \xi} \quad (3)$$

it results that the PI controller parameters can be calculated with the following equations:

$$K_p = \frac{2 \cdot \xi \cdot \omega_n \cdot T - 1}{K}; T_i = \frac{2 \cdot \xi \cdot \omega_n \cdot T - 1}{\omega_n^2 \cdot T} \quad (4)$$

where  $\omega_n$  is the natural frequency of the system and  $\xi$  is the damping ratio.

In order to improve the step response on the system (to reduce the overshoot) the zero of the closed loop system (see equation (2)) must be compensated. For this purpose two methods are used. The first method is to use an IP (Integral Proportional) type control structure and the second one is to use a setpoint filter block. In both cases it results the following closed loop transfer function:

$$H_o(s) = \frac{K \cdot K_p}{T_i \cdot T \cdot s^2 + (K \cdot K_p \cdot T_i + T_i) \cdot s + K \cdot K_p} \quad (5)$$

The IP structure is presented in Figure 5. It contains two loops thus imposing the same poles for the system, but without the zero.

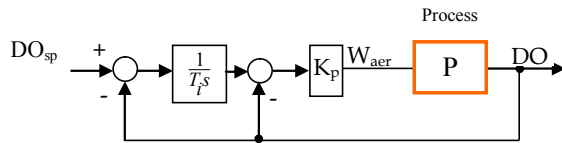


Fig. 5. IP control structure system

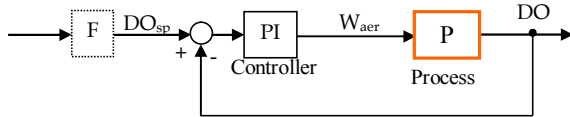


Fig. 6. PI control structure with filter

The second method is presented in Figure 6 and uses a filter block for the setpoint. The filter block is a first order system with the pole having the value equal to the zero of the closed loop system.

## V. SIMULATION AND EXPERIMENTAL RESULTS

The behavior of the closed loop system for the seven operating points was tested in simulation. The obtained results are presented in Figure 7, where one can notice approximately the same response of the seven close loop systems.

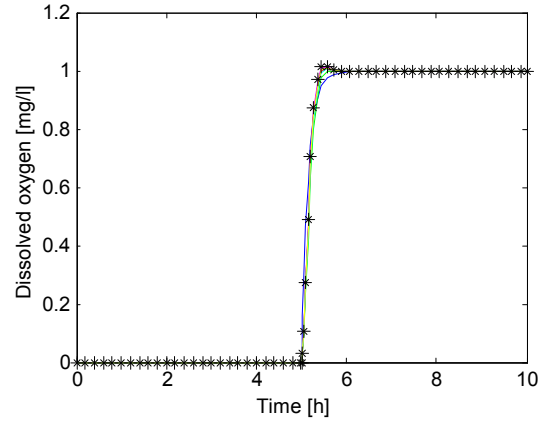


Fig. 7. Closed-loop response to the same step variation of dissolved oxygen setpoint for the seven operating points

Given the properties of the wastewater treatment process and the technical limitations of the pilot plant (particularly the dynamic properties of the valve from the aeration pump and the maximum value of the aeration rate) there are two main operating points that occurs: OP2 and OP6. For this two operating points the Gain Scheduling control strategy was extensively tested in simulation. The two controllers are corresponding to the variation of the dilution rate and have the following parameters:

$$K_{p2}=5.1199; T_{i2}=0.00528 \quad (6)$$

$$K_{p6}=5.9; T_{i6}=0.00521 \quad (7)$$

The simulation results for the two main operating points are presented in Figure 8 and these results shows that by properly choose the controller the similar tracking performances can be obtained.

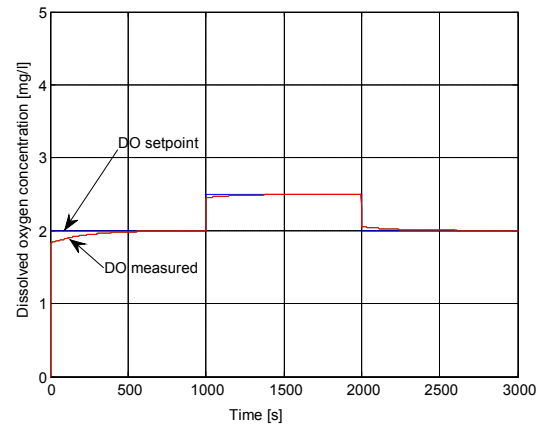


Fig. 8. DO setpoint tracking performances with the GS method

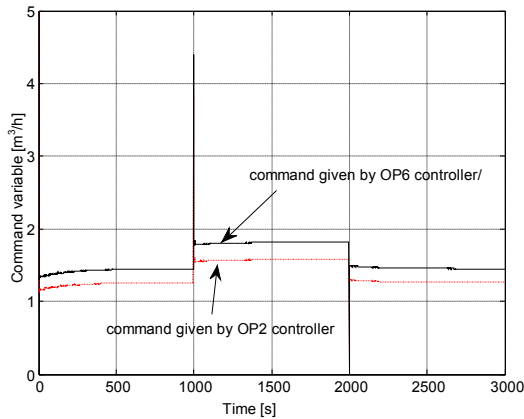


Fig. 9. The evolution of the command variable (aeration rate) with GS method at step variations of dissolved oxygen setpoint

The experimental results obtained on the wastewater treatment pilot plant are presented in Figures 10 and 11. In Figure 10 is presented the dissolved oxygen concentration evolution when using the Gain Scheduling control strategy. The control strategy switches between controllers designed for operating points OP2 and OP6 based on the information regarding the dilution rate. The sample time used on the application is 5 seconds. In order to avoid the saturation of the integral part of the controller, the PI controller contains an antiwindup structure. From this figure one can notice that the dissolved oxygen setpoint is accurately followed. In Figure 11 is presented the organic substrate concentration evolution. This information is obtained off-line by COD analysis of the wastewater. The presented results points out that by ensuring an appropriate oxygen concentration in the water the biological processes are taken place and the organic substrate will become smaller than the one imposed by legislation (NTPA 001).

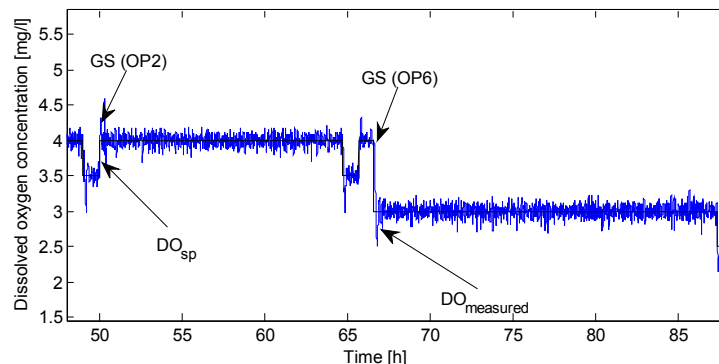


Fig. 10. Experimental performances of the dissolved oxygen concentration control loop of with GS method

## VI. CONCLUSION

A very important issue regarding the efficiency of a wastewater treatment process is the appropriate control of the dissolved oxygen concentration. As the evolution of dissolved oxygen concentration is strongly influenced by the evolution of biomass, organic substrate and environmental conditions (temperature, pH etc.), for its control the Gain Scheduling robust control method has been chosen. The obtained results were experimentally validated on a wastewater treatment pilot plant. These show a very good behaviour of dissolved oxygen concentration control loop, the concentration of the organic substrate (quality variable) being under the limit specified by the legislation. the system dealing with the imposed design specifications.

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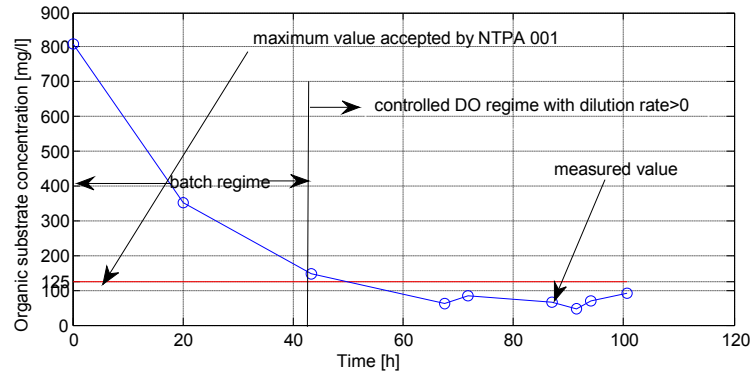


Fig. 11. The evolution of the effluent organic substrate for the system with dissolved oxygen concentration control loop