Numerical Simulation and Automatic Control of the pH Value in an Industrial Blunting System

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Abstract: A solution for the pH control of the residual water in an industrial blunting system is proposed. The technological process associated to the blunting system is decomposed in four sub-processes connected in series and in parallel, each of them being a distributed parameter one. The mathematical models of the sub-processes are expressed using partial differential equations. Both this procedure and the advanced structure of the control system generate very high control performances. For the numerical simulation of the control system, a numerical method based on the Matrix of Partial Derivatives of the State Vector, associated with Taylor series is proposed. This method permits the numerical simulation of the systems that include in their structure distributed parameter processes. The conducted simulations proved high accuracy of our original method.

1 INTRODUCTION

The blunting system treated in this paper belongs to a metallurgical factory. Its purpose is to assure a value of the pH of residual water around 7 at the overflowing point. The pH control of the residual water is necessary in order to avoid the pollution of the closest river (in general the residual water is overflowed in the closest river) (Moore, 1978). The residual water has an acid character (pH < 7) and the reacting substance used in order to neutralize the acid is the cream of lime (with pH value 12).

The system contains four tanks in its structure, with the same role and the same technical characteristics, connected in series through some orifices (Mureşan et al., 2012). The two reactants are introduced in the chemical reaction at the edge of the first tank, edge which does not communicate with the second tank. The overflowing point from the system is placed at the edge of the fourth tank, edge which doesn't communicate with the third tank. In order to apply an advanced control structure (for example the cascade one (Love, 2007)) the system is decomposed in two subsystems, the first one being associated to the first tank and the second one including the last three tanks. The last three tanks will be treated as an equivalent tank with the length three times bigger than the length of the initial ones. Both the technical characteristics of the tank number 1 associated to the first subsystem and of the equivalent tank associated to second one, are presented in the Table 1:

Table 1: The technical characteristics of the tanks.

The technical characteristics of the tank	The length	The width	The depth	The volume
Tank 1	5 m	2 m	1.5 m	15 m^3
The equivalent Tank (Tank 2 + Tank 3 + Tank 4)	15 m	2 m	1.5 m	45 m^3

The pH value of the residual water can be controlled adjusting the flow of the cream of lime that is introduced in the process (Vînătoru, 2001), (Golnaraghi and Kuo, 2009). The control signals generated by the pH controllers are unified current ones (4-20 mA). The final control signal (unified current signal) is applied to the actuator (an electro-valve on the cream of lime pipe). The output signals from the pH transducers (the feedback signals) are unified current signals, too.

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2 MODELING THE TECHNOLOGICAL PROCESS AND THE AUTOMATIC CONTROL SYSTEM

The general structure of both tank number 1 and equivalent tank is presented in Fig. 1, without considering, in this moment, the difference of length between them. The two dashed lines near the origin line are associated only to the first tank, respectively the third dash line and the difference of level are associated only to the equivalent tank. The substances circulation from the input to the output point of the tanks appears both due to the small level differences between the consecutive tanks and due to the barbotage mix-up systems from the tanks structure. In this case, the chemical reaction occurs progressively, the pH value depending both on time and the position in the tanks. The conclusion is the fact that the technological blunting processes associated to the tanks are distributed parameter ones.

In Fig. 1, the pH variation in relation to position in the tanks volume (Li and Qi, 2011) is highlighted through the axes of the Cartesian system. As it can be remarked in Fig. 1, the origin of the Cartesian system is the center of the origin line (in relation to the tanks width) and the pH variation in relation to the tanks length, width and depth corresponds with the pH variation along the axes 0p, 0q, respectively 0r. Due to the efficient homogenization of the pH in the tanks width and depth assured by the barbotage system, the weight of the pH variation along the 0q and 0r axes is insignificant in comparison with the 0p axis case. Hence, in the model of the processes only the pH variation in the tanks length (on the 0p axis) is considered.

The two technological processes associated to the two tanks (tank 1 and the equivalent tank) can be decomposed each in two sub-processes connected in parallel. In each case, the sub-processes are associated with the acid's, respectively the cream of lime's effects and they are modeled considering the indifferent pH value (7). The output signal from each process results as the sum of the output signals from the corresponding sub-processes. Also the output signals from the sub-processes of the same process have an antagonistic effect one in relation to other, introducing the possibility of the pH control.

In Fig. 2, the proposed control structure is presented. Due to the fact that the two processes are connected in series and they contain each two sub-processes connected in parallel, the whole blunting process contains four sub-processes connected in series and in parallel, as it can be remarked in Fig. 2.

Our solution is a combined control structure cascade + feed-forward. The C elements are the controllers (including CB – the compensation block), the A element is the actuator (an electro-valve on the cream of lime pipe) and K_{pH} is a constant equal to 5 (pH of cream of lime – 7). MT1, MT2, and MT3 are pH transducers and MT4 is a flow transducer. The significance of the signals

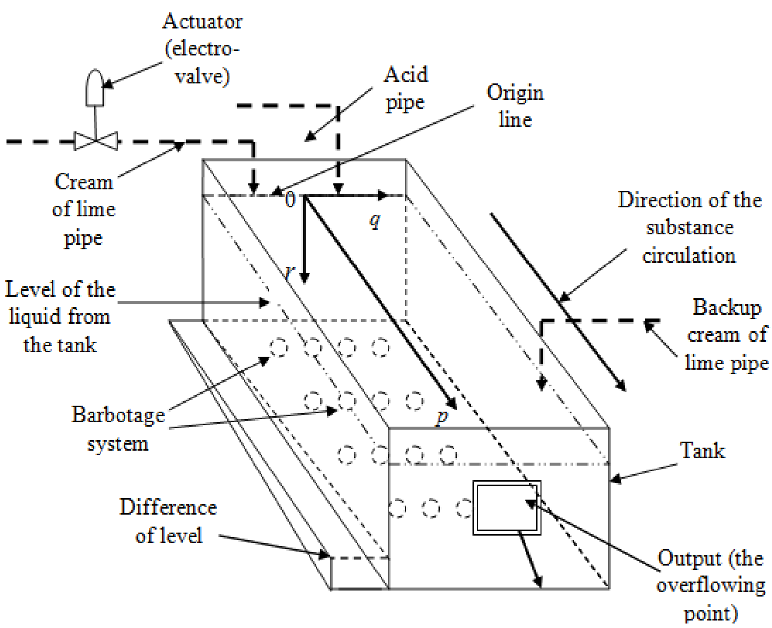

Figure 1: The general structure of the tanks from the blunting system.

notations is: y – output signals of processes and sub-processes, m – measurement signals, c – control signals, w – the reference signal, a – error signal, u – input signals in the process and f – actuating signal (the flow of cream of lime). These general notations are singularized in Fig. 2 for each element. The input signals u are equal to the product between the flow of the reactants and their pH. In the control structure, the effect of the acid, propagated through PDEA1 and PDEA2 (Fig. 2) is treated as a disturbance.

The model of the distributed parameter sub-processes from the structure of the blunting process is expressed using partial differential equations (PDEs in Fig. 2) (Krstic, 2006), (Curtain and Morris, 2009), (Smyshlyaev and Krstic, 2005). The control effect is propagated at the process output through the effect of the base (cream of lime), more exactly through PDEB1 and PDEB2 elements. The reference w is fixed at a value in unified current, proportional with 7 (pH indifferent value). The equipment from the control structure works in unified current.

The general form of the partial differential equation that describes the working of each sub-process from Fig. 2, is presented in relation 1.

$$a_{00} \cdot y_{00} + a_{10} \cdot y_{10} + a_{01} \cdot y_{01} + a_{20} \cdot y_{20} + a_{11} \cdot y_{11} + a_{02} \cdot y_{02} = \varphi_{00}, \qquad (1)$$

In relation (1), the notations $y_{....} = y_{....}(t,p)$, $\varphi_{00} = \varphi_{00}(t,p)$, $y_{TP} = (\partial^{T+P} y / \partial t^T \partial p^P)$, T=0,1,2…., and P=0,1,2,.., are used and (t), respectively (p) are the independent variables time and length. Also, in this paper, only one numerical index attached to a signal represents the differentiation order of that signal in relation to the independent variable time (t).

Relation (1) can be singularized for each PDE A1, A2, B1 and B2. In (1) the (a...) coefficients are constant and depend as value on the values of the time constants of the sub-processes and the values of their "length constants". The time constants are identified using the tangent method applied on the experimental curves. In the modeling procedure the linear increasing of these constants along the 0p axis is considered. The length constants are identified using a method based on interpolation. y(t,p) (y represents the pH value) and φ(t,p) functions respect

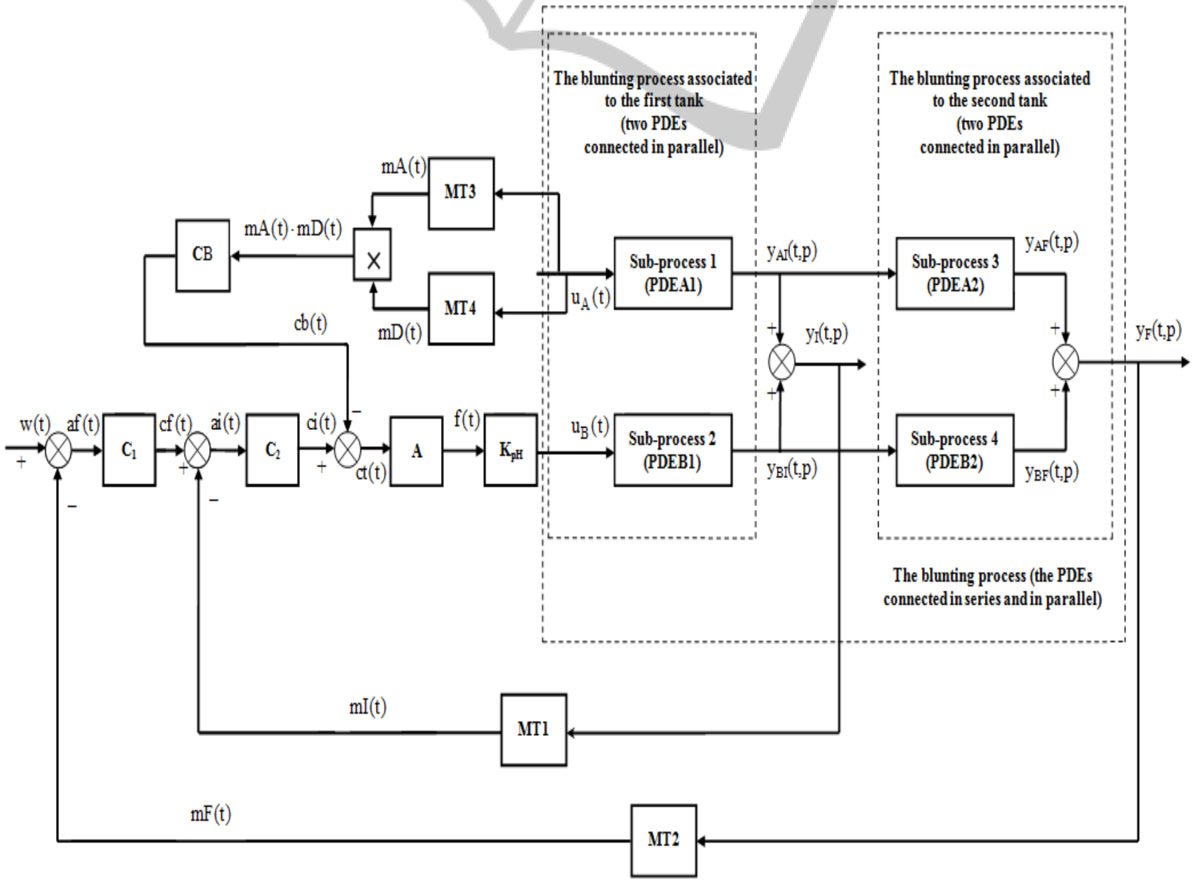

Figure 2: The proposed control structure.

the Cauchy continuity conditions. Relation (1) can be rewritten so that in the right member remains only the element y_{20}, being obvious the fact that the state variables are y_{00} and y_{10}. The other state variables result from the equations that describe the working of the other elements from the control structure, these being lumped parameter ones (their working depends only by (t) independent variable and it can be modeled using ordinary differential equations (ODE)) (Love, 2007), (Golnaraghi and Kuo, 2009). All the transducers from the control structure and the actuator are first order elements, the controllers C_1 and C_2 are of PID type (Proportional Integrator Derivative), respectively the compensation block is of PD type. The modeling procedure starts from the system of equations that describe, in transitory regime, the working of each element form Fig. 2. The system of equations is following presented:

Transducer 1 (MT1):

$$\begin{cases} m_{I0} \\ m_{I1} = \dfrac{1}{T_T} \cdot [K_T \cdot y_{I00} - m_{I0}]. \end{cases} \tag{2}$$

Transducer 2 (MT2):

$$\begin{cases} m_{F0} \\ m_{F1} = \dfrac{1}{T_T} \cdot [K_T \cdot y_{F00} - m_{F0}]. \end{cases} \tag{3}$$

Transducer 3 (MT3):

$$\begin{cases} m_{A0} \\ m_{A1} = \dfrac{1}{T_T} \cdot [K_T \cdot A_{A0} - m_{A0}]. \end{cases} \tag{4}$$

Transducer 4 (MT4):

$$\begin{cases} m_{D0} \\ m_{D1} = \dfrac{1}{T_{TD}} \cdot [K_{TD} \cdot D_{A0} - m_{D0}]. \end{cases} \tag{5}$$

PID controller 1 (C1):

$$\begin{cases} cf_0 \\ cf_1 = \dfrac{1}{T_C} \cdot [K_{PC1} \cdot (w_0 - m_{F0}) + K_{DC1} \cdot (w_1 - m_{F1}) - cf_0] \\ cf_2 = \dfrac{1}{T_C} \cdot [K_{PC1} \cdot (w_1 - m_{F1}) + K_{IC1} \cdot (w_0 - m_{F0}) + \\ \quad + K_{DC1} \cdot (w_2 - m_{F2}) - cf_1] \end{cases} . \tag{6}$$

PID controller 2 (C2):

$$\begin{cases} ci_0 \\ ci_1 = \dfrac{1}{T_C} \cdot [K_{PC2} \cdot (cf_0 - m_{I0}) + K_{DC2} \cdot (cf_1 - m_{I1}) - ci_0] \\ ci_2 = \dfrac{1}{T_C} \cdot [K_{PC2} \cdot (cf_1 - m_{I1}) + K_{IC2} \cdot (cf_0 - m_{I0}) + \\ \quad + K_{DC2} \cdot (cf_2 - m_{I2}) - ci_1] \end{cases} . \tag{7}$$

Actuator (A):

$$\begin{cases} u_{B0} \\ u_{B1} = \dfrac{1}{T_A} \cdot (K_{pH} \cdot K_A \cdot ct_0 - u_{B0}). \end{cases} \tag{8}$$

Compensation block (CB)

$$\begin{cases} cb_0 \\ cb_1 = \dfrac{1}{T_{CB}} \cdot [K_{PCB} \cdot (mD_0 \cdot mA_0) + \\ \quad + K_{DCB} \cdot (\dfrac{d}{dt}(mD_0 \cdot mA_0)) - cb_0] \\ cb_2 = \dfrac{1}{T_{CB}} \cdot [K_{PCB} \cdot (\dfrac{d}{dt}(mD_0 \cdot mA_0)) + \\ \quad + K_{DCB} \cdot (\dfrac{d^2}{dt^2}(mD_0 \cdot mA_0)) - cb_1] \end{cases} . \tag{9}$$

The final control signal:

$$ct_0 = ci_0 - cb_0 \tag{10}$$

Sub-processes 1-4 ($i \in \{AI, AF, BI, BF\}$) (PDE II·2):

$$\begin{cases} y_{i00} \\ y_{i10} \\ y_{i20} = \dfrac{1}{a_{20}} \cdot [\varphi_{i00} - (a_{00} \cdot y_{i00} + a_{10} \cdot y_{i10} + \\ \quad + a_{01} \cdot y_{i01} + a_{11} \cdot y_{i11} + a_{02} \cdot y_{i02})] \end{cases} \tag{11}$$

The output signal from the process associated to the first tank:

$$y_{I0} = y_{AI0} + y_{BI0} \tag{12}$$

The output signal from the process associated to the second tank:

$$y_{F0} = y_{AF0} + y_{BF0} \tag{13}$$

Relation (11) results from relation (1) rewritten in the presented form. Using the equations associated to these elements and relation (1) singularized for the four sub-processes, two state vectors result. The first state vector is associated to the main control system from Fig. 2 and results from

$x_B^T =$	mI_0	mI_1	mF_0	mF_1	mA_0	mA_1	mD_0	mD_1	cf_0	cf_1	ci_0	ci_1	cb_0	cb_1	u_{B0}	u_{B1}	y_{BI00}	y_{BI10}	y_{BF00}	y_{BF10}

Figure 3: The state vector associated to the main control signal.

$x_A^T =$	y_{AI00}	y_{AI10}	y_{AF00}	y_{AF10}

Figure 4: The state vector associated to the propagation of the acid effect.

relations (2), (3), (4), (5), (6), (7), (8), (9), respectively (11) (for $i \in \{BI,BF\}$). The first state vector contains 20 elements. The second one is associated to the disturbance propagation effect, containing 4 elements (the y_{00} and y_{10} elements associated to PDEA1 and PDEA2 from relation (11)). The two state vectors, in transposed form, are presented in Fig. 3 and Fig. 4. The significance of the new notations used in relations (2) – (13) is: K_T – proportionality constant of the pH transducers; T_T – time constant of the pH transducers; K_{TD} – proportionality constant of the flow transducer; T_{TD} – time constant of the flow transducer; A_{A0} – pH value of the acid at the input in the tank; D_{A0} – acid flow at the input in the tank; T_C – time constant of the two controllers C_1 and C_2; K_{PC1} and K_{PC2} – proportionality constants of the two controllers C_1 and C_2; K_{IC1} and K_{IC2} – – integral constants of the two controllers C_1 and C_2; K_{DC1} and K_{DC2} – derivative constants of the two controllers C_1 and C_2; T_A – time constant of the actuator; K_A – proportionality constant of the actuator; K_{pH} – proportionality constant equal to 5 (the difference between the cream of lime pH and the indifferent pH value (7)); T_{CB} – time constant of the compensation block; K_{PCB} – proportionality constant of the compensation block; K_{DCB} – – derivative constant of the compensation block.

In order to simulate the control structure that includes 4 PDEs (that involve major simulation problems) on the computer and using the state vectors, the two Matrices of Partial Derivatives of the State Vector (Mpdx) (Coloşi et al., 2013) can be determined, with the general form presented in relation (14).

In (14) the significance of the notations is: $\mathbf{x}$ – – the state vector, $\mathbf{x_{Ti}}$ – the vector of partial derivatives of the state vector in relation to time (t) (the first elements of the $\mathbf{x_{Ti}}$ vector are the pivot elements), $\mathbf{x_{Pi}}$ – the matrix of partial derivatives of

$$\mathbf{M}_{\mathbf{pdxi}} = \overset{\quad 1 \qquad\quad M}{\begin{bmatrix} \mathbf{x_i} & \mathbf{x_{Pi}} \\ \mathbf{x_{Ti}} & \mathbf{x_{TPi}} \end{bmatrix}} \begin{matrix} n \\ N \end{matrix} \tag{14}$$

the state vector in relation to length (p), $\mathbf{x_{TPi}}$ – the matrix of partial derivatives of the state vector in relation both to time (t) and length (p). Also the index i signifies that relation (14) can be singularized for the two previous mentioned cases. The (Mpdx) associated to the control system has the dimension (70×9) (M = 8; n = 20; N = 50). Morever, the (Mpdx) associated to the propagation of the acid effect has the dimension (14×9) (M = 8; n = 4; N = 10). For the initialization of the matrices from (14), the analytical approximating solution that verifies (1) can be used, solution that is a product of exponential functions. In the case of PDEA1 and PDEA2, the analytical approximating solution has a decreasing evolution both in relation to (t) and (p). Differently, in the case of PDEB1 and PDEB2, the solution has an increasing evolution in relation with both independent variables. After the initialization, the numerical simulation algorithm can start. To advance from the sequence (k) to the next one (k+1) the Taylor series are used, resulting the elements of the $\mathbf{x}$ vector and of the $\mathbf{x_{Pi}}$ matrix. Using these values, the elements of the $\mathbf{x_{Ti}}$ vector and of the $\mathbf{x_{TPi}}$ matrix. The algorithm stops at the predefined period of time and the integration step is considered small enough for a correct numerical integration.

3 THE SIMULATIONS RESULTS

The simulations are made in MATLAB.

The imposed performances to the control structure are: steady state error at position equal to 0, overshoot smaller, in module, than 2.5%, settling time smaller than 20 min, respectively the actuating signal not to increase over the saturation limit. Also one of the purposes of this paper is to determine the control structure that generates the best set of performances.

The two feedback signals associated to the cascade structure result measuring the pH values at the output of the two processes (at the output of tank 1, respectively equivalent tank). The process associated to tank 1, due to the smaller length of this tank, is faster than the process associated to equivalent tank and it is included in the internal loop. The compensation block CB (see Fig. 2) receives the measurement signals of the flow and of the pH value of the disturbance (of the acid introduced in the reaction) and generates a control signal that is finally subtracted from the control signal C_2. The compensation generated by CB represents the feed-forward component of the structure. The tuning of both controllers C_1 and C_2 is made using an adapted form of module criterion for the case when the model of the process is expressed through PDEs (for this type of processes do not exist specific tuning methods). Using the module criterion (applied for second order processes) is obtained the general form of the controller parameters, valid for both controllers: $K_{PC} = \frac{T_1 + T_2}{2 \cdot K_{EX} \cdot T_\Sigma}$, $K_{IC} = \frac{1}{2 \cdot K_{EX} \cdot T_\Sigma}$, $K_{DC} = \frac{T_1 \cdot T_2}{2 \cdot K_{EX} \cdot T_\Sigma}$, where T_1 and T_2 (through singularization) are the time constants corresponding to each of the two processes (these constants are calculated in each of the two cases for the corresponding values of (p)). Also, $T_\Sigma = T_T + T_A + T_C$. The K_{EX} constant is present in all three formulae and, while changing its value, the three controller parameters are simultaneously modified. Firstly, the value of the K_{EX} is fixed for the controller from the internal loop. After that, another value of the K_{EX} constant is chosen for the controller from the external loop. The numerical simulation of the control structure is made in order to obtain the system performances. If the performances are not enclosed in the imposed limits, the value of K_{EX} associated to C_1 is decreased progressively, for each decrease the simulation of the structure being repeated and, in each case the obtained performances being evaluated. Hence, the tuning method is an iterative one. In the case when, from a simulation to the following one, the performances of the system do not have a significant improvement, the K_{EX} constant associated to C_2 is decreased as value and keeping this value constant, the iterative procedure previously presented is repeated (modifying only the parameters of C_1) until the imposed performances are obtained. In order to obtain much better performances than the imposed ones, the iterative tuning procedure can be continued, but taking into consideration the variation form and limits of the actuating signal. The variation of the K_{EX} constants between two successive iterations, in both controller cases, has not an imposed value (being modified considering the grade of the performances improvement from an iteration to the next one). In each controller case, decreasing the value of the K_{EX} constant we can obtain a stronger control effect (action).

After obtaining the parameters of C_1 and C_2, the tuning of CB can be made. Using the same general formulae, as in the case of C_1 and C_2, but only a PD structure, the K_{EX} constant is decreased progressively until the best possible performances are obtained. After applying the presented procedure, the following parameters are obtained: for C_1: $K_{EX1} = 437.93$, for C_2: $K_{EX2} = 0.35$, respectively for CB: $K_{EXCB} = 10$.

In Fig. 5, the comparative graph between the automatic system's analytical and numerical step response is presented, at the overflowing point from the system (the overflowing point of the equivalent tank), considering the components of the disturbance constants at the values $pH_A = 3$ and $D_A(t) = 3$l/s (step disturbance, usual in the treated case).

On the graph the two responses cannot be differentiated with the free eye due to the very small errors between them. In steady state regime, the value of cumulated relative error in percents (Ungureșan and Niac, 2011) is proportional to 10^{-3}%, this value very close to 0 showing the very good numerical simulation performances. Also the obtained control performances are very high ones, the steady state error at position being 0 (the effect of the disturbance is rejected), the settling time can be considered 0 min because the value of the response is enclosed in the stationary band of ±1% around the steady state value (7) and the overshoot module has an insignificant value of 0.03 % (the pH variation around 7 does not affect the good working of the system).

The necessity of using a very complex control structure appears due to the fact that the imposed performances to the control structure are very restrictive ones, due to the sensitive character of the application. In order to study the possibility of reducing the cost of the control system, the structure for Fig. 2 can be singularized to a simple cascade structure or a simple feed-forward one. The comparative graph between the responses of the three structures, in the same simulation conditions as in Fig. 5 case and for the controllers that generate the best results that could be obtained is shown in Fig. 6. For the case of cascade structure the proportionality constant of the element CB is considered 0. For the feed-forward structure, the C_2 equivalent value is considered 1 and the proportionality constant of the MT element is considered 0. It can be remarked from Fig. 6 that the performances of the system decrease significantly if we reduce the complexity of the control structure, but, for this value of the disturbance, the simple cascade or feed-forward structure can be used, too.

Also the using of a simple monocontour structure (in Fig. 2 the compensation and the internal loops will not appear and C_2 is made 1) is not an option because it generates, in the best case an overshoot with a value in module 7%, that is not functionally permitted. This phenomenon is highlighted in Fig. 7 where the comparative graph between the system's numerical responses in the case of using a simple feedback (monoconture) structure, respectively in the case of using the advanced control structure proposed in this paper, is presented.

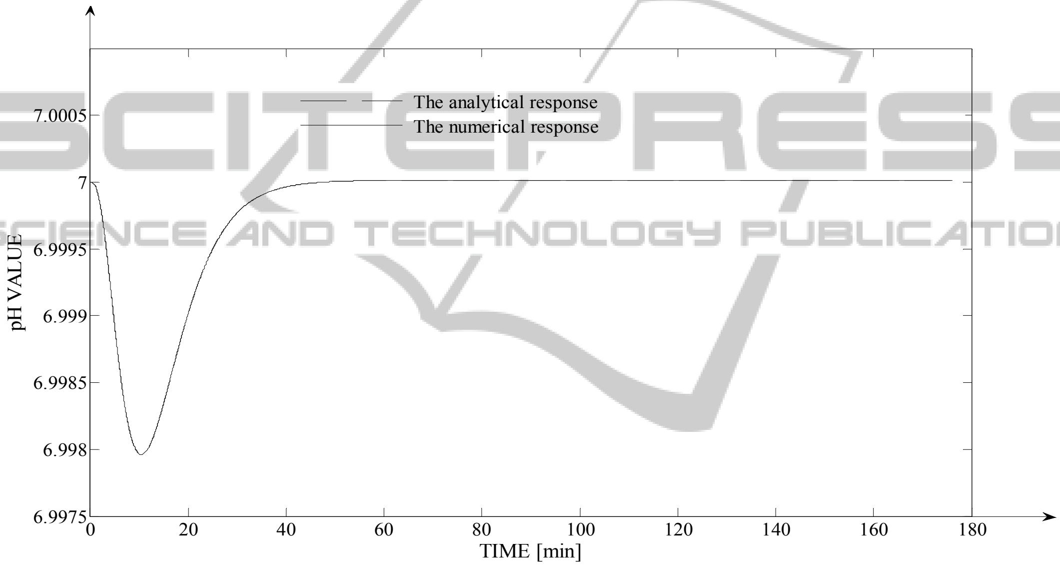

Figure 5: Analytical and numerical step response of the system at the overflowing point.

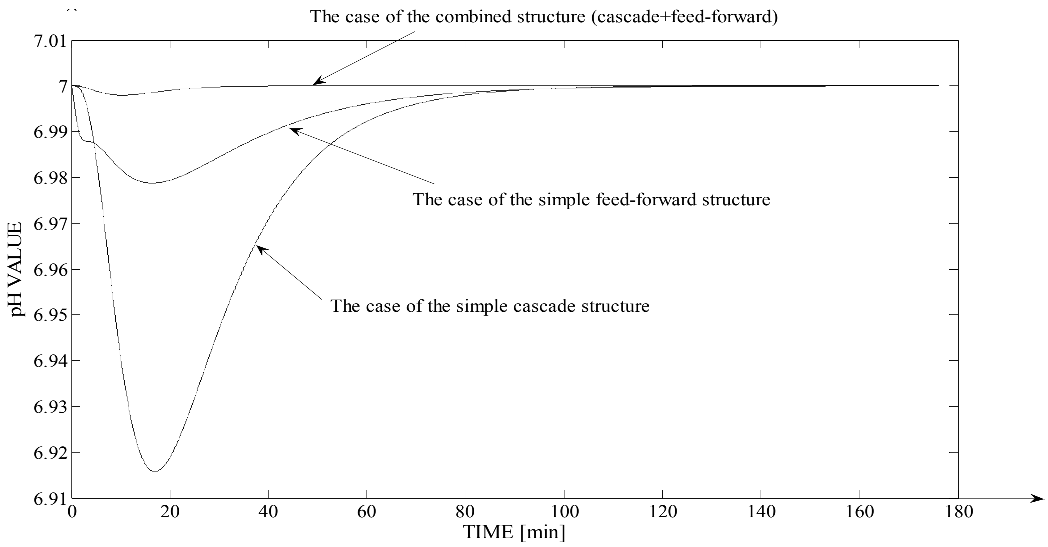

Figure 6: Comparative graph between the simulations of different control structures.

The simulation from Fig. 6 is made for the best controller that could be obtained for the simple feedback control structure ($K_{PR} = 8.2286$, $K_{IR} = 0.4675\,\text{min}^{-1}$ and $K_{DR} = 34.7575\,\text{min}$). Another major disadvantage in using the simple feedback control structure is an unacceptable value of the response settling time, in this case 64 min.

In Fig. 8, the evolutions in time of the actuating signals corresponding to the responses from Fig. 7, are presented. From Fig. 8, it can be remarked that the two actuating signals do not present value "jumps", respectively their maximum value (2.4 l/s) is smaller than the saturation limit (4 l/s). The main advantage of using the advanced control structure is the fact that, due to the effect generated by the two controllers and by the compensation block, the corresponding actuating signal increases much faster than in the case of using the simple control structure. Practically, the three control elements force the rapid increasing of the value of the actuating signal.

The control performances obtained in the case of the four studied control structures are summarized in Table 2. From Table 2 it obviously results that the complex control structure from Fig. 2 generates the best performances. Also, it results that, from the other three (more simple) treated control structures, the feed-forward type one generates good results.

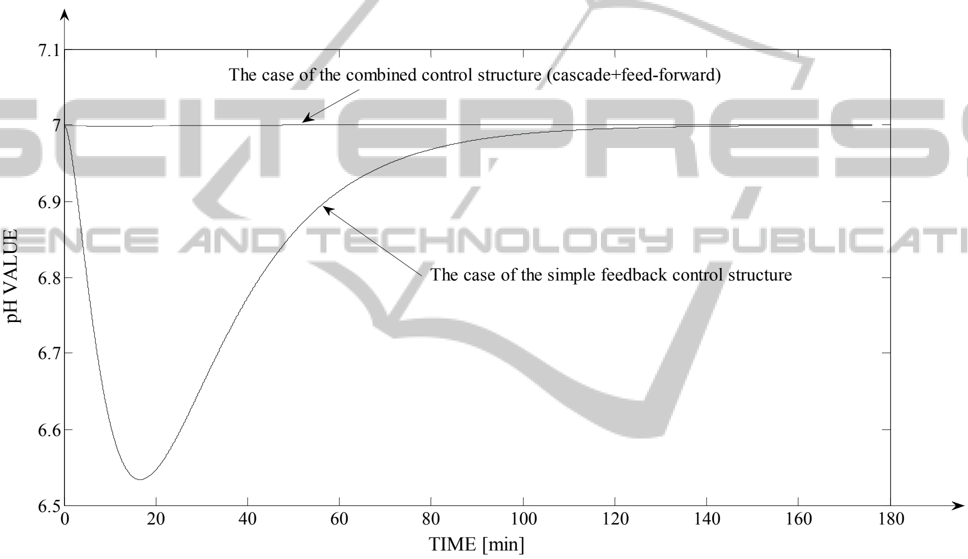

Figure 7: Comparative graph between the responses of the advanced control system and of the simple feedback system.

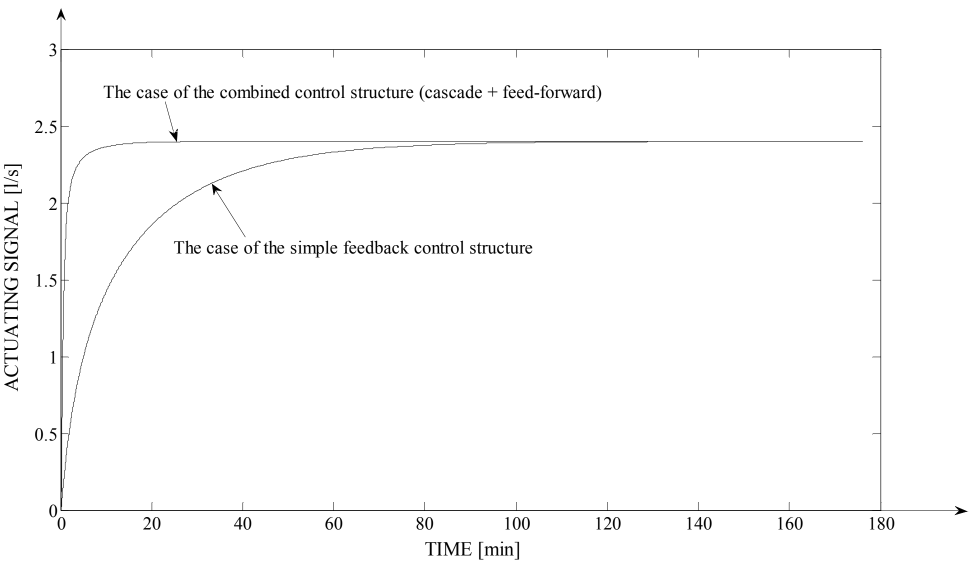

Figure 8: The actuating signals.

Table 2: The obtained performances.

Control structure	Steady state error at position	Overshoot (in module)	Settling time
The combined structure (cascade + feed-forward)	0	0.03 %	≈0 min
The simple cascade structure	0	1.21 %	24 min
The simple feed-forward structure	0	0.28 %	≈0 min
The simple feedback control structure	0	7%	64 min

From the other simulations, it resulted that the initial structure (Fig. 2) can efficiently reject the effect of other types of disturbances, for example sine type disturbances. In Fig. 9, the effect of a more severe disturbance (pH_A = 2 and $D_A(t)$ = 4 l/s) that occurs in the process is presented. In this case, too, the controllers, respectively the compensation block reject very efficient the effect of the disturbance, the obtained performances being comparable with the case of the initial disturbance. The corresponding actuating signal does not increase over the saturation value, neither in this case.

4 CONCLUSIONS

We argue that the advanced control strategy proposed in this paper (Fig. 2) assures good performance (justified by Fig. 5-9).

The very high obtained control performances prove that the advanced control strategy proposed by the author in Fig. 2 is justified, the blunting process being very restrictive from the ecological point of view.

The fact that the process is viewed as a distributed parameter one offers an important technological advantage because the user has the possibility to control the pH value in each point from the tanks.

The original numerical simulation procedure based on Mpdx and Taylor series, proposed in this paper, generates a very high accuracy of the simulation and offers the possibility to simulate systems that include distributed parameter processes.

The simulations were made to test the system before its physical implementation. In all the simulation the value of the actuating signal does not exceed the saturation limit.

In the presented approach, the effect of the acid propagation phenomenon in the system is treated as a disturbance. In this case, the value of the disturbance is given by two components: the acid pH and the acid flow at the input in the system. The control system offers high performances even in the case when a more severe disturbance occurs in the process.

The main contributions of the authors in elaborating this paper are: the process modeling using partial differential equations; the decomposition of the main process in four sub-processes connected in series and in parallel; the

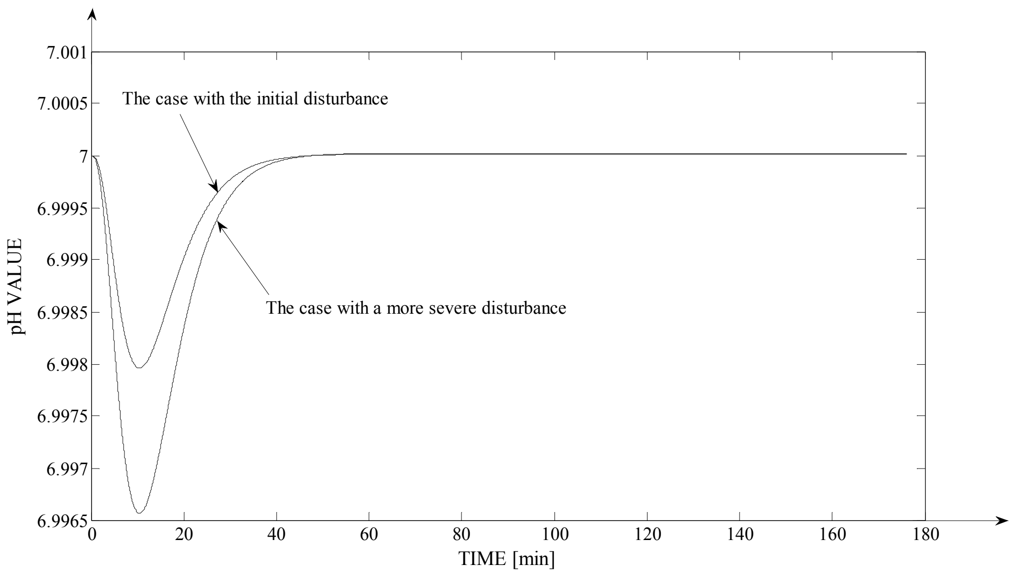

Figure 9: The effect of a more severe disturbance.

including of the four distributed parameter sub-processes in a control structure; the usage of a combined cascade + feed-forward control structure for the pH control; the numerical simulation of the proposed control structure using an original method for the simulation of the distributed parameter systems.

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