ISSN 1392 – 124X INFORMATION TECHNOLOGY AND CONTROL, 2011, Vol. 40, No. 3

DIGITAL SELF-TUNING PID CONTROL OF PRESSURE PLANT WITH CLOSED-LOOP OPTIMIZATION

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crossref http://dx.doi.org/10.5755/j01.itc.40.3.628

Abstract. In this paper we propose a method for optimization of closed-loop parameters and continuous-time sampling period by digital self-tuning PID control of pressure plant. The quality of pressure plant control is experimentally compared between two modifications of digital self-tuning PID controllers. The results of adaptive pressure plant control show that the optimization of closed-loop parameters and sampling period provides significantly improved control performance.

Keywords: pressure plant, self-tuning PID controller, closed-loop parameters, sampling period, optimization.

1. Introduction

Nowadays, modern modelling, simulation, adaptation and intellect methods in control systems of various technological processes and plants are used [1, 5, 7-9, 11]. Technological processes commonly are continuous-time plants. For the digital control of continuous-time plant a sampling period of the signals is necessary to choose, which impacts the closed-loop characteristics [2].In digital PID control, the closed-loop characteristics are commonly decided by two parameters – the natural frequency of oscillation and the damping factor. The digital self-tuning PID control based on direct model identification is associated with the discrete model building and online identification of its parameters. Sampling period influences the location of the roots of model polynomials in the unit circle. On a short sampling period, the roots of model polynomials locate close to the limit of stability domain. In the process of online identification, this can cause the discrete model to become unstable [6]. All of this affects control error.

In this paper, a new method, as a solution for this problem, is proposed – the closed-loop parameters and sampling period are chosen by optimizing the control quality criterion. The experimental investigation of method effectiveness for pressure plant is performed by comparing two digital self-tuning PID controllers [10].

2. The plant

The scheme of pressure plant is demonstrated in Figure 1. The plant consists of four main components: the combined air inlet (no. 1) and outlet (no. 4) tanks, two air chambers (no. 2) and two tubes (no. 3) with balls (no. 6) in them. The air from the inlet tank flows to air channels through air chambers and leaves the equipment through the upper outlet tank. The distance to balls is measured using ultrasound distance sensors (no. 5). The fans (no. 7) are used to create pressure in the air channels in order to lift the balls in tubes. The air chambers are utilized for the purpose to stabilize oscillations of the pressure in each tube.

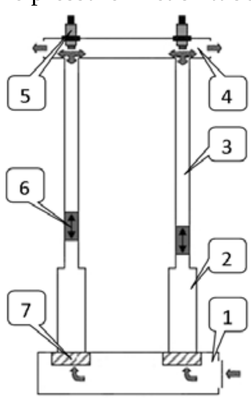

Figure 1. The scheme of pressure plant

The momentum of the fan, the inductance of the fan motor, air turbulence in the tube leads to complex physics governing ball's behaviour. Slightly different weights of the balls and the location of air feeding vent additionally impact the behaviour of ball in the tubes.

The input signals of the plant are the voltage values for each fan and the output signals are the distances between balls and the bottom of their tubes in centimetres.

The control objective of pressure plant is to regulate the speed of a fan supplying the air into a tube so as to keep a ball suspended at some predetermined level in the tube.

Such plants exist in air conditioning and cooling systems.

The elements of control system and technical characteristics of the plant are as follows: the volume of air inlet tank is about 7000 cm^3, the diameter of air feeding valve – 7 cm. The volume of each air chamber is about 1300 cm^3. Each tube is 110 cm long with a diameter of 4 cm. The volume of air outlet tank is about 2900 cm^3, the diameters of air outlet vents - 6.5 cm. The weights of the balls for the first and for the second tube are 3.62 g. and 3.58 g. respectively. For each air chamber, two coupled “Zalman PS80252H” fans are utilized and “Nivelco Microsonar UTP-212-4” ultrasound sensors are used for sensing the positions of the balls. The Beckhoff BK9000 PLC is used for digital control of pressure plant, i.e. reading output signals from sensors and sending input signals to the control mechanism of the fans. Controller is configured and controlled by TwinCat software.

3. Digital self-tuning PID controllers

The tubes of pressure plant are defined by discrete linear second order models, that is

$$A^{(i)}(z^{-1})y_t^{(i)} = B^{(i)}(z^{-1})u_t^{(i)} + \xi_t^{(i)}, \tag{1}$$

$$B^{(i)}(z^{-1}) = b_1^{(i)}z^{-1} + b_2^{(i)}z^{-2}, \tag{2}$$

$$A^{(i)}(z^{-1}) = 1 + a_1^{(i)}z^{-1} + a_2^{(i)}z^{-2}, \tag{3}$$

where $i = 1,2$ denotes the ith tube of the plant, $y_t^{(i)} = y^{(i)}(tT_0)$, $u_t^{(i)} = u^{(i)}(tT_0)$ – output and input signals with sampling period T_0, respectively, $\xi_t^{(i)}$ – a white noise of the ith tube with a zero mean and finite variance and z^{-1} is the backward-shift operator. The digital control of pressure plant is modelled by two types of digital self-tuning PID controllers: PID-A and PID-B [10]. The PID-A controller is defined as [10]

$$S^{(i)}(z^{-1})u_t^{(i)} = R^{(i)}(z^{-1})e_t^{(i)}, \tag{4}$$

$$S^{(i)}(z^{-1}) = (1 - z^{-1})(1 + \gamma^{(i)}z^{-1}), \tag{5}$$

$$R^{(i)}(z^{-1}) = r_0^{(i)} + r_1^{(i)}z^{-1} + r_2^{(i)}z^{-2}, \tag{6}$$

$$e_t^{(i)} = y_t^{(i)^*} - y_t^{(i)}, \tag{7}$$

where $y_t^{(i)^*}$ is a reference signal, $e_t^{(i)}$ - a control error and $\gamma^{(i)}, r_0^{(i)}, r_1^{(i)}, r_2^{(i)}$ are the parameters of PID-A controller of the ith tube.

In order to calculate the parameters of PID-A controller the desired polynomial of closed-loop characteristic is needed, which for the ith tube is formulated as

$$D^{(i)}(z^{-1}) = 1 + \sum_{j=1}^{n_d} d_j^{(i)} z^{-j},\ n_d \le 4, \tag{8}$$

and is defined by converting continuous-time second order system

$$s^2 + 2\zeta_i\omega_i s + \omega_i^2 = 0, \tag{9}$$

to its discrete analogue by Laplace transformation. The coefficients of this polynomial are then calculated by [4]

$$\begin{aligned} d_1^{(i)} &= \begin{cases} -2\exp(-\zeta_i\omega_i T_0)\cos(\omega_i T_0\sqrt{1-\zeta_i^2}), & if\ \zeta_i \le 1 \\ -2\exp(-\zeta_i\omega_i T_0)\cosh(\omega_i T_0\sqrt{\zeta_i^2 - 1}), & if\ \zeta_i > 1 \end{cases}, \\ d_2^{(i)} &= \exp(-2\zeta_i\omega_i T_0), \\ d_3^{(i)} &= d_4^{(i)} = 0, \end{aligned} \tag{10}$$

where ω_i is the natural frequency of oscillation, ζ_i is the damping factor.

The parameters of PID-A controller are computed by [4]

$$\gamma^{(i)} = r_2^{(i)}\frac{b_2^{(i)}}{a_2^{(i)}}, \tag{11}$$

$$r_0^{(i)} = \frac{1}{b_1^{(i)}}(d_1^{(i)} + 1 - a_1^{(i)} - \gamma^{(i)}), \tag{12}$$

$$r_1^{(i)} = \frac{a_2^{(i)}}{b_2^{(i)}} - r_2^{(i)}\left(\frac{b_1^{(i)}}{b_2^{(i)}} - \frac{a_1^{(i)}}{a_2^{(i)}} + 1\right), \tag{13}$$

$$r_2'^{(i)} = a_2^{(i)}[(b_1^{(i)} + b_2^{(i)})(a_1^{(i)}b_2^{(i)} - a_2^{(i)}b_1^{(i)})], \tag{14}$$

$$r_2''^{(i)} = a_2^{(i)}b_2^{(i)}(b_1^{(i)}d_2^{(i)} - b_2^{(i)}d_1^{(i)} - b_2^{(i)}), \tag{15}$$

$$r_2^{(i)} = \frac{r_2'^{(i)} + r_2''^{(i)}}{[b_1^{(i)} + b_2^{(i)}][a_1^{(i)}b_1^{(i)}b_2^{(i)} - a_2^{(i)}(b_1^{(i)})^2 - (b_2^{(i)})^2]}, \tag{16}$$

The PID-B controller is defined as [10]

$$S^{(i)}(z^{-1})u_t^{(i)} = \beta^{(i)}e_t^{(i)} - R^{(i)}(z^{-1})y_t^{(i)}, \tag{17}$$

$$S^{(i)}(z^{-1}) = (1 - z^{-1})(1 + \gamma^{(i)}z^{-1}), \tag{18}$$

$$\begin{aligned} R^{(i)}(z^{-1}) &= r_0^{(i)}(1 - z^{-1})\left(1 - \frac{r_2^{(i)}}{r_0^{(i)}}z^{-1}\right) \\ &= r_0^{(i)} - (r_0^{(i)} + r_2^{(i)})z^{-1} + r_2^{(i)}z^{-2}. \end{aligned} \tag{19}$$

The parameters of PID-B controller of the ith tube are computed by [4]

$$\beta^{(i)} = \frac{1}{b_1^{(i)}}(d_1^{(i)} + 1 - a_1^{(i)} - \gamma^{(i)} - b_1^{(i)}r_0^{(i)}), \tag{20}$$

$$\gamma^{(i)} = r_2^{(i)}\frac{b_2^{(i)}}{a_2^{(i)}}, \tag{21}$$

$$r_0^{(i)} = r_2^{(i)}\left(\frac{b_1^{(i)}}{b_2^{(i)}} - \frac{a_1^{(i)}}{a_2^{(i)}}\right) - \frac{a_2^{(i)}}{b_2^{(i)}}, \tag{22}$$

$$r_2'^{(i)} = a_2^{(i)} b_2^{(i)} [a_1^{(i)} (b_1^{(i)} + b_2^{(i)}) + b_1^{(i)} (d_2^{(i)} - a_2^{(i)})], \tag{23}$$

$$r_2''^{(i)} = -a_2^{(i)} [(b_2^{(i)})^2 (d_1^{(i)} + 1) + a_2^{(i)} (b_1^{(i)})^2], \tag{24}$$

$$r_2^{(i)} = \frac{r_2'^{(i)} + r_2''^{(i)}}{[b_1^{(i)} + b_2^{(i)}][a_1^{(i)} b_1^{(i)} b_2^{(i)} - a_2^{(i)} (b_1^{(i)})^2 - (b_2^{(i)})^2]}. \tag{25}$$

Since the model parameters of each tube are unknown, the technique of adaptive control with indirect adaptation [3, 4] is applied (Figure 2).

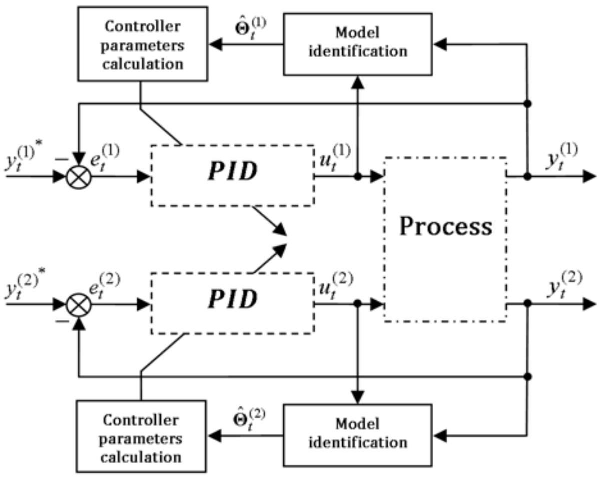

Figure 2. The scheme of digital self-tuning PID control of pressure plant

The unknown model parameters of the ith tube are obtained by recursive least squares algorithm with forgetting factor [4]

$$\hat{\mathbf{\Theta}}_t^{(i)} = \begin{cases} \hat{\mathbf{\Theta}}_{t-1}^{(i)}, & \text{if } \left|e_t^{(i)}\right| \le \delta_e^{(i)} \text{ or } \left|z_j^{(i)}\right| < 1 \\ \hat{\mathbf{\Theta}}_{t-1}^{(i)} + \dfrac{\mathbf{C}_t^{(i)} \mathbf{\varphi}_{t-1}^{(i)}}{1 + \eta_t^{(i)}} \hat{\varepsilon}_t^{(i)}, & \text{otherwise} \end{cases}, \tag{26}$$

$$\hat{\mathbf{\Theta}}_t^{(i)T} = [\hat{a}_1^{(i)}, \hat{a}_2^{(i)}, \hat{b}_1^{(i)}, \hat{b}_2^{(i)}], \tag{27}$$

$$\mathbf{\varphi}_{t-1}^{(i)T} = [-y_{t-1}^{(i)}, -y_{t-2}^{(i)}, u_{t-1}^{(i)}, u_{t-2}^{(i)}], \tag{28}$$

$$\eta_t^{(i)} = \mathbf{\varphi}_{t-1}^{(i)T} \mathbf{C}_t^{(i)} \mathbf{\varphi}_{t-1}^{(i)}, \tag{29}$$

$$\hat{\varepsilon}_t^{(i)} = y_t^{(i)} - \hat{\mathbf{\Theta}}_{t-1}^{(i)T} \mathbf{\varphi}_{t-1}^{(i)}, \tag{30}$$

$$\mathbf{C}_t^{(i)} = \begin{cases} \mathbf{C}_{t-1}^{(i)} - \dfrac{\mathbf{C}_{t-1}^{(i)} \mathbf{\varphi}_{t-1}^{(i)} \mathbf{\varphi}_{t-1}^{(i)T} \mathbf{C}_{t-1}^{(i)}}{\lambda_t^{-1(i)} + \eta_t^{(i)}}, & \text{if } \eta_t^{(i)} > 0 \\ \mathbf{C}_{t-1}^{(i)}, & \text{if } \eta_t^{(i)} = 0 \end{cases}, \tag{31}$$

$$\lambda_t^{(i)} = \varphi^{(i)} - \frac{1 - \varphi^{(i)}}{\eta_{t-1}^{(i)}}, \tag{32}$$

where $\hat{\mathbf{\Theta}}^{(i)}$ is the estimated vector of model parameters, $\mathbf{C}^{(i)}$ – a square covariance matrix, $\mathbf{\varphi}^{(i)}$ – a data vector, $\hat{\varepsilon}^{(i)}$ – the prediction error, $\varphi^{(i)}$ – the forgetting factor, $\eta^{(i)}, \lambda^{(i)}$ – auxiliary variables, $\delta_e^{(i)}$ – a constant that defines the admissible interval of control error and $z_j^{(i)}$, $j = 1,2$ are the roots of polynomial $\hat{A}_t^{(i)}(z^{-1})$ of the ith tube.

In the modification of the algorithm (26), the estimates of model parameters are updated only if the value of $e_t^{(i)}$ is outside of the admissible interval defined by $\delta_e^{(i)}$ and the model after its last estimation remains stable.

4. Closed-loop optimization

The required control response or error of closed-loop by digital self-tuning PID-A or PID-B controllers can be achieved by appropriate selection of ω_i, ζ_i, T_0 parameters of the ith tube.

The control quality of the ith tube can be defined by criterion

$$Q_i(\omega_i, \zeta_i, T_0) = \frac{1}{N} \sum_{t=1}^{N} [(y_t^{(i)*} - y_t^{(i)})^2 + \rho (u_t^{(i)} - u_{t-1}^{(i)})^2], \tag{33}$$

where N is the number of observations, $\rho \ge 0$ is a weight coefficient.

In such a case, it is reasonable to find parameters $\omega_i^*, \zeta_i^*, T_0^*$ that minimize criterion (33)

$$\omega_i^*, \zeta_i^*, T_0^*: \quad Q_i(\omega_i, \zeta_i, T_0) \to \min_{\omega_i, \zeta_i, T_0}(Q_i). \tag{34}$$

This problem is solved using sub-component optimization methodology [6]

$$\begin{aligned} \omega_i^{(j)}, \zeta_i^{(j)}: &\quad Q_i(\omega_i, \zeta_i, T_0^{(j-1)}) \to \min_{\omega_i, \zeta_i}(Q_i) \\ T_0^{(j)}: &\quad Q_i(\omega_i^{(j)}, \zeta_i^{(j)}, T_0) \to \min_{T_0}(Q_i) \end{aligned} \quad j = 1, 2, \ldots \tag{35}$$

Each of those problems is solved as follows. Since the functions

$$J_i^{(j)}(T_0) = Q_i(\omega_i^{(j)}, \zeta_i^{(j)}, T_0), \tag{36}$$

at the jth stage in sub-component optimization are one-variable functions, it is reasonable to use one of the most effective direct search method – golden section method for their minimization [6]. Search algorithm is related with an initial uncertainty interval

$$[T_{01}, T_{04}] \subset [0, T_{0\max}^{(j)}], \tag{37}$$

reduction to the interval

$$[T_{01}^{(L)}, T_{04}^{(L)}], \quad \text{if } T_{04}^{(L)} - T_{01}^{(L)} \le \Delta T_0^{(j)}, \tag{38}$$

where its length is not longer than desired $\Delta T_0^{(j)}$, and with a function (36) minimum inside.

For this purpose, at the jth iteration of the search procedure two new values of sampling period T_0 are chosen

$$\begin{aligned} T_{02}^{(l)} &= 0.382 \times (T_{04}^{(l)} - T_{01}^{(l)}) + T_{01}^{(l)} \\ T_{03}^{(l)} &= 0.618 \times (T_{04}^{(l)} - T_{01}^{(l)}) + T_{01}^{(l)} \end{aligned}, \tag{39}$$

and a new uncertainty interval is then defined by the rule

$$\begin{aligned} [T_{01}^{(l+1)}, T_{04}^{(l+1)}] &= [T_{01}^{(l)}, T_{03}^{(l)}], \quad \text{if } J_i^{(j)}(T_{02}^{(l)}) < J_i^{(j)}(T_{03}^{(l)}) \\ [T_{01}^{(l+1)}, T_{04}^{(l+1)}] &= [T_{02}^{(l)}, T_{04}^{(l)}], \quad \text{otherwise} \end{aligned} \tag{40}$$

Sampling period $T_0^{(j)}$ at the jth stage in sub-component optimization is then calculated by

$$T_0^{(j)} = \frac{T_{01}^{(L)} + T_{04}^{(L)}}{2}. \tag{41}$$

The maximum sampling period $T_{0\max}^{(j)}$ is obtained by [2]

$$T_{0\max}^{(j)} = \frac{0.6}{\omega_i^{(j)}}. \tag{42}$$

The functions of two variables

$$F_i^{(j)}(\omega_i, \zeta_i) = Q_i(\omega_i, \zeta_i, T_0^{(j-1)}) \tag{43}$$

are also minimized using sub-component optimization method, where the golden section algorithms, analogous to (37) – (42), are used for the search of the parameters ω_i and ζ_i.

The optimization of closed-loop parameters and sampling period is performed offline.

The reference signals with representative spectral density must be applied in order to satisfy closed-loop identifiability conditions [6]. A step form signal or the signal with step changes are examples of such reference signal.

5. Experimental analysis

The pressure plant has been experimentally analysed using two types of digital self-tuning PID controllers – PID-A and PID-B. The same closed-loop characteristics have been used for digital control of both tubes. The initial parameters of the algorithm (26) are as follows: the main diagonal of covariance matrix $\mathbf{C}^{(i)}$ is selected equal to 1000 while the rest entries are equal to zero, the forgetting factor $\varphi^{(i)}$ is equal to 0.99 and initial values of model parameters' vector $\hat{\mathbf{\Theta}}_0^{(i)}$ are set to zero. The same reference signal for both tubes has been applied which has a step form of repeatable values of 75 and 40, and with $\delta_e^{(i)}$ equal to 1. The observation time of each signal is 1000 seconds, collecting data from the plant at one-second intervals. Only the last 800 values of the signals are included in criterion calculation, thereby eliminating the impact of the initial controller training process from it. The weight coefficient ρ of criterion is set to 9 (in general, the control error of the tube is up to 90 centimetres, whereas the differences between two individual values of input signal can be up to 10 volts).

The results of criterion optimization showed that optimal closed-loop parameters and sampling period for PID-A control are $\omega_i^* = 0.17$, $\zeta_i^* = 0.9$, $T_0^* = 0.08$, $i = 1,2$, and $\omega_i^* = 0.15$, $\zeta_i^* = 0.9$, $T_0^* = 0.08$ for PID-B control. The minima of (33) with optimal closed-loop parameters and sampling period for the first and the second tubes of PID-A control are 65.82 and 49.40 respectively, while in PID-B control - 45.36 and 36.46, i.e. the minimal values of criterion of PID-B control as compared to PID-A are less than 31% for the first tube and 26% for the second.

Figure 3 illustrates the dependency of control quality on sampling period T_0 with optimal closed-loop parameters ω_i^*, ζ_i^*, $i = 1,2$. Points (circles and squares) in graphs denote criterion values of each tube and curves depict the smoothed version of those values. We can see that the values of criterion of each tube little vary when sampling period T_0 is between 0.06 and 0.125, but significantly increase if the sampling period is chosen outside of this range.

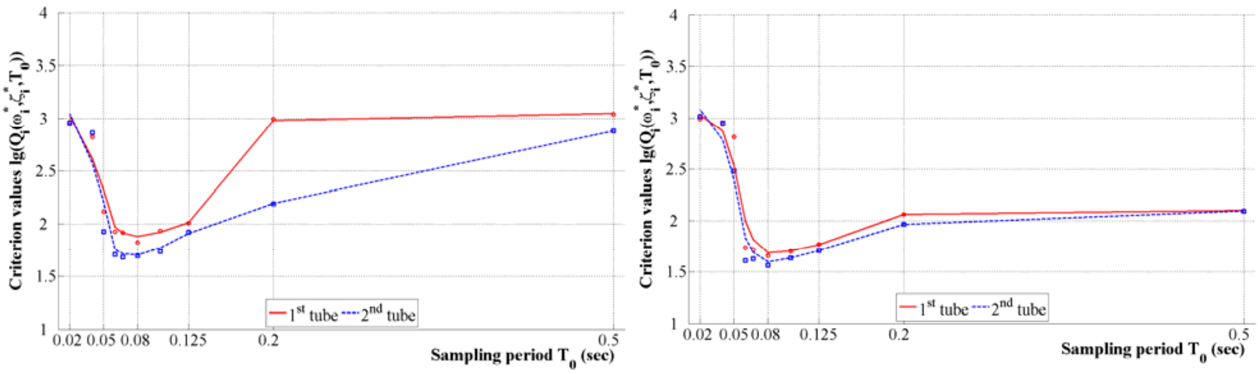

Figure 3. The influence of sampling period T_0 on criterion values with optimal closed-loop parameters $\omega_i^* = 0.17, \zeta_i^* = 0.9$ for PID-A (left-hand graph) and $\omega_i^* = 0.15, \zeta_i^* = 0.9$ for PID-B (right-hand graph)

The dependency of control quality on closed-loop parameters ω_i, ζ_i, $i = 1,2.$ with a fixed sampling period is demonstrated in Figures 4 and 5. Notice that the closed-loop selected with natural frequency between 0.08 and 0.17, and the damping factor between 0.8 and 1.2 gives close to minimum criterion values for both controls.

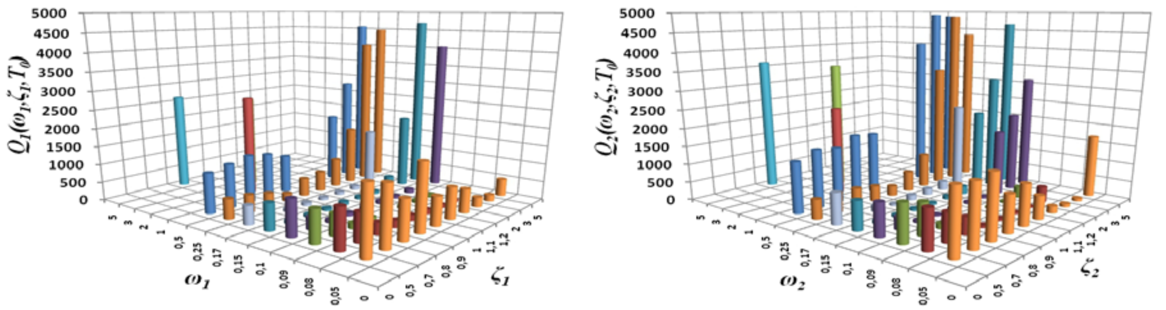

Figure 4. Criterion values of PID-A control of each tube on various closed-loop parameters ω_i, ζ_i with sampling period $T_0 = 0.1$

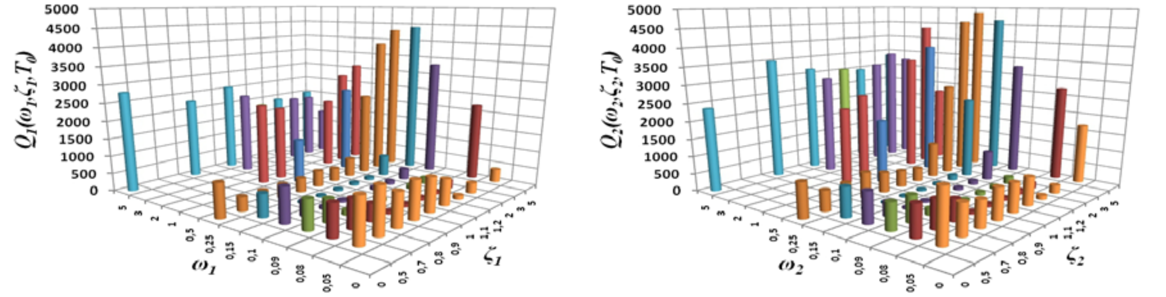

Figure 5. Criterion values of PID-B control of each tube on various closed-loop parameters ω_i, ζ_i with sampling period $T_0 = 0.1$

The process of adaptive pressure plant digital control with optimal parameters of closed-loop and optimal sampling period is depicted in Figure 6 and model parameters of online identification of each pressure plant tube are depicted in Figure 7.

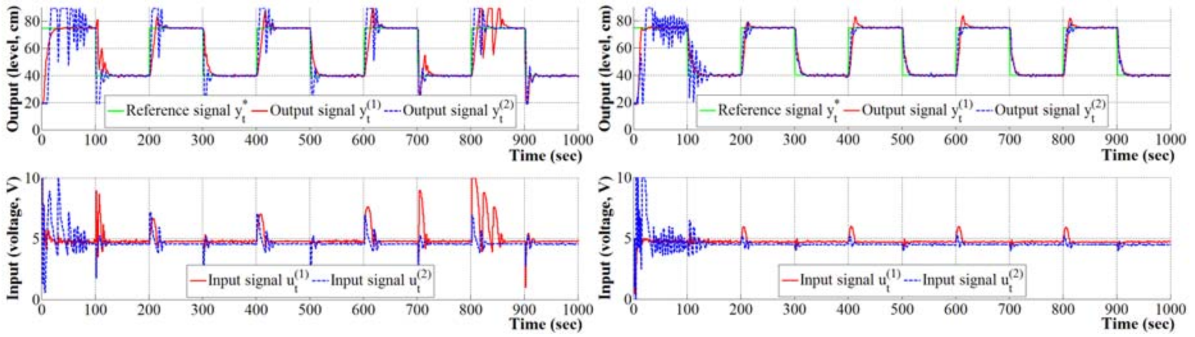

Figure 6. Control process of pressure plant with optimal closed-loop parameters and optimal sampling period $T_0^* = 0.08$,
left-hand graph – PID-A ($\omega_i^* = 0.17$, $\zeta_i^* = 0.9$, $Q_1^* = 65.82$, $Q_2^* = 49.40$),
right-hand graph – PID-B ($\omega_i^* = 0.15$, $\zeta_i^* = 0.9$, $Q_1^* = 45.36$, $Q_2^* = 36.46$)

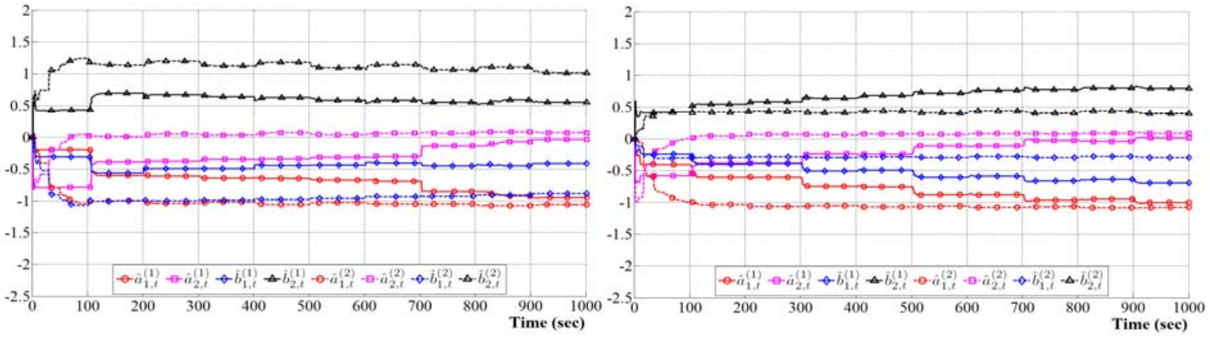

Figure 7. Online identification of pressure plant with optimal closed-loop parameters and optimal sampling period, left-hand graph – PID-A, right-hand graph – PID-B

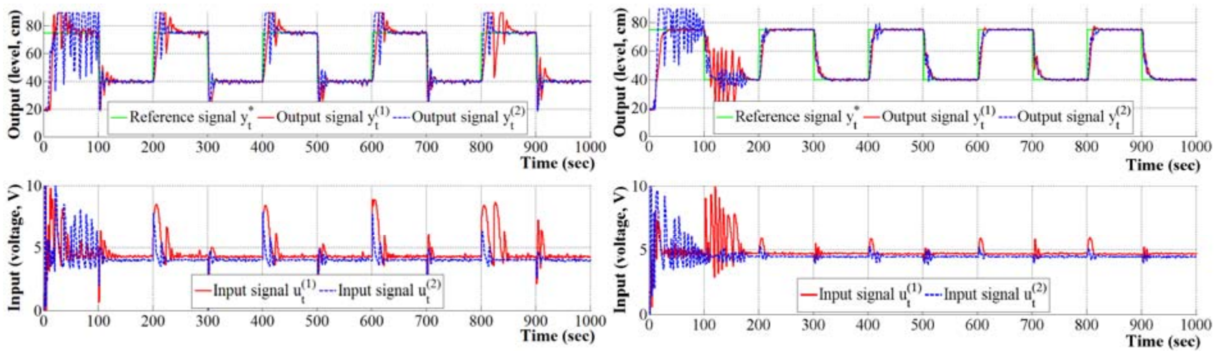

Figure 8. Control process of pressure plant with optimal closed-loop parameters and sampling period $T_0 = 0.1$, left-hand graph – PID-A ($\omega_i^* = 0.17, \zeta_i^* = 0.9, Q_1 = 85.16, Q_2 = 54.55$), right-hand graph – PID-B ($\omega_i^* = 0.15,\ \zeta_i^* = 0.9, Q_1 = 50.09, Q_2 = 43.31$)

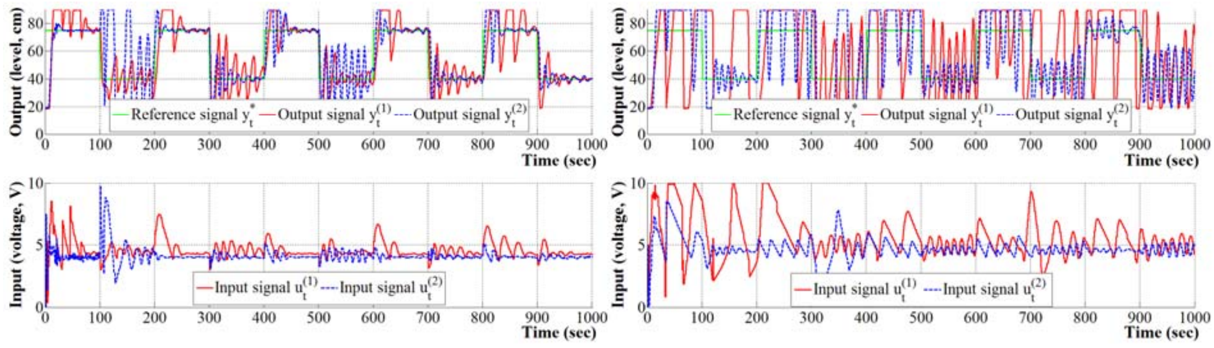

Figure 9. Control process of pressure plant with optimal closed-loop parameters and sampling period $T_0 = 0.05$, left-hand graph – PID-A ($\omega_i^* = 0.17, \zeta_i^* = 0.9, Q_1 = 130.52, Q_2 = 83.51$), right-hand graph – PID-B ($\omega_i^* = 0.15,\ \zeta_i^* = 0.9, Q_1 = 650.16, Q_2 = 304.84$)

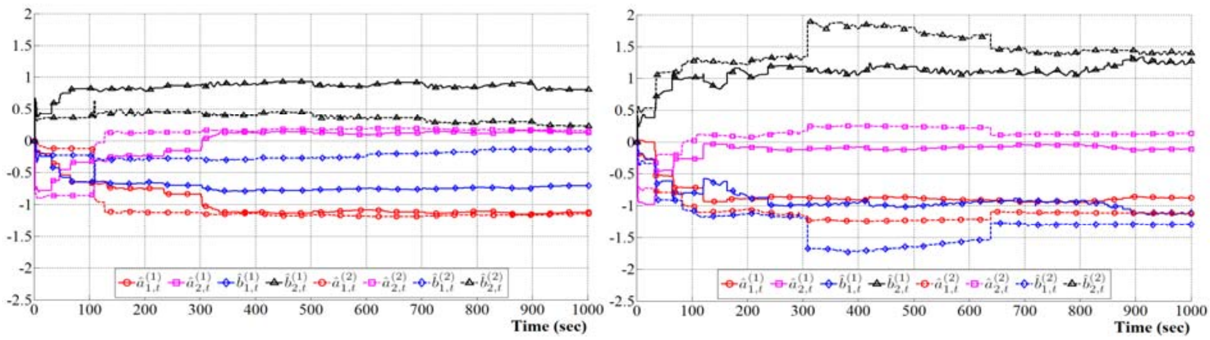

Figure 10. Online identification of pressure plant with optimal closed-loop parameters and sampling period $T_0 = 0.05$, left-hand graph – PID-A, right-hand graph – PID-B

Figure 8 shows the control process of the plant with optimal closed-loop parameters and sampling period shifted to $T_0 = 0.1$. Notice that a small increase of sampling period T_0 slightly increases the values of criterion. The control results of the plant with optimal closed-loop parameters, but with decreased sampling period almost twice ($T_0 = 0.05$) from its optimal value (Figure 9) show that the choice of too small sampling period substantially decreases the quality of adaptive control. Model parameters of online identification of each pressure plant tube are illustrated in Figure 10.

Åström and Wittenmark recommends to select natural frequency ω_i and sampling period T_0 so that inequality $0.1 \le \omega_i T_0 \le 0.6$ would be valid [2]. Figure 11 illustrates that the selection of sampling period T_0 is unable to improve the performance of adaptive control with selected closed-loop parameter ω_i further from its optimal value (ω_i^*). This recommendation causes to choose a relatively big ω_i with a relatively small T_0 or vice versa. Figure 12 presents the control process of the plant with a big value of ω_i and a small T_0, when its model parameters of online identification of each pressure plant tube are presented in Figure 13. The control process of pressure plant with a small value of ω_i and a big T_0 is depicted in Figure 14. In both cases, the quality of adaptive control is heavily decreased as compared to the control quality of the plant with optimal closed-loop parameters (ω_i^*, ζ_i^*) and optimal sampling period T_0^*, which are obtained by (33) and (34).

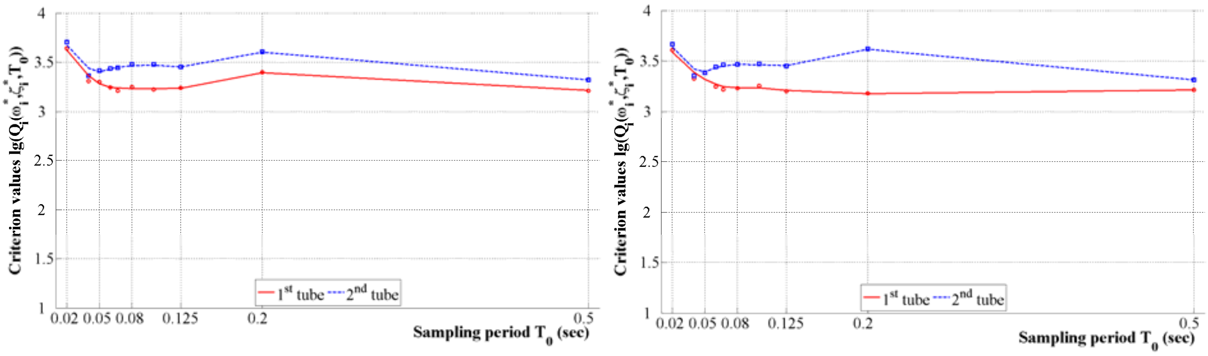

Figure 11. The influence of sampling period T_0 on criterion values with closed-loop parameters $\omega_i = 1.0, \zeta_i = 0.9$ for PID-A (left-hand graph) and PID-B (right-hand graph)

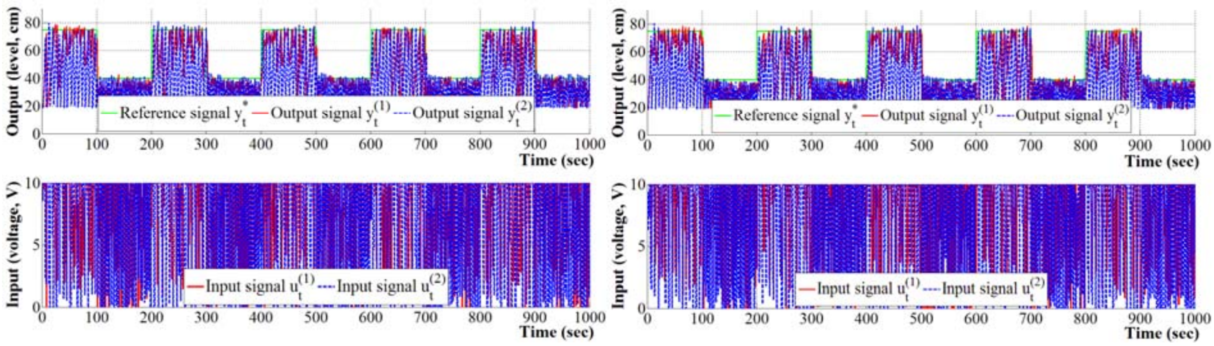

Figure 12. Control process of pressure plant with closed-loop parameters $\omega_i = 1.0$, $\zeta_i = 0.9$ and sampling period $T_0 = 0.1$, left-hand graph – PID-A ($Q_1 = 1673.02, Q_2 = 3001.57$), right-hand graph – PID-B ($Q_1 = 1794.74, Q_2 = 2951.48$)

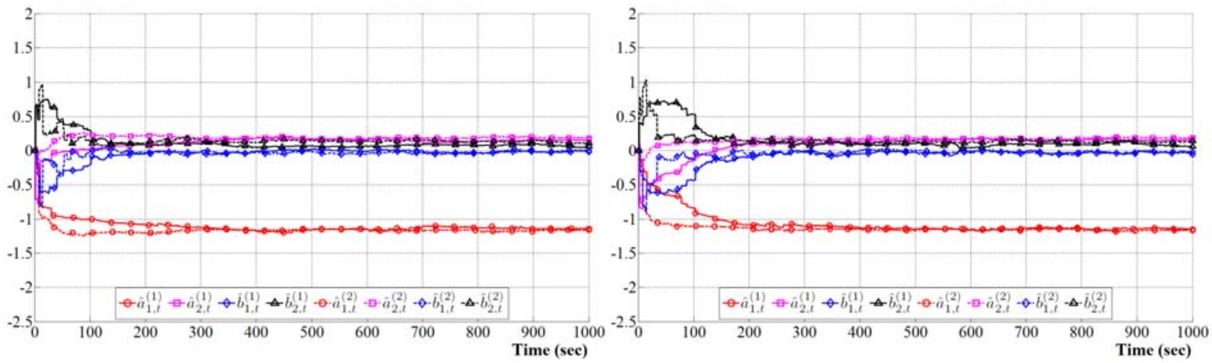

Figure 13. Online identification of pressure plant with closed-loop parameters $\omega_i = 1.0$, $\zeta_i = 0.9$ and sampling period $T_0 = 0.1$, left-hand graph – PID-A control, right-hand graph – PID-B control

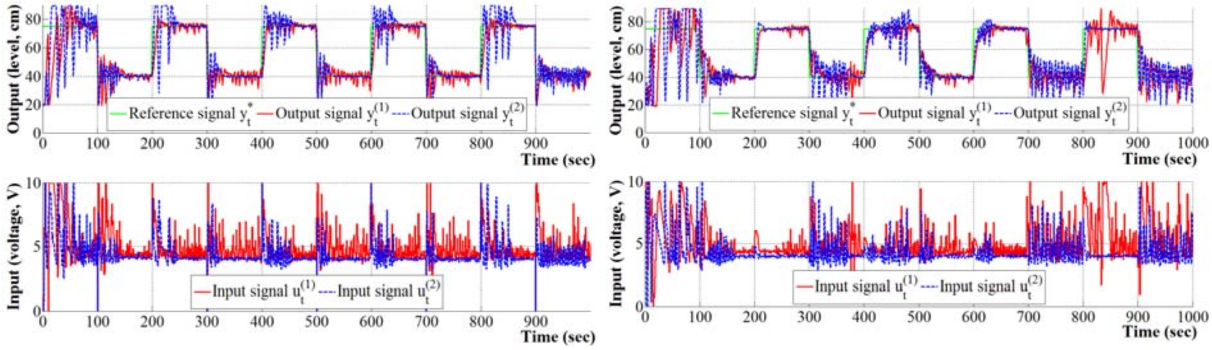

Figure 14. Control process of pressure plant with closed-loop parameters $\omega_i = 0.2, \zeta_i = 1.0$ and sampling period $T_0 = 1.0$, left-hand graph – PID-A ($Q_1 = 200.28, Q_2 = 180.40$), right-hand graph – PID-B ($Q_1 = 231.37, Q_2 = 161.02$)

6. Conclusions

The optimization method of closed-loop parameters and sampling period for continuous-time plant digital control has been proposed. The experimental results showed that the quality of digital self-tuning PID control of the pressure plant substantially depends on the right choice of closed-loop parameters and continuous-time sampling period. Additionally, we have shown that control quality of the plant is significantly improved by optimizing those parameters. The optimal values of natural frequency and sampling period for digital control of pressure plant substantially differ from those that are chosen using conventional methodology.

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Received March 2011.