Using of the Hammerstein and Wiener Models in Adaptive Control of the Nonlinear Processes

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Abstract— The using of the Hammerstein and Wiener models in the linear adaptive control of the nonlinear processes is described in this paper. The main aim of this research study is an increasing of the adaptive control quality by using of the factorable methods which are based on the fact that many nonlinear systems can be factorized into the linear and the nonlinear parts.

The factorization of the nonlinear system into the nonlinear static part and the linear dynamic part is assumed in this paper.

The transfer function of the linear dynamic part of the nonlinear system is assumed in the time-discrete second-order Z-model form. Its parameters are estimated by the using of the time-discrete least-squares method with the directive forgetting.

The estimated parameters of the linear dynamic part are used for the design of the linear time-discrete control system, which is represented by the two-degree of freedom control system configuration (2DOF). The resulting controller is derived by the using of the polynomial approach and the characteristic polynomial of the closed control loop is chosen by the using of the optimal LQ approach and Pole Placemen Method (PPM).

The described method is tested on the nonlinear system which is represented by the servo-speed mechanism AMIRA DR300.

Keywords — adaptive control, optimal LQ control, pole placement method, nonlinear systems, cascade models, Hammerstein and Wiener models, 2DOF configuration, servo-speed mechanism AMIRA DR300.

I. Introduction

The nonlinear system control theory is an area of the control theory which is examines less than the classical linear system control. Many books and papers about linear system control theory exist there, for example [3], [6] and many others, but only a few about nonlinear control [1], [2], [15]. There are many reasons for it, but the most important reasons are these: firstly, for description of nonlinear systems and design of nonlinear control systems we cannot use methods like Laplace transformation or Z-transformation, secondly, only a few general methods which can be applicable for all (or at least for the majority) types of nonlinear systems exist there and finally, the design of nonlinear control systems have to be done originally for every nonlinear system and its mathematical complexity is many times higher than a design of the linear control systems.

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However, in practice, the majority of real systems have, more or less, a nonlinear behavior or nonlinear properties. The most frequently used method how we can solve this problem is a substitution of the nonlinear system by one or more linear models in the neighborhood of the operating points. But this method, when we use the linear control systems designed for the linear approximations of the nonlinear system, has a lot of limitations. The most important problem is: the quality of real control process, when the linear controller designed for the linear approximation is used for the control of the nonlinear system, is generally significantly worse than for the linear approximation simulations because there are many unpredictable influences which can be significant for the nonlinear system behavior but insignificant for the behavior of the linear approximation. For many types of the nonlinear systems we cannot use this method because the quality of control process is very bad or the control process is unstable.

One possible solution of this problem is the using of the adaptive process control [3], [4], [5], [15], [16], [17]. The quality of control process is being increased in many cases but on the other hand, there are many problems too. For example, the important condition of high quality of the adaptive control is following: the quality of adaptive control is high in the cases when the rate of change of the adaptive-models parameters is higher than the rate of change of the real-systems parameters. In practice, this condition could not be real. The following problem is the fact that the adaptive control works no suitably for the systems with some types of nonlinearities like a dead zone or the saturation.

Another possible solution is the using of cascade models when we consider that the system can be factorable - these systems consist of the linear and nonlinear parts [1], [6], [9], [10]. Then, the nonlinear part of the nonlinear system can be linearized and its influence on the system behavior can be minimized. Models are consisting of the nonlinear static and the linear dynamic parts are the most frequently used ones in practice. On the basis of their mutual position, the Hammerstein or the Wiener model can be distinguished.

The using of the cascade models is quite simple and effective method how the quality of control can be increased significantly in many cases. But on the other hand, this method has some limitations too. For example, many nonlinear system cannot be factorable clearly – the static nonlinearity is dominant but there is also a dynamic nonlinearity, or linear model´s parameters are variable – a

time variable or by change of the operating modes.
Method which combines both approaches mentioned above will be presented in this paper. The main aim of this research study is to find the method which increases the quality of linear adaptive control of the nonlinear systems by using of the relatively simple approaches.

II. Hammerstein and Wiener Model

The nonlinear process will be factorable into the nonlinear static block and the linear dynamic block. On the basis of their mutual position, the Hammerstein or the Wiener model can be distinguished.

A. *Basic description of the Hammerstein model*

In Figure 1, we can see the basic schematic structure of the Hammerstein model.

Fig. 1 Hammerstein model of the nonlinear system [6]

The basic Hammerstein model $\boldsymbol{N_H}$ is a cascade structure of the nonlinear static block and the linear dynamic block which can be described by following formulas:

$$X_H(k) = f_H(U(k)) \tag{1}$$

$$\begin{aligned} Y(k) &= b_0 X_H(k) + b_1 X_H(k-1) + \ldots + \\ &+ b_m X_H(k-m) - a_1 Y(k-1) - \ldots - a_n Y(k-n) \end{aligned} \tag{2}$$

The H-models (HM) can describe many different processes, especially if their main nonlinear behavior is caused by actuators (dead zone, saturation, etc.).

B. *Basic description of the Wiener model*

In Figure 2, we can see the basic schematic structure of the Wiener model.

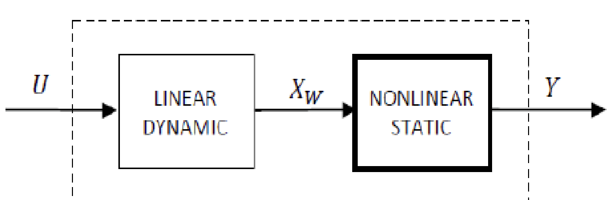

Fig. 2 Wiener model of the nonlinear system [6]

The basic Wiener model N_W is the cascade structure of the linear dynamic block and the nonlinear static block which can be described by the following formulas:

$$\begin{aligned} X_W(k) &= b_0 U(k) + b_1 U(k-1) + \ldots + b_m U(k-m) \\ &- a_1 X_W(k-1) - \ldots - a_n X_W(k-n) \end{aligned} \tag{3}$$

$$Y(k) = f_W(X_W(k)) \tag{4}$$

The W-models (WM) are appropriate for systems whose outputs are measured by sensors with nonlinear characteristic or for the controller design.

Hammerstein and Wiener model formulas are derived from the time-discrete models but very similarly can be derived also for the time-continuous models.

III. Basic closed control loop with using Hammerstein and Wiener models

In Fig. 3, we can see a schematic plan of the basic closed control loop with HM and WM which is used for linearizing of the non-linear processes.

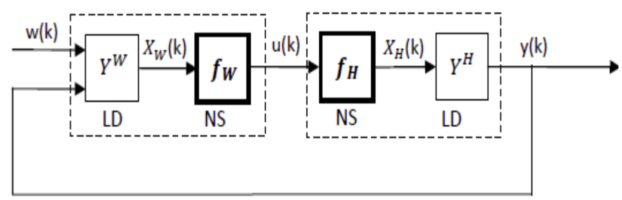

Fig. 3 Closed control loop with the controlled system of the Hammerstein type and the controller of the Wiener type.

where:
Y_W – the linear dynamic part of the control system (the general linear controller designed by any linear method for the linear part of controlled system)
f_W – the nonlinear static part of the control system
f_H – the nonlinear static part of the controlled system
Y_H – the linear dynamic part of the controlled system

If we choose $f_W = f_H^{-1}$, then we can write (from Fig. 3):

$$\begin{aligned} X_H(\cdot) &= f_H(u(\cdot)) = f_H(f_W(X_W(\cdot))) = \\ &= f_H(f_H^{-1}(X_W(\cdot))) = X_W(\cdot) \end{aligned} \tag{5}$$

From the formula (5) we can deduce the following conclusion:
If we can describe the system nonlinearity and it can be inversible (minimally in parts) then we have to study only the properties of the linear dynamics of the controlled system for the design of controllers. The formula (5) is derived for the time-discrete models but basic principles are similar for all types of linear models (Z-model, S-model and δ-model).

IV. Hammerstein model of the linear system

In this part, the basic principles of the described method will be explained for linear example.
The linear transfer function will be assumed in the form:

$$G(s) = \frac{K}{(T_1 s + 1)(T_2 s + 1)} \tag{6}$$

This system can be factorable to:

Static gain:

$$K = \lim_{s \to \infty} G(s) \tag{7}$$

Dynamic part:

$$G^*(s) = \frac{1}{(T_1 s + 1)(T_2 s + 1)} \tag{8}$$

This factorization is applicable only for the stable systems.

The Hammerstein model of the linear system can be assumed in the form:

- for time-continuous models:

$$G(s) = \frac{Y(s)}{U(s)} = \lim_{s \to \infty} G(s) \cdot \left[G^*(s)\right] = K_{(s)} \cdot \frac{Y(s)}{U^*(s)} \tag{9}$$

- for time-discrete models:

$$G(z^{-1}) = \frac{Y(z^{-1})}{U(z^{-1})} = \lim_{z \to 1} G(z^{-1}) \cdot \left[G^*(z^{-1})\right] = K_{(z)} \cdot \frac{Y(z^{-1})}{U^*(z^{-1})} \tag{10}$$

Very similar process will be assumed for nonlinear systems: The static characteristic of the nonlinear system:

$$Y^S(\cdot) = f_{stat}(U^S(\cdot)) \tag{11}$$

Dynamic models of the nonlinear system will be assumed in the form:

$$\begin{aligned} Y^{(*)}(\cdot) &= f_{stat}(U(\cdot)) \\ G^{(*)}(\cdot) &= \frac{Y(\cdot)}{Y^{(*)}(\cdot)} = \frac{Y(\cdot)}{f_{stat}(U(\cdot))} \end{aligned} \tag{12}$$

For simplification, we assume the following fact:

- for the time-continuous system: $\lim_{t \to \infty} Y^*(t) = Y^S(t)$

- for the time-discrete system: $\lim_{z \to 1} Y^*(z) = Y^S(z)$

- for the system without dynamic: $Y^*(\cdot) = f_{stat}(U(\cdot))$ for all $U(\cdot)$

V. Servo-speed mechanism AMIRA DR300

The servo-speed mechanism AMIRA DR300 is a laboratory model which consists of two identical electro motors which are interconnected inseparably, the speed-voltage generator used for the speed of rotation measurement and the IRC sensor is used for measurement of the spindle angular displacement.

Fig. 4 Nonlinear system – the servo-speed mechanism AMIRA DR300

The first electromotor is used as a variable load torque generator and the second electromotor is controlled by the controller signal.

The nonlinear system AMIRA DR300 can be approximately described by these formulas:

$$\begin{aligned} L\frac{di(t)}{dt} &= -Ri(t) - k_e\omega(t) + u_m(t) \\ J\frac{d\omega(t)}{dt} &= k_m i(t) - b\omega(t) - m_z(t) \\ \frac{d\varphi(t)}{dt} &= \omega(t) \end{aligned} \tag{13}$$

where:

i [A] – electromotor current, ω [s^{-1}] - motor speed, φ [rad] – motor spindle angular displacement, u [V] – input motor voltage, m_z [Nm] – external load torque, R [Ω] – motor electrical resistance, L [H] – motor inductivity, J [kgm^2s^{-1}] – motor moment of inertia, b – motor friction torque, k_e [sV^{-1}] – motor electrical constant, k_m [kgm^2s^{-1}] – motor mechanical constant

VI. Controller Design

The linear time-discrete control system, which is represented by the two-degree of freedom control system configuration (2DOF), is depicted in Fig. 5.

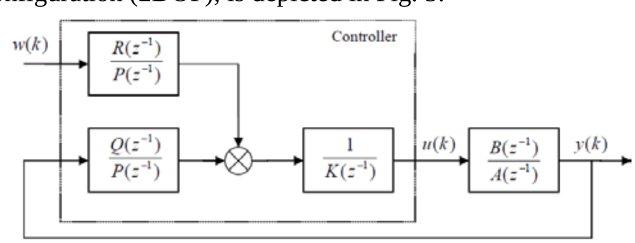

Fig. 5 2DOF control system configuration [5]

where:

$w(k)$ - reference signal, $u(k)$ - control action, $y(k)$ - output signal

From Fig. 5, we can write the following formula for the control action:

$$u(k)=\frac{1}{K\left(z^{-1}\right)}\left[\frac{R\left(z^{-1}\right)}{P\left(z^{-1}\right)}w(k)-\frac{Q\left(z^{-1}\right)}{P\left(z^{-1}\right)}y(k)\right] \quad (14)$$

If we choose $u(k)=\frac{A\left(z^{-1}\right)}{B\left(z^{-1}\right)}y(k)$ than we can transform formula (14) into the transfer function of the closed control loop:

$$G_w(z)=\frac{Y(z)}{W(z)}= \\ =\frac{B(z^{-1})R(z^{-1})}{A(z^{-1})K(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})} \quad (15)$$

The controller parameters are computed from the following polynomial formulas:

$$A(z^{-1})K(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})=D(z^{-1}) \quad (16)$$

$$K(z^{-1})S(z^{-1})+B(z^{-1})R(z^{-1})=D(z^{-1}) \quad (17)$$

The transfer function of the control process is assumed in the form:

$$G\left(z^{-1}\right)=\frac{B\left(z^{-1}\right)}{A\left(z^{-1}\right)}=\frac{b_1z^{-1}+b_2z^{-2}}{1+a_1z^{-1}+a_2z^{-2}} \quad (18)$$

The transfer function of direct part of the controller is assumed in the form

$$G_R\left(z^{-1}\right)=\frac{R\left(z^{-1}\right)}{P\left(z^{-1}\right)}=\frac{r_0}{\left(1-z^{-1}\right)\left(p_0+p_1z^{-2}\right)} \quad (19)$$

and the transfer function of the feedback part of the controller is assumed in the form:

$$G_Q\left(z^{-1}\right)=\frac{Q\left(z^{-1}\right)}{P\left(z^{-1}\right)}=\frac{q_0+q_1z^{-1}+q_2z^{-2}}{\left(1-z^{-1}\right)\left(p_0+p_1z^{-2}\right)} \quad (20)$$

The degrees of the polynomials $R\left(z^{-1}\right)$, $Q\left(z^{-1}\right)$ and $P\left(z^{-1}\right)$ were chosen on the basis of the polynomial algebra principles [3], [5], [11].

The characteristic polynomial of the closed control loop will be chosen in the basic form:

$$D\left(z^{-1}\right)=1+d_1z^{-1}+d_2z^{-2}+d_3z^{-3}+d_4z^{-4} \quad (21)$$

Now, from the formulas (16), (20) and (21) we obtained the matrix formula:

$$\begin{bmatrix} b_1 & 0 & 0 & 1 \\ b_2 & b_1 & 0 & a_1-1 \\ 0 & b_2 & b_1 & a_2-a_1 \\ 0 & 0 & b_2 & -a_2 \end{bmatrix}\begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ p_1 \end{bmatrix}=\begin{bmatrix} d_1+1-a_1 \\ d_2+a_1-a_2 \\ d_3+a_2 \\ d_4 \end{bmatrix} \quad (22)$$

By its solution, we obtained the parameters of the feedback part of the controller.

The parameters of the direct part of the controller will be obtained by solution of the formulas (17) and (19) for $z=-1$:

$$\left(1-z^{-1}\right)S(z^{-1})+B(z^{-1})r_0=D(z^{-1}) \quad (23)$$

From this, we can write:

$$r_0=\frac{D(1)}{B(1)}=\frac{1+d_1+d_2+d_3+d_3}{b_1+b_2} \quad (24)$$

VII. Pole Placement Method

For Pole Placement Method, the characteristic polynomial $D\left(z^{-1}\right)$ was chosen as:

$$D\left(z^{-1}\right)=1+d_1z^{-1}+d_2z^{-2} \quad (25)$$

where:

$$d_1=-2\cdot e^{-\xi\omega_nT_0}\cdot\cos\left(\omega_nT_0\sqrt{1-\xi^2}\right) \text{ for } \xi\le 1 \quad (26)$$

$$d_1=-2\cdot e^{-\xi\omega_nT_0}\cdot\cosh\left(\omega_nT_0\sqrt{1-\xi^2}\right) \text{ for } \xi>1 \quad (27)$$

$$d_2=e^{-2\xi\omega_nT_0} \quad (28)$$

where: ω_n - circular frequency, ξ - damping ratio

VIII. Optimal LQ Control

Optimal LQ control methods are based on the minimizing the quadratic criterion with control action penalization:

$$J=\sum_{k=0}^{\infty}\left\{\left[w(k)-y(k)\right]^2+q_u\left[u(k)\right]^2\right\} \quad (29)$$

The quadratic criterion has minimal value for the formula:

$$A(z^{-1})K(z^{-1})P(z^{-1})+B(z^{-1})Q(z^{-1})=D(z^{-1}) \quad (30)$$

where the polynomial $D(z^{-1})$ is obtained by solution of the spectral factorization of the formula:

$$A(z^{-1})q_u A(z) + B(z^{-1})B(z) = D(z^{-1})\delta D(z) \qquad (31)$$

Detailed deduction of this condition can be found for example in [11].

The parameters of the polynomial $\mathrm{D}(z^{-1})$ can be obtained by solution of the following formulas [5].

We compute auxiliary parameters:

$$\begin{aligned} m_{r0} &= q_u\left(1 + a_1^2 + a_2^2\right) + b_1^2 + b_2^2 \\ m_{r1} &= q_u\left(a_1 + a_1 a_2\right) + b_1 b_2 \\ m_{r2} &= q_u a_2 \\ \lambda &= \frac{m_{r0}}{2} - m_{r2} + \sqrt{\left(\frac{m_{r0}}{2} + m_{r2}\right)^2 - m_{r1}^2} \\ \delta &= \frac{\lambda + \sqrt{\lambda^2 - 4m_{r2}^2}}{2} \end{aligned} \qquad (32)$$

which are used for the computing of the parameters of the polynomial $\mathrm{D}(z^{-1})$:

$$\begin{aligned} d_1 &= \frac{m_{r1}}{\delta + m_{r2}} \\ d_2 &= \frac{m_{r2}}{\delta} \end{aligned} \qquad (33)$$

The exact derivation of this algorithm was described in [5], [11].

IX. Linear Dynamic Part of the Nonlinear System AMIRA DR300

The linear dynamic part of the nonlinear system will be assumed in the second order time-discrete linear form

$$\begin{aligned} &y(k) + a_1 y(k-1) + a_2 y(k-2) = \\ &= b_1 u(k-1) + b_2 u(k-2) \end{aligned} \qquad (34)$$

which can be rewrited into the transfer function form:

$$G\left(z^{-1}\right) = \frac{Y(z)}{U(z)} = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \qquad (35)$$

The parameters of the linear transfer function (35) will be estimated by the time-discrete least-squares method from regression vector:

$$\Phi_\delta^T(k-1) = \left[-y(k-1) \quad -y(k-2) \quad u(k-1) \quad u(k-2)\right] \qquad (36)$$

Vector of the time-discrete models parameters

$$\Theta_\delta^T(k) = \left[a_1 \quad a_2 \quad b_1 \quad b_2\right] \qquad (37)$$

will be estimated recursive from the formula:

$$y(k) = \Theta_\delta^T(k)\Phi_\delta(k-1) + \varepsilon(k) \qquad (38)$$

The exact description of the time-discrete least-squares method can be found, for example, in [2], [3], [6], [16].

X. Nonlinear Static Part of the Nonlinear System AMIRA DR300

From measured data, the static characteristic of the nonlinear servo-speed mechanism AMIRA DR300 had been determinate.

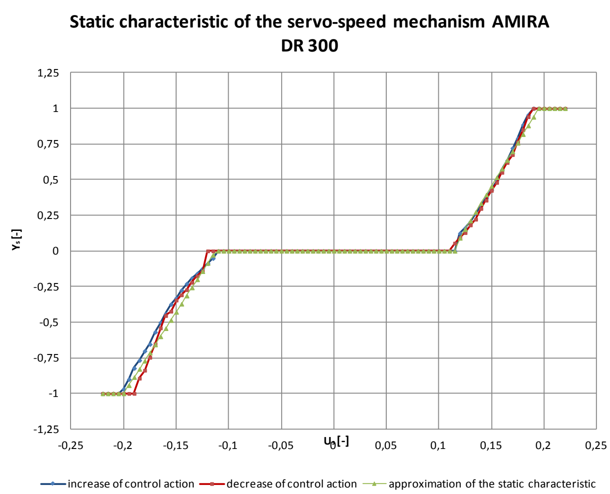

Fig. 6 Static characteristic of the nonlinear system AMIRA DR300

For the purpose of this research, the static characteristic will be considered as the dominant static nonlinearity of the controlled system.

The static characteristic will be approximated by function $Y^S = f_{stat}(U^S)$.

Table 1: Approximated static characteristic of the system AMIRA DR300

Static control action	**Static output signal (approximated)**
$U^S \le U^S_{-\max}$	$Y^S = Y^S_{-\max}$
$U^S_{-\max} < U^S < U^S_{-\min}$	$Y^S = \frac{Y^S_{-\max} - Y^S_{-\min}}{U^S_{-\max} - U^S_{-\min}} \cdot \left(U^S - U^S_{-\min}\right)$
$U^S_{-\min} \le U^S \le U^S_{+\min}$	$Y^S = 0$

$U_{+\min}^{S} < U^{S} < U_{+\max}^{S}$	$Y^{S} = \frac{Y_{+\max}^{S} - Y_{+\min}^{S}}{U_{+\max}^{S} - U_{+\min}^{S}} \cdot \left(U^{S} - U_{+\min}^{S}\right)$
$U^{S} \geq U_{+\max}^{S}$	$Y^{S} = Y_{+\max}^{S}$

where: $U_{-\max}^{s} = -0.20$, $U_{-\min}^{s} = -0.1125$, $U_{+\min}^{s} = 0.1125$, $U_{+\max}^{s} = 0.195$

For the best linearization of the static nonlinearity $Y^{S}(k) = f_{stat}(U^{S}(k))$, we have to consider the following manners:

The saturation of the control action cannot be compensated, but we should include it into the computation of the control action.

The dead zone of the control action can be compensated in the following way:

$$\left\langle 0 \quad U_{+\min}^{S} \right\rangle \quad u(k) = f_{W}(X_{W}(k)) = X_{W}(k) + U_{+\min}^{S} \tag{39}$$

$$\left\langle U_{-\min}^{S} \quad 0 \right\rangle \quad u(k) = f_{W}(X_{W}(k)) = X_{W}(k) + U_{-\min}^{S} \tag{40}$$

For the control action computation, the values of $X_{W}(k)$ has to be used, we cannot use the linearized values of $u(k)$.

XI. Real Measurement of Control Process – Pole Placement Method

The quality of control process is assessed in the following criterion:

$$J = J_{Y} + J_{U} \tag{41}$$

where:

$$J_{Y} = \frac{1}{n-1} \cdot \sum_{i=1}^{n} (w(i) - y(i))^{2}$$
$$J_{U} = \frac{1}{n-1} \cdot \left[u(1)^{2} + \sum_{i=2}^{n} (u(i) - u(i-1))^{2} \right] \tag{42}$$

A. Simple Control Process – Detailed View

Control system parameters:

Sampling period 1: $T_{0} = 0.125s$

Sampling period 2: $T_{0} = 0.15s$

Poles of the characteristic polynomial were chosen under rules discussed in section VII.

circular frequency: $\omega_{n} = 0.1 / T_{0}$

damping ratio: $\xi = 1$

Identification process parameters:

Exponential forgetting parameter: $\varphi = 0.85$

Other parameters were chosen under rules mentioned in [5].

B. Control process without control action limitation

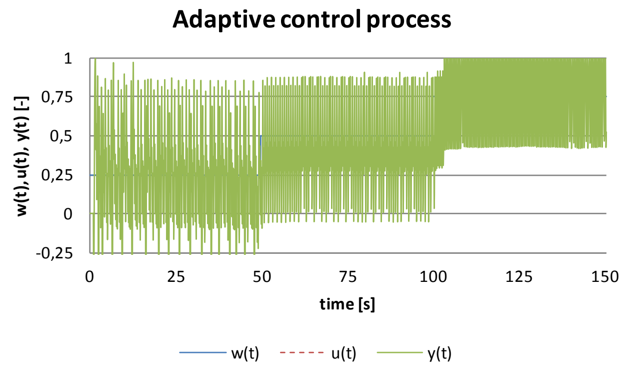

Fig. 7 Control process without control action limitation for $T_{0} = 0.125s$

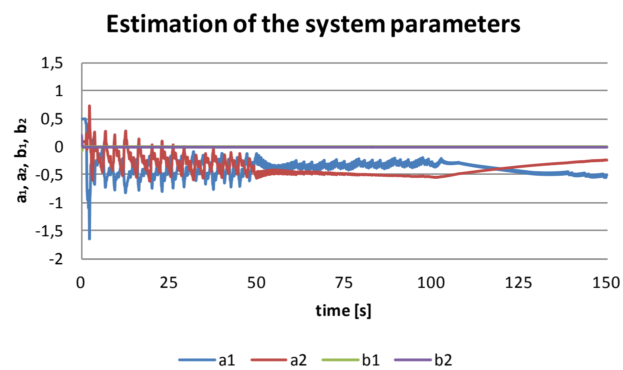

Fig. 8 Estimation of system parameters for $T_{0} = 0.125s$

Control Quality: $J_{Y} = 0.0926$, $J_{U} = 4.64 \cdot 10^{12}$

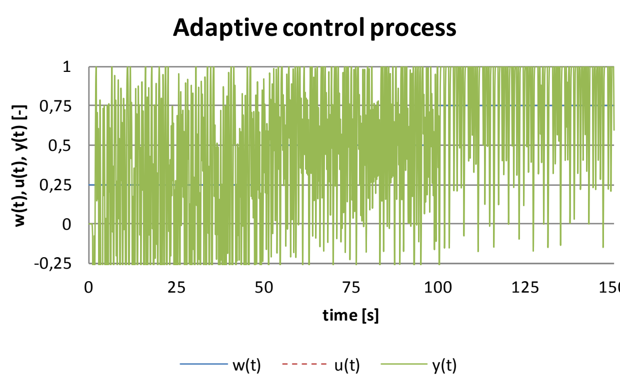

Fig. 9 Control process without control action limitation for $T_{0} = 0.15s$

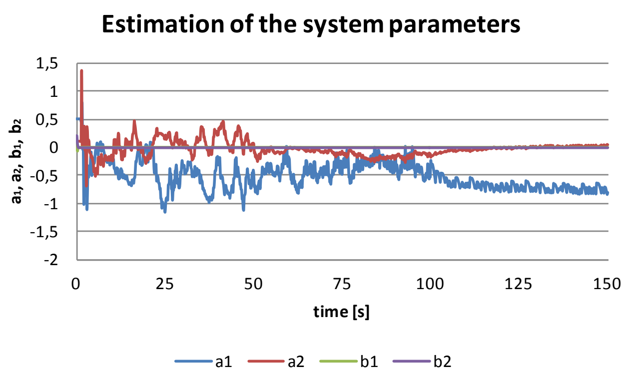

Fig. 10 Estimation of system parameters for $T_0 = 0.15s$

Control Quality: $J_Y = 0.1828$, $J_U = 7.14 \cdot 10^8$

C. *Control process with control action limitation*

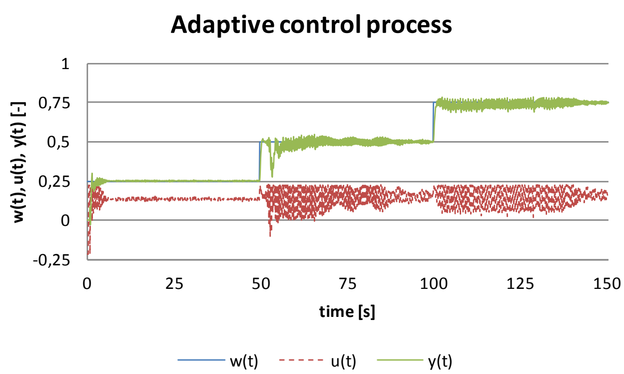

Fig. 11 Control process with control action limitation for $T_0 = 0.125s$

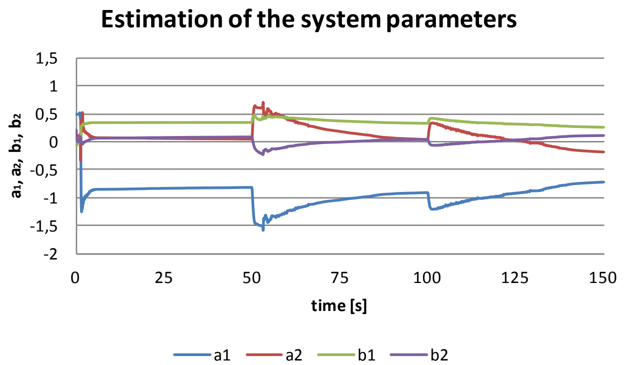

Fig. 12 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J = 0.0123$, $J_Y = 0.0015$, $J_U = 0.0108$

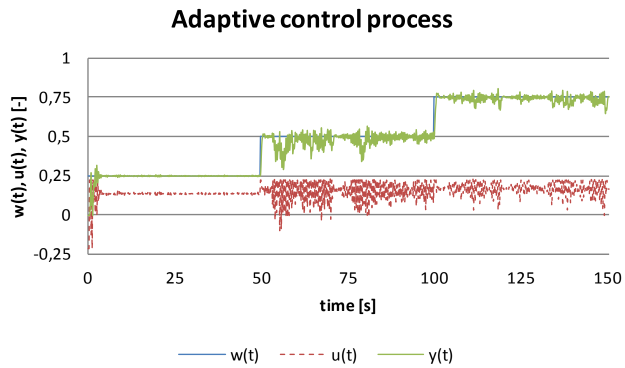

Fig. 13 Control process with control action limitation for $T_0 = 0.15s$

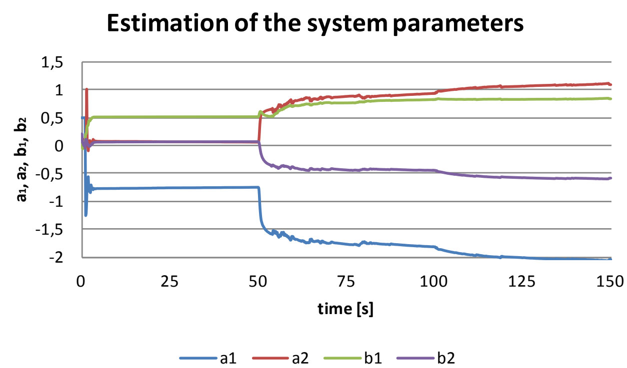

Fig. 14 Estimation of system parameters for $T_0 = 0.15s$

Control Quality: $J = 0.0092$, $J_Y = 0.0020$, $J_U = 0.0072$

As we can see in figure 7 and 9, the using of the control action limitation is necessary, because without it, the control processes are unstable and useless.

To compare the control quality criterions, we can derive the following facts: the changing of the sampling period has only limited influence for the quality of control process. The evidence of this we can see in figures 11 and 13.

Generally we can say that the extension of the sampling period decreases the quality of control slightly but nonlinear behavior of the controlled system is the main reason for the low quality of control when the linear adaptive control is used.

D. Control process with using of the Hammerstein and Wiener models

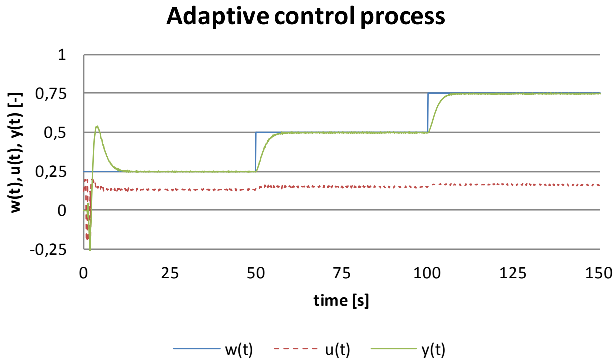

Fig. 15 Control process with using of the Hammerstein and Wiener models for $T_0 = 0.125s$

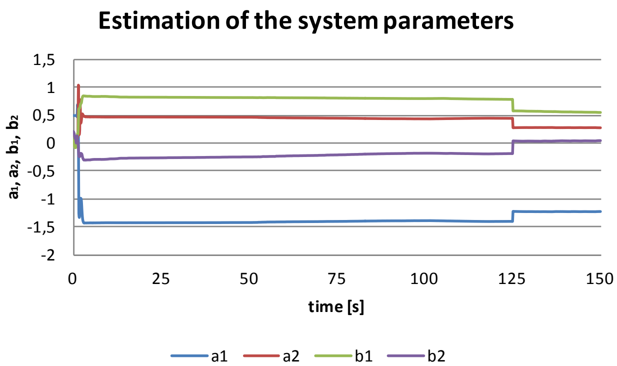

Fig. 16 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J = 0.0045$, $J_Y = 0.0039$, $J_U = 0.0006$

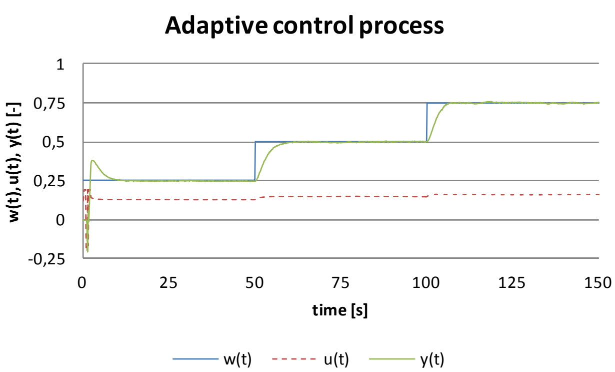

Fig. 17 Control process with using of the Hammerstein and Wiener models for $T_0 = 0.15s$

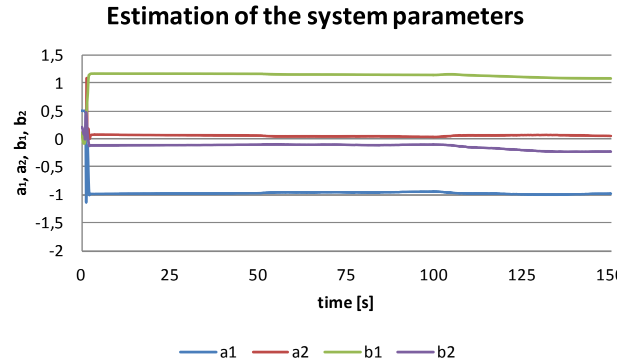

Fig. 18 Estimation of system parameters for $T_0 = 0.15s$

Control Quality: $J = 0.0034$, $J_Y = 0.0028$, $J_U = 0.0006$

As we can see in figures 15 and 17, the using of the Hammerstein and Wiener models of the control and controlled systems has radical influence for the quality of control process which is less oscillating and more stable. The quality of control process increases rapidly.

XII. Real Measurement of Control Process – LQ Approach

The quality of control process is assessed in the criterion mentioned in section XI:

A. Simple Control Process – Detailed View

Control system parameters:

Sampling period 1: $T_0 = 0.125s$

Sampling period 2: $T_0 = 0.15s$

Poles of the characteristic polynomial were chosen under rules discussed in section 8.

Identification process parameters:

Exponential forgetting parameter: $\varphi = 0.85$

Other parameters were chosen under rules mentioned in [5]

B. Control process without control action limitation

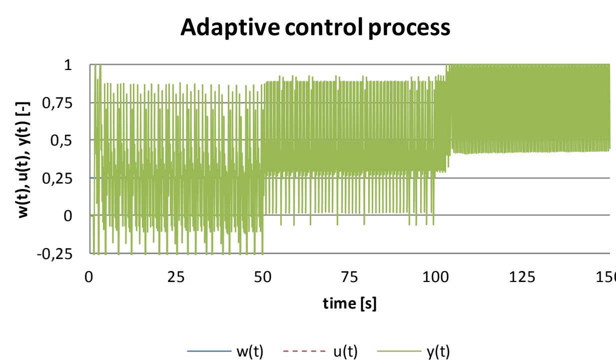

Fig. 19 Control process without control action limitation for $T_0 = 0.125s$

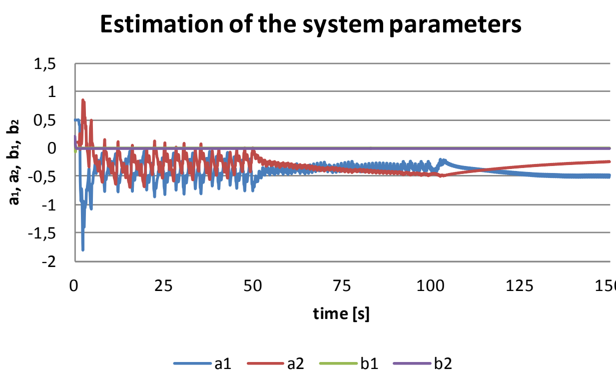

Fig. 12 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J_Y = 0.0919$, $J_U = 3.818 \cdot 10^{12}$

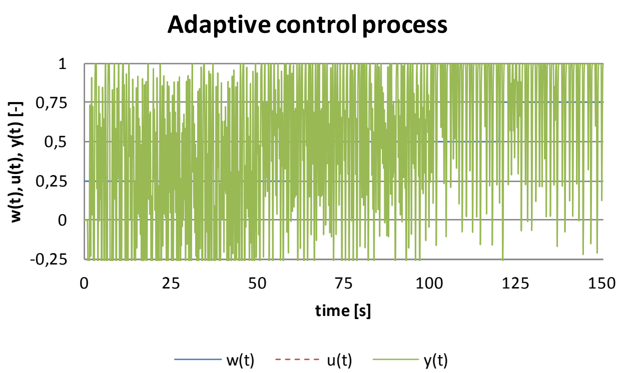

Fig. 21 Control process without control action limitation for $T_0 = 0.15s$

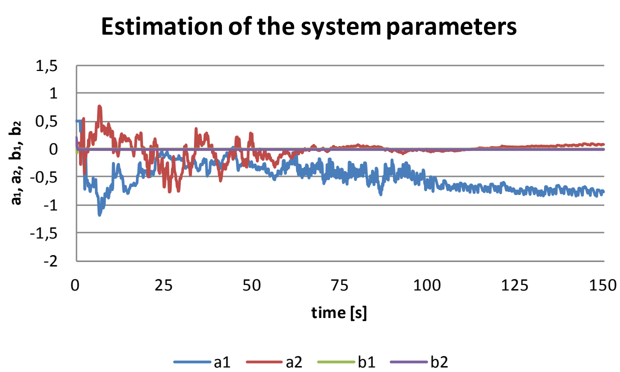

Fig. 22 Estimation of system parameters for $T_0 = 0.15s$

Control Quality: $J_Y = 0.1936$, $J_U = 6.07 \cdot 10^7$

C. *Control process with control action limitation*

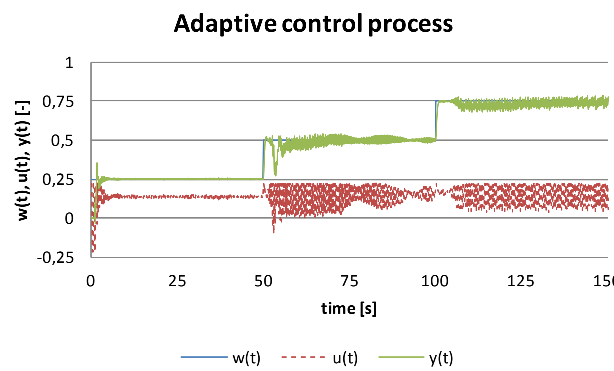

Fig. 23 Control process with control action limitation for $T_0 = 0.125s$

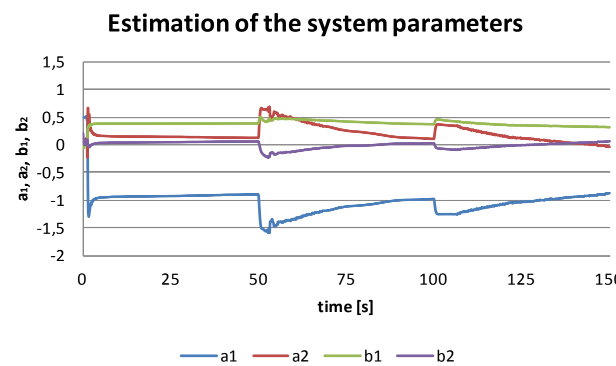

Fig. 24 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J = 0.0129$, $J_Y = 0.0017$, $J_U = 0.0112$

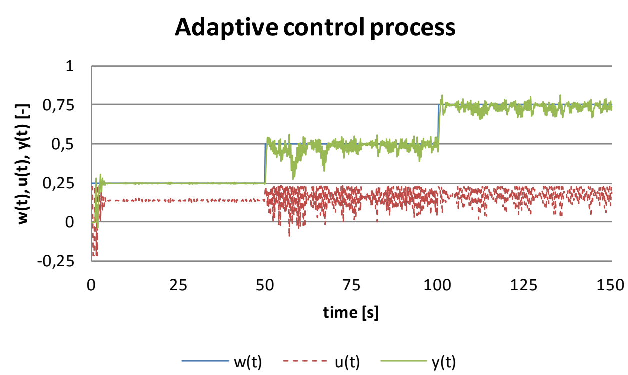

Fig. 25 Control process with control action limitation for $T_0 = 0.15s$

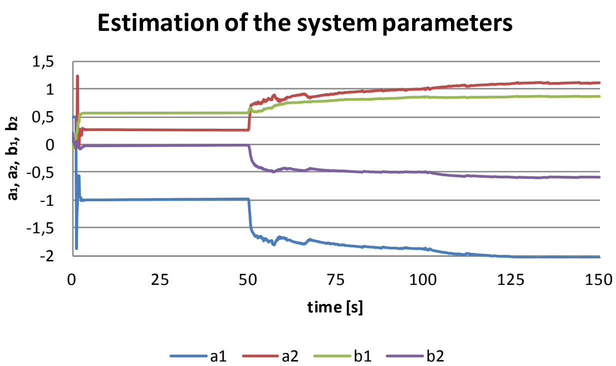

Fig. 26 Estimation of system parameters for $T_0 = 0.15s$

Control Quality: $J = 0.0103$, $J_Y = 0.0021$, $J_U = 0.0082$

To compare the control quality criterions from sections XI.b, XI.c and XII.b, XII.c we can derive the following facts: the changing of the sampling period or the poles of the characteristic polynomial has only limited influence for the quality of control process. The evidence of this we can see in figures 7, 9, 19 and 21.

Using of the LQ approach boosts the quality of control. On the other hand, using of the linearization method is necessary for attainment of the high quality of control.

The using of the control action limitation is still necessary, because without it, the control processes are unstable and useless.

D. Control process with using of the Hammerstein and Wiener models

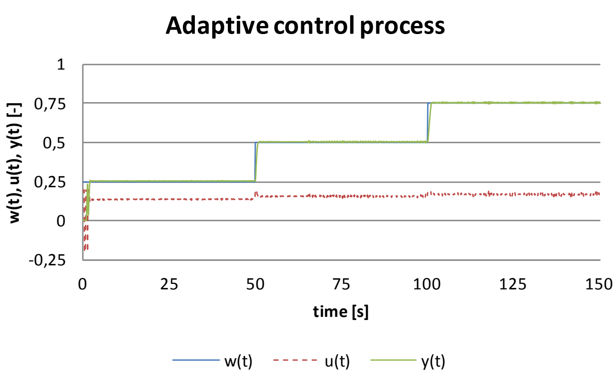

Fig. 27 Control process with using of the Hammerstein and Wiener models for $T_0 = 0.125s$

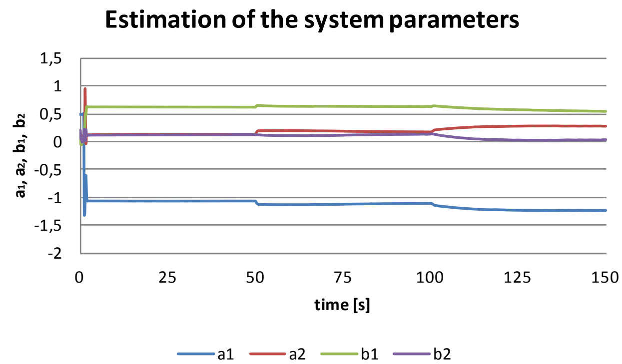

Fig. 28 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J = 0.0015$, $J_Y = 0.0009$, $J_U = 0.0006$

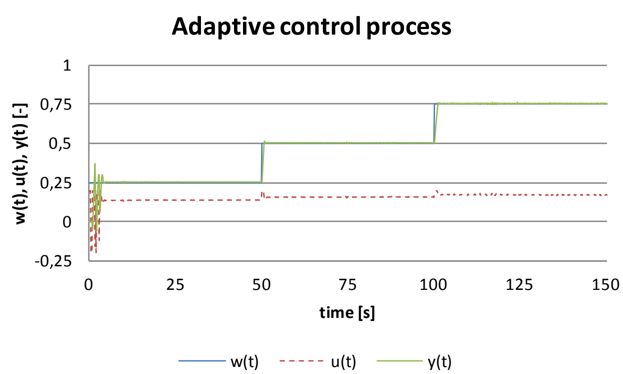

Fig. 29 Control process with using of the Hammerstein and Wiener models for $T_0 = 0.15s$

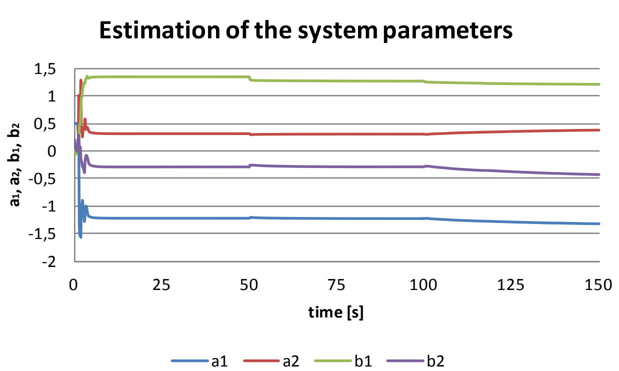

Fig. 30 Estimation of system parameters for $T_0 = 0.15s$

Control Quality: $J = 0.0023$, $J_Y = 0.0011$, $J_U = 0.0012$

As we can see in figures 15, 17, 27 and 29, the using of the LQ approach increase the quality of control but using of the Hammerstein and Wiener models is more significant for attainment of the high-quality control process.

XIII. MULTI-LEVEL CONTROL PROCESS

Control system parameters:

Sampling period: $T_0 = 0.125s$

Poles of the characteristic polynomial were chosen under section VII and VIII.

Identification process parameters:

Exponential forgetting parameter: $\varphi = 0.85$

Other parameters were chosen under [5]

A. Multi-level control process with control action limitation (Pole Placement Method)

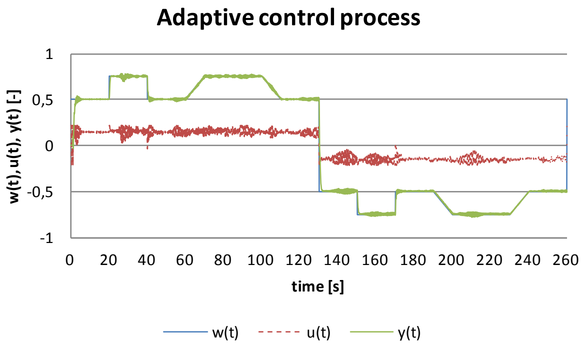

Fig. 31 Multi-level control process with control action limitation for $T_0 = 0.125s$

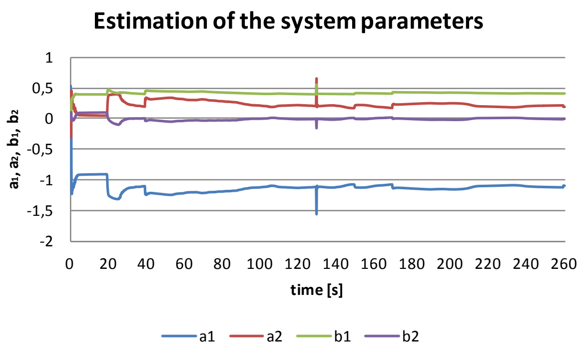

Fig. 32 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J = 0.0073$, $J_Y = 0.0033$, $J_U = 0.0039$

B. Multi-level control process with using of the Hammerstein and Wiener models (Pole Placement Method)

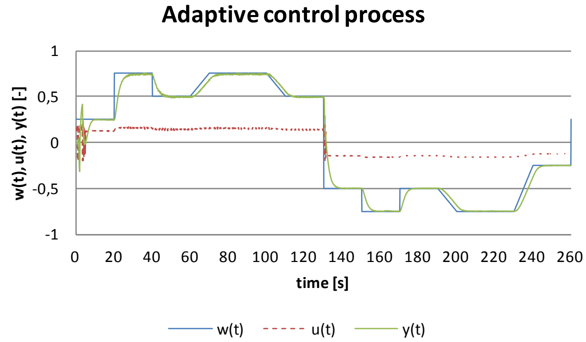

Fig. 33 Multi-level control process with using of the Hammerstein and Wiener models for $T_0 = 0.125s$

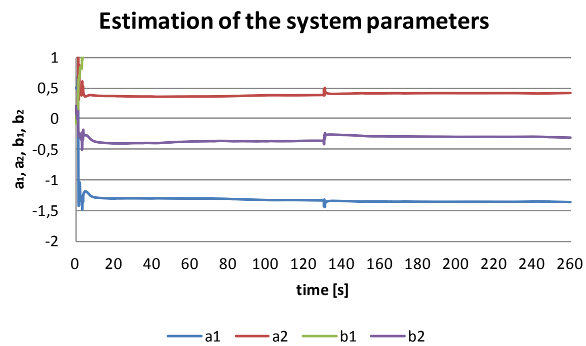

Fig. 34 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J = 0.0100$, $J_Y = 0.0088$, $J_U = 0.0012$

C. Multi-level control process with control action limitation (LQ approach)

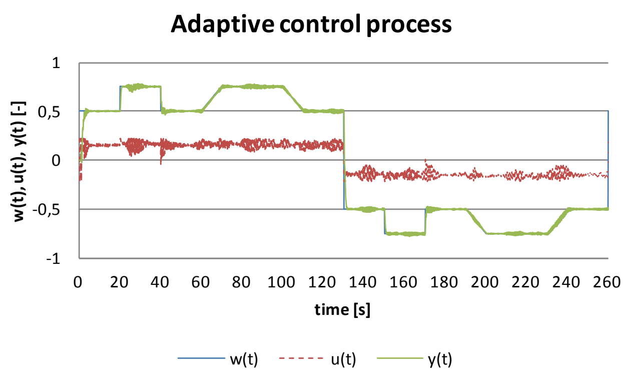

Fig. 35 Multi-level control process with control action limitation for $T_0 = 0.125s$

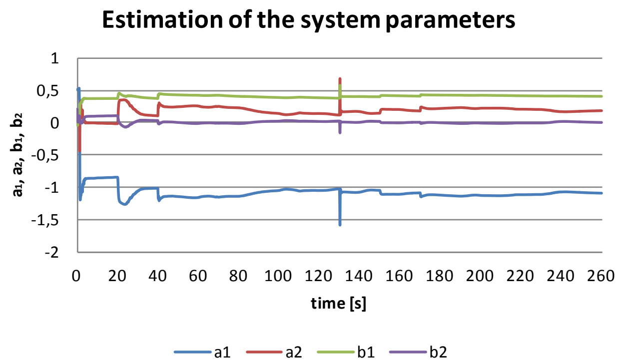

Fig. 36 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J = 0.0036$, $J_Y = 0.0015$, $J_U = 0.0021$

D. Multi-level control process with using of the Hammerstein and Wiener models (LQ approach)

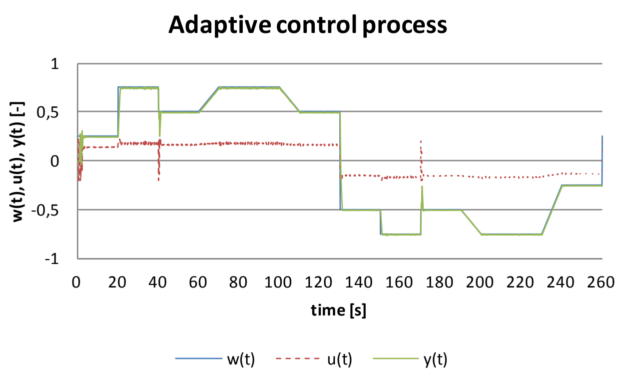

Fig. 37 Multi-level control process with using of the Hammerstein and Wiener models for $T_0 = 0.125s$

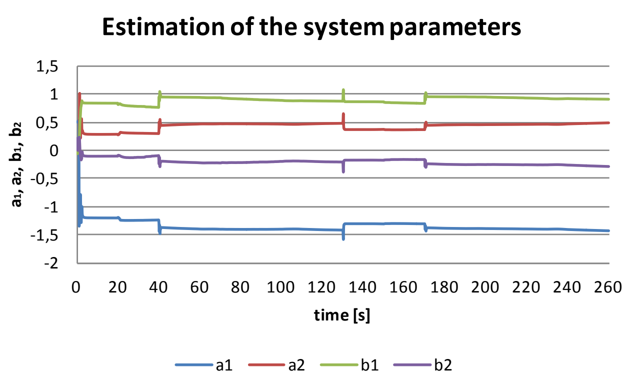

Fig. 38 Estimation of system parameters for $T_0 = 0.125s$

Control Quality: $J = 0.00163$, $J_Y = 0.001$, $J_U = 0.00063$

XIV. Discussion

The control processes when the linear adaptive control without Hammerstein and Wiener models is used we can see in figures 11, 13, 23, 25, 31 and 35. The control action had to be limited, because without it, the control processes were unstable and useless – as we can see in figure 7, 9, 19 and 21. The using of the control action limitation increase the quality of control processes but they are still not optional.

The control processes when the Hammerstein and Wiener models are used are displayed in figures 15, 17, 29, 27, 33 and 37. We can derive the following facts from this measured data. The using of the linear adaptive control with the Hammerstein and Wiener models increases the quality of control process rapidly. Also, the control processes are less oscillating and more stable.

On the other hand, some limitations exist there too. Firstly, the using of the Hammerstein and Wiener models is not suitable for all types of the nonlinear systems – the static nonlinearity has to be more dominant than other ones and nonlinear system has to be factorable to static and dynamic parts. Secondly, for the design of the controller with Wiener models, the knowledge of the static characteristic of the nonlinear system is necessary and this measurement cannot be fully automated. The design of the control system is unique for every nonlinear system.

This method can be interesting in practice applications because it is quite easy to use and it can be combined with almost all types of the linear controllers – time-continuous or time-discrete [14], [17].

Limitations of this method can be minimizing and quality of control can be increased by a future research. Many possible ways exist there. For example, we can apply the predictive control approaches [19], [20], [22] the optimization and evolutionary techniques [23], neural network methods [24] and many others [26].

The next important way for a future research of this method is its extension for using for the Multi-Inputs and Multi-Outputs (MIMO) nonlinear systems.

Acknowledgements

This work was partly supported by the Tomas Bata University in Zlín under the grant IGA/FAI/2013/004 and partly with support of Operational Program Research and Development for Innovations co-funded by the European Regional Development Fund (ERDF) and national budget of Czech Republic, within the framework of project Centre of Polymer Systems (reg. number: CZ.1.05/2.1.00/03.0111).

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