ADAPTIVE FILTER USED AS A DYNAMIC COMPENSATOR IN AUTOMATIC GAUGE CONTROL OF STRIP ROLLING PROCESSES

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Abstract: The paper deals with a control structure of the strip thickness in a rolling mill of quarto type (AGC – Automatic Gauge Control). It performs two functions: the compensation of errors induced by unideal dynamics of the tracking systems lead by AGC system and the control adaptation to the change of dynamic properties of the tracking systems. The compensation of dynamical errors is achieved through inverse models of the tracking system, implemented as adaptive filters.

Keywords: Automatic gauge control, adaptive control, inverse model, adaptive filtering, optimization

1. INTRODUCTION

Increasing the qualitative level of the rolled products required the promoting of a wide range of control methods: adaptive (Asada, *et al*., 2003), robust (Hearns and Grimble, 2000), predictive control (Bulut, *et al*., 2002), H_{inf} control (Imanari, et al., 1997), linearizing control (Choi, *et al*., 2007), artificial intelligence methods (Janabi-Sharifi,F., 2005).

This paper does refer to the rolling mills of "quarto" type, designed to produce very thin strips, to which particularly interests the thickness uniformity of the finite product. In this case the process consists in a number of succesive passes, through the succesive reduction of the gap between rolls.

Let us consider H^* and h^* the nominal values of the strip thickness to the input and output respectively. The corresponding real values H and h, are different from the nominal ones. As a consequence, the deviations $\Delta H = H^* - H$ and $\Delta h = h^* - h$ can be calculated. The objective of

Automatic Gauge Control (AGC) is to minimize the variances ratio of the deviations mentioned before: $I = \sigma_{\Delta h} / \sigma_{\Delta H}$. This objective can be achieved through two types of controls:

1. *through the control in position*, so that modifying the distance *u* between the working rolls, on the basis of a closed loop hydraulic servo-system;
2. *through the control of the strip traction*, in the section of the winding and/or unwinding.

Figure 1 presents the simplified scheme of the reversible quarto rolling mill (Roman *et al*., 2010). For the control in position, AGC system generates the setpoint Δu^* of the sevo-system SH, aiming to compensate the thickness variations, ΔH. The control in traction is achieved considering the variations ΔT_1^* and ΔT_2^* applied to the setpoins T_{01}^* and T_{02}^* of the winding and/or unwinding traction control loops, that means the control of the motors $M_{1,2}$. The traction control systems ($STL_{1,2}$) are strongly variant due to the modification of the winding diameter and to the modification of the

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rezistence of the motor's inductance. The industrial expertise have shown that the positioning servo-system of the rolls *SH* is also variant.

This paper deals with an AGC structure that offers the possibility to adjust the control algorithm to the current modifications of the plasticity module of the rolled product. Moreover, it achieves the error compensation induced by the unideal dynamics of the tracking systems led by AGC system. It also achieves the control adaptation to the changes of the dynamic properties of these tracking systems. The presentation of the proposed structure is done only for the control in position of the gap between the working rolls.

2. CONTROL STRUCTURE

The thickness deviations to the stand output, Δh, come from two sources:

1. thickness deviations due to material properties, which, at their turn, could be thickness deviation at the strip input (ΔH) and deviations due to variation of deformation resistance ($\Delta\sigma$) due to the compression and traction forces;
2. thickness deviations that could appear due to the rolling equipment. These are given by the stand yield, being dependent of the stand elasticity module, *M*, and of the variation of the friction coefficient of the working mills with rolled strip, $\Delta\mu$.
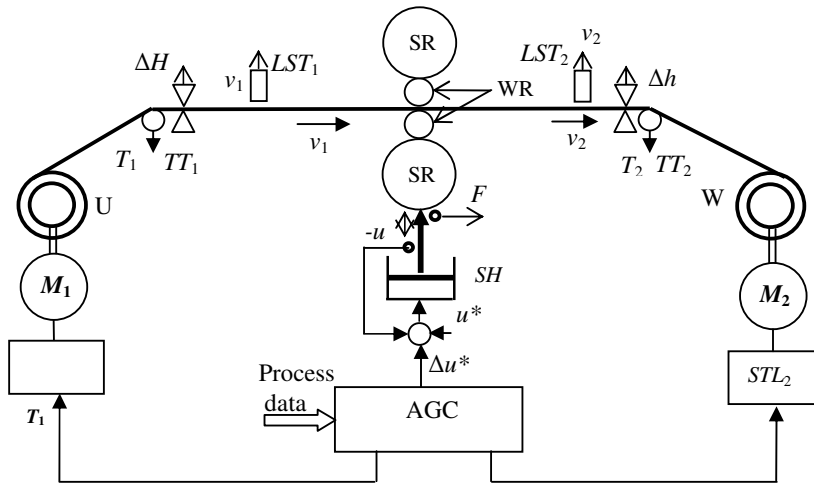

Fig.1 The control structure of the quarto rolling mill: *WR* - working rolls, *SR* – support rolls, *W* – winding, *U* – unwinding, *SH* – hydraulic servo-system for roll positioning, *AGC* – automatic gauge control system, *E* – angular speed transducer of encoder type, $LST_{1,2}$ – linear speed transducer of the strip, $TT_{1,2}$ – traction transducer.

The model of the plastic deformation of the rolled product reflects the dependence of thickness deviation, Δh, by the mentioned variables, but also by the variations Δu^*, ΔT_1^* and ΔT_2^*, that represents the controls of AGC system. Using the notation

$$h = h(H, u, T_1, T_2, \sigma, \mu, ...) \qquad (1)$$

the generic model of the strip thickness to the stand output, Δh, is

$$\Delta h = S_H \Delta H + S_u \Delta u + S_{T1} \Delta T_1 + S_{T2} \Delta T_2 + S_\sigma \Delta\sigma + S_\mu \Delta\mu$$
$$(2)$$

where

$$S_H = \frac{\partial h}{\partial H}; S_u = \frac{\partial h}{\partial u}; S_{T1} = \frac{\partial h}{\partial T_1}; S_{T2} = \frac{\partial h}{\partial T_2}; S_\sigma = \frac{\partial h}{\partial \sigma}; S_\mu = \frac{\partial h}{\partial \mu}$$
$$(3)$$

are the sensitivity functions with respect to the variables that affect the thickness deviation to the output. Both sensitivity functions, S_H and S_u, depend on the plasticity module of the material, *m*, and on the elasticity module of the stand, *M*:

$$S_H = \frac{m}{m+M} \; ; \qquad S_u = \frac{M}{m+M} \qquad (4)$$

The sensitivity functions S_{Ti}, *i*=1,2, are given by the following expressions:

$$S_{Ti} = 1/(\sigma_{ci} L_t), \quad i = 1, 2 \qquad (5)$$

where σ_{ci} represents the flow limits of the material imposed by the tractions between unwinding and stand and between stand and winding respectively. L_t represents the strip breadth. In the expression (2) ΔH and Δh represent disturbance and output

variable respectively, and Δu, ΔT_1, ΔT_2 are controls given by AGC system. In the simplest formulation the effect of the term $S_H \Delta H$ from expression (2) should be compensated by the terms $S_u \Delta u$, $S_{T1} \Delta T_1$ and $S_{T2} \Delta T_2$, corresponding to the control given by AGC system, while the parameters S_σ and S_μ intervene in the disturbance term

$$\Delta w = S_\sigma \Delta \sigma + S_\mu \Delta \mu \qquad (6)$$

that cannot be evaluated. The linearized equation of the process within a pass is

$$\Delta h = A\Delta H + B\Delta u + B_1 \Delta T_1 + B_2 \Delta T_2 + \Delta w; \quad (7)$$

where $A = S_H$, $B = S_u$, $B_1 = S_{T1}$, $B_2 = S_{T2}$. Considering the condition $\Delta h = 0$ and making abstraction by the unmeasurable disturbance term, it results the control that must be applied:

$$\Delta u = -\frac{\alpha m}{M}\Delta H - \frac{\beta m}{(m+M)S_{T1}}\Delta H - \frac{\gamma m}{(m+M)S_{T2}}\Delta H;$$

$$\alpha + \beta + \gamma = 1 \qquad (8)$$

In equation (8) α, β and γ are wheighting factors of the control effects Δu, ΔT_1 and ΔT_2 respectively.

The plasticity module of the stand can be measured enough accurate when the stand is calibrated, so that the available value, $\hat{M}$, can be used in equation (8), instead of variable M. In exchange, the plasticity module m of the material is known only with a rough approximation. At the same time the flow limits of the material given by the traction before and behind the stand are not known. Using preliminary estimations, $\hat{m}$, $\hat{\sigma}_{ci}$, of these variables, it is necessary to introduce the gains G, G_1 and G_2 in the control equation (8), so that $\hat{m}.G \quad m$, $\hat{S}_{T1}G_1 = S_{T1}$, $\hat{S}_{T2}G_2 = S_{T2}$. In these conditions the control equation becomes

$$\Delta u = -\frac{\alpha \hat{m}}{\hat{M}}.G.\Delta H - \frac{\beta G \hat{m}}{(G\hat{m}+M)G_2 \hat{S}_{T1}}\Delta H - \frac{\gamma G \hat{m}}{(G\hat{m}+M)G_2 \hat{S}_{T2}}\Delta H$$

$$(9)$$

The gains G, G_1, G_2 represent the adaptation parameters of the process, in the conditions in which the criterion's minimization is imposed: $I = \sigma_{\Delta h} / \sigma_{\Delta H}$.

Now let us consider the rolling process with more passes in which the pass current number is specified by index k within a strip rolling. In this case, the thickness deviation to the output is noticed by Δh_k and $\Delta H_k = \Delta h_{k-1}$. In these conditions, from equation (7), it is obtained:

$$\Delta h_k = A_k \Delta h_{k-1} + B_k \Delta u_k + B_{k1}\Delta T_1 + B_{k2}\Delta T_2 + \Delta w_k; \quad k = \overline{1, N}$$

$$(10)$$

where N is the total number of passes (maximum 5). In relation to the strip thickness, h_k, the controled process does behave as a dynamic system with variable parameters, due to the modification of the plasticity module m and of the flow limits of the material σ_{ci}, as a result of the rolled material hardening.

Figure 2 presents the structure of AGC system where k represents the current number during a strip rolling. The thickness deviation transducer to the input supplies information shifted in advance relating to the thickness deviation of the strip. The signal taken by the transducer is transferred in a shifting register that exists in the controller (see LI in Figure 2) and it is extracted from this register with a delay calculated as a function of the measured speed v_1. On the basis of the available signal, ΔH_k, it should be assured the movement Δu_k of the working rolls, produced by the hydraulic servo-system having the transfer function $H_{SH}(s)$, such as the traction controls through the transfer functions $H_{T1}(s)$ and $H_{T2}(s)$. In the controller structure there are three subsystems that make an approximation of the inverse functions of the mentioned actuators: $\hat{H}_{SH}^{-1}(s)$, $\hat{H}_{T1}^{-1}(s)$ and $\hat{H}_{T2}^{-1}(s)$. The control structure purpose is the following: the ensemble inverse subsystem – actuator has to perform a transfer of the controls given by AGC system to the variations Δu_k, Δu_{k1}, Δu_{k2} as fast as possible (Tao, 1999). Because the main uncertainties from the model are found in the estimations of the plasticity module ($\hat{m}_k \neq m_k$) and of the flow limits σ_{c1} and σ_{c2} from the expressions (5) of the sensitivity functions S_{Ti}, the gains G, G_1, G_2 should be adopted so that the imposed performance criterion has a minimum value.

The analysis of the system from Figure 2 has been made through numerical simulation considering that AGC structure does only assure the control in position. Real signals, $\Delta H(i)$, taken from an industrial plant with a sample period equal to $T_s = 0.002$s, has been used.

Figure 3 presents a sample from the time series $\Delta H(i)$. The autocorrelation function of the signal $\Delta H(i)$, presented in Figure 4, shows that the process data also contain pseudo-periodical components, introduced by the technological equipment. The high frequency components from the spectrum of the signal $\Delta H(i)$ have a crucial importance that is the fastest random variations from this time series. Using the dynamic compensator of inverse model type $\hat{H}_{SH}^{-1}(s)$, these variations must be produced with a phase shift as reduced as possible of the variable Δh_2, aiming to compensate the variation Δh_1. Considering the variant character of the servo-system, an adaptive filter has been used for the compensator design.
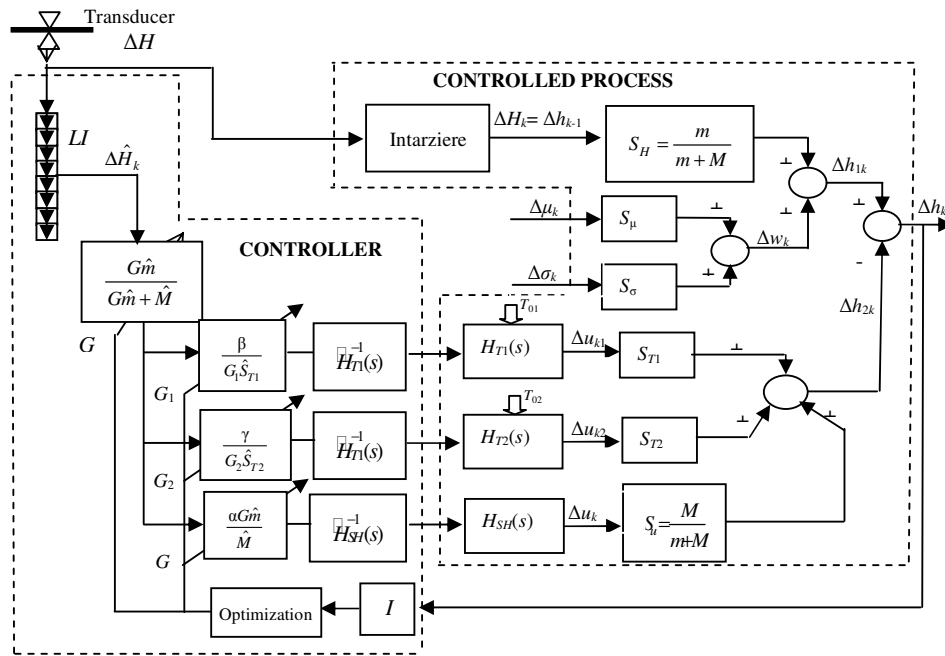
Fig. 2: The thickness control system through the commands in position of the rolls and in streep traction on the basis of the measured thickness deviations masurate ΔH
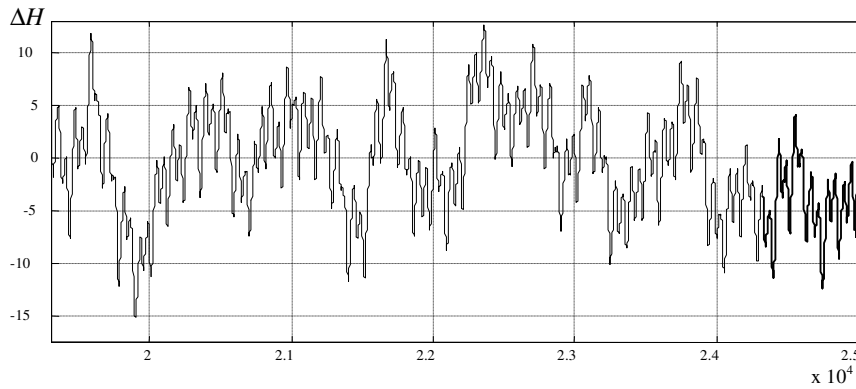
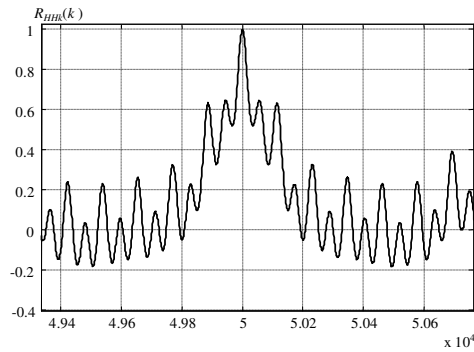

Fig.3: Sample from the time series $\Delta H(i)$

Fig. 4 The autocorrelation function of the time series $\Delta H(i)$

The variant discreet time inverse model of the servo-system is of convolution type:

$$y(i) = h^T(i) \cdot x(i) \tag{11}$$

where: $y(i)$ is the control Δu given by AGC system. The vector $x(i)$ has the following form:

$$x(i) = [x(i) \quad x(i-1) \quad x(i-2) .... x(i-n+1)]^T \tag{12}$$

where $x(i)$ represents the measured variation of the gap between the mills at the current discreet time i and $h(i)$ is the response vector to the impulse of the adaptive filter:

$$h(i) = [h_0(i) \quad h_1(i) ..... h_i(i) .... h_{n-1}(i)]^T \tag{13}$$

The parameter vector $h(i)$ is chosen so the performance criterion has a minimum value

$$I(i) = \frac{1}{2}\sum_{k=1}^{i}\lambda^{i-k}[y(k) - h^T(i)x(k)]^2 \tag{14}$$

where λ is the forgetting factor. The parameter estimation is done using the classic RLS algorithm, that assumes the recursive calculus of the following variables:
- adaptation gain:

$$g(i) = \lambda^{-1}C_{xx}^{-1}(i-1)x(i)\left[1 + \lambda^{-1}x^T(i)C_{xx}^{-1}(i-1)x(i)\right]^{-1} \tag{15}$$

- a priori error:

$$e(i) = y(i) - p^T(i-1)x(i) \tag{16}$$

- adaptive filter parameters:

$$h(i) = h(i-1) + .g(i).e(i) \tag{17}$$

- inverse of autocorrelation matrix:

$$C_{xx}^{-1}(i) = C_{xx}^{-1}(i-1) - g(i).x^T(i)C_{xx}^{-1}(i-1) \tag{18}$$

3. NUMERICAL RESULTS

Figure 5 shows the tipical shape of response to the impulse of the discreet time invers model of the servo-system. It can be observed that the number of samples $h_i(i)$, $i = \overline{1,n-1}$, is reduced, which provides a good adaptation ability of the dynamic compensator. Figure 6 presents Bode characteristics of the hydraulic servo-system (solid line), dynamic compensator (dot line) and compensated servo-system (dash line). The compensation of the frequency characteristic is done in a large domain, but the limits of this compensation are given by the non-linearities of saturation type and the noise level.

The sensitive decrease of the magnitude of the variations Δh takes place as a result of control structure tuning with respect to two freedom degrees:
- the gain G, that determines the magnitude of the variable $\Delta h_{2k}(t)$.
- the compensation of the servo-system dynamics SH using the adaptive filter, that is accomplished through the phasing of the variable $\Delta h_{2k}(t)$ with respect to $\Delta h_{1k}(t)$ (in fact, the phase shift reducing between these two variables).
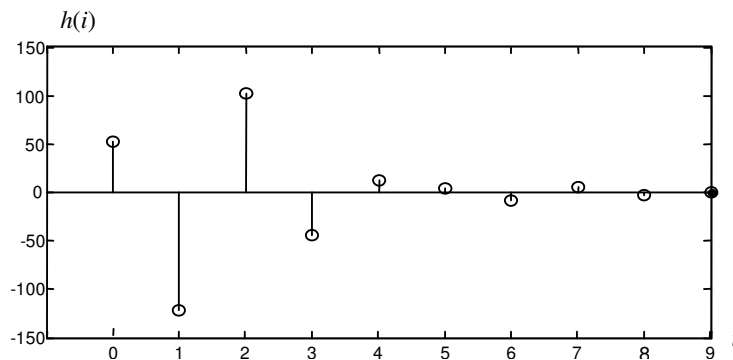

Fig. 5 Response to the impulse of the adaptive filter

Figure 7 presents the evolution of the variable Δh, in a time interval equal to 100s, when the gain G has a slop evolution, so that the variation domain includes the optimal value. Figure 8 shows the evolution of the standard deviation $\sigma_{\Delta h}$ in the searching process, in a time period equal to 100s. At the moment $t = 50s$, meaning after 2500 sample steps, the plasticity module has been modified through a step variation of 300%. For illustrating the importance of the dynamic compensator in

system operating, two operating regimes with and without the adaptive filter that implements the dynamic compensator were achieved. The evolution of the performance criterion in the two situations is presented in Figure 9. The explanation of the reducing of the system performances without compensator results from Figures 10 and 11. It can

be noticed that the phase shift of the variable $\Delta h_2(i)$ with respect to $\Delta h_1(i)$ leads to the sensitive increase of the difference $\Delta h(i) = \Delta h_1(i) - \Delta h_1(i)$.
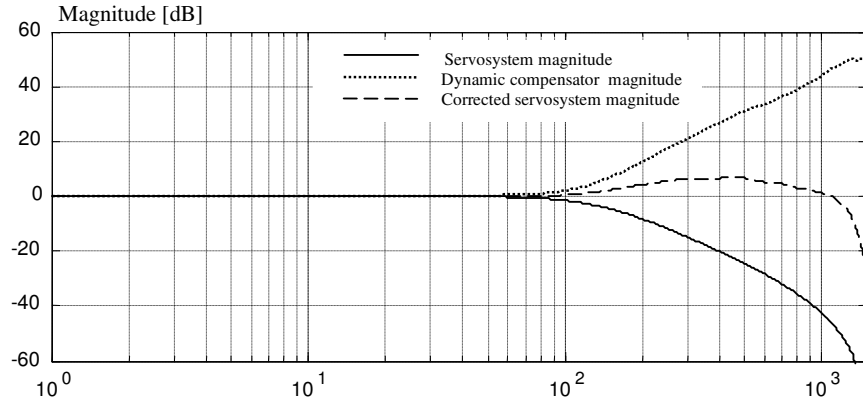
Fig. 6 Bode characteristics of servo-system, dynamic compensator and compensated servo-system
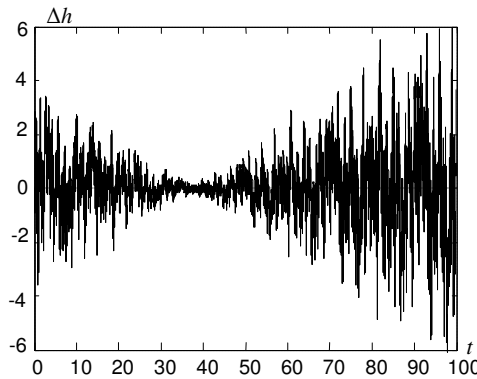

Fig.7 The evolution of the variable Δh to a slop variation of the gain G
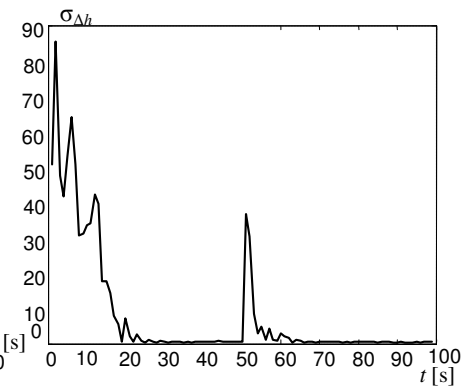
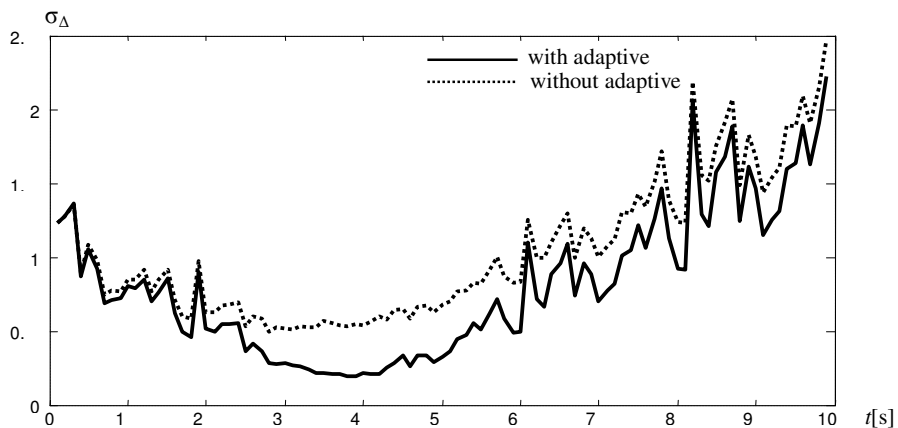Fig.8 The evolution of the variable $\sigma_{\Delta h}$ in the adaptation process

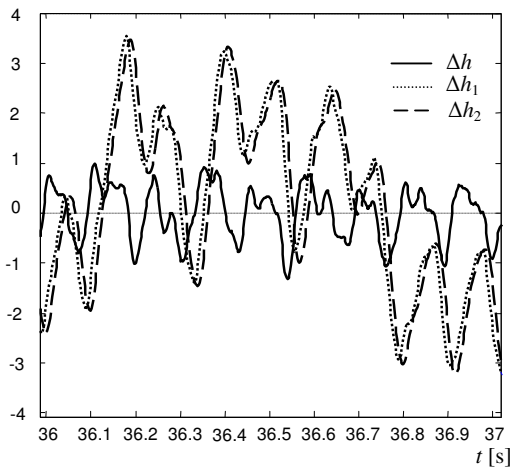Fig. 9 Evolutions of the performance criterion with and without dynamic compensator

Fig.10 Evolution of variables Δh_1 (dot), Δh_2 (dash), Δh (solid) without dynamic compnsator
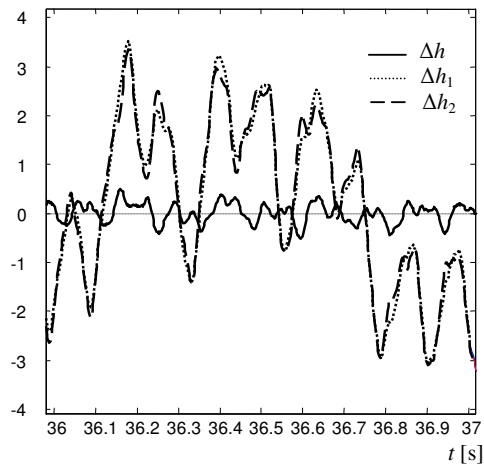
Fig.11 Evolutions of variables Δh_1 (dot), Δh_2 (dash), Δh (solid) with dynamic compensator

CONCLUSIONS

The AGC structure proposed in this paper offers the posibility of the control algorithm adaptation to the current modifications of the plasticity module of the rolled product, performing two important properties: the compensation of the errors induced by the unideal and variant dynamics of the actuators and the adjutment of the controller's gain so that the performance criterion having a minimum value respectively. The compensation of the dynamic errors is made through inverse models at causal limit of the actuators. These inverse models are implemented as adaptive filters because the actuators are considered variant systems. Moreover, the use of adaptive filters does not involved the a priori knowledge of the mathematical model structure.

Numerical results presented in the paper are refering to the control in position, through the modification of the gap between the working mills. The obtained results emphasized the fact that the thickness variations Δh are determined by two factors that are equally important: the control gain given by the controller, so that the variation Δh_2 be as closed as possible to Δh_1 and the phasing of the variation Δh_2 with respect to Δh_1, through the dynamic compensator.

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