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Control Solutions in Mechatronics Systems

Dedicated to Professor Milić Stojić on the occasion of his 65th birthday

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Abstract: This paper presents control solutions dedicated to a class of controlled plants widely used in mechatronics systems, characterized by simplified mathematical models of second-order and third-order plus integral type. The conventional control solution is focused on the Extended Symmetrical Optimum method proposed by the authors in 1996. There are proposed six fuzzy control solutions employing PI-fuzzy controllers. These solutions are based on the approximate equivalence in certain conditions between fuzzy control systems and linear ones, on the application of the modal equivalence principle, and on the transfer of results from the continuous-time conventional solution to the fuzzy solutions via a discrete-time expression of the controller where Prof. Milić R. Stojić's book [1] is used. There is performed the sensitivity analysis of the fuzzy control systems with respect to the parametric variations of the controlled plant, which enables the development of the fuzzy controllers. In addition, the paper presents aspects concerning Iterative Feedback Tuning and Iterative Learning Control in the framework of fuzzy control systems. The theoretical results are validated by considering a real-world application.

Keywords: Fuzzy controllers, mechatronics systems, Extended Symmetrical Optimum method, sensitivity analysis, Iterative Feedback Tuning, Iterative Learning Control.

1 Introduction

Control systems (CSs) used in mechatronics systems (MSs) applied in production and transportation must ensure very good steady-state and dynamic performance. This is the reason why they need high quality actuators that must ensure both stabilization and tracking. The MSs considered in this paper are applied in case of

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several actuators - sub-systems belonging to the speed CSs of hydro-generators, to the position CSs in mobile robots and in machine tool servo-systems - and can be seen as particular cases of benchmark systems [2]. With this respect, these MSs are considered as local CSs. A relatively difficult and challenging task is represented by the assurance of very good performance for these local CSs by means of low-cost solutions.

A way to fulfill this task is to employ fuzzy control. The development of fuzzy control systems (FCSs) is usually performed by heuristic means, incorporating human skills, but the drawback is in the lack of general-purpose development methods. A major problem, which follows from this way of developing fuzzy controllers (FCs) is the analysis of several properties of the CS including stability, controllability or sensitivity and robustness [3]-[5] resulting immediately in the necessity for systematic development methods devoted to relatively simple FCs. One way to cope with this problem is proposed here by developing firstly some conventional controllers dedicated to partial stabilization of the controlled plants (CPs) followed by the development of PI-fuzzy controllers (PI-FCs). The Extended Symmetrical Optimum (ESO) method [6]-[7] originally applied to linear systems guarantees the stability of the FCSs and ensures very good CS performance by accepting the well acknowledged equivalence in certain conditions between FCSs and linear / linearized CSs [8]-[9].

The paper addresses the following topics. The simplified models of the second-order and third-order controlled plants as electro-hydraulic servo-systems (EHSs) used in speed control of hydro-generators will be discussed in the next Section together with the an overview on the ESO method used in tuning the linear PI controllers as part of six control structures dedicated to the accepted CPs. Then, Section 3 presents the development method for the proposed PI-FCs, which ensures the stability and CS performance of the FCSs. Section 4 is dedicated to the sensitivity analysis of the FCSs exemplified for one of the FCSs. Section 5 presents considerations on using Iterative Feedback Tuning (IFT) and Iterative Learning Control (ILC) in FCSs. Section 6 deals with the case study, a nonlinear servo-system with variable load, applicable as actuator as part of position EHSs or of CSs in mobile robots, and validates the proposed fuzzy controllers and development method by including experimental results. The final Section outlines the conclusions.

2 Conventional Control Solution and Fuzzy Control System Structures

The dynamics of the considered CPs is described in its simplified linearized form by the structures presented in Figure 1 and Figure 2 corresponding to the secondand third-order integrator, respectively, exemplified in case of MSs of EHS type, where u_P represents the control signal, y is the controlled output, x_1, x_2 and x_3 stand for the state variables, T_{i1}, T_{i2} and T_{i3} are the integral time constants and k_A is the gain of the proportional amplifier. The presence of the third integrator (in Figure 2) as additional hydraulic amplifier becomes necessary when a large power actuator is desired.

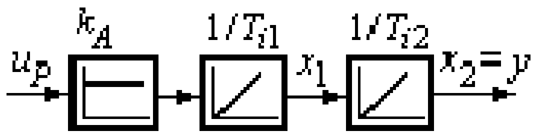

Fig. 1. Simplified structure of second-order EHS as controlled plant.

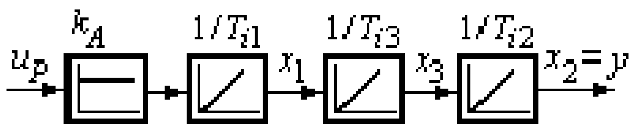

Fig. 2. Simplified structure of third-order EHS as controlled plant.

The considered CPs are structurally unstable systems that must be firstly stabilized. So, the aim of controller development is to ensure very good dynamic and steady-state CS performance obtained in the controlled output y (the position of the actuator) and characterized by very good regulation and tracking of reference input r as well. The first way to accomplish this aim is to develop state feedback CSs. By performing only the partial state feedback stabilization of the CPs and by including the FCs there can be constructed six versions of FCSs (1 ... 6) illustrated in Figure 3 ... Figure 8 (e - control error, u - control signal).

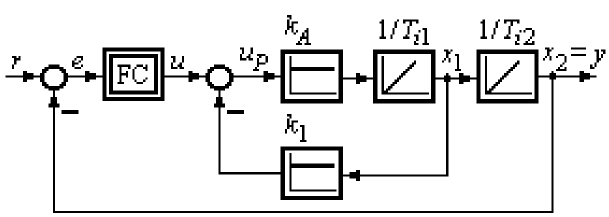

Fig. 3. Version 1 of FCS structure.

For all FCSs the transfer function (t.f.) of the CP seen by the FC (with u as input and y as output) can be approximated by Eq. (1):

$$H_P(s) = k_P/[s(1 + sT_\Sigma)], \tag{1}$$

where k_P is the controlled plant gain, T_Σ is the small time constant or the sum of parasitic time constants. The connections between the parameters in (1) and the parameters of the CP in Figure 1 and Figure 2 are illustrated in Eq. (2):

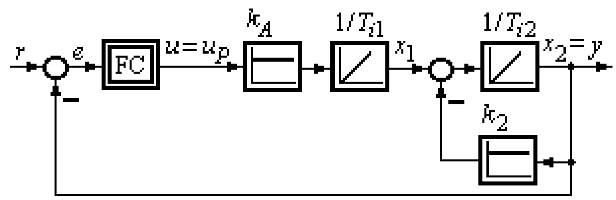

Fig. 4. Version 2 of FCS structure.

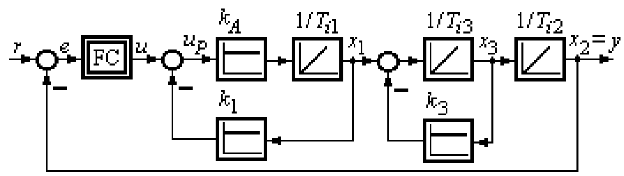

Fig. 5. Version 3 of FCS structure.

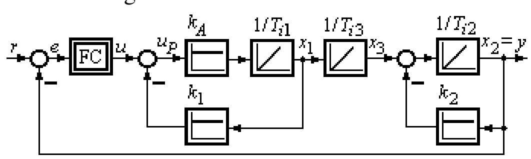

Fig. 6. Version 4 of FCS structure.

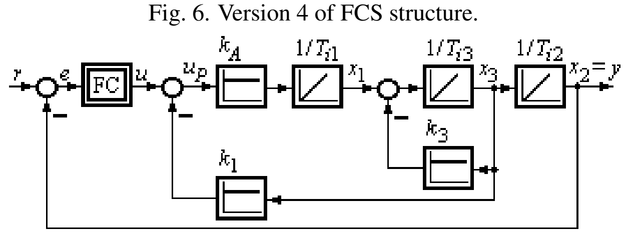

Fig. 7. Version 5 of FCS structure.

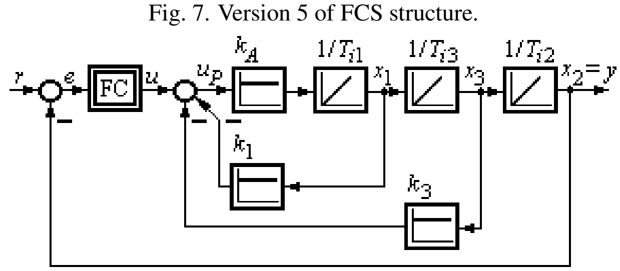

Fig. 8. Version 6 of FCS structure.

$$k_P = \begin{cases} 1/(k_1 T_{i2}) & \text{for FCS in version 1} \\ k_A/(k_2 T_{i1}) & \text{for FCS in version 2} \\ 1/(k_1 k_3 T_{i2}) & \text{for FCS in version 3} \\ 1/(k_1 k_2 T_{i3}) & \text{for FCS in version 4} \\ 1/(k_1 T_{i2}) & \text{for FCS in version 5} \\ 1/(k_3 T_{i2}) & \text{for FCS in version 6} \end{cases},$$

$$T_\Sigma = \begin{cases} T_{i1}/(k_A k_1) & \text{for FCS in version 1} \\ T_{i2}/k_2 & \text{for FCS in version 2} \\ T_{i1}/(k_A k_1) + T_{i3}/k_3 & \text{for FCS in version 3} \\ T_{i1}/(k_A k_1) + T_{i2}/k_2 & \text{for FCS in version 4} \\ T_{\Sigma 1} + T_{\Sigma 2}, T_{\Sigma 1} + T_{\Sigma 2} = k_3 T_{i1}/(k_A k_1) \\ T_{\Sigma 1} T_{\Sigma 2} = T_{i1} T_{i3}/(k_A k_1) & \text{for FCS in version 5} \\ T_{\Sigma 1} + T_{\Sigma 2}, T_{\Sigma 1} + T_{\Sigma 2} = k_1 T_{i3}/k_3 \\ T_{\Sigma 1} T_{\Sigma 2} = T_{i1} T_{i3}/(k_A k_3) & \text{for FCS in version 6} \end{cases}. \quad (2)$$

By accepting the plant t.f. in Eq. (1), the use of PI controllers with the t.f. (3):

$$H_C(s) = k_c(1 + sT_i)/s = k_C(1 + 1/sT_i), \quad k_C = T_i k_c, \quad (3)$$

where k_C is the controller gain and T_i is the integral time constant, can ensure acceptable CS performance when the controllers are tuned in terms of the Symmetrical Optimum method [10].

A simple and efficient way to determine the parameters of a PI controller (3) is represented by the ESO method developed in [6]-[7]. The method is characterized by only one design parameter, β. By the choice of the parameter β within the domain $1 < \beta < 20$, the CS performance indices (σ_1 - overshoot, $\hat{t}_r = t_r/T_\Sigma$ - normalized rise time, $\hat{t}_s = t_s/T_\Sigma$ - normalized settling time defined in the unit step modification of r, φ_m - phase margin) can be accordingly modified and a compromise to these performance indices can be reached by using the diagrams presented in Figure 9.

The PI tuning conditions, specific to the ESO method, can be expressed as:

$$k_c = 1/(\beta^{3/2} T_\Sigma^2 k_P), \;\; T_i = \beta T_\Sigma. \quad (4)$$

The CS performance can be further improved by the reference filter with the t.f. $H_{RF}(s)$ to suppress the action of the zero in the closed-loop t.f. with respect to r:

$$H_{RF}(s) = 1/(1 + \beta T_\Sigma s). \quad (5)$$

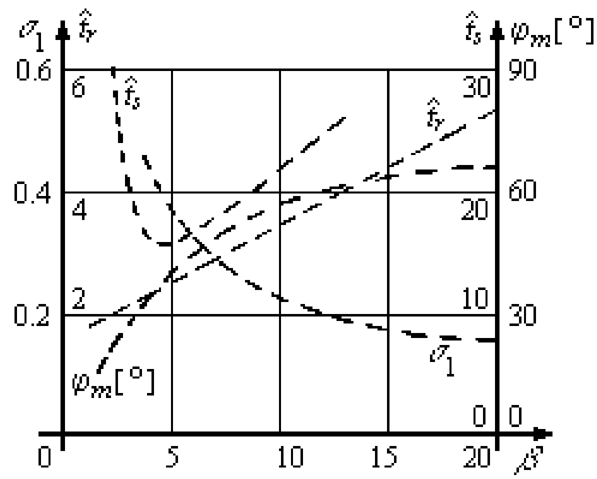

Fig. 9. CS performance indices versus β.

3 Development Method for PI-Fuzzy Controllers

The PI-FC represents a discrete-time FC with dynamics, introduced by the numerical differentiation of the control error e_k expressed as the increment of control error, $\Delta e_k = e_k - e_{k-1}$, and by the numerical integration of the increment of control signal, Δu_k. The structure of the considered PI-FC is illustrated in Figure 10, where B-FC represents the basic fuzzy controller, without dynamics.

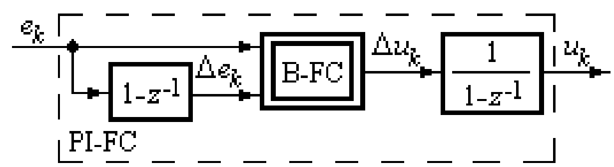

Fig. 10. Structure of PI-FC.

The block B-FC is a nonlinear two inputs-single output system, which includes among its nonlinearities the scaling of inputs and output as part of its fuzzification module. The fuzzification is solved in terms of the regularly distributed - chosen in the initial phase - input and output membership functions shown in Figure 11. Other membership function distributions can modify in a desired way the controller nonlinearities.

The inference engine in B-FC employs Mamdani's MAX-MIN compositional rule of inference assisted by the rule base presented in Table 1, and the centre of

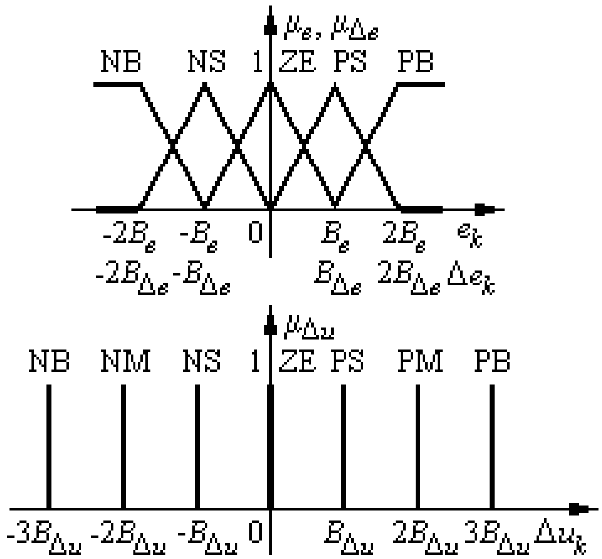

Fig. 11. Membership functions of B-FC.

gravity method for singletons is used for defuzzification.

Table 1. Decision table of B-FC.

$\Delta e_k / e_k$	NB	NS	ZE	PS	PB
PB	ZE	PS	PM	PB	PB
PS	NS	ZE	PS	PM	PB
ZE	NM	NS	ZE	PS	PM
NS	NB	NM	NS	ZE	PS
NB	NB	NB	NM	NS	ZE

The development method of the considered PI-FCs consists of the following steps:

1. Determine the state feedback gains k_1, k_2 and k_3 by using Eq. (2) and an acceptable value of T_Σ.
2. Choose the value of the design parameter β and tune the linear PI controller in terms of (4) by taking into account the aspects highlighted in Section 2.
3. Set the value of the sampling period T_s in accordance with the requirements of quasi-continuous digital control (see, e.g., [1]).
4. Express the discrete-time equation of a digital PI controller in its incremental version:
$$\Delta u_k = K_P \cdot \Delta e_k + K_I \cdot e_k = K_P(\Delta e_k + \gamma \cdot e_k), \tag{6}$$

and calculate the parameters $\{K_P, K_I, \gamma\}$. For example, the expressions of the digital PI controller are (7) in case of Tustin's discretization method:

$$\begin{aligned} &K_P = k_C[1 - T_s/(2T_i)],\ K_I = k_C T_s/T_i, \\ &\gamma = K_I/K_P = 2T_s/(2T_i - T_s). \end{aligned} \tag{7}$$

5. Apply the modal equivalence principle [9] resulting in Eq. (8):

$$B_{\Delta e} = \gamma B_e,\ B_{\Delta u} = K_I B_e, \tag{8}$$

where the free parameter B_e represents designer's option.

4 Sensitivity Analysis of Fuzzy Control Systems

To perform the sensitivity analysis of the FCSs with respect to the parametric variations of the CP there must be derived sensitivity models [11] for the FCs and for the overall FCSs. Since the FCSs can be accepted, as mentioned in Section 1, to be approximately equivalent with the linear CSs, it is justified to consider that the sensitivity models of the FCSs are approximately equivalent to those of the linear CSs. Therefore, it is necessary to obtain firstly the sensitivity models of the linear CSs (the structures in Section 1 with the linear PI controllers instead of the FCs). To derive the sensitivity models of the linear CS it will be performed with respect to the variations of CP parameters k_P and T_Σ in Eq. (1). The analysis can be done also with respect to the CP parametric variations in terms of Figure 1 and Figure 2 with no major difficulties, but this approach ensures the unified sensitivity analysis for all six FCS structures.

For the sake of simplicity it will be considered in the sequel that the disturbance input is absent. However, several types of disturbance inputs can be defined specific to the application field of the considered MSs.

By considering the state variables x_{S1} (the controlled output) and x_{S2} (the integrator output in relation with Eq. (1)), the state mathematical model (MM) of the CP results as:

$$\begin{aligned} &\dot{x}_{S1}(t) = -(1/T_\Sigma)x_{S1}(t) + (k_P/T_\Sigma)x_{S2}(t), \\ &\dot{x}_{S2}(t) = u(t), \\ &y(t) = x_{S1}(t), \end{aligned} \tag{9}$$

and the state MM of the linear PI controller can be expressed in its parallel form:

$$\begin{aligned} &\dot{x}_{S3}(t) = (1/T_i)e(t), \\ &u(t) = k_C(x_3(t) + e(t)), \end{aligned} \tag{10}$$

where x_{S3} is the output of the integral component of the controller.

It is considered that the linear PI controller is tuned in terms of (4) by considering the nominal values of CP parameters, $\{k_{P0}, T_{\Sigma 0}\}$. Therefore, the state MM of the PI controller will become (11):

$$\begin{aligned} &\dot{x}_{S3}(t) = [(1/\beta T_{\Sigma 0})]e(t), \\ &u(t) = [1/(\beta^{1/2} k_{P0} T_{\Sigma 0})](x_3(t) + e(t)). \end{aligned} \tag{11}$$

The state MM of the closed-loop system can be obtained by the merge of the models in (9) and (11):

$$\begin{aligned} &\dot{x}_{S1}(t) = -(1/T_\Sigma)x_{S1}(t) + (k_P/T_\Sigma)x_{S2}(t), \\ &\dot{x}_{S2}(t) = -[1/(\beta^{1/2}k_{P0}T_{\Sigma 0})]x_{S1}(t) + [1/(\beta^{1/2}k_{P0}T_{\Sigma 0})]x_{S3}(t)+ \\ &\qquad + [1/(\beta^{1/2}k_{P0}T_{\Sigma 0})]r(t), \\ &\dot{x}_{S3}(t) = -[1/(\beta T_{\Sigma 0})]x_{S1}(t) + [1/(\beta T_{\Sigma 0})]r(t), \\ &y(t) = x_{S1}(t). \end{aligned} \tag{12}$$

For the system (12) there can be derived the state sensitivity functions $\{\lambda_1, \lambda_2, \lambda_3\}$ and the output sensitivity function, σ:

$$\begin{aligned} &\lambda_j(t) = [\partial x_{Sj}(t)/\partial \alpha]_{\alpha 0}, \\ &\sigma(\mathrm{t}) = [\partial y(t)/\partial \alpha]_{\alpha 0}, \mathrm{j} = 1 \ldots 3, \end{aligned} \tag{13}$$

where the subscript '0' stands for the nominal values of CP parameters, $\alpha \in \{k_P, T_\Sigma\}$.

In this context, the sensitivity model with respect to the variation of k_P and the step modification of r can be derived and expressed in terms of Eq. (14):

$$\begin{aligned} &\dot{\lambda}_1(t) = \lambda_2(t), \\ &\dot{\lambda}_2(t) = -[1/(\beta^{1/2}T_{\Sigma 0}^2)]\lambda_1(t) - (1/T_{\Sigma 0})\lambda_2(t) + [1/(\beta^{1/2}T_{\Sigma 0}^2)]\lambda_3(t)- \\ &\qquad - [1/(\beta^{1/2}k_{P0}T_{\Sigma 0}^2)]x_{S10}(t) + [1/(\beta^{1/2}k_{P0}T_{\Sigma 0}^2)]x_{S30}(t)+ \\ &\qquad + [1/(\beta^{1/2}k_{P0}T_{\Sigma 0}^2)]r_0(t), \\ &\dot{\lambda}_3(t) = -[1/(\beta T_{\Sigma 0})]\lambda_1(t), \\ &\sigma(t) = \lambda_1(t). \end{aligned} \tag{14}$$

The sensitivity model with respect to the variation of T_Σ and the step modification of r can be expressed as:

$$\begin{aligned} &\dot{\lambda}_1(t) = \lambda_2(t), \\ &\dot{\lambda}_2(t) = -[1/(\beta^{1/2}T_{\Sigma 0}^2)]\lambda_1(t) - (1/T_{\Sigma 0})\lambda_2(t) + [1/(\beta^{1/2}T_{\Sigma 0}^2)]\lambda_3(t)+ \\ &\qquad + [1/(\beta^{1/2}T_{\Sigma 0}^3)]x_{S10}(t) + (1/T_{\Sigma 0}^2)x_{S20}(t)- \\ &\qquad - [1/(\beta^{1/2}T_{\Sigma 0}^3)]x_{S30}(t) - [1/(\beta^{1/2}T_{\Sigma 0}^3)]r_0(t), \\ &\dot{\lambda}_3(t) = -[1/(\beta T_{\Sigma 0})]\lambda_1(t), \\ &\sigma(t) = \lambda_1(t). \end{aligned} \tag{15}$$

The variables $\{x_{S10}, x_{S20}, x_{S30}\}$ - the nominal values of the state variables, and r_0 - the nominal value of the reference input, determine the nominal trajectory of the CS or its fundamental motion.

The sensitivity models derived here can be accepted as valid for both the original linear CSs and for the FCSs with PI-FCs due to the approximate equivalence mentioned in Section 1, the only difference being in the generation of the nominal trajectories.

5 Iterative Feedback Tuning and Iterative Learning Control as Fuzzy Control Solutions

Iterative model-free control solutions employ optimization methods that have been shown to ensure good results in controlling a wide range of industrial plants. Two of these solutions, with great potential in mechatronics systems control, will be analyzed shortly in this Section, the IFT and the ILC.

The aim of IFT is to solve a parameter optimization problem, the minimization of an objective function representing a quadratic performance criterion as function of its manipulated variables, the controller tuning parameters. IFT is based on performing an iterative sequence of special online closed-loop experiments to compute the gradient of the objective function with respect to the controller parameters. These experiments are interlaced with periods of data collection under normal operating conditions. Very good overviews on IFT are presented in [12] and [13].

IFT represents in fact a stochastic gradient descent scheme in a finitely parametrized controller space. In the conditions of certain assumptions the IFT algorithm converges to a local minimum of the objective function. The main implementation problems are in the calculation of control signal and controlled output gradient estimates with respect to the controller parameters.

Consider the FCSs with the structures presented in Figure 3 Figure 8, where the FC can be developed according to the development method presented in Section 3. The digital PI controller tuned in step 4 is characterized by the parameter vector $\rho = [\ K_P \quad K_I\ ]^T \in R^2$. Define:

- the control signal vector $u^{1\ldots N}(\rho) = [\ u_1(\rho) \quad u_2(\rho) \quad \ldots \quad u_N(\rho)\ ]^T \in R^N$ and

- the controlled output vector $y^{1\ldots N}(\rho) = [\ y_1(\rho) \quad y_2(\rho) \quad \ldots \quad y_N(\rho)\ ]^T \in R^N$,

with N - the number of experiments, $u_i(\rho)$ and $y_i(\rho)$ - the control signal and the controlled output in the experiment $'i'$, respectively, and $i\ \ (i = 1 \cdots N)$ - the index of current closed-loop experiment. Note that the subscript $'k'$ in Section 3 represents the index of current sampling interval.

The following objective function can be defined:

$$J(u^{1...N}(\rho), y^{1...N}(\rho)) = (0.5/N)\sum_{i=1}^{N}[\psi_i^2(r_i - y_i(\rho))^2 + \zeta_i^2(\Delta u_i(\rho))^2], \qquad (16)$$

where r_i and $\Delta u_i(\rho) = u_i(\rho) - u_{i-1}(\rho)$ are the reference input and the increment of control signal (between two adjacent experiments) in the experiment $'i'$, ψ_i and ζ_i represent the weighting sequences.

The optimization problem to be solved by the IFT algorithm can be stated as [14]:

$$\begin{array}{ll} \text{minimize} & J(u^{1...N}(\rho), y^{1...N}(\rho)) \\ \text{subject to} & u_{\min} \le u_i(\rho) \le u_{\max} \\ & y_{\min} \le y_i(\rho) \le y_{\max} \\ & \Delta u_{\min} \le \Delta u_i(\rho) \le \Delta u_{\max} \\ & i = 1...N \end{array} \qquad (17)$$

A serious problem coming from the optimization problem (17) concerns the choice of the weighting sequences. One approach is to relate these sequences with the step response specifications [14]. Another approach is to use sensitivity functions resulting in a set of objective functions [15].

Connecting the IFT algorithm with fuzzy logic control in terms of [15] and of the considered control system structures or of two degree of freedom control structures (see, e.g., [16]), an IFT control solution dedicated to PI-FCs can be expressed by means of on a new development method. This method replaces the digital PI controller tuning performed in the step 4 as part of the development method shown in Section 3 with an IFT algorithm.

A similar idea can be used in case of ILC to be presented as follows resulting in another development method for PI-FCs, but by replacing in this case the step 5 as part of the development method presented in Section 3 with an ILC algorithm.

The ILC algorithms [16]-[17] have been introduced for control system performance enhancement from the point of view of tracking, and these algorithms are specific to systems operating repetitively [18]-[20]. The operating mechanism of ILC is based on performing several experiments (trials). During the i-th trial the control signal $u_i(t)$ is applied to the CP, with the effect in the controlled output $y_i(t)$. Then, the control error $e_i(t) = r(t) - y_i(t)$, with r - the reference input, is employed by the ILC algorithm to calculate the control signal during the next trial, $u_{i+1}(t)$. This control signal during the $(i+1)$-th trial, $u_{i+1}(t)$, generated to alleviate the control error in comparison with the previous trial, will be stored in a memory until the system operates and applied to the CP.

To express the ILC it is considered that the CP (in its SISO mathematical characterization) can be described by the nonlinear operator F:

$$y(t) = F(u(t), \tag{18}$$

when the control system structures presented in Figure 3 Figure 8.

The aim of ILC is to solve the optimization problem (19):

$$\hat{u}(t) = \arg\min_{u_i(t)} ||r(t) - F(u_i(t)||, \tag{19}$$

and an ILC algorithm will produce a control signal sequence $\{u_i(t)\}_{i\geq 0}$ that converges to the optimal control signal, $\hat{u}(t)$:

$$\lim_{i\to\infty} u_i(t) = \hat{u}(t). \tag{20}$$

The most general ILC linear algorithm can be expressed in the two degree-of-freedom form (21):

$$u_{i+1}(t) = T_u u_i(t) + T_e e_i(t), \tag{21}$$

with T_u and T_e - linear operators.

Another ILC algorithm employs the PID-type form of the control error:

$$u_{i+1}(t) = u_i(t) + \Phi e_i(t) + \Gamma \dot{e}_i(t) + \Psi \int e_i(t)\, dt, \tag{22}$$

and other algorithms can solve several optimization problems [16]-[20].

The main problem appearing in the ILC algorithms is the assurance of the following convergence condition:

$$\lim_{i\to\infty} y_i(t) = r(t). \tag{23}$$

The condition in Eq. (23) can be imposed by stating sufficient analytical conditions. Applications of ILC algorithms in fuzzy control have been reported in [21] and [22].

6 Case Study

To validate the proposed development method and the sensitivity models in fuzzy control of MSs it is considered a case study with the CP characterized in its linearized simplified form by the structure shown in Figure 1.

To use the development method presented in Section 3 the CP must be brought to the form characterized by the t.f. (1) (and this is not a difficult task), with the nominal values of CP parameters $k_{P0} = 1$ and $T_{\Sigma 0} = 1s$. These parameter values correspond to a simplified MM of the nonlinear laboratory DC drive AMIRA DR300, a nonlinear servo-system belonging to the accepted class of mechatronics systems. The DC motor is loaded using a current controlled DC generator, mounted on the same shaft, and the drive has built-in analog current controllers for both DC machines having rated speed equal to 3000 rpm, rated power equal to 30 W, and rated current equal to 2 A. The speed control of the DC motor is digitally implemented using an A/D - D/A data converter card. The speed sensors are a tacho generator and an additional incremental rotary encoder mounted at the free drive-shaft. A schema of the hardware station is presented in Figure 12.

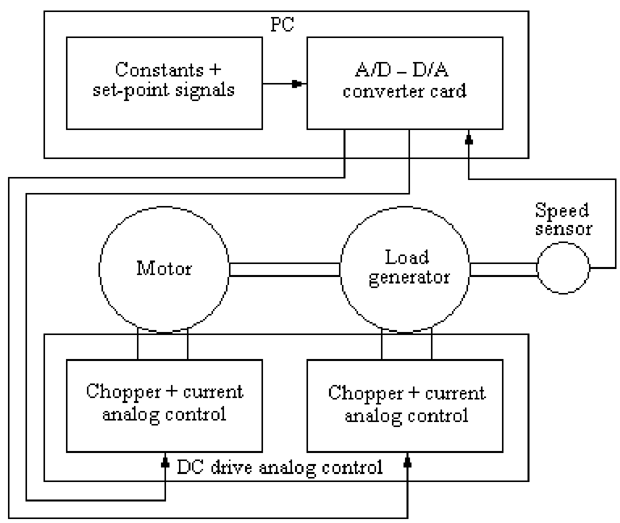

Fig. 12. Schema of hardware station.

For the development of the PI-FC in the considered case study it is applied the development method in Section 3, which continues with choosing $\beta = 6$, and the parameters of the PI controller obtain their nominal values $k_{c0} = 0.068$, and $T_{i0} = 6s$. The values of the tuning parameters of the PI-FC result as follows: $B_e = 0.3, B_{\Delta e} = 0.03, B_{\Delta u} = 0.0021$ for $T_s = 0.005s$.

The behaviors of the conventional CS and of the version 6 of FCS are presented in Figure 13 and Figure 14, respectively, with respect to the modification of the disturbance input and without load.

The behaviors of the sensitivity models (14) and (15) - obtained for the unit step modification of r followed by a unit step modification of an additive disturbance applied to the input of the integrator with the t.f. $1/T_{i2}s$ (after 250 s), in the initial conditions $\lambda_1(0) = 2, \lambda_2(0) = 1, \lambda_3(0) = 0$ - are presented in Figure 15 and Figure

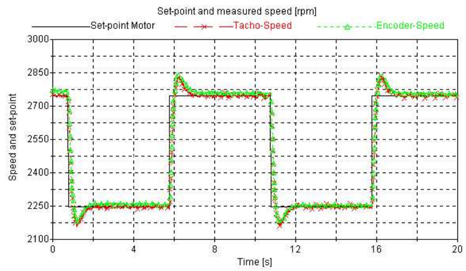

Fig. 13. Speed response of conventional CS PI controller.

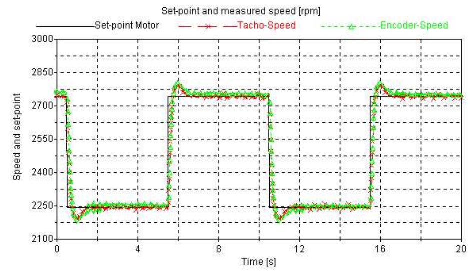

Fig. 14. Speed response of CS with PI-FC.

16, respectively.

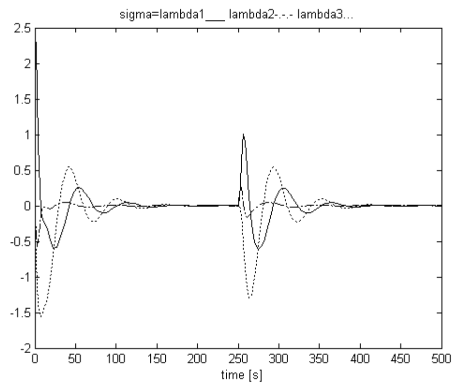

Fig. 15. Sensitivity functions of model (14) versus time.

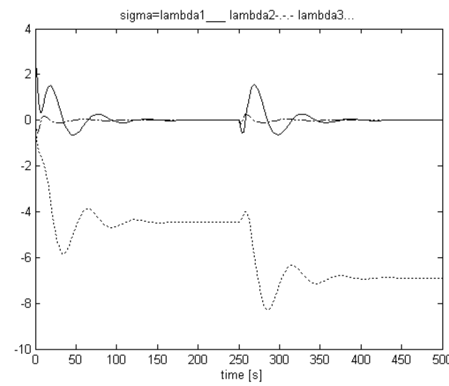

Fig. 16. Sensitivity functions of model (15) versus time.

7 Conclusion

The paper has presented a conventional control solution and fuzzy control solutions focused on a stable development method dedicated to Mamdani-type PI-FCs as part of six CSs meant for a class of mechatronics systems applicable to position control of mobile robots and servo-systems in machine tools, and to speed control of hydrogenerators. The method consists of useful and transparent development steps.

Experimental results results prove the performance enhancement ensured by the FCSs and validate the proposed method. However, the aim is to control complex CPs for which the presented models are only simplified linearized ones. With this respect, the sensitivity analysis performed here enables the FC implementation.

The FC implementation in case of relatively complex plants is assisted by the considerations presented in the paper regarding the IFT and ILC control solutions.

These approaches have been taken into account in the case study - validating the theoretical approaches - dedicated to fuzzy control of a nonlinear servo-system.

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