FACTA UNIVERSITATIS
Series: **Automatic Control and Robotics** Vol. 9, N° 1, 2010, pp. 1 - 18

ASPECTS CONCERNING THE TUNING OF 2-DOF FUZZY CONTROLLERS

UDC 681.327.2 681.5.01

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Abstract. *The paper presents aspects concerning the tuning of two-degree-of-freedom (2-DOF) fuzzy controllers focused on 2-DOF PI-fuzzy controllers and 2-DOF PID-fuzzy controllers. 2-DOF Mamdani and Takagi-Sugeno fuzzy control system structures are offered. The tuning is based on mapping the parameters of the linear PI and PID controllers to the parameters of the fuzzy controllers in terms of the modal equivalence principle. The linear controllers are tuned by Preitl's and Precup's Extended Symmetrical Optimum method. Some experimental results dealing with the speed control of a servo system are given.*

Key words: *2-DOF PI-fuzzy controllers, 2-DOF PID-fuzzy controllers, PI controllers, PID controllers*

1. INTRODUCTION

The two-degree-of-freedom (2-DOF) controllers are advantageous in comparison with the 1-DOF ones because they ensure high control system (CS) performance concerning the set-point tracking and the regulation with respect to the disturbance inputs [1]–[4]. But, the main drawback of 2-DOF controllers is that the overshoot reduction is paid by a slower set-point response.

The fuzzy logic is inserted in 2-DOF CS structures to improve the CS performance with respect to the modifications of set-point and load disturbance inputs and to ensure simultaneously small overshoot and settling time as well. Some approaches are proposed

Received November 19, 2010

for 2-DOF fuzzy control systems ensuring rather complicated tuning. A 2-DOF fuzzy controller composed of two fuzzy controllers to ensure is proposed and applied in [5] to the speed control of an induction motor drive. A fuzzy inference system is suggested in [6] to determine the value of the weight that multiplies the set-point for the proportional action in PID controllers. A 2-DOF controller consisting of a one-step-ahead fuzzy pre-filter in the feed-forward loop and a PI-fuzzy controller in the feedback loop dedicated to the foot trajectory tracking control of a hydraulically actuated hexapod robot is discussed in [7]. The online tuning of a set-point regulator with a blending mechanism of a 2-DOF PI controller is conducted in [8] and applied to a laboratory heat transfer experimental setup. Self-tuning and model reference adaptive 2-DOF PID-fuzzy controllers are analyzed in [9] and [10], respectively. A 2-DOF control system structure consisting of a conventional foreword internal model controller and a feedback fuzzy controller is designed in [11], and simulation results for an electro-hydraulic servo system are offered. A 2-DOF Mamdani fuzzy controller for automotive semi-active suspension control with simulation results are outlined in [12]. Several structures of 2-DOF Takagi-Sugeno PI-fuzzy controllers are given in [13] and [14]; use is made of the Extended Symmetrical Optimum (ESO) method proposed in [15] to tune and validate these controllers by real-time experimental results for a class of servo systems. The computer aided-design of 2-DOF fuzzy controllers developed by inserting fuzzy logic in 2-DOF linear CS structures tuned by algebraic methods is analyzed in [16] and [17].

This paper is based on the generic 2-DOF linear PI and Takagi-Sugeno PI-fuzzy controller structures suggested in [14] and on our previous papers [13], [16] and [17] that fuzzify several components of 2-DOF linear controllers. The new contributions of this paper are:

1. 2-DOF Mamdani and Takagi-Sugeno PI-fuzzy controller and PID-fuzzy controller structures.
2. A unified tuning approach of the 2-DOF fuzzy controllers in these structures which enables the implementation of low-cost 2-DOF fuzzy controllers.

The paper is structured as follows. The 2-DOF fuzzy controller structures and their tuning approach are presented in the next section. A case study on the tuning of the 2-DOF PI-fuzzy controllers and the 2-DOF PID-fuzzy controllers for two classes of servo systems is treated in Section III. Experimental results on a laboratory servo system are given. The conclusions are discussed in Section IV.

2. STRUCTURES AND TUNING OF 2-DOF FUZZY CONTROLLERS

The 2-DOF linear CS structures are presented in Fig. 1 which points out several 2-DOF PID controller structures [2] or 2-DOF PI controller structures [14], where: r – the set-point, y – the controlled output, $e = r - y$ or $e = r_1 - y$ – the control error, u – the control signal, r_1 – the filtered set-point, $P(s)$ – the transfer function of the process which is linear in Fig. 1 and nonlinear in the 2-DOF fuzzy CS structures, and d_1, d_2 and d_3 – the three types of load disturbance input scenarios.

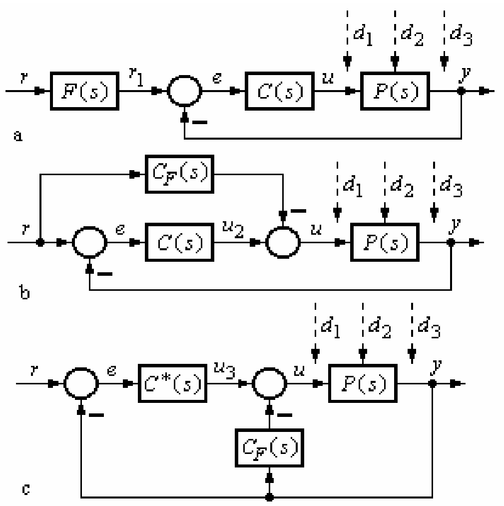

Fig. 1. Structures of the 2-DOF control systems

The 2-DOF CS structures presented in Fig. 1 are referred to as the set-point filter structure (Fig. 1 a), the feedforward structure (Fig. 1 b) and the feedback structure (Fig. 1 c). Other 2-DOF CS structures can be defined as well but the aim of this paper is to ensure the unified presentation of 2-DOF PI-fuzzy controllers and 2-DOF PID-fuzzy controllers.

The transfer function of the PI or PID controller $C(s)$ defined in Fig. 1 a and Fig. 1 b is

$$C(s)=\begin{cases} C_{PI}(s)=k_C(1+\dfrac{1}{T_i s}) = \dfrac{k_c(1+T_c s)}{s} & \text{PI controller} \\ C_{PID}(s)=k_C[1+\dfrac{1}{T_i s}+ D(s)]=\dfrac{k_c(1+T_c s)(1+T_c^{'} s)}{s[1+(T_d/N)s]}, & \text{PID controller} \\ D(s)=\dfrac{T_d s}{1+(T_d/N)s} \end{cases} \quad (1)$$

where k_c is the controller gain, T_i is the integral time constant, T_d is the derivative time constant, $D(s)$ is the approximate derivative term, and $N >> 1$, with typical values $8 \le N \le 20$. The interacting forms of the transfer functions in (1) highlight other versions of tuning parameters like k_c – the controller gain and T_c, $T_c^{'}$ – the controller time constants.

Accepting the condition

$$(T_i - T_d/N)^2 - 4T_i T_d \ge 0 \quad (2)$$

the relations between the (strictly positive) tuning parameters of the non-interacting and interacting controller forms in (1) are

$$\begin{array}{ll} k_C = k_c T_i ,\ T_i = T_c & \text{PI controller} \\ k_C = k_c T_i ,\ T_i + T_d / N = T_c + T_c^{'} , \quad T_i (T_d + T_d / N) = T_c T_c^{'} & \text{PID controller} \end{array} \tag{3}$$

The transfer function of the set-point filter in Fig. 1 a is

$$F(s) = (1 + T_F s)/(1 + T_c s) \tag{4}$$

where the parameter (time constant) T_F fulfils the condition

$$T_F \geq 0 , \tag{5}$$

in order to avoid the non-minimum phase character of the CS.

The three 2-DOF CS structures presented in Fig. 1 are equivalent because they have the same controller transfer functions, $G_{u,y}(s)$ with the input u and the output y, and $G_{u,r}(s)$ with the input u and the output r

$$G_{u,y}(s) = -C(s) = \begin{cases} -\dfrac{k_c (1 + T_c s)}{s} & \text{PI controller} \\ -\dfrac{k_c (1 + T_c s)(1 + T_c^{'} s)}{s[1 + (T_d / N)s]} & \text{PID controller} \end{cases} \tag{6}$$

$$G_{u,r}(s) = C(s)F(s) = \begin{cases} \dfrac{k_c (1 + T_F s)}{s} & \text{PI controller} \\ \dfrac{k_c (1 + T_F s)(1 + T_c^{'} s)}{s[1 + (T_d / N)s]} & \text{PID controller} \end{cases} \tag{7}$$

where the computation was done for the set-point filter structure (Fig. 1a).

The different expressions of the transfer functions defined in (6) and (7) highlight the idea of 2-DOF controllers.

The other two blocks in Fig. 1 b and Fig. 1 c are characterized by the following transfer functions that ensure the transfer functions in (6) and (7):

$$C_F(s) = \begin{cases} k_c (T_c - T_F) & \text{PI controller} \\ \dfrac{k_c (T_c - T_F)(1 + T_c^{'} s)}{1 + (T_d / N)s} & \text{PID controller} \end{cases} \tag{8}$$

$$C^*(s)=\begin{cases}\dfrac{k_c(1+T_F s)}{s} & \text{PI controller}\\ \dfrac{k_c(1+T_F s)(1+T_c^{'} s)}{s[1+(T_d/N)s]} & \text{PID controller}\end{cases} \tag{9}$$

The 2-DOF PI-fuzzy controllers and the 2-DOF PID-fuzzy controllers are developed to improve the CS performance. The development starts with the definition of the generic PI block with the transfer function

$$G^{\tau}(s)=k_c(1+\tau s)/s,\ \tau\geq 0 \tag{10}$$

The block with the generic transfer function defined in (10) is used next in particular forms to express the components with dynamics in Fig. 1 which are fuzzified. With this regard the block $C(s)$ is fuzzified in the set-point filter structure (Fig. 1 a) and in the feed-forward structure (Fig. 1 b), and the transfer function $C(s)$ is expressed as

$$C(s)=\begin{cases}G^{T_c}(s) & \text{PI controller}\\ G^{T_c}(s)\dfrac{1+T_c^{'} s}{1+(T_d/N)s} & \text{PID controller}\end{cases} \tag{11}$$

The block $C^*(s)$ is fuzzified in the feedback structure (Fig. 1 c), and the transfer function $C^*(s)$ is expressed as

$$C^*(s)=\begin{cases}G^{T_F}(s) & \text{PI controller}\\ G^{T_F}(s)\dfrac{1+T_c^{'} s}{1+(T_d/N)s} & \text{PID controller}\end{cases} \tag{12}$$

The fuzzification of the generic PI block with the transfer function $G^{\tau}(s)$ leads to the fuzzy block FB-τ. It is accepted that the continuous-time linear block with the transfer function $G^{\tau}(s)$ has the input e (the control error) and the output u (the control signal). The structure of the block FB-τ is presented in Fig. 2, where FB is the Mamdani fuzzy block or the Takagi-Sugeno fuzzy block without dynamics, $\Delta e(k) = e(k) - e(k-1)$ is the increment of control error, $\Delta u(k) = u(k) - u(k-1)$ is the increment of control signal, and k is the index of the current sampling interval because the block FB-τ is implemented as a digital controller.

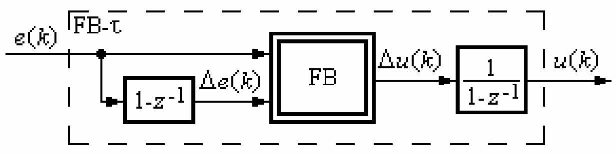

Fig. 2. Structure of the block FB-τ

The fuzzification in the block FC is based on the input membership functions illustrated in Fig. 3 which is applied for both the Mamdani fuzzy block and the Takagi-Sugeno fuzzy block, but the output membership functions are defined only for the Mamdani fuzzy block. The eventually nonlinear scaling factors of the input and output variables of the block FC are inserted in the controlled process.

Only three input membership functions are defined initially to have in mind the low-cost implementation of the 2-DOF fuzzy controllers. More membership functions can be defined for nonlinear processes and high performance specifications.

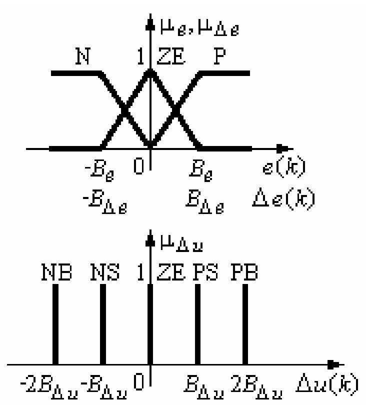

Fig. 3. Membership functions of the block FB-τ.

Fig. 3 points out the tuning parameters of the block FB-τ: B_e, $B_{\Delta e}$ and $B_{\Delta u}$ for the Mamdani fuzzy block FB-τ, and B_e and $B_{\Delta e}$ for the Takagi-Sugeno fuzzy block FB-τ.
The sampling period T_s is next set according to the requirements of quasi-continuous digital control and Tustin's method is applied to discretize the continuous-time linear generic PI block with the transfer function $G^{\tau}(s)$. This results in the following recurrent equation of the incremental digital generic PI block and its parameters:

$$\begin{aligned} &\Delta u(k) = K_P[\Delta e(k) + \mu\, e(k)], \\ &K_P = k_c\,(\tau - T_s/2), \mu = 2T_s/(2\tau - T_s). \end{aligned} \tag{13}$$

The complete rule base of the Mamdani fuzzy block FB-τ is

$$\begin{aligned}
&\text{Rule 1: IF } e(k) \text{ IS N AND } \Delta e(k) \text{ IS P} && \text{THEN } \Delta u(k) \text{ IS ZE},\\
&\text{Rule 2: IF } e(k) \text{ IS ZE AND } \Delta e(k) \text{ IS P} && \text{THEN } \Delta u(k) \text{ IS PS},\\
&\text{Rule 3: IF } e(k) \text{ IS P AND } \Delta e(k) \text{ IS P} && \text{THEN } \Delta u(k) \text{ IS PB},\\
&\text{Rule 4: IF } e(k) \text{ IS N AND } \Delta e(k) \text{ IS ZE} && \text{THEN } \Delta u(k) \text{ IS NS},\\
&\text{Rule 5: IF } e(k) \text{ IS ZE AND } \Delta e(k) \text{ IS ZE} && \text{THEN } \Delta u(k) \text{ IS ZE},\\
&\text{Rule 6: IF } e(k) \text{ IS P AND } \Delta e(k) \text{ IS ZE} && \text{THEN } \Delta u(k) \text{ IS PS},\\
&\text{Rule 7: IF } e(k) \text{ IS N AND } \Delta e(k) \text{ IS N} && \text{THEN } \Delta u(k) \text{ IS NB},\\
&\text{Rule 8: IF } e(k) \text{ IS ZE AND } \Delta e(k) \text{ IS N} && \text{THEN } \Delta u(k) \text{ IS NS},\\
&\text{Rule 9: IF } e(k) \text{ IS P AND } \Delta e(k) \text{ IS N} && \text{THEN } \Delta u(k) \text{ IS ZE}.
\end{aligned} \tag{14}$$

Mamdani's MAX-MIN composition is used in the inference engine of the Mamdani fuzzy block FB-τ, and the center of gravity method is used in the defuzzification.

The complete rule base of the Takagi-Sugeno fuzzy block FB-τ is

$$
\begin{aligned}
&\text{Rule 1: IF } e(k) \text{ IS N AND } \Delta e(k) \text{ IS P} \\
&\quad \text{THEN } \Delta u(k) = K_P^1[\Delta e(k) + \mu^1 e(k)], \\
&\text{Rule 2: IF } e(k) \text{ IS ZE AND } \Delta e(k) \text{ IS P} \\
&\quad \text{THEN } \Delta u(k) = K_P^2[\Delta e(k) + \mu^2 e(k)], \\
&\text{Rule 3: IF } e(k) \text{ IS P AND } \Delta e(k) \text{ IS P} \\
&\quad \text{THEN } \Delta u(k) = K_P^3[\Delta e(k) + \mu^3 e(k)], \\
&\text{Rule 4: IF } e(k) \text{ IS N AND } \Delta e(k) \text{ IS ZE} \\
&\quad \text{THEN } \Delta u(k) = K_P^4[\Delta e(k) + \mu^4 e(k)], \\
&\text{Rule 5: IF } e(k) \text{ IS ZE AND } \Delta e(k) \text{ IS ZE} \\
&\quad \text{THEN } \Delta u(k) = K_P^5[\Delta e(k) + \mu^5 e(k)], \\
&\text{Rule 6: IF } e(k) \text{ IS P AND } \Delta e(k) \text{ IS ZE} \\
&\quad \text{THEN } \Delta u(k) = K_P^6[\Delta e(k) + \mu^6 e(k)], \\
&\text{Rule 7: IF } e(k) \text{ IS N AND } \Delta e(k) \text{ IS N} \\
&\quad \text{THEN } \Delta u(k) = K_P^7[\Delta e(k) + \mu^7 e(k)], \\
&\text{Rule 8: IF } e(k) \text{ IS ZE AND } \Delta e(k) \text{ IS N} \\
&\quad \text{THEN } \Delta u(k) = K_P^8[\Delta e(k) + \mu^8 e(k)], \\
&\text{Rule 9: IF } e(k) \text{ IS P AND } \Delta e(k) \text{ IS N} \\
&\quad \text{THEN } \Delta u(k) = K_P^9[\Delta e(k) + \mu^9 e(k)].
\end{aligned}
\tag{15}
$$

The rule base presented in (15) highlights by the additional upper indices in the rule consequents that the Takagi-Sugeno fuzzy block FB-τ can be obtained from the separate tuning of nine linear blocks FB-τ. Therefore the Takagi-Sugeno fuzzy block FB-τ exhibits like a bumpless interpolator of nine separately tuned linear PI blocks defined in accordance with (10).

The SUM and PROD operators are used in the inference engine of the Takagi-Sugeno fuzzy block FB-τ, and the weighted average method is used in the defuzzification.

The modal equivalence principle [18] is applied to guarantee the quasi-PI behavior of the Mamdani fuzzy block FB-τ and of the Takagi-Sugeno fuzzy block FB-τ. This results in the useful tuning conditions

$$B_{\Delta e} = \mu\, B_e\,,\ B_{\Delta u} = K_P\, \mu\, B_e \tag{16}$$

where both tuning conditions are applied in the tuning of the Mamdani fuzzy block FB-τ, and the first one is applied in the tuning of the Takagi-Sugeno fuzzy block FB-τ.

The following new 2-DOF fuzzy controller structures are defined on the basis of the Mamdani and Takagi-Sugeno fuzzy blocks FB-τ:

1. The set-point filter 2-DOF PI-fuzzy controller (Fig. 4).
2. The set-point filter 2-DOF PID-fuzzy controllers (Fig. 5).
3. The feedforward 2-DOF PI-fuzzy controller (Fig. 6).
4. The feedforward 2-DOF PI-fuzzy controllers (Fig. 7).
5. The feedback 2-DOF PI-fuzzy controller (Fig. 8).
6. The feedforward 2-DOF PI-fuzzy controllers (Fig. 9)

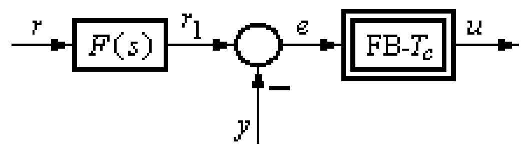

Fig. 4. Structure of the set-point filter 2-DOF PI-fuzzy controller

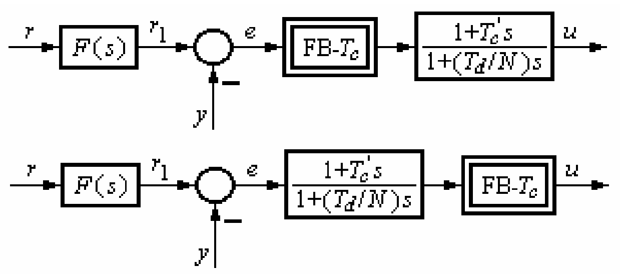

Fig. 5. Structures of the set-point filter 2-DOF PID-fuzzy controllers

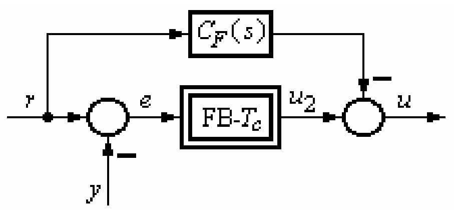

Fig. 6. Structure of the feedforward 2-DOF PI-fuzzy controller

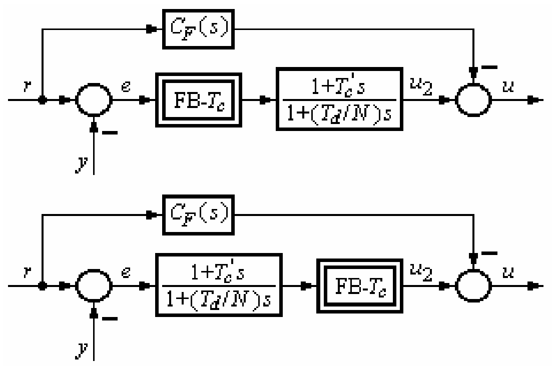

Fig. 7. Structures of the feedforward 2-DOF PID-fuzzy controllers

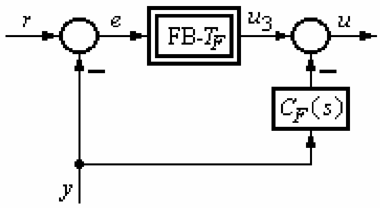

Fig. 8. Structure of the feedback 2-DOF PI-fuzzy controller

The linear blocks in Fig. 4 … Fig. 9 are presented in their continuous-time forms for the sake of simplifying the presentation. This hybrid treatment can lead to complicated problems in the systematic analysis of the fuzzy CS structures. However the discrete-time forms of the linear blocks in the 2-DOF controller structures are implemented actually.

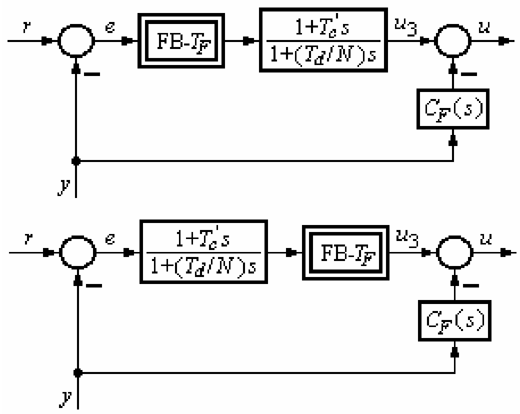

Fig. 9. Structures of the feedback 2-DOF PID-fuzzy controllers

The unified tuning approach for the 2-DOF PI-fuzzy controllers and the 2-DOF PID-fuzzy controllers consists of the following steps 1 to 4.

Step 1. Apply a linear design and tuning method to tune the parameters of the 2-DOF linear PI and PID controllers with the transfer functions defined in (1) … (9).

Step 2. Set the sampling period according to the requirements of quasi-continuous digital control, take into account the zero-order hold and discretize the continuous-time linear controllers.

Step 3. Set the parameter B_e and apply the tuning conditions (16).

The setting of the parameter B_e is important. The experience of the CS designer can be taken into consideration but the stability analysis can be performed, too. Several stability analysis approaches can be applied in this context [19]–[23].

3. Case Study and Experimental Results

The controlled processes considered in the case study to validate a part of the structures of 2-DOF PI-fuzzy controllers and 2-DOF PID-fuzzy controllers is characterized by the two transfer functions

$$P(s) = k_P / [s(1 + T_\Sigma s)]\,, \tag{17}$$

$$P(s) = k_P / [s(1 + T_1 s)(1 + T_\Sigma s)]\,, \tag{18}$$

where k_P is the controlled plant gain, T_Σ is the small time constant or the sum of parasitic time constants, and T_1 is the large time constant. Such processes are used as controlled plants in control systems themselves or in local control systems in a wide area of applications [24]–[41]. The transfer functions presented in (17) and (18) correspond to the simplified linearized models of these processes.

As shown in [1], for the given controlled processes the PI controllers for the process with the transfer function defined in (17) and the PID controllers for the process with the transfer function defined in (18) can ensure acceptable control system performance indices (overshoot, settling time, rise time). These PI and PID controllers can be tuned by the ESO method [15] to improve the control system performance indices and to guarantee a good trade-off to the desired or imposed control performance indices by a single design parameter referred to as β. The PI and PID tuning conditions are expressed as follows for the 2-DOF CS structure presented in Fig. 1 a and for the transfer functions of the controller defined in (1):

$$k_c = 1/(\beta\sqrt{\beta}T_\Sigma^2 k_P),\, T_c = \beta T_\Sigma\,,\, T_c^{'} = T_1 \tag{19}$$

and the control system performance indices can be improved further by introducing the reference filter with the transfer function

$$F(s) = 1/(1 + \beta T_\Sigma s) \tag{20}$$

The ESO method is applied in step 1 of the tuning approach for the 2-DOF PI-fuzzy controllers and the 2-DOF PID-fuzzy controllers presented in Section II.

Useful diagrams concerning the choice of the design parameter β and the tuning relations of a second order set-point filter as well are given in [15].

Two laboratory setups based on electrical drives (Fig. 10 and Fig. 11) implemented in the Intelligent Control Systems Laboratory with the "Politehnica" University of Timisoara, Romania, are considered to validate a part of the 2-DOF fuzzy CS structures suggested here.

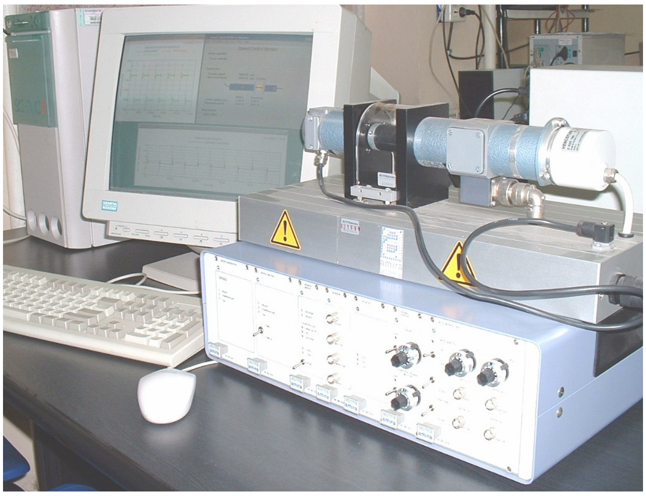

Fig. 10. AMIRA DR 300 laboratory setup

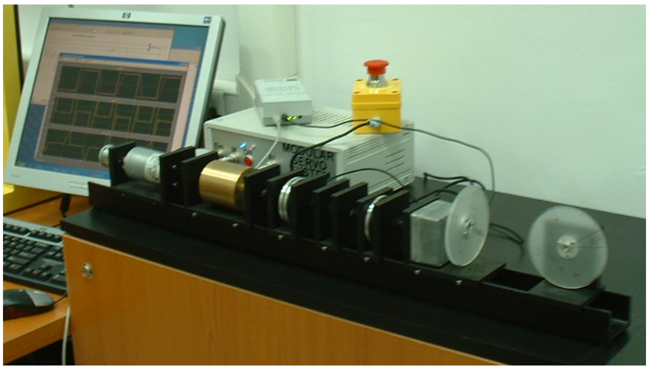

Fig. 11. INTECO modular servo laboratory setup

The parameters of the controlled process used in the speed control of the laboratory setup presented in Fig. 10 are

$$k_P = 4900,\ T_\Sigma = 0.035\ \text{s} \tag{21}$$

The parameters of the controlled process used in the (angular) position control of the laboratory setup presented in Fig. 11 are

$$k_P = 139.88,\ T_\Sigma = 0.92\ \text{s} \tag{22}$$

The tuning steps presented in the previous section were applied and the main parameters involved in the tuning of the 2-DOF PI-fuzzy controllers are pointed out as follows.

A Takagi-Sugeno set-point filter 2-DOF PI-fuzzy controller is tuned for the process described in Fig. 10 and (21). Two separate linear PI controllers are first designed. They have the values of the design parameters

$$\beta^1 = \beta^2 = \beta^4 = \beta^5 = \beta^6 = \beta^8 = \beta^9 = 16 \tag{23}$$

for the rules 1, 2, 4, 5, 6, 8 and 9, and

$$\beta^3 = \beta^7 = 4 \tag{24}$$

for the rules 3 and 7. Therefore the parameters of the continuous-time linear PI controllers are

$$k_C^1 = k_C^2 = k_C^4 = k_C^5 = k_C^6 = k_C^8 = k_C^9 = 0.0015 \tag{25}$$

$$T_i^1 = T_i^2 = T_i^4 = T_i^5 = T_i^6 = T_i^8 = T_i^9 = 0.56\,\mathrm{s} \tag{26}$$

$$k_C^3 = k_C^7 = 0.0029 \tag{27}$$

$$T_i^3 = T_i^7 = 0.14\,\mathrm{s} \tag{28}$$

Accepting the sampling period $T_s = 0.005$s the parameters of the digital PI controllers are

$$K_P^1 = K_P^2 = K_P^4 = K_P^5 = K_P^6 = K_P^8 = K_P^9 = 0.0014, \tag{29}$$

$$\mu^1 = \mu^2 = \mu^4 = \mu^5 = \mu^6 = \mu^8 = \mu^9 = 1.8571 \tag{30}$$

$$K_P^3 = K_P^7 = 0.0024 \tag{31}$$

$$\mu^3 = \mu^7 = 8.6667 \tag{32}$$

The parameters of the block FB-T_c are

$$B_e = 75,\ B_{\Delta e} = 869.57 \tag{33}$$

The fuzzy CS with this 2-DOF Takagi-Sugeno PI-fuzzy controller was tested by real-time experiments and compared with the linear CS with the PI controllers designed for $\beta = 6$. The speed responses exhibited by the designed linear and by the fuzzy CSs are presented in Fig. 12 and Fig. 13, respectively. These results correspond to the rectangular modification of the set-point r and to the rectangular modification of the d_3 type load disturbance input.

The experimental results prove that the 2-DOF CS with the fuzzy controller outperforms the 2-DOF CS with the linear controller. An analysis concerning the comparison of the experimental results from the point of view of smallest settling time and overshoot is offered in [14].

Another Takagi-Sugeno set-point filter 2-DOF PI-fuzzy controller is tuned for the process described in Fig. 11 and (22). Two separate linear PI controllers are first designed for this fuzzy controller, too. They have the values of the design parameters

$$\beta^1 = \beta^2 = \beta^4 = \beta^5 = \beta^6 = \beta^8 = \beta^9 = 7.24 \tag{34}$$

for the rules 1, 2, 4, 5, 6, 8 and 9, and

$$\beta^3 = \beta^7 = 4.8 \tag{35}$$

for the rules 3 and 7. Therefore the parameters of the continuous-time linear PI controllers are

$$k_C^1 = k_C^2 = k_C^4 = k_C^5 = k_C^6 = k_C^8 = k_C^9 = 0.0029 \tag{36}$$

$$T_i^1 = T_i^2 = T_i^4 = T_i^5 = T_i^6 = T_i^8 = T_i^9 = 6.6636\,\text{s} \tag{37}$$

$$k_C^3 = k_C^7 = 0.0035 \tag{38}$$

$$T_i^3 = T_i^7 = 4.4197\,\text{s} \tag{39}$$

The sampling period $T_s = 0.005$s is accepted for this fuzzy controller. The parameters of the block FB-T_c are

$$B_e = 0.3012\,,\ B_{\Delta e} = 29.9897 \tag{40}$$

The fuzzy CS with this 2-DOF Takagi-Sugeno PI-fuzzy controller was tested by real-time experiments and compared with the linear CS with the PI controllers designed for $\beta = 6$. The speed responses exhibited by the designed linear and by the fuzzy CSs are presented in Fig. 14 and Fig. 15, respectively. These results correspond to the step modification of the set-point r followed by the step modification of the disturbance input applied after 25 s. The experimental results prove that the 2-DOF CS with the fuzzy controller outperforms the 2-DOF CS with the linear controller.

4. CONCLUSIONS

Unified structures of Mamdani and Takagi-Sugeno 2-DOF PI-fuzzy controllers and 2-DOF PID-fuzzy controllers are proposed in this paper. They use the original definition and tuning of Mamdani and Takagi-Sugeno fuzzy blocks FB-τ which is inserted in the unified tuning approach.

The performance of the 2-DOF fuzzy CSs with such blocks FB-τ can be further improved. The consequents in the rules 3 and 7 can be modified in this context. Other membership functions can cope with additional nonlinearities of the controlled process.

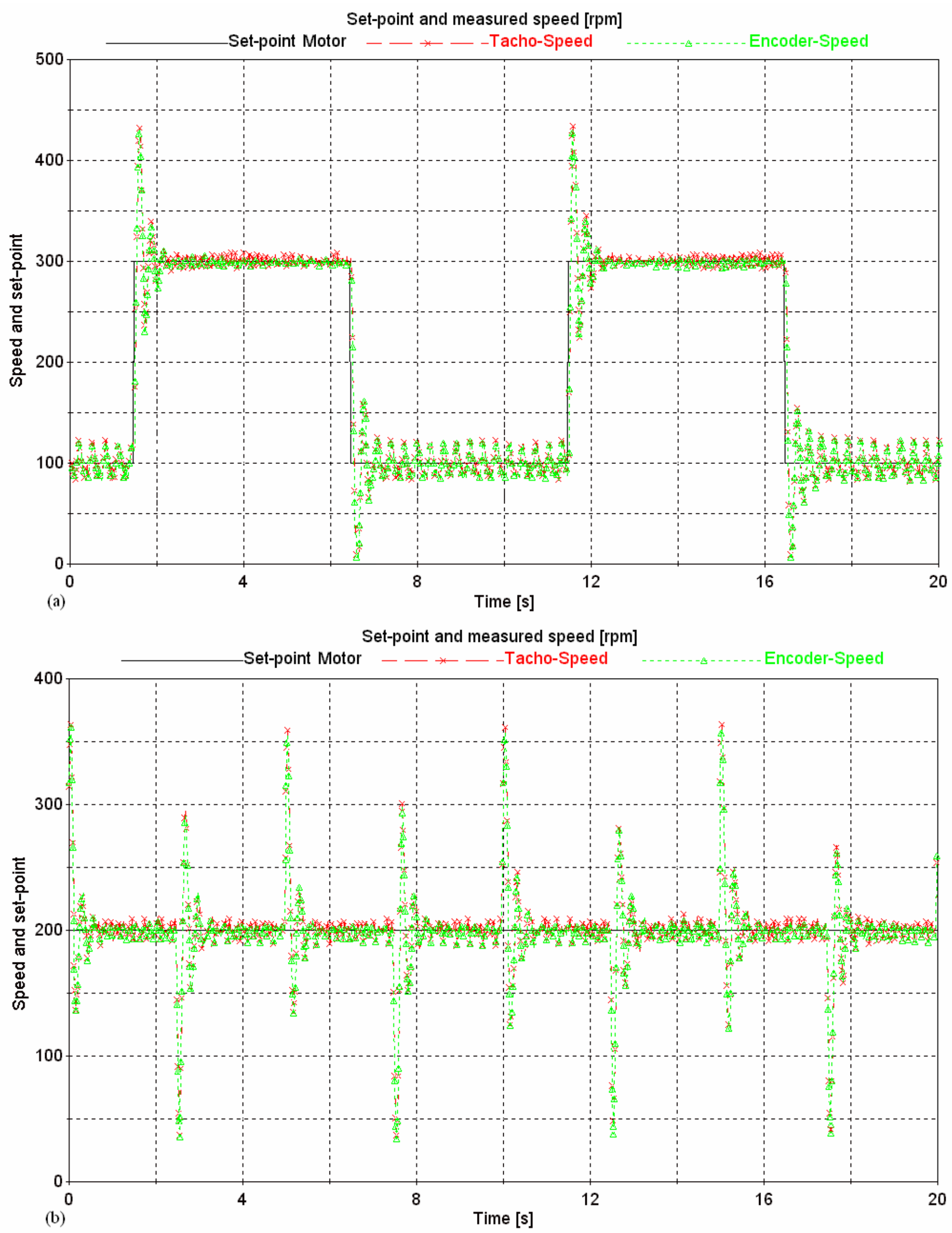

Fig. 12. Speed response of linear CS with 2-DOF PI controller without load (a) for r = 300 rpm and 5 s period of 10 % d3 rated load (b)

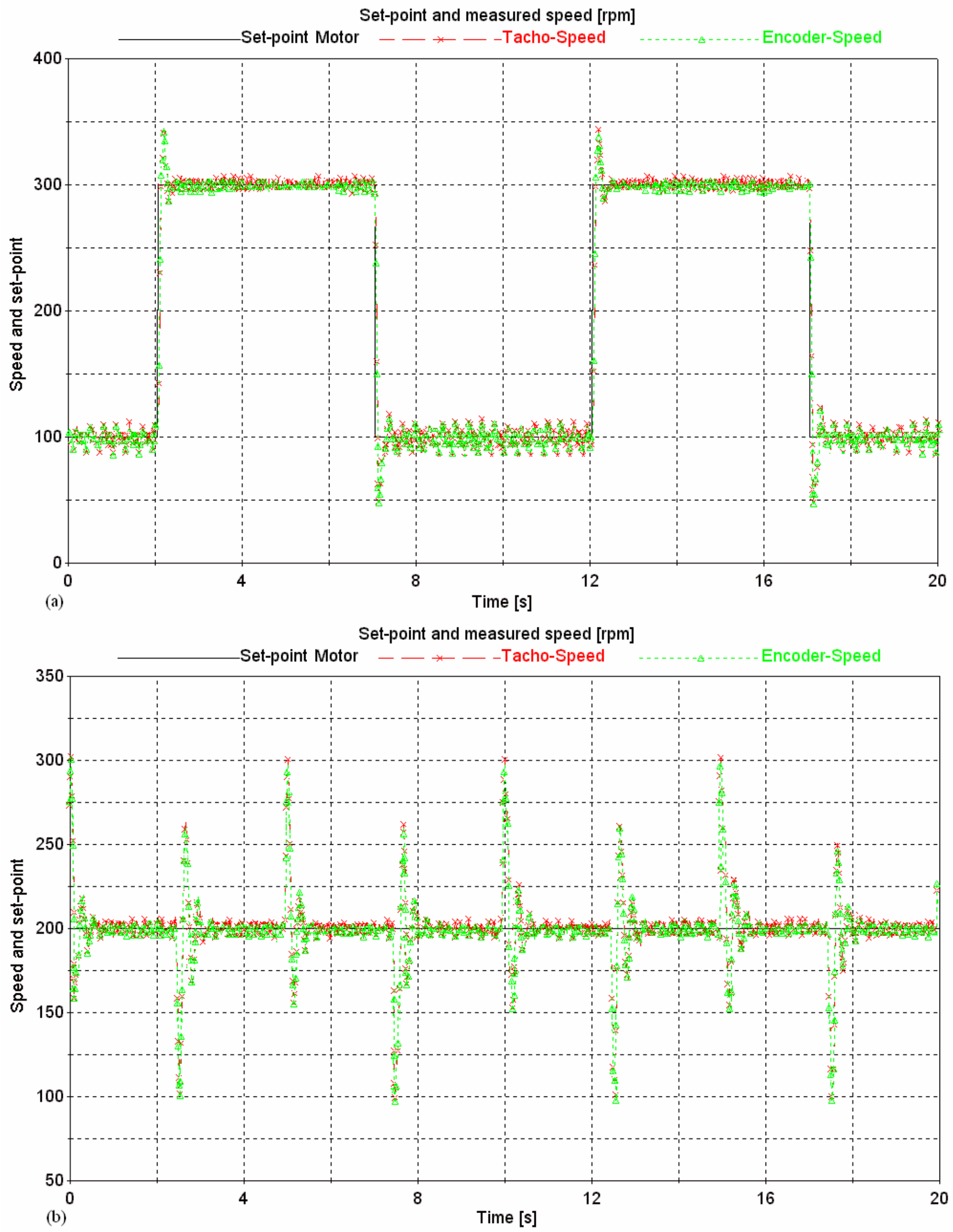

Fig. 13. Speed response of fuzzy CS with 2-DOF PI-fuzzy controller without load (a) for r = 300 rpm and 5 s period of 10 % d3 rated load (b)

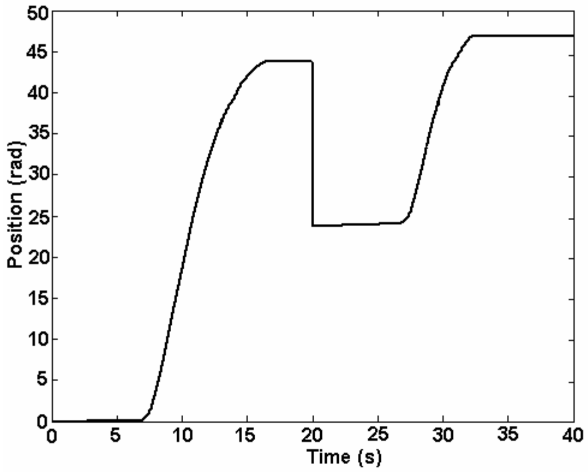

Fig. 14. Position response of linear CS with 2-DOF PI controller

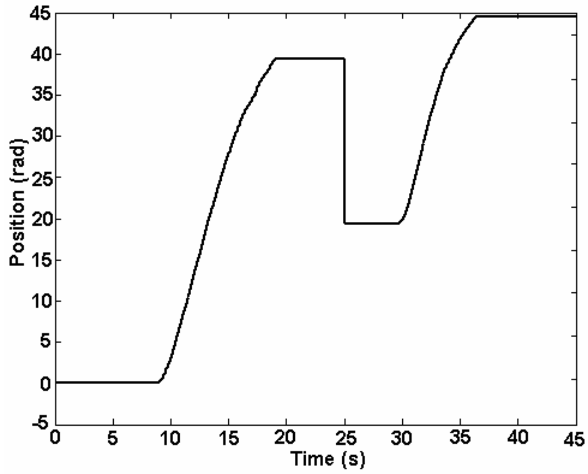

Fig. 15. Position response of fuzzy CS with 2-DOF PI-fuzzy controller

The suggested structures are transparent and relatively simple. Their limitation concerns the necessity of systematic analyses including the stability, parametric sensitivity and robustness which represent the directions of future research.

Acknowledgement: *This work was supported by the CNCSIS and CNMP of Romania and the co-operation between the Óbuda University, Budapest, Hungary, the University of Ljubljana, Slovenia, and the "Politehnica" University of Timisoara, Romania, in the framework of the Hungarian-Romanian and Slovenian-Romanian Intergovernmental Science & Technology Cooperation Programs.*

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ASPEKTI PODEŠAVANJA 2-DOF FAZI KONTROLERA

Stefan Preitl, Radu-Emil Precup, Zsuzsa Preitl

Ovaj rad predstavlja aspekte podešavanja fazi kontrolera sa dva stepena slobode (2-DOF) sa težištem na 2-DOF PI-fazi kontrolerima i 2-DOF PID-fazi kontrolerima. Ponuđene su strukture sa dva stepena slobode Mamdani i Takagi-Sugeno fazi upravljačkih sistema. Podešavanje je zasnovano na mapiranju parametara linearnih PI i PID kontrolera sa parametrima fazi kontrolera u pogledu principa jednakosti. Linearni kontroleri su podešeni proširenim metodom simetričnog optimuma Preitl-a i Precup-a. Dati su neki eksperimentalni rezultati u vezi sa kontrolom brzine servo sistema.

Ključne reči: *2-DOF PI-fazi kontroleri, 2-DOF PID-fazi kontroleri, PI kontroleri, PID kontroleri*