# NEW TWO-TERM PARAMETER ADAPTIVE FUZZY CONTROL STRUCTURE FOR TIME-DELAY SYSTEMS

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## Abstract
In this work a novel two-term parameter adaptive fuzzy logic controller structure is proposed. This new structure is especially suitable for delay compensation. The idea explored here is the variation with time of the integral component of a Fuzzy Control System (FCS) structured as PI type (FZ-PI). If it is detected that a delay is present in the system, then the integral gain can be reduced gradually in order to increase the damping of the system and increase the system stability. At the same time the proportional factor of the FZ-PI is increased in order to maintain quick response against any error. The effect of these two actions is to compensate the time delays present in the process. Another one-input-one-output FCS is used to monitor the output process and adjust on-line the parameter which is used to increase or decrease the proportional and integral gains. This adjustment is done in accordance with the magnitude of the time delay present in the process. The effectiveness of this approach is shown in one benchmark process taken from the literature.

**Key Words**: Fuzzy control system, PI controller, adaptive control, time delay compensation, variable integration gain.

## 1. Introduction
It can be said that almost any industrial process has inherent time delays (dead times). Delays often occur due to the presence of transport lags, recycling loops, or the dead time associated with compensation analysis [Li and Tso, 1999]. Delays will deteriorate the performance of the control system and may cause instability, e.g. oscillations around the set point. Extensive research has been carried out in conventional control to find solutions to this problem [Horowitz, 1983; Leva et al, 1994]. However, few studies have been reported to treat the problem of delays in the context of fuzzy control [Li and Tso, 1999; Escamilla, 1999].

In a two-term fuzzy control system (FCS) [Driankov *et al*, 1993; Li and Gatland, 1996], the rules take into account the error and its rate of change to obtain the control input to the process. However, these rules not take into account the effects that this input has on the process output. Additionally if the process has inherent delays it is harder to achieve good control using these types of controllers. Under these circumstances it is necessary that the controller takes action after it detects if a correction was made or not. In their early work, King and Mamdani [1977] suggested two alternatives to try to solve this problem. First, increase the number of rules in order to take into account the dead times involved in the process. Second, construct a predictive fuzzy model in order to predict the future state of the process and use this to make the control decisions. The objective of both alternatives is to diminish the effect of the delays present in the process, that is, to fit the controller to the process dynamics.

The first alternative mentioned above can be implemented by introducing into the controller certain elements which indicate how the process has evolved as a result of the applied control actions in addition to the current state of the error and its rate of change. This can be done using a FCS structured as PID [Driankov, 1993]. Obviously this increases the number of variables and the number of rules in an exponential way. At the same time, the computational effort to implement the controller is increased too.

An idea explored recently is the utilisation of a delay compensation factor added to the control loop [Li and Gatland, 1999]. However, in this case it is assumed that the delay is reasonably small and known. The delay compensation factor is approximated by a first-order polynomial. This reduces the applicability of this approach.

In this work a novel structure of a two-term FCS that deals with the problem of delays is presented. This structure takes into account the evolution of the process not only from the current error and its change but also from the effects of the previous control actions. The idea explored here is the variation with time of the integral component of a FCS structured as PI type (FZ-PI). If it is detected that a delay is present in the system, then the integral gain can be reduced gradually in order to increase the damping of the system and increase the system stability. At the same time the proportional factor of the FZ-PI is increased in order to maintain quick response against any error. Another one-input-one-output FCS is used to monitor the output process and adjust on-line the parameter which is used to increase or decrease the proportional and integral gains. The results obtained from a simulation example shows the effectiveness of this approach for several time delay magnitudes.

This work is presented in the following way. In Section 2 a review of two-term FCS is given. The new two-term FCS structure is described in Section 3, and a simulation example is presented in Section 4. Finally, discussions and conclusions are given in the final section.

## 2. Two-term fuzzy logic controllers

In traditional control the PI control algorithms is expressed as:

$$u_{PI} = K_p e + K_I \int e \, dt$$
$$= K_p \left( e + \frac{1}{T_i} \int e \, dt \right) \qquad (1)$$

and the PD control algorithm is expressed as:

$$u_{PD} = K_p e + K_D \dot{e}$$
$$= K_p \left( e + T_d \dot{e} \right) \qquad (2)$$

where $e$ is the error signal (set point – process output), $\dot{e}$ is the time derivative of the error, $T_i = K_p / K_I$, and $T_d = K_D / K_p$. The gains $K_p$, $K_I$ and $K_D$ are called the proportional gain, integral gain and derivative gain. The parameters $T_i$ and $T_d$ are known as the integral time and the derivative time respectively.

In fuzzy control there are the analogous FCS structured as PD type (FZ-PD) and PI type (FZ-PI) [Driankov *et al*, 1993; Li and Gatland, 1996]. Their basic structures for continuous time are shown in Fig. 1., and the structures for discrete time are shown in Fig. 2. Inside these structures a FCS develops the well known three processes of fuzzification, rule evaluation and defuzzification [Lee, 1990; Driankov *et al*, 1993]. If the sum-product compositional rule of inference [Kosko, 1992] is used in the process of rule evaluation, and singletons are employed as conclusions of each rule, then a graphical representation of these processes can be constructed as shown in Fig. 3. From this representation it is deduced that the output of the FCS is given as:

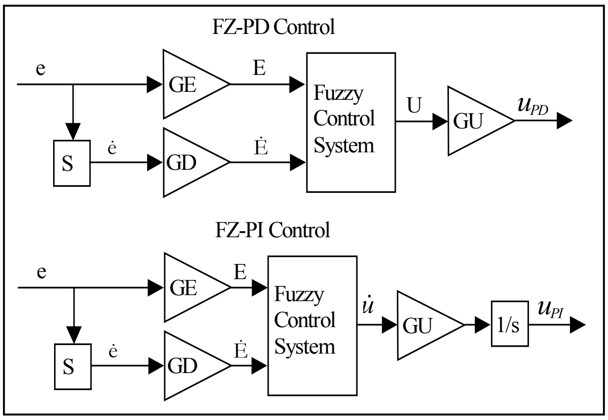


Fig. 1. Structure of fuzzy two-term controllers (continuous-time).

$$U_k = \frac{\sum_{i=1}^{n} {}_k w_i * S_i}{\sum_{i=1}^{n} {}_k w_i} \qquad (3)$$

where $U_k$ = crisp control action (global centre of area); $w_i$ = degree of activation of the rule $i$; $S_i$ = singleton as conclusion of the rule $i$. $i$ = 1, 2,..., $n$. $n$ = number of rules activated in the rule evaluation process; $k$ denotes the instant of time.

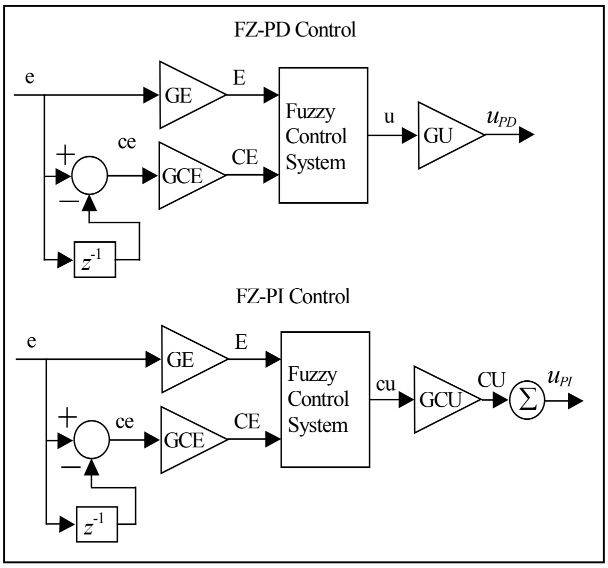


Fig. 2. Structure of fuzzy two-term controllers (discrete-time).

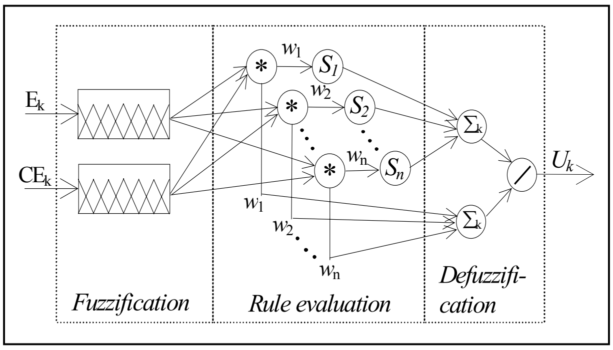


Fig. 3. Graphical representation of the three processes of a FCS.

In the next section it is shown how Eq. 3 can be simplified under certain considerations and how a FZ-PI can be equivalent to its traditional counterpart. After this analysis the formulation of the new two-term parameter adaptive FCS structure is explained.

## 3. Proposed new structure for two-term fuzzy logic controllers

In order to derive the new structure, first an analysis of the FZ-PI structure is given. For this analysis the following assumptions are made:

1. The membership functions of the input variables to the FCS are triangular complementary adjacent fuzzy sets [Escamilla, 1999].
2. The membership functions of the output of the FCS are singletons determined by the sum of the peak positions of the input sets.
3. The sum-product compositional rule of inference [Kosko, 1992] is used in the stage of rule evaluation.
4. The centre of area method is used in the defuzzification process.

If all the above are met, then the FCS is simplified as shown in Fig. 4. This is because the denominator of Eq. 3 is always equal to 1 [Yamakawa, 1992; Gravel and Mackenberg, 1995]. Additionally Jentzen [1999] has shown that the FZ-PI type structure, under the considerations mentioned above, is equivalent to its traditional counterpart. This point is explained next because, from its analysis, the new structure is derived.

The control output $u_{PI}$ of the discrete-time FZ-PI type (see Fig. 2) is the sum of all previous increments,

$$u_{PI} = \sum_{i=1}^{k} cu_i * GCU$$

$$= GCU * \sum_{i=1}^{k} [GE * e_i + GCE * (e_i - e_{i-1})]$$

$$= GCU * GE * \sum_{i=1}^{k} e_i + GCU * GCE * \sum_{i=1}^{k} (e_i - e_{i-1})$$

$$= GCU * GE * \sum_{i=1}^{k} e_i + GCU * GCE * e_k \quad (4).$$

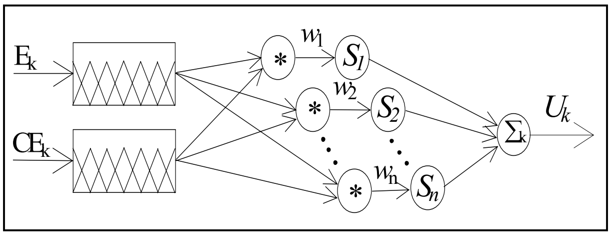


Fig. 4. Graphical representation of the simplified FCS.

As can be observed in Eq. 4 the FZ-PI controller works like a traditional PI controller. The equivalent proportional and integral components are,

$$K_p = GCU * GCE \quad (5)$$

$$K_I = GCU * GE \quad (6)$$

The integration component of the FZ-PI controller has an important effect on the performance of the fuzzy controller. If the integration component is too weak, then the response is slow, and if the integration component is too strong, then the system will become unstable [Quiao and Mizumoto, 1996]. If there is delay in the process then the information taken by the FCS arrives later and hence a delayed control action is generated. The importance of the integration component grows in this case. From control experience it is known that delays are one of the main causes of oscillations [King and Mamdani, 1977].

At this point there are two facts, first, delays cause instability in the form of oscillations. Second, a very strong integration component will contribute to the instability. From here we developed the idea of having an integration component that can vary with time in order to compensate the delay effects and, in this way, increase the stability of the system.

The mechanism of putting a time varying integration component into practice is to introduce a varying integration gain. If there is no delay in the system then the integration gain is not affected and remains constant. But, if there is a delay in the system then the integration gain is gradually reduced with time in order to increase the damping of the system and increase the stability.

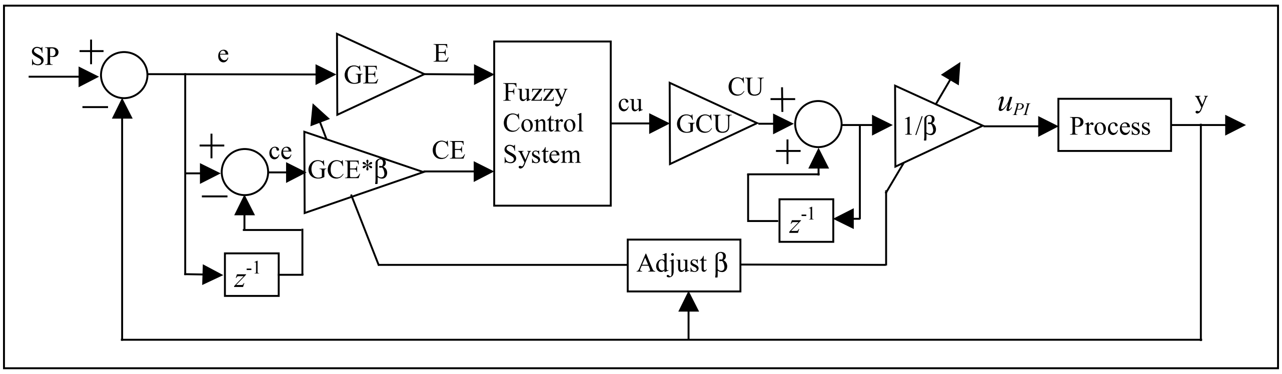


Fig. 5. General structure of the Parameter Adaptive FZ-PI type controller (PAFZ-PI).

From Eq. 6 it can be seen that changing the gain *GCU* also modifies the integration gain, according to:

$$K_I = \left( GCU \ * \frac{1}{\beta} \right) * GE \qquad (7)$$

where $\beta$ is the factor that is increased with time in order to reduce the integration component. From Eq. 5 it is seen that *GCU* is included in the proportional gain. Because of this, a decrement in the integral component will decrease the proportional component and will reduce the reaction of the FZ-PI type controller against the error. This problem is solved if, while decreasing the integral gain, the proportional gain is increased at the same rate,

$$K_p = \left( GCU \ * \frac{1}{\beta} \right) * (GCE \ * \beta) \qquad (8),$$

in this way the proportional control strength will remain unchanged and the system can always respond quickly to errors. Finally, the control output $u_{PI}$ is:

$$u_{PI} = \left( GCU * \frac{1}{\beta} \right) * GCE * \beta * e_k + \left( GCU * \frac{1}{\beta} \right) * GE * \sum_{i=1}^{k} e_i$$
$$= \left( GCU * GCE * \beta * e_k + GCU * GE * \sum_{i=1}^{k} e_i \right) * \frac{1}{\beta} \qquad \ldots(9).$$

Thus the general structure of the Parameter Adaptive FZ-PI type controller (PAFZ-PI) is shown in Fig. 5. This structure takes into account the evolution of the process not only from the current error and its change but also from the effects of the previous control actions. This is achieved due to the location in the structure of the factor β and the way in which it is adjusted.

The idea explored in the mechanism of adjustment of $\beta$ is the fact that delays generally affect the process in such a way that the oscillation around the set point is increased [King and Mamdani, 1977; Li and Tso, 1999]. Thus a one-input-one-output FCS is used to monitor the rate of change in the process output,

$$cy = y_i - y_{i-1} \qquad (10a)$$

$$CY = GCY * cy \qquad (10b).$$

High rate means large delay and then a big change in $\beta$ is needed. Small or null rate means small or null delay, then the change on $\beta$ is small or null. The structure of the block used to adjust $\beta$ is shown in Fig. 6. As can be observed, the output of this block is given by,

$$\beta_k = 1 + c\beta \qquad (11)$$

where $c\beta$ is the output of the FLC. In this way $\beta$ is continuously adjusted on-line in accordance with a non-linear function (the output of the FCS) of *CY*.

In next section the effectiveness of this approach is shown by a simulated example.

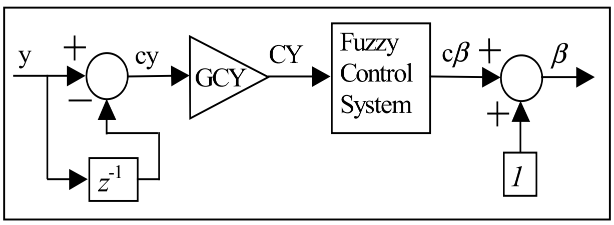


Fig. 6. Block Adjust $\beta$ used to adjust the parameter $\beta$.

## 4. Simulation example

In order to test the proposed PAFZ-PI structure, a system with oscillatory modes, taken from Janzen [1999], was simulated with a varying time delay introduced in the system. The simulation environment is Matlab (v. 5.3.1.29215a) for Windows together with Simulink (v. 3.0.1) and the Fuzzy Logic Toolbox (v. 2.0.1) for use with Matlab. The plant transfer function is given by:

$$G(s) = \frac{e^{-Ts}}{s(s+1)^3} \qquad (12).$$

The simulation is used to illustrate the robustness of the new PAFZ-PI structure against variations of the time delay. The time delay *T* varies between 0 and 3 sec. The simulation is carried out in the following sequence:

1. Tuning of the FZ-PI and the PAFZ-PI for the plant without time delay.
2. Adjust the gain *GCY* in the PAFZ-PI for the plant with a time delay of 3s. Fix this gain in that value.
3. Performance comparison of the conventional FZ-PI and the PAFZ-PI for the plant with a time delay of 0s, 1s, 2s, and 3s.
4. Performance comparison of the conventional FZ-PI and the PAFZ-PI for the plant with a varying time delay from 0 to 3s.

The membership functions of the FCS inputs *E* and *CE*, and the FCS output *cu* are shown in Fig. 7. The rule base used is given in Table 1. Fig. 8 shows the control surface, as can be observed, the FCS output is determined by the sum of the peak positions of the input sets.

Fig. 9 shows the membership functions for *CY* in block Adjust $\beta$. The rules used by the FCS in this block are:

1. If CY is ZERO then $c\beta$ is 0
2. If CY is NOTZERO then $c\beta$ is 1.

Table 1

| E\CE | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | NVB | NB | NM | NS | ZE |
| NS | NB | NM | NS | ZE | PS |
| ZE | NM | NS | ZE | PS | PM |
| PS | NS | ZE | PS | PM | PB |
| PB | ZE | PS | PM | PB | PVB |

The max-prod compositional rule of inferences and the centre of area defuzzification method are employed in block Adjust $\beta$.

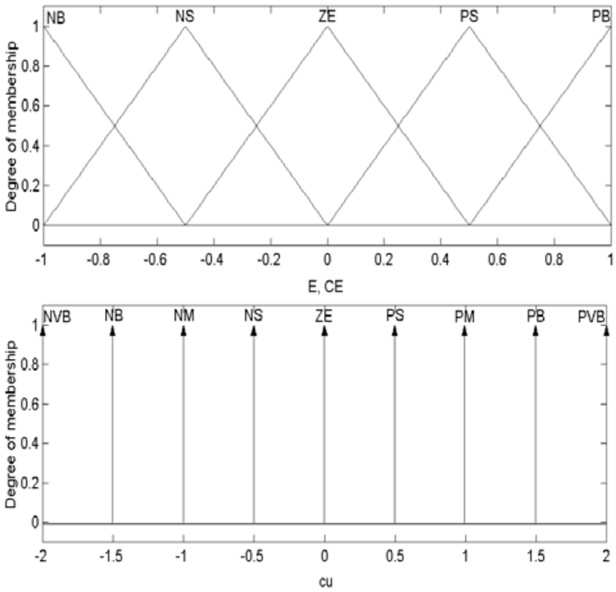


Fig. 7. Membership functions for the FCS inputs *E* and *CE*, and the FCS output *cu*.

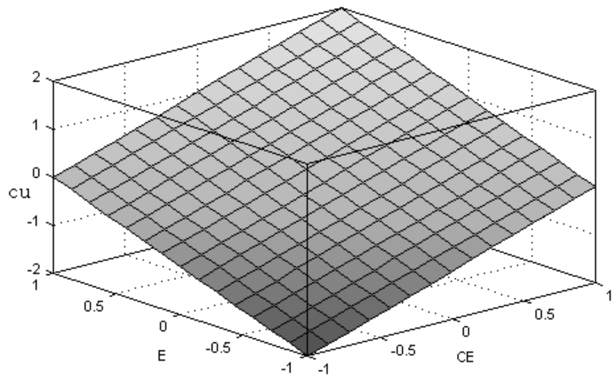


Fig. 8. Control surface.

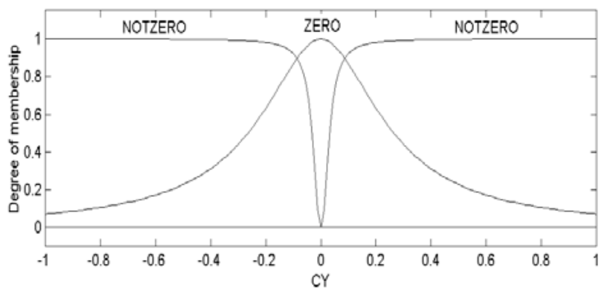


Fig. 9. Membership functions for *CY*.

The quantitative criteria for measuring the performance of both structures, traditional FZ-PI and PAFZ-PI, is the integral of absolute error (*IAE*) which is calculated as:

$$IAE = \int |e| \; dt \qquad (13).$$

For the point 3 mentioned above the system was simulated for 300 sec. with a sample time of 0.2 sec. The tuned gains and the IAE obtained for the conventional FZ-PI and the PAFZ-PI for each case are shown in Table 2. Satisfactory performance is obtained in all cases.

For point 4 the system was simulated for 900 sec with a sample time of 0.2 sec. The tuned gains for the conventional FZ-PI and the PAFZ-PI are the same shown in Table 2. The process responses for both traditional FZ-PI and PAFZ-PI are shown in Fig. 10. Observe how the new structure is more robust against different magnitudes of time delays. The adjustment of the parameter $\beta$ for this case is shown in Fig. 11.

Table 2

| Actual delay | GE | GCE | GCU | GCY PAFZ-PI | IAE FZ-PI | IAE PAFZ-PI |
|---|---|---|---|---|---|---|
| T=0 | 1 | 50 | 3.35E-3 | 10 | 12.97 | 14.75 |
| T=1 | 1 | 50 | 3.35E-3 | 10 | 15.75 | 14.60 |
| T=2 | 1 | 50 | 3.35E-3 | 10 | 28.35 | 16.27 |
| T=3 | 1 | 50 | 3.35E-3 | 10 | 256.92 | 28.73 |

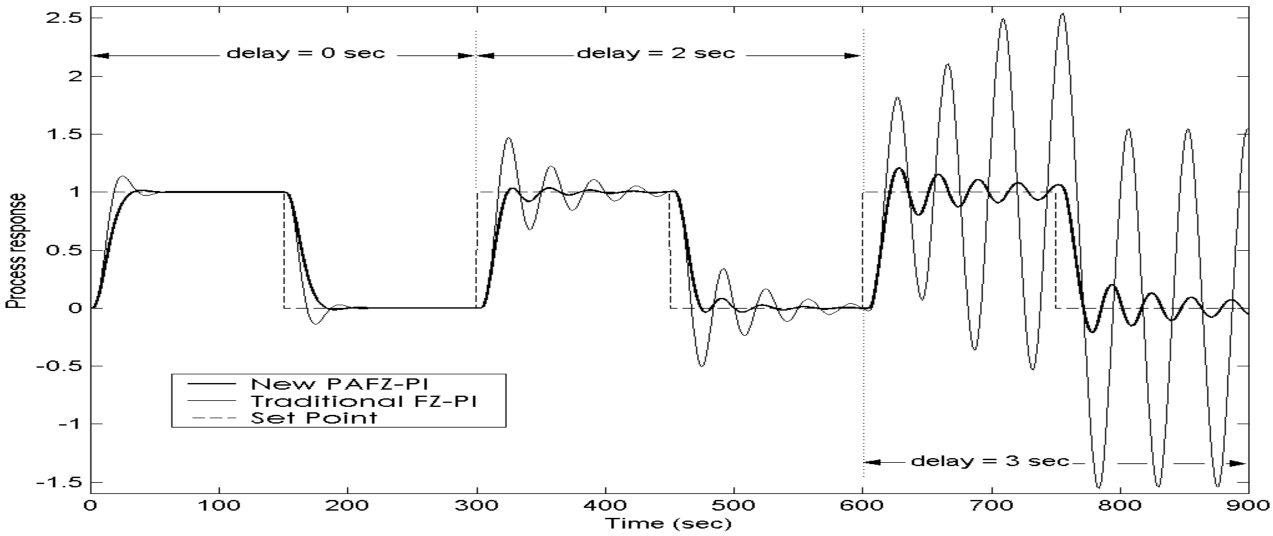

Fig. 10. Process responses of the PAFZ-PI and the traditional FZ-PI.

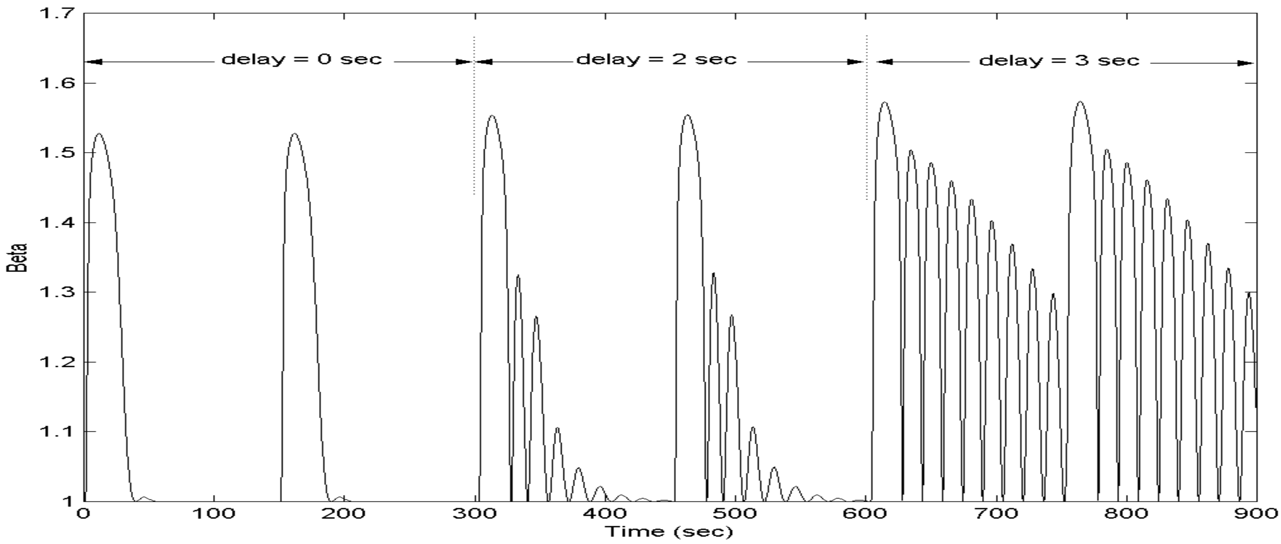

Fig. 11. Adjustment of the parameter $\beta$.

## 5. Conclusions

In this work a new two-term Parameter Adaptive FZ-PI type controller (PAFZ-PI) structure has been presented. This structure has the capability of compensating for time delays present in the process being controlled. The basic idea behind the compensation is the automatic variation with time of the integral gain. If it is detected that a delay is present in the system, then the integral gain is reduced through an adjusting factor in order to increase the damping of the system and increase the system stability. At the same time the adjusting factor affects the proportional factor of the PAFZ-PI in order to maintain quick response against any error. Due to the strategic location of the adjusting factor in the PAFZ-PI structure and the way in which it is adjusted, this structure takes into account the evolution of the process not only from the current error and its change but also from the effects of the previous control actions.

From the results obtained on the simulated example it is deduced that the performance of the new PAFZ-PI controller structure is superior than that observed in the traditional FZ-PI controller structure when delays exist in the plant being controlled. This superiority increases as the delay present in the system increases (see Table 2).

It is relevant that the adjustment of the adjusting factor ($\beta$) for different time delays is done automatically. If the system time delay is not known then only estimating the biggest possible time delay in the system and adjusting the gain in the block Adjust $\beta$, for this value, time delay compensation can be obtained.

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