

# Optimal Tuning of a Fuzzy Immune PID Parameters to Control a Delayed System

S. Gherbi, F. Bouchareb

**Abstract**—This paper deals with the novel intelligent bio-inspired control strategies, it presents a novel approach based on an optimal fuzzy immune PID parameters tuning, it is a combination of a PID controller, inspired by the human immune mechanism with fuzzy logic. Such controller offers more possibilities to deal with the delayed systems control difficulties due to the delay term. Indeed, we use an optimization approach to tune the four parameters of the controller in addition to the fuzzy function; the obtained controller is implemented in a modified Smith predictor structure, which is well known that it is the most efficient to the control of delayed systems. The application of the presented approach to control a three tank delay system shows good performances and proves the efficiency of the method.

**Keywords**—Delayed systems, Fuzzy Immune PID, Optimization, Smith predictor.

## I. INTRODUCTION

THE control system methods based on the evolutionary algorithms have become very popular these recent years, especially those inspired by the biology as: neural-fuzzy system, genetic algorithm, particle swarm optimization ...etc.

These methods offer a good alternative to the classical control system approaches, especially for the non-linear, ill-conditioned, non-minimum phase and delayed systems. This paper focus at the dead time system control; it is well known that the delay term introduce much difficulties for the control system strategies (the non-minimum phase effect...etc) [1]-[4]. The Smith predictor method [5] is very efficient for the delayed system control but unfortunately, it suffer from its poor robustness against the system parameters variations.

Recently, to avoid the delay term difficulties, researchers propose different evolutionary algorithms based methods as: the neural-fuzzy, genetic and immune mechanism based algorithms [6], [7]. In this paper, we propose a simple optimal PID controller parameters tuning, based on the immune feedback control system in combination with a fuzzy logic function, we also employ a modified Smith predictor structure (IMC structure) to take advantage of its efficiency while increasing the system robustness. Finally, in order to show the performances of the presented method, we applied it at the well known three tank system.

S. G. is with the Faculty of Technology, Electrical Engineering Department, Laboratoire d'automatique de Skikda. 20 août 1955 University Skikda, BP:26 Route El hadaiek, Skikda, Algeria (e-mail: sgherbi@gmail.com).

F. B. is with the Faculty of Technology, Electrical Engineering Department, Laboratoire d'automatique de Skikda. 20 août 1955 University Skikda, BP:26 Route El hadaiek, Skikda, Algeria.

## II. FEEDBACK CONTROL INSPIRED BY BIOLOGICAL IMMUNE SYSTEM

Biological immune system is the mechanism that intercepts and eliminates the exogenous infectious microorganisms (antigens); it is mainly composed by lymphocytes cells and antibody molecules. There are two kinds of lymphocytes [8]: T cells (divided into helper cells  $T_h$  and suppressor cells  $T_s$ ) and B cells. The mechanism acts like follow: during the invasion of the organism by the antigens, information is perceived by  $T_h$  cells which in turn stimulate B cells to produce antibodies to eliminate the antigens; the amount of  $T_h$  cells continues to increase as antigens are increasing. When the amount of antigens decrease,  $T_s$  cells begins to eliminate  $T_h$  cells and at the same time B cells until the total elimination of all antigens (and also the other cells) leading to the stabilization of the immune system.

## III. THE ANALOGY BETWEEN BIOLOGICAL IMMUNE AND FEEDBACK CONTROL SYSTEMS

As mentioned before, we can see that the immune mechanism acts clearly like a feedback control system. The figure below describes the immune processes operating:

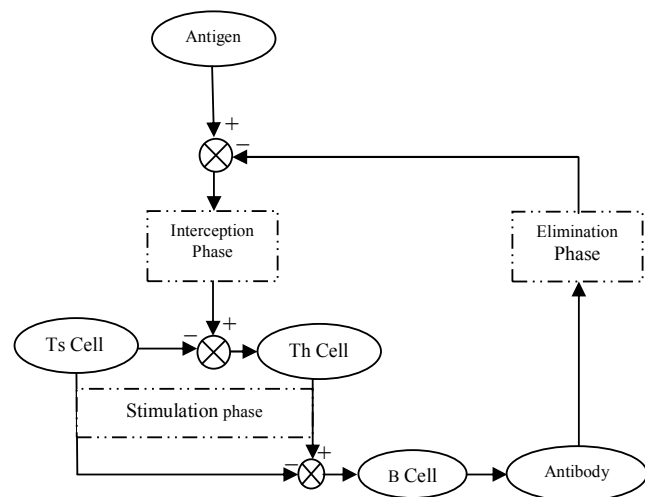


Fig. 1 The immune system operating

As we can see, this figure presents lots of similitude with the classical feedback control system shown below:

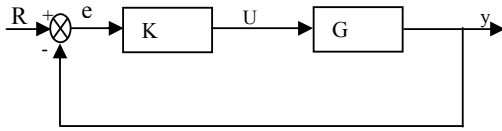


Fig. 2 Classical Feedback system: K the controller, G the system, R the reference signal, U the control signal, e the error and y the output

The analogy between the immune system Fig. 1 and the classical feedback control system Fig. 2 can be resumed by the following table:

TABLE I  
ANALOGY BETWEEN IMMUNE AND FEEDBACK CONTROL SYSTEM

Feedback control system	Immune system
e: the gap between the signal reference and the actual output	The antigen agent (Ag) amount
U: the control signal (controller output)	B cells concentration

While the objective of any control system is to cancel the error between the actual output and the reference signals, the main goal of the immune system is to eliminate the invasive antigens.

#### A. The Inspired Feedback Control Law

As mentioned before, the suppressor cells  $T_s$  cells play an important role to stabilize the immune system; they regulate the amount of  $T_h$  and B cells in order to deliver the appropriate concentration to eliminate the antigens. At the  $k^{ieme}$  generation of antigens and cells production, the total B cells stimulation can be expressed by [9]:

$$B(k) = T_h(k) - T_s(k) \quad (1)$$

where

$$T_h(k)' = K_1 \xi(k) \quad (2)$$

$\xi(k)$  is the amount of the antigens at the  $k^{ieme}$  generation and  $K_1$  is the helper cells stimulation factor, therefore the amount of the suppressor cells can be given by:

$$T_s(k) = K_2 \{f[B(k), \Delta B(k-d)]\} \xi(k) \quad (3)$$

$K_2$  is the inhibition factor.

$\Delta B(k-d)$  is the variation of the B cells amount at the  $k^{ieme}$  generation, it is given by:

$$\Delta B(k-d) = B(k-d) - \Delta B(k-d-1) \quad (4)$$

$d$  is the immune system delay (reaction time)

$f(\cdot)$  is an nonlinear function expressing the interaction between the antibodies stimulated by B cells and the antigens at the  $k-d$  generation [9].

By subtracting (2) and (3) in (1), we obtain:

$$B(k) = K_1 \xi(k) - K_2 \{f[B(k), \Delta B(k-d)]\} \xi(k) \quad (5)$$

or

$$B(k) = K_1 \{1 - \mu f[B(k), \Delta B(k-d)]\} \xi(k) \quad (6)$$

$\mu = \frac{K_2}{K_1}$  represents the proportion coefficient of interaction between  $T_h(k)$  and  $T_s(k)$ . From (6), we can see that: increasing  $K_1$  will improve the immune response time (faster reaction), while increasing  $\mu$  contribute to stabilize the system. Equation (6) is similar to the classical proportional control law given by:

$$U(k) = K_p e(k) \quad (7)$$

$K_p$  is the proportional coefficient, one can remark the analogy between (6) and (7), here the proportional coefficient of the immune controller is nonlinear, from there we can establish the immune inspired proportional control law as follow:

$$U(k) = K_p \{1 - \mu f[U(k), \Delta U(k-d)]\} \xi(k) \quad (8)$$

Unfortunately, for most real systems, the proportional controller alone could not compensate the error from the external perturbation, it seems so obvious that a combination of the immune proportional controller with a classical PID one offers a powerful controller called (IMF PID); such controller law can be expressed by:

$$U(k) = K_p \{1 - \mu f[U(k), \Delta U(k-d)]\} \left(1 + \frac{T_i}{z-1} + T_d \frac{z-1}{z}\right) \xi(k) \quad (9)$$

with  $T_i$  and  $T_d$  are respectively the integral and derivative coefficients of the PID controller. This structure offers many advantages in comparison with a classical PID: more parameters to tune, the nonlinear proportional parameter ...etc.

#### IV. THE SMITH PREDICTOR STRUCTURE

Smith predictor structure [5], is a commonly used structure for the delayed system control (see the following figure).

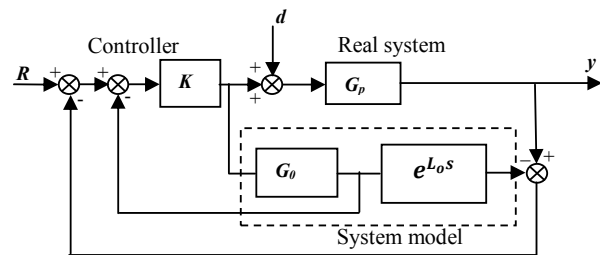


Fig. 3 Classical Smith predictor structure

$d$  is the disturbance signal.

The main difficulty for the delayed system control is the presence of the delay term in the feedback chain; this can lead to the instability (non minimum phase effect). The idea of the Smith predictor structure is then to design a controller for the nominal delay free part of the system model ( $G_0$ ).

From Fig. 3, we can express the transfer function of the closed loop system as:

$$\frac{y}{R}(s) = \left( \frac{K(s)G_p(s)}{1+K(s)(G_0(s)-G_0(s)e^{-L_0s}+G_p(s))} \right) \quad (10)$$

We can clearly see that if we choose a convenient system model, the delay term no longer appear in the characteristic equation and the transfer function become:

$$\frac{y}{R}(s) = \left( \frac{K(s)G_p(s)}{1+K(s)G_0(s)} \right) \quad (11)$$

#### V. THE MODIFIED SMITH PREDICTOR STRUCTURE

In this paper we use the modified smith predictor control scheme [10], called the internal model control structure IMC, it is represented by the following figure:

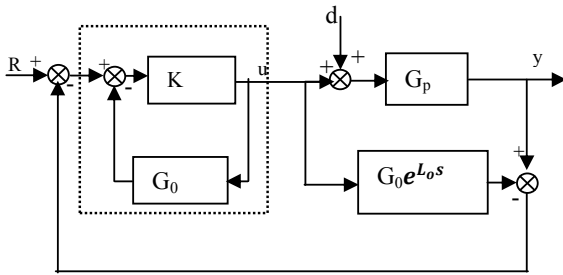


Fig. 4 The IMC Smith predictor structure

This structure offers the opportunity to design the controller based on the free delay part of model, completely separated from the delayed model.

#### VI. OPTIMAL FUZZY IMMUNE PID CONTROLLER DESIGN

In the following, we propose an optimal control design procedure for delayed systems, based on an Fuzzy IMF-PID controller implanted in a modified Smith predictor structure (Fig. 4). The IMF-PID control law is given by (9), the problem is then to find the optimal parameters values, in order to minimize the tracking error  $e = R - y$ . This is an optimization problem; it can be expressed and solved via the minimization of different criterion. In this paper we choose the Integral Time Absolute Error criterion ITAE [11], given by:

$$J = \int_0^{\infty} t|e(t)| dt \quad (12)$$

This criterion is required for the systems with long time error, (contain an additional time multiplier).

Thus, we can put the optimization problem mathematically as:

$$\min_{\{K_p, T_i, T_d, \mu\}} \left\{ \int_0^{\infty} t|e(t)| dt \right\} \quad (13)$$

This optimization problem is easily resolved by different software packages as: the optimization toolbox of Matlab [12].

##### A. Design of the Fuzzy Function $f(\cdot)$

The nonlinear function  $f(u(k), \Delta u(k))$  express the fact that the more cells are stimulated, the less they have inhibition

ability and the opposite is true [9]-[14]. This principle can be formulated via a fuzzy function with two inputs ( $u(k)$ ,  $\Delta u(k)$ ) which can be positive (P) or negative (N), the output can be positive (P), Zero (Z) or negative (N), then the following rules are used to determine the function output for each set of the inputs [14], [15] :

- 1- If  $u(k)$  is P and  $\Delta u(k)$  is P then  $f(u(k), \Delta u(k))$  is N.
- 2- If  $u(k)$  is P and  $\Delta u(k)$  is N then  $f(u(k), \Delta u(k))$  is Z.
- 3- If  $u(k)$  is N and  $\Delta u(k)$  is P then  $f(u(k), \Delta u(k))$  is Z.
- 4- If  $u(k)$  is N and  $\Delta u(k)$  is N then  $f(u(k), \Delta u(k))$  is P.

##### B. Example of Application

In this section, in order to show the effectiveness of our method, we apply it to a typical delayed system: a three tank level control.

##### 1. System Presentation

The figure below presents a typical three tank system, it consists of three tank connected by valves.

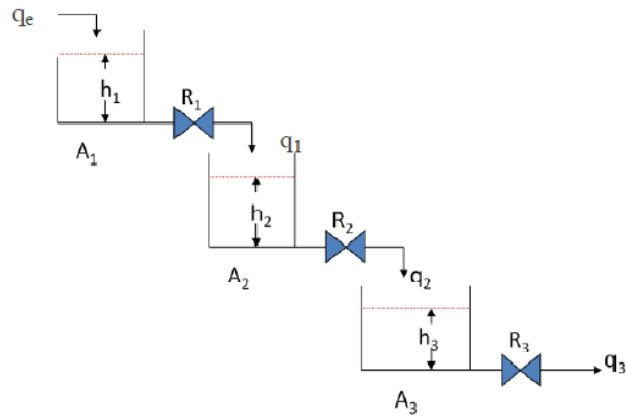


Fig. 5 Three tank system

$A_i$  are the section area of the three tanks,  $R_i$  are the liquid resistance of the three tanks valves,  $q_i$  are the liquid flow of each tank. The input of system is the flow in the first tank  $q_e$  and the output is the level in the third tank  $h_3$ , the transfer function from the input to the output is given by [13]:

$$F(s) = \frac{H_3(s)}{Q_e(s)} = \frac{R_1 R_2 R_3}{(R_1 A_1 s + 1)(R_2 A_2 s + 1)(R_3 A_3 s + 1)} e^{\zeta s} \quad (14)$$

Suppose that  $\frac{\zeta}{3}$  is the time that take the level  $h$  to change, by changing the liquid flow in the input, then the total delay time of the three tank system is  $\zeta$ .

For our simulation tests, let us use the following transfer function:

$$F(s) = \frac{2}{(3s + 1)(3s + 1)(3s + 1)} e^{2s}$$

##### 2. Simulations Results

We apply our method to the three tank system using the IMC Smith predictor structure (Fig. 4),  $K$  is then a Fuzzy

IMF-PID controller with 4 parameters ( $K_p, T_i, T_d, \mu$ ) and a fuzzy function as showed by the following Simulink Matlab software model:

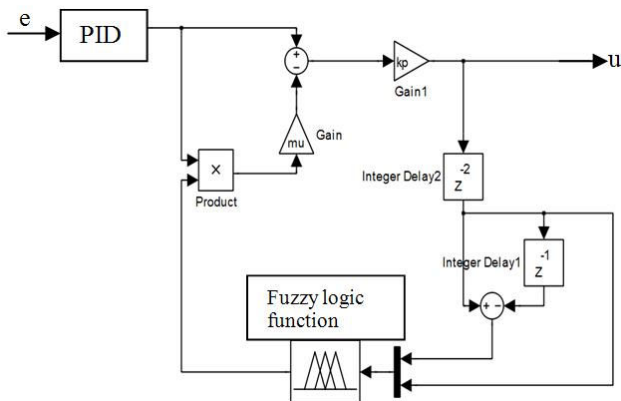


Fig. 6 Fuzzy IMF-PID controller Simulink model

By solving the optimization problem (13), we find the following optimal IMF-PID controller parameters:

$$K_p = 0.5000, T_i = 0.1000, T_d = 3.5349, \mu = 0.5000$$

The following figures show respectively the step time response and a 10% step perturbation introduced at time 40 sec of the closed loop system. A good system performances (fast rise time and no overshoot) and fast perturbation rejection are obtained.

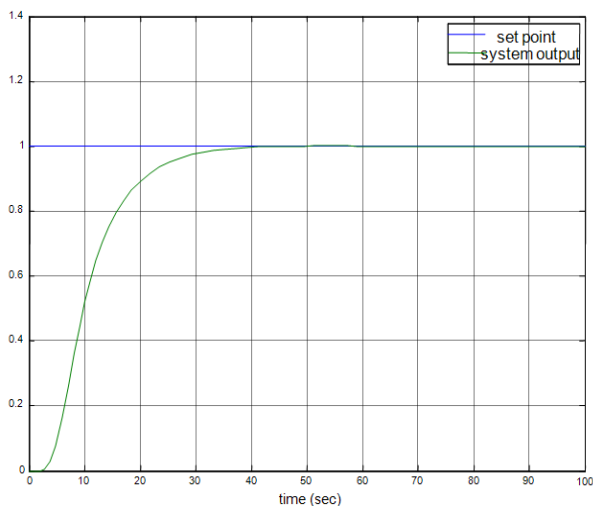


Fig. 7 Step response of the controlled system

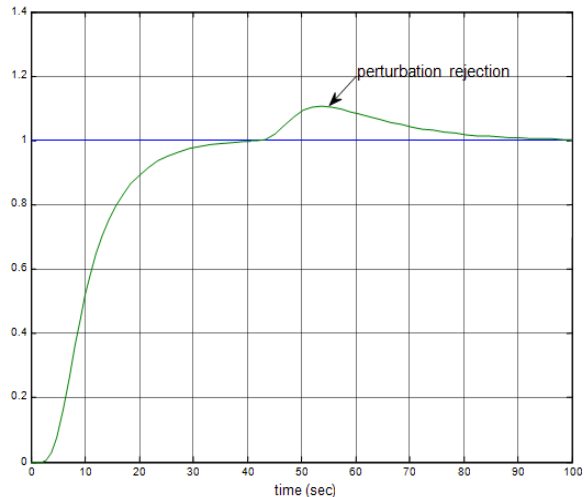


Fig. 8 Perturbation rejection of the controlled system

#### IV. CONCLUSION

An optimal Fuzzy immune PID controller tuning method is presented in this paper, it is based on an immune feedback control system PID controller, we used a fuzzy function in order to express the stimulation and inhibition principle of immune cells. The parameters of this controller are optimally obtained by the minimization of the ITAE criterion. The application of the proposed method at a three tank system shows its effectiveness.

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**S. Gherbi** received the Doctoral degree in automatic from Annaba University, Algeria, in 2009. Currently he is with the Department of Electrical Engineering, Skikda University. His fields of interest are the robust and intelligent advanced control methods.