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Design of a Fractional Order CRONE and PID Controllers for Nonlinear Systems using Multimodel Approach

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Abstract

This paper deals with the output regulation of nonlinear control systems in order to guarantee desired performances in the presence of plant parameters variations. The proposed control law structures are based on the fractional order PI (FOPI) and the CRONE control schemes. By introducing the multimodel approach in the closed-loop system, the presented design methodology of fractional PID control and the CRONE control guarantees desired transients. Then, the multimodel approach is used to analyze the closed-loop system properties and to get explicit expressions for evaluation of the controller parameters. The tuning of the controller parameters is based on a constrained optimization algorithm. Simulation examples are presented to show the effectiveness of the proposed method.

Keywords: Fractional order controller; Nonlinear Systems; Multimodel approach; Robustness.

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1. Introduction

Since the first presentation of the control of the systems by PID controller in the years 1910 [1], and after the techniques of synthesis proposed by Ziegler-Nichols in 1942 [2], the popularity of PID controller continues to increase as it is the most widely used technique in the control of industrial processes. The major reasons for its wide acceptance in industry are its ability to control the majority of processes, its ease of use and its simplicity of implementation. Although there are several techniques for setting the parameters of the PID controller, a continuous and intensive research work is still in progress to improve the performance of this order. Recently, a generalization of the conventional PID controller has been proposed [18]; it is the fractional PID controller noted $PI^{\alpha}D^{\beta}$. The interest of this type of controller is justified by a better flexibility in its setting since there are two additional parameters which are added; a fractional integration of order α and a fractional derivation of order β [22]. The idea of using a robust fractional order controllers for the control of these systems return to Oustaloup, who developed the CRONE regulator [3]. Oustaloup had in particular presented the advantage of the CRONE controller compared to the conventional PID from a robustness point of view. Benefiting of the advantageous properties of the fractional derivative, this regulator allowed to ensure the robustness of the control in a given frequency band [21]. Otherwise, the modeling techniques of a process have always been concerned with establishing the relationships that bind its characteristic variables to each other and to represent in a way rigorous behavior in a given area of operation. Depending on the prior knowledge of the process to be studied, we can consider different types of models to represent his behavior [4], it is the multimodel approach, which seems to be a powerful tool in this sense, will be used in our case to help modeling nonlinear systems for their control by non-integer regulators ensuring certain performance in robustness. The multimodel approach [5,20] has recently been developed and applied in several science and engineering domains. It was proposed as an efficient and powerful method to cope with modeling and control difficulties when complex non linear and/or uncertain processes are concerned. The multimodel approach supposes the definition of a set of models. Then, it becomes possible to replace the unique model by a set of simpler models thus making a so-called models base. Each model of this base describes the behavior of the considered process at a specific operating point. The multimodel approach objective is to decrease the process complexity by its study under certain specific conditions. Several researchers have been interested in multimodel analysis and control approaches [6,7,8] and many applications have been proposed in different contexts. In [9], a model-based diagnostic method is implemented for non-linear systems that are modeled using Takagi-Sugeno models with unmeasurable decision variables. A new approach for complex systems modeling based on both neural and fuzzy clustering algorithms is proposed, which aims to derive different models describing the system in the whole operating domain has been studied in [10]. In [11] a multi-model approach, based on Takagi-Sugeno form is used to perform identification of fractional non-linear systems, applying fractional local models. In this purpose, an output error method is used, and the algorithm is extended to the fractional case. Also, in [12] a design of non-integer controller for fractional order systems with temporal specifications such that rise time and overshoot. These performances are defined by a target model using the Characteristic Ratio Assignment (CRA) method. This paper deals with, the output regulation problem for nonlinear system in order to guarantee desired performances in the presence of parameter variation using the multimmodel approach. The proposed strategy allows to provide efficient control of nonlinear systems in the presence of uncertainty. A multimodel control approach is used to analyze the closed-loop system properties. In the following section, the multimodel approach principle are detailed. The synthesis of the partial and global control for the fractional PI controller and CRONE controller for a nonlinear system are then presented. Two simulation examples are presented in this paper to confirm the effectiveness of the proposed approach.

2. Multimodel approach principle

The multimodel structure was introduced as a global approach based on multiple local LTI models (linear or affine). Consequently, it assumes that it is possible to replace a unique nonlinear representation by a combination of simpler models thus building a so-called model-base. Each model of this base describes the behavior of the considered process at a specific operating point. The interaction between the different models of the base through normalized activation functions allows the modeling of the global nonlinear and complex system. Therefore, the multimodel approach aims at lowering the system complexity by studying its behavior under specific conditions. The multimodel principle is given in figure (1).

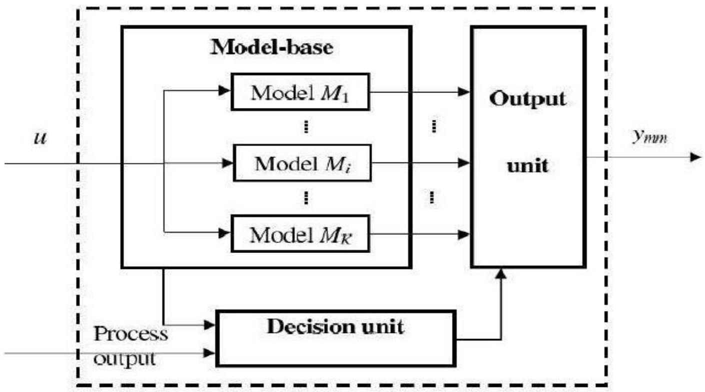

Figure 1: Multimode Approach Principle

In figure (1), there are three main blocks:

- **Model-base:** A multimodel uses several models. These models constitute what is called base or library of models. These models can be local or generic, of the same structure or of different structures and orders.
- **Decison unit:** Each element of the base is a simplified representation of the global system and can not reproduce the behavior of the system only in one or a few very particular areas of operation, hence the role of the decision block.
- **Output unit:** This is the final step, which determines the global output of the multimodel. Indeed, if we have the validity vector i of each model of the base, two techniques are possible: commutation and fusion.

In this paper we will interested by the fusion that will be defined in the following section

2.1. Fusion principle

By a fusion at the output, the output of the multimodel y_{mm} is equal to the sum of outputs y_i of models M_i weighted by their validities υ_i corresponding, with $i = 1, ..., k$ and all models are excited by the same control signal u . The fusion principle is illustrated by the system (1) and figure (2).

$$\begin{aligned} y_{mm}(k) &= \sum_{i=1}^{K} y_i(k)\upsilon_i(k) \\ \sum_{i=1}^{K} \upsilon_i(k) &= 1 \end{aligned} \quad (1)$$

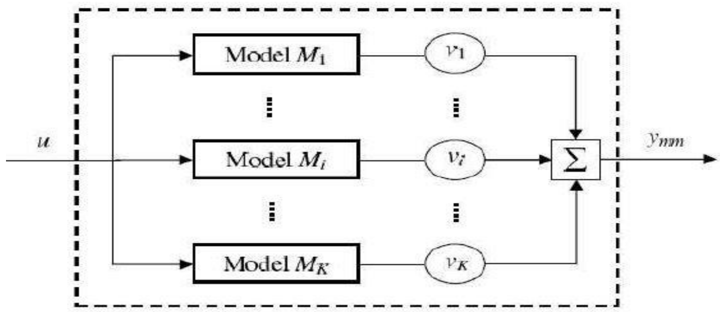

Figure 2: Fusion Principle

2.2. Validity computation

The validity coefficient is a number belonging to the interval [0,1]. It represents the relevance degree of each base-model calculated at each instant. In literature, several methods have been proposed to deal with the validity issue. In our study, the residues approach was adopted for the calculation of validities. This method is based on the distance measurement between the process and the considered model. For example, the residue can be given by the following expression:

$$r_i = |y - y_i| \; i = 1, ..., N \quad (2)$$

Where N is the number of base-models, y is the process output and y_i is the output of the model M_i . If this residue value is equal to zero, the corresponding model M_i perfectly represents the process at that time. On the contrary, a non-null value translates the fact that the model M_i represents the system partially. The normalized

residues are given by:

$$r_i^{'} = \frac{r_i}{\sum_{j=1}^{N} r_j} \quad (3)$$

Within the context of the residues approach, several methods have been proposed for the calculation of validities [13], [14], [15]. Only two methods will be considered: the simple and the reinforced validities. The validities are given by:

$$\upsilon_i = 1 - r_i^{'} \quad (4)$$

The simple and reinforced validities are defined by using the following formulas:

- ***Simple validities***: the normalized simple validities are defined so that their sum must be equal to 1 at each time:

$$\upsilon_i^{simp} = \frac{\upsilon_i}{1-N} \quad (5)$$

- ***Reinforced validities:*** for this type of validities, the reinforcement expression is introduced as:

$$\upsilon_i^{'renf} = \upsilon_i \prod_{j=1,\, j\neq 1}^{N} \left(1-\upsilon_j\right) \quad (6)$$

The normalized reinforced validities could be written as follows:

$$\upsilon_i^{renf} = \frac{\upsilon_i^{'renf}}{\sum_{j=1}^{N} \upsilon_j^{'renf}} \quad (7)$$

3. Multimodel control of a nonlinear system

The main goal is to determine a global control for the considered system using the basemodel determined by the multimodel representation approach. This command is obtained from the partial commands outcome from the different models is called multimodel command. On the other hand, multi-model control strategies can be grouped into two broad classes: commutation strategies or fusion strategies. In this paper we will interested by the fusion strategies which consists of applying to the system a global control computed directly through a fusion of the partial control, relating to the different base-models, weighted by their respective coefficients of validity, given by the following expression:

$$u_k\left(k\right) = \sum_{i=1}^{K} \upsilon_i\left(k\right) u_i\left(k\right) \quad (8)$$

3.1. CRONE Controller

3.1.1. Synthesis of partial CRONE controller

For each base model M_i $\left(i = 1, .., K\right)$, we associate a CRONE controller and we calculate the partial control u_{ci} illustrated by the following equation:

$$u_{ci}\left(k\right) = C_{0i} s^{\upsilon_i}, i = 1, ..., K \quad (9)$$

where C_{0i} is the static gain and υ_i is the non integer order.

The transfer function of the M_i model is given by

$$F_i\left(s\right) = \frac{B_i\left(s\right)}{A_i\left(s\right)} \quad (10)$$

Where

$$\begin{aligned} \mathrm{B}_i\left(s\right) &= b_{i0} + b_{i1}s + b_{i2}s^2 + ... + b_{in_b}s^{n_b} \\ \mathrm{A}_i\left(s\right) &= a_{i0} + a_{i1}s + a_{i2}s^2 + ... + a_{in_a}s^{n_a}, a_{i0} \neq 0 \end{aligned} \quad (11)$$

The closed-loop transfer function of the Mimodel with the u_{ci} command is then written

$$F_i^{bf}\left(s\right) = \frac{C_{0i}s^{\upsilon_i}F_i\left(s\right)}{1 + C_{0i}s^{\upsilon_i}F_i\left(s\right)} \quad (12)$$

In order to calculate the parameters of each regulator associated with the various models of the base, we apply each regulator for its corresponding model in closed loop and we sum the outputs of each model corrected then we compare the result obtained with that obtained by the global regulator applied to the nonlinear system.

3.1.2. Synthesis of global CRONE controller

Once the parameters of the partial controllers are obtained, we will now present the method of deduction of the global control to be applied to the nonlinear system considered. In this case, we will use the fusion control strategy since it is more suitable for our modeling. In the case where the system can be adequately represented by a weighted sum of local models, we can use a technique of fusion of the elementary control to determine the global command, that is:

$$u_{cg}(k)=\sum_{i=1}^{K}\upsilon_i\left(k\right)u_i(k) \quad (13)$$

where $\upsilon_i(k)$ are the degrees of validity associated to each local model M_i and $u_i(k)$ is the command associated with it. The obtained regulator is called implicit global model. The proposed approach for multimodel control has been tested for a nonlinear system that will be presented in next section.

3.1.3. Simulation Example 1

Consider the nonlinear system given by [19]

$$\text{y}+\left(15-10y\right)\dot{y}=\left(36y\left(y-1\right)+10\right)u \quad (14)$$

We consider a pulsation $\omega_u=30rad/s$ and the desired overshoot is $D=10\%$. The use of the multimodel approach has made it possible to construct a base of four first-order linear models whose transfer functions are given by the following expressions:

$$G_1\left(s\right)=\frac{1}{1+5s} \quad (15)$$

$$G_2\left(s\right)=\frac{1}{1+15s} \quad (16)$$

$$G_3\left(s\right)=\frac{10}{1+5s} \quad (17)$$

$$G_4\left(s\right)=\frac{10}{1+15s} \quad (18)$$

After defining the models, we will proceed to the design of the multimodel controller starting with the partial CRONE controller then the Global CRONE one.

- ***Calculation of partial CRONE controller***

The cutoff frequency of model G_1 and G_3 is equal to 0.2 and that of G_2 and G_4 is equal to 0.06, so we chose a pulsation $\omega_u=30rad/s$ around which the behavior of the phase of the four models is asymptotic, hence the use of the first generation CRONE controller. The first step is to associate a CRONE controller for each base model. The various parameters associated with it are: the gain C_i

and the non-integer order $\upsilon_i\left(i=1,\ldots,4\right)$. The values of these parameters, for each regulator, are given by the table (1).

Table 1: Partial CRONE controller parameters

Model	Controller parameters
M_1	$C_1=117.64, \upsilon_1=0.24$
M_2	$C_2=352.85,\ \upsilon_2=0.24$
M_3	$C_3=11.76,\ \upsilon_3=0.24$
M_4	$C_4=53.28,\ \upsilon_4=0.24$

The step responses of the four models are shows in figures (3), (4), (5) and (6). It is clear that the CRONE controller guarantees the desired performances

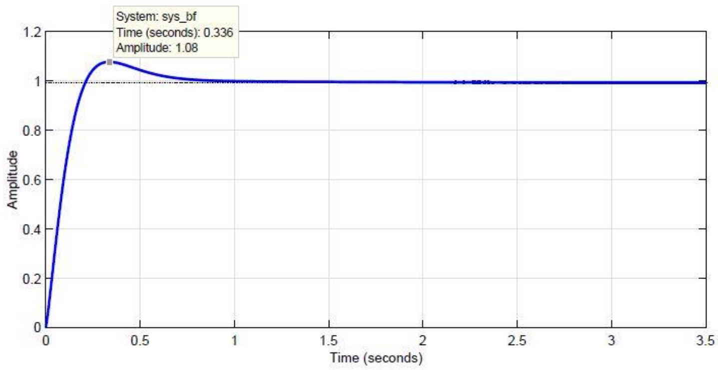

Figure 3: Step response of the model 1

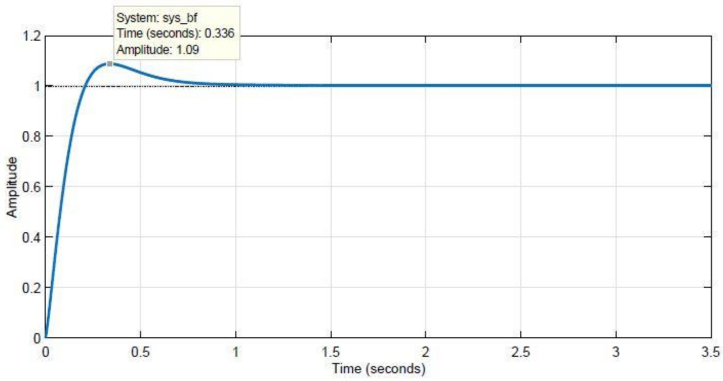

Figure 4: Step response of the model 2

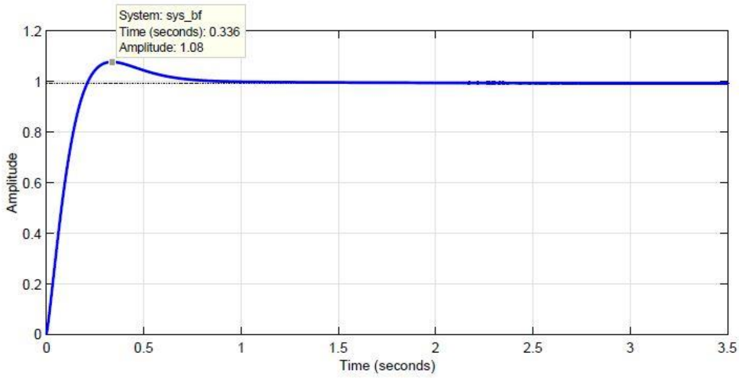

Figure 5: Step response of the model 3

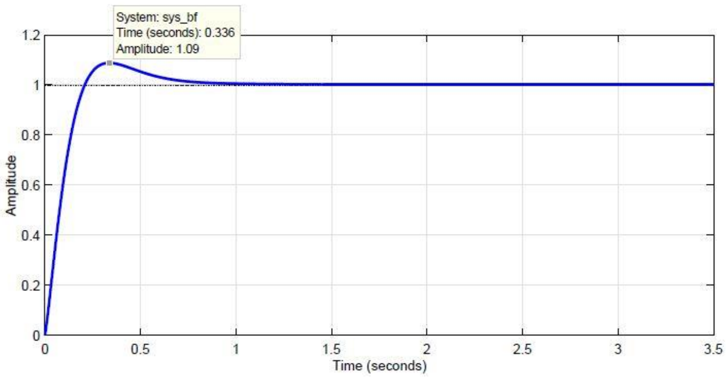

Figure 6: Step response of the model 4

For different setpoints r (r = 0.1, ..., 1), the CRONE control law makes it possible to calculate the various partial commands ui according to the expression (3.21). The figures (7), (8), (9) and (10) gives the evolution of these commands.

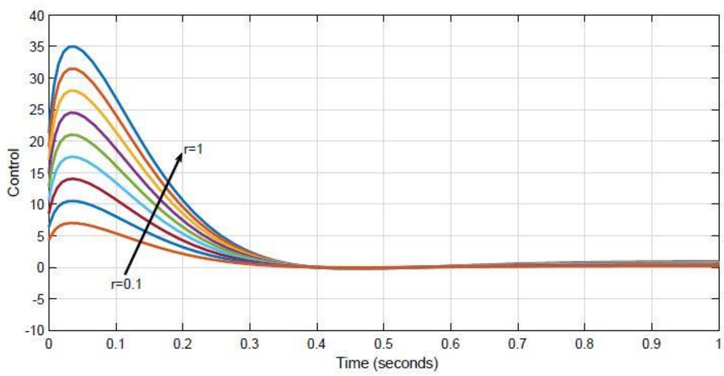

Figure 7: CRONE control of the model 1

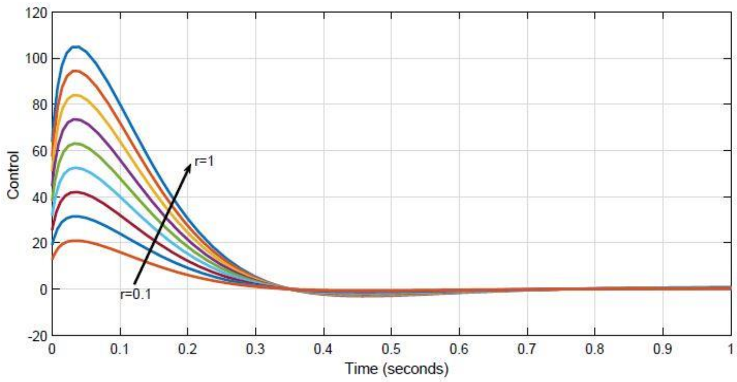

Figure 8: CRONE control of the model 2

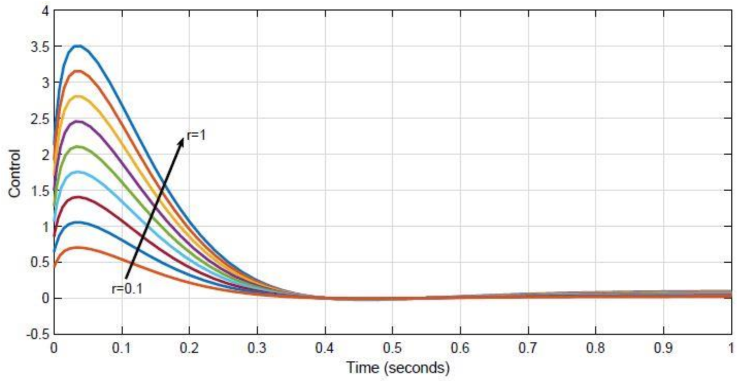

Figure 9: CRONE control of the model 3

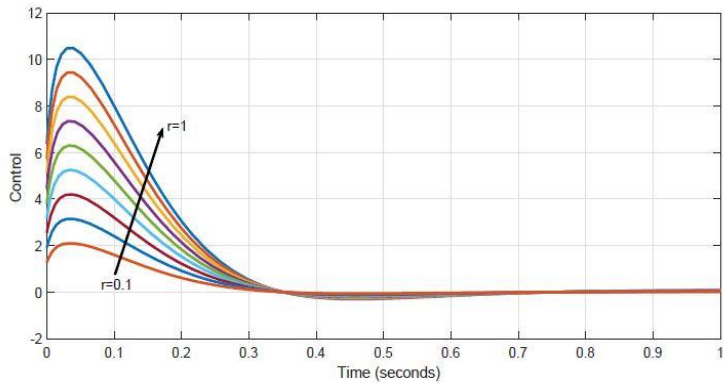

Figure 10: CRONE control of the model 4

From the previous figures, it is clear that the maximum value of the command for the model 3 is equal to 10 times that the model 1 since the transfer functions G_1 and G_3 differ by a gain of 10, then the command u_3 will be 10 times low than the u_1 command. Similarly, the maximum value of the command for the model 4 is 10 times that the model 2, since the transfer functions G_2 and G_4 also differ by a gain of 10, so that the u_4 command will be 10 times low than u_2. On the other hand, we notice that the controller for the four models generates a control peak at the initial moment due to the presence of a gain equivalent of a proportional action in the CRONE controller.

- ***Calculation of global CRONE controller***

For the calculation of the global CRONE control, we will proceed to a fusion of partial CRONE commands. The values of the validities associated with each model M_i are given by the table (2).

Table 2: The values of the validities

Model	Values of the validities
M_1	$\upsilon_1 = 0.4$
M_2	$\upsilon_2 = 0.5$
M_3	$\upsilon_3 = 0.01$
M_4	$\upsilon_4 = 0.09$

The global CRONE controller is defined by the following equation:

$$C_g(s) = 121.68 s^{0.24} \quad (19)$$

The figure (11) shows the global CRONE control for different setpoints.

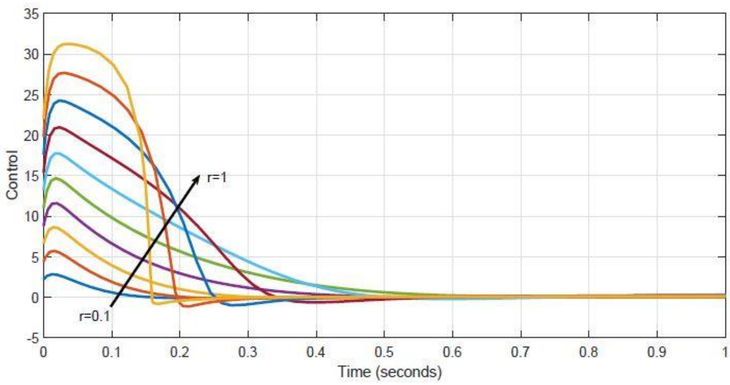

Figure 11: Global CRONE control

The step responses of the nonlinear system and multimodel corrected by the CRONE controller for different setpoint values are given in figures (12).

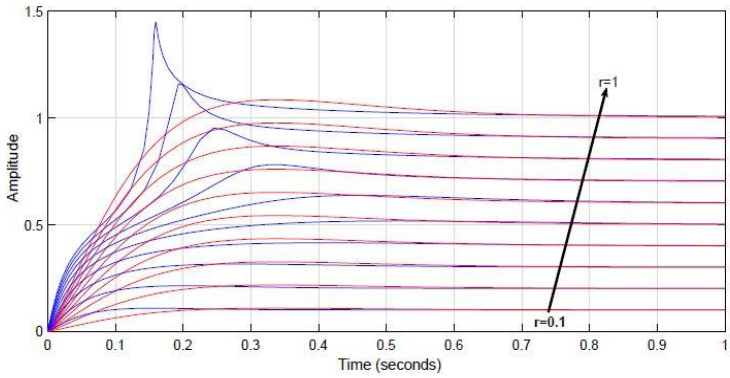

Figure 12: Step responses of the nonlinear system (blue) and multimodel(red) corrected by the CRONE controller.

The results presented allow us to conclude that if the setpoint $r \leq 0.6$, the behavior obtained is very close to correctedmultimodel and if $r \succ 0.6$, the behavior is seen to be non-linearized but the two nonlinear and multimodel responses remain close in performance. So the CRONE control is able to give a good performance.

- ***Gain variation effects***

To verify the robustness, we consider a variation of gain and we calculate the overshoot of the nonlinear system and the multimodel as shown in the table (3).

Table 3: Overshoot comparison for the nonlinear system and multimodel for different setpoint

Setpoint	Overshoot of nonlinear system	Overshoot of multimodel
0.1	9.85	9.93
0.2	9.68	9.84
0.3	9.51	9.83
0.4	9.41	9.84
0.5	9.38	9.84
0.6	9.63	9.84
0.7	10.12	9.83
0.8	10.76	9.84
0.9	11.86	9.84
1	45	9.84

From the table (3), we note that, if the setpoint $r \succ 0.6$, the system obtained by the corrected multimodel guarantees the desired performances except that the value of the first overshoot is important for the nonlinear system step response. We can conclude that the CRONE control is very robust for the variation of the gain.

Table 4: Difference at 0.5s for the nonlinear system and multimodel for different setpoint

Setpoint	Difference
0.1	0.004
0.2	0.0077
0.3	0.0086
0.4	0.0074
0.5	0.0093
0.6	0.0057
0.7	0.0039
0.8	0.0142
0.9	0.0199
1	0.025

The table below gives the value of the difference found at the instant $t = 0.5s$ between the nonlinear system and its multimodel corrected by the CRONE controller. The results show that the nonlinear system and multimodel corrected by the CRONE controller achieved the steady state rapidly.

3.2. Fractional PI Controller

3.2.1. Synthesis of global and partial fractional PI controller

In [17], we propose a fractional PI controller defined by:

$$\varepsilon \frac{d^{\alpha}u}{dt^{\alpha}} = k_0 \left[\left(\frac{r-y}{T} \right) - \frac{d^{\alpha}y}{dt^{\alpha}} \right] \quad (20)$$

The control law (20) can be expressed in terms of transfer functions, it's the structure of the fractional PI controller.

$$U(s) = \frac{k_0}{T\varepsilon} \frac{E(s)}{s^{\alpha}} - \frac{k_0}{\varepsilon} Y(s) \quad (21)$$

where $E(s) = R(s) - Y(s)$. We note by $k_p = -\frac{k_0}{\varepsilon}$ and $k_i = -\frac{k_0}{T\varepsilon}$ the equation (21) will be

$$U(s) = k_p Y(s) + \frac{k_i}{s^{\alpha}} E(s) \quad (22)$$

For the calculation of the fractional PI control u_j, we must associate for each model from the base

$M_i\left(i=1,\dots,K\right)$, a fractional PI controller defined by the following equation:

$$u_j\left(s\right)=k_{p_j}y\left(s\right)+\frac{k_{i_j}}{s^{\alpha_j}}e\left(s\right) \quad (23)$$

So, to each basic model we associate a fractional PI controller whose the structure is given by the figure (13) where:

- $e\left(t\right)$ is the difference between the setpoint $r\left(t\right)$ and the output $y_j\left(t\right)$.
- $-u_j$ is the partial control.

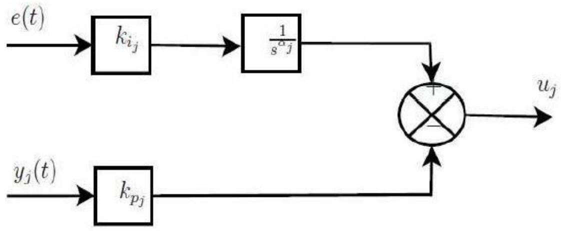

Figure 13: Structure of the fractional PI controller

In order to calculate the value of the partial fractional PI control u_j, we will calculate the global fractional PI controller given by the following equation:

$$u_{pg}\left(k\right)=\sum_{j=1}^{K}\upsilon_j\left(k\right)u_j\left(k\right) \quad (24)$$

To see the effect of the fractional PI control to a nonlinear system by the multimodel approach, an illustrative example will be presented in the next section.

3.2.2. Simulation Example 2

We consider the simulation example presented in the previous section whose their equation is defined by:

$$\text{y}+\left(15-10y\right)\dot{y}=\left(36y\left(y-1\right)+10\right)u \quad (25)$$

Using the multimodel approach, we will have four model defined by the following equations:

$$G_1\left(s\right)=\frac{1}{1+5s} \quad (26)$$

$$G_2(s)=\frac{1}{1+15s} \quad (27)$$

$$G_3(s)=\frac{10}{1+5s} \quad (28)$$

$$G_4(s)=\frac{10}{1+15s} \quad (29)$$

Once the models are developed, the first step is to associate a fractioanl PI controller to each model. By applying the method of synthesis of the fractional PI controller for $N=20$, $\omega_u=10rad/s$, $\omega_h=1000rad/s$, $\omega_b=0.1rad/s$, $\left[\alpha^-,\alpha^+\right]=\left[0,2\right]$, $T=1$, $\varepsilon=0.03$ and $k=-0.5$, we obtain the partial fractional PI control of each model for different setpoints illustrated by the figures (14), (15), (16) and (17).

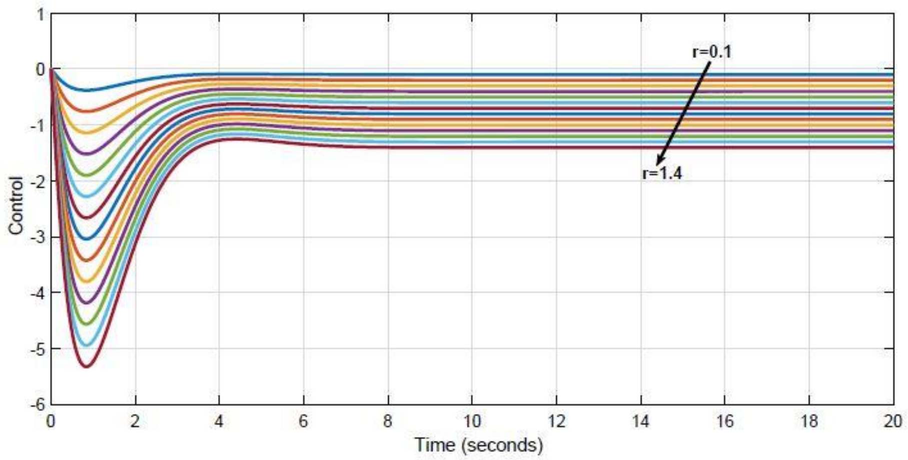

Figure 14: Fractional PI control of the model 1

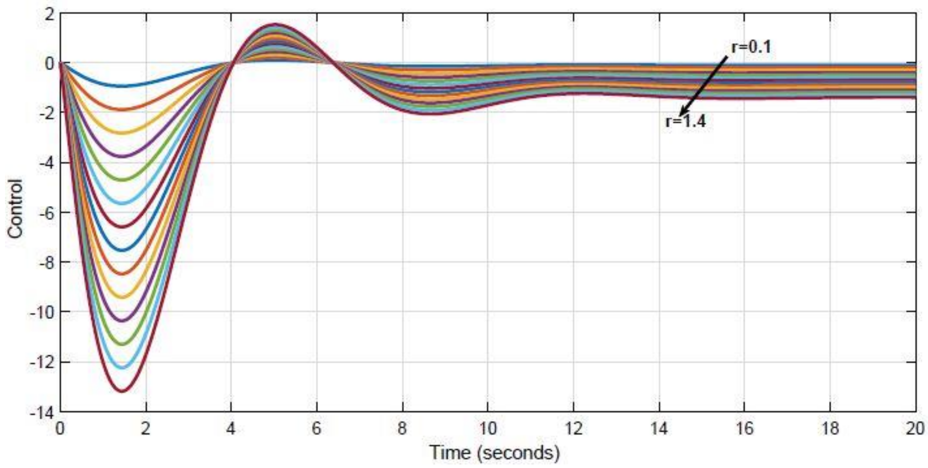

Figure 15: Fractional PI control of the model 2

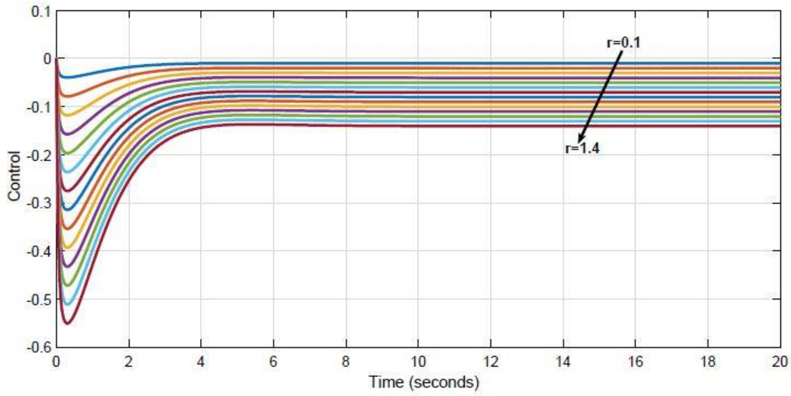

Figure 16: Fractional PI control of the model 3

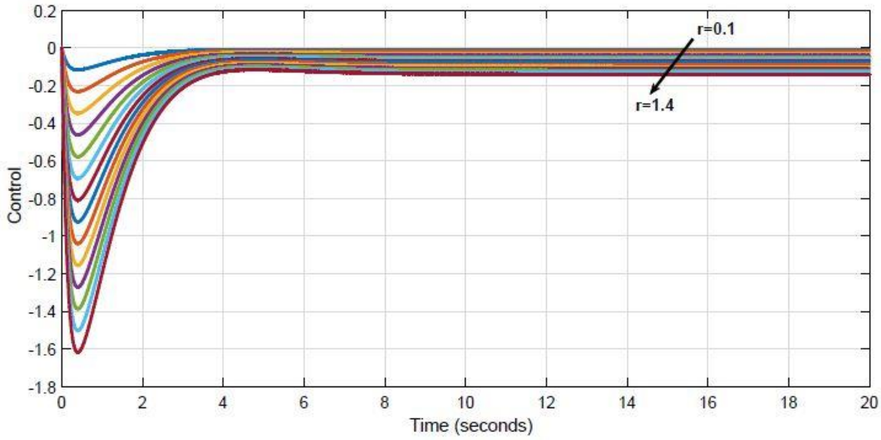

Figure 17: Fractional PI control of the model 4

After calculating the fractional PI controller of each model, the second step is to associate a global fractional PI controller for the nonlinear system. Figure (18) illustrate the global control for different setpoints. The step responses of the nonlinear system corrected by the fracional PI controller are given in figures (19).

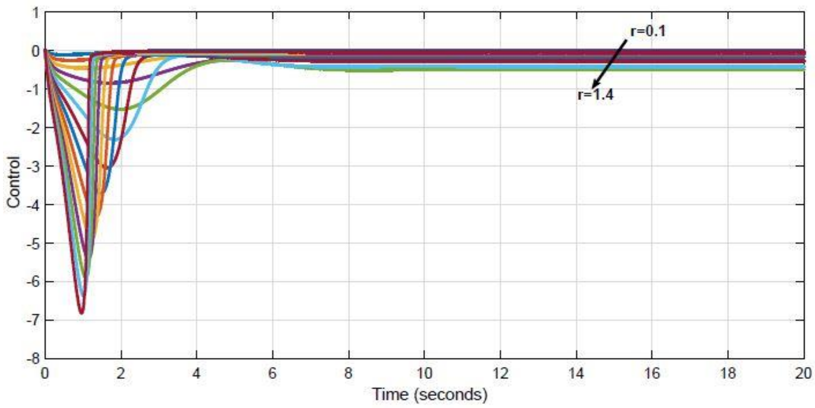

Figure 18: Global Fractional PI control

Through the results obtained, we found that, for step responses we have a linear close behavior which is very close to the multimodel for the values of setpoints $r \leq 0.6$, whereas if $r \succ 0.6$ the behavior is not linearized but the two responses of the nonlinear system and the multimodel remain close in performance.

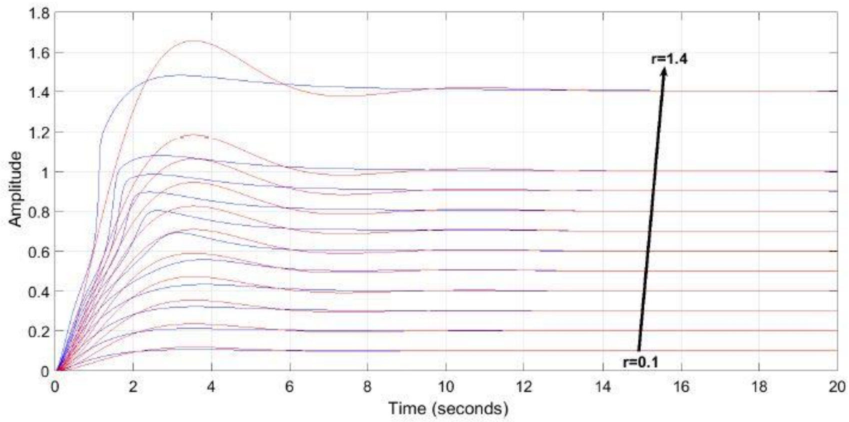

Figure 19: Step responses of the nonlinear system (blue) and multimodel (red) corrected by the fractional PI controller.

Therefore, the fractional PI control performed is satisfactory and ensures good robustness with respect to the setpoint variation.

4. Conclusion

In this paper a method of output regulation for a nonlinear systems is presented. It is based on fractional PID controllers and the CRONE controller used the multimodel approach. It has been shown that the proposed fractional PID controller and the CRONE controller allows to provide robust output control and almost good tracking in presence of plant parameter variations as well as providing desired performances under step change of set point. An illustrative numerical example shows that the proposed method provides a robust controller satisfying the desired transient performances by inducing the multimodel approach in the closed-loop system**.**

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