On the Internal Model Control of the Fuzzy Discrete-time Nonlinear Affine in the Control Systems

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Abstract— **In this paper, we are interested in the modeling and the regulation of discrete nonlinear systems affine in control. In this sense, we propose, first, to apply, in a discrete representation in input-output fuzzy description of nonlinear systems considered based on the structural properties of fuzzy systems of Takagi-Sugeno at constant conclusions, and secondly, to apply the Fuzzy Internal Model Control F.I.M.C.**

In this direction, a method of description of the complex fuzzy system is developed based on the system's decomposition into elementary fuzzy subsystems defined each on a fuzzy elementary mesh. This decomposition ensures the instant representation of the fuzzy system using the elementary subsystems in order to satisfy the elaboration of regulator. The F.I.M.C is exploited, following the various steps of description and developing models of the system dealt, in view to improving its behavior and its performances

I. INTRODUCTION

To guarantee the desired properties for a physical process it is required to develop a control law [1,2]. In this sense, an alternative is or to dress a mathematical model of the process to be controlled, that will be exploited for the synthesis of the controller and for the simulation of the performance obtained in closed loop [3,4,5,6]. The models obtained by input-output representation are of major interest in the problems of system's identification and fuzzy control [7]. On the one hand, they have a simpler structure than the models of state and on the other hand, they insure a direct relationship between the command and the output. The output allows the construction of an inverse system and so the resolution of the problem of trajectory tracking. In this paper, we are interested in discrete nonlinear systems affine in control.

We propose to apply the fuzzy input-output representation of discrete nonlinear systems of Takagi-Sugeno TSK type in there descriptions [8,19]. Decomposition of the overall fuzzy system into fuzzy elementary subsystems, each defined on a fuzzy elementary mesh which facilitates the study of complex fuzzy systems. Hence, the development of the mechanism of inversion of the fuzzy system will be allowed [19,20].

These proposed steps will be exploited in the implementation of the I.M.C in the regulation of nonlinear system ("Duffing forced-oscillation") in order to show the interest of the representation's method and the robustness of the control law adopted views stabilization and improvement of performance for the considered system.

II. FUZZY SYSTEMS OF TAKAGI-SUGENO AT CONSTANT CONCLUSIONS

Currently, a major role in the synthesis of fuzzy controllers is taken up by the fuzzy systems of Takagi-Sugeno based on their structure [14,18]. Which provides a simple analytical expression of the output based on inputs fuzzy controllers [19,14]. Suppose a fuzzy Takagi-Sugeno constant at conclusion, multi-input single-output MISO, with n inputs $e_1,\cdots$ and one output *s*. The fuzzy system is then represented by a collection of rules of the following form (1):

$$\begin{aligned}&R^{(i_1,\cdots}\quad .\\&\text{If } e_1 \text{ is } A_1^{i_1} \text{ and}\cdots \quad \text{is } A_n^{i_n}\\&\text{Then } s=\Theta(i_1,\cdots\end{aligned}\qquad(1)$$

with:

$A_k^{i_k}, k=1,\cdots$ is the i_k fuzzy symbol associated to the variable e_k and $\Theta(i_1,\cdots$ is the real constant in the conclusion of the indexed rule $(i_1,\cdots$ .If L_k are fuzzy symbols to describe e_k such as $I_k=\{1,2,\cdots$, of complete rules consists then of $L=\prod_{k=1}^{n}L_k$ rules. For $e=[e_1,e_2,\cdots \quad \Re^n$, the output generated by the fuzzy system is given by (2):

$$s=\frac{\sum_{i_1}^{i_n}\theta^{(i_1,\cdots}\quad(\text{ج})\Theta(i_1,\cdots}{\sum_{i_1}^{i_n}\theta^{(i_1,\cdots}\quad(\text{ج})},(i_1,\cdots\qquad(2)$$

Ikbel Ben Cheikh Ahmed, Dhaou Soudani and Mohamed Benrejeb are with LARA Automatic, ENIT BP 37 le Belvédère, Tunis 1002, Tunisia; ikbel_ben_cheikh@yahoo.fr,Dhaou.Soudani@enit.rnu.tn, mohamed.benrejeb@enit.rnu.tn with: $\theta^{(i_1,\cdots}\quad)$ the degrees of validity of the premises of rules $R^{(i_1,\cdots}$.

Such as:

$$\theta^{(i_1,\cdots}\quad) = \prod_{k=1}^{n} \mu_{A_k^{i_k}}(e_k) \tag{3}$$

Assume a strict partition universe of discourse of inputs with triangular functions of membership regularly distributed, then:

$$\sum_{i_1}^{i_n} \theta^{(i_1,\cdots}\quad) = 1;\ e \in \Re^n, (i_1,\cdots \tag{4}$$

In that case, the equation (2) becomes:

$$s = \sum_{i_1}^{i_n} \theta^{(i_1,\cdots}\quad)\Theta(i_1,\cdots \qquad \cdots \tag{5}$$

A multi-input multi-output fuzzy system of Takagi-Sugeno at constant conclusions with n inputs $e_1,\cdots$ and m outputs $s_1,\cdots$ can be represented by a collection of fuzzy subsystems in multi-input single-output given by the form (1).

III. FUZZY REPRESENTATION OF NON LINEAR DISCRETE AFFINE IN CONTROL SYSTEMS

The representation of a process by a mathematical model, essential for the synthesis of control laws, is characterized by recurrent equations between linear and nonlinear inputs, states and outputs. One solution to this problem can been seen from a representation of the input-output behavior of nonlinear process explicitly with a fuzzy model [14,20] where relations between inputs, outputs and states are expressed by fuzzy rules. Consider a nonlinear discrete system whose state representation is given by expression (6) follows:

$$\begin{cases} X(k+1) = f\left[X(k), u(k)\right] \\ y(k) = h\left[X(k)\right] \end{cases} \tag{6}$$

where:

$X = \left[X_1, X_2, \cdots \quad \Re^n\right.$ is the state vector and $u(k), y(k) \in \Re$ are respectively the input and output system (6). The vectors $f = (f_1, f_2, \cdots$ are nonlinear analytical form and are nonlinear unknown analytic functions [12,17]. From (6), it is necessary to approximate $2n+1$ nonlinear functions (the n nonlinear functions of the vector field f, the n nonlinear functions of the vector field and the nonlinear function h), that is generally not affordable.

To overcome these constraints frequently encountered, a transformation of the state representation (6) to an input-output representation is used. This one is adopted to produce an explicit relationship between control and output is proposed. Discrete processes, studied in this section, are assumed to have at least one equilibrium point (chosen the origin zero).

A. *Input-Output Discrete Representation*

In this section we focus on establishing a direct relationship between input and output system (6). The system has a relative degree r if:

$$\frac{d}{du}\left[h \circ \qquad)\right] = 0 \qquad \forall (x,u) \in \Re^n \times \Re \text{ et } \eta \le r-1 \tag{7.a}$$

and

$$\frac{d}{du}\left[h \circ \qquad)\right] \ne 0 \tag{7.b}$$

with: $f^{(i)}$ the i^{th} iterative composition. The delay between input $u(k)$ and output $y(k)$ is indicated by the relative degree r, which means that the measured input at a time k shall affect the system output after r time units.

Assuming that the system under consideration is at its minimum phase, the output $y(k)$ is evaluated at sampling times successively taken until the appearance of the input $u(k)$. Then the recurrence relation expressing the output $y(k+r)$ and input $u(k)$ is then obtained by the following equation (7.c):

$$y(k+r) = h \circ \qquad), u(k)\big] \tag{7.c}$$

If $\frac{dy(k+r)}{dx(k)}$ is nonsingular at the equilibrium (chosen in this part originally), we can express the state as a function of past inputs and outputs [7,11,13,15]. The output of the system can be rewritten as follows (8):

$$\begin{aligned} y(k+r) &= \Psi_d\left[y(k),\cdots \qquad \cdots\right. \\ &= \Psi_d\left[E_1(k), u(k)\right] \end{aligned} \tag{8.a}$$

where:

$$E_1(k) = \left[y(k),\cdots \qquad \cdots \qquad \Re^{n+m}\right. \tag{8.b}$$

$m \le n$ and Ψ_d nonlinear function.

Using an input-output representation of the form (8) requires the fuzzy approximation of the nonlinear function Ψ_d instead of the $2n+1$ non-linear function in a state representation of the form (6).

B. *Development of the inverse model*

The objective, of this part, is to develop a method for decomposing a fuzzy system into elementary fuzzy subsystems defined each on a fuzzy elementary mesh illustrated in figure 1.

This decomposition ensures the instant representation of the fuzzy system using the elementary subsystems. Suppose a TSK type fuzzy system [1,12] of the form (1) having n

inputs e_n , the fuzzy system (1) is defined by the universe of input discourse E^n given by the next expression (9):

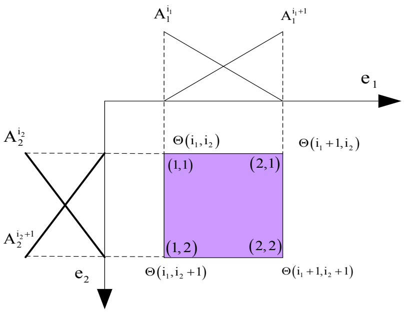

Fig. 1- Mesh for a Basic 2-Input Fuzzy System

$$E^n = E_1 \times \cdots \quad \bigcup \quad \cdots \tag{9}$$

The system is formed of $\prod_{p=1}^{n}\left(L_p-1\right)$ fuzzy subsystems is defined by 2^n fuzzy rules. The generated output of the fuzzy system given by (10):

$$\begin{aligned} &R_{(i_1,\cdots}^{(v_1,\cdots} \quad \text{If } e_1 \text{ is } A_1^{i_1+v_1} \text{ and} \cdots \quad \text{is } A_n^{i_n+v_n} \\ &\text{Then } s_{(i_1,\cdots} = \Theta\left(i_1+v_1,\cdots \quad \cdots\right. \end{aligned} \tag{10}$$

is rewritten by the following expression (11):

$$\begin{aligned} &s = s_{(i_1,\cdots} = \\ &\sum_{(v_1,\cdots \quad 0,1\}^n} \theta^{(i_1+v_1,\cdots \quad)}(e).\Theta\left(i_1+v_1,\cdots \quad \right) \end{aligned} \tag{11}$$

Let $a_p^{i_p}$ is the modal value of fuzzy symbol $A_p^{i_p}$ such as: $\mu_{A_p^{ip}}\left(a_p^{i_p}\right)=1$

It is proposed to transform a subsystem with n inputs and one output MISO in a subsystem into one input and one output SISO. The concept of transferring the $n-1$ variables of the input of the e_{n-1} of premises to the conclusions of rules.

This procedure aims to reduce the number of fuzzy rules for each subsystem and to spend a TSK fuzzy system with multiple inputs to a fuzzy system to one, allowing then the procedure of reversing mechanism of fuzzy model [8,10]. For a system with n inputs the output of the subsystem (11) can be rewritten in vector form following (12):

$$\begin{aligned} &s_{(i_1,\cdots} = \theta^{(i_1,\cdots}(e).T\left(i_1,\cdots\right. \\ &\sum_{(v_1,\cdots \quad 0,1\}^n} \theta^{(i_1+v_1,\cdots \quad)}(e).\Theta\left(i_1+v_1,\cdots \quad \right) \end{aligned} \tag{12}$$

For a fuzzy system to n inputs the output generated, obtained following the parameterization of fuzzy symbols represented in figure 2, can be expressed by the following generalized relation (13):

$$\begin{aligned} &s_{(i_1,\cdots} \quad \sum_{(\tau_1,\cdots} \frac{1}{2^n \prod_{b=1} \delta_b^{i_b}} \sum \cdots \quad (-1)^{(1+v_1)\tau_1+\cdots \quad)\tau_n}. \\ &\left[(e_1)^{\tau_1}+\left((-1)^{v_1}c_1^{i_1}+\delta_1^{i_1}\right)^{(1-\tau_1)}\right]\cdots\left[\quad +\left((-1)^{v_n}c_n^{i_n}+\delta_n^{i_n}\right)^{(1-\tau_n)}\right]. \\ &\Theta\left(i_1+v_1,\cdots \quad \right) \end{aligned} \tag{13}$$

If we set $P1=\left(e_1,\cdots\right.$ the vector formed of $n-1$ inputs, the output expression can be rewritten as follows:

$$s_{(i_1,\cdots} = \sum_{v_n\in\{0,1\}} \Theta_{(i_1,\cdots} \left(\quad {}_n+v_n,P1\right).\mu_{A_n^{i_n}}\left(e_n\right) \tag{14.a}$$

with:

$$\begin{aligned} &\Theta_{(i_1,\cdots}\left(\quad {}_n+v_n,P1\right)=\sum_{(v_1,\cdots} \xi^{(i_1+v_1,\cdots \quad {}_{n-1})}(P1). \\ &\Theta\left(i_1+v_1,\cdots \quad {}_{n-1},i_n+v_n\right);v_n\in\{0,1\} \end{aligned} \tag{14.b}$$

From this transformation, for each unit cell, there are only two rules instead 2^n . We can then write (15):

$$\text{If } e_n \text{ is } A_n^{i_n} \text{ Then } s_{(i_1,\cdots} \quad \cdots \quad P1) \tag{15.a}$$

$$\text{If } e_n \text{ is } A_n^{i_n+1} \text{ Then } s_{(i_1,\cdots} \quad \cdots \quad 1,P1) \tag{15.b}$$

The transformations of each output generated by the corresponding fuzzy subsystem are of major interest for the realization of the inversion of the appropriate fuzzy model. The problem of trajectory tracking lies on the determining of an inlet (command) capable of returning the output from one system to the monitoring of the reference trajectory.

To solve this problem, we assume that the inversion of the system's model [13,14,15,16,17] in the presence of the trajectory eligible to provide input, led to convergence of its output to the reference trajectory. In general, for an affine fuzzy system, if (16) is verified then the fuzzy inverse model is given analytically by the relation (17).

$$\frac{ds_{(i_1,\cdots}}{de_n} \neq 0 \tag{16}$$

The fuzzy model is then given by the analytic relationship (17) which is an exact reversal of the model:

$$e_n = \frac{-\Psi_1^{(i_1,\cdots}\left(P1\right) \quad s_{(i_1,\cdots}}{\Psi_2^{(i_1,\cdots}\left(P1\right) \quad \Psi_2 \quad \left(P1\right)} \tag{17}$$

This version is actually conditioned by the membership of the input e_n to the corresponding cell.

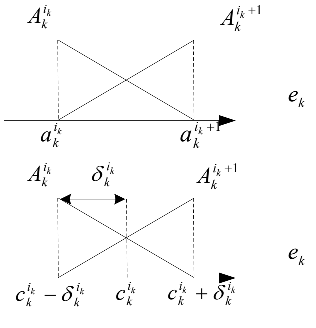

Fig. 2- Parameterization of Fuzzy Symbols Inputs

IV. ON FUZZY INTERNAL MODEL CONTROL OF DISCRETE NON LINEAR SYSTEMS

Deal with the complexities presented by nonlinear dynamical systems, several nonlinear control strategies have been developed, In this work, we are interested in applying such strategies to the fuzzy internal model control (F.I.M.C)[6,12,18].

The structure of the F.I.M.C is given by figure 3. In each unit cell, the fuzzy system and the blur correction corresponding to the inverse model is obtained by applying the principle of inversion developed previously [12,14,15,16].

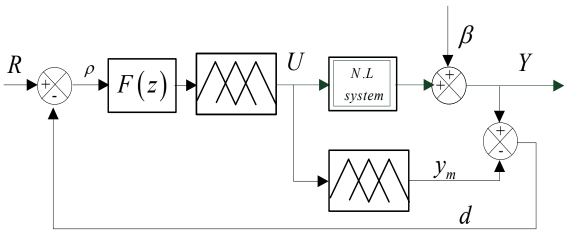

Fig. 3- Structure of the Fuzzy Internal Model Control F.I.M.C for Nonlinear Systems

V. EXPERIMENTAL RESULT

We propose control the electrical system of nonlinear oscillatory "Duffing forced-oscillation" treated in [9] by F.I.M.C, described by the following dynamic equations:

$$\begin{cases} \qquad (t) \\ \qquad .1x_2(t) - x_1^3(t) + 12\cos(t) + u(t) \\ y(t) = x_1(t) \end{cases} \qquad (18)$$

The relative degree r of system (18) is equal to its order n, as $r = n = 2$.

The fuzzy model of the TSK system is given by a collection of rules of the form:

$$\begin{aligned} &R^{(i_1,i_2,i_3)}: \text{If } y(k) \text{ is } A_1^{i_1} \text{ and } y(k+1) \text{ is } A_2^{i_2} \text{ and } u(k) \text{ is } A_3^{i_3} \\ &\text{Then } y(k+2) = \Theta_{df}(i_1,i_2,i_3); i_1 = 1,\cdots \qquad ,2 \text{ and } i_3 = 1,2 \end{aligned} \qquad (19)$$

Consider the basic rules, illustrated in Table (1) according to the description of the fuzzy model of our system.

The fuzzy model is identified around the desired trajectory $y_{des}(k) = 2\sin(k)$.

The universe of discourse of inputs $y(k)$, $y(k+1)$ and $u(k)$ are:

$[y_{min}(k), y_{max}(k)] = [y_{min}(k+1), y_{max}(k+1)] = [-3,3]$;

$[u(k), u(k)] = [-1.5, 1.5]$

TABLE I. BASE OF THE FUZZY SYSTEM RULES OF TSK

	A_1^1	A_1^2	A_1^3	A_1^4	A_1^5	A_1^6
A_2^1	$A_3^1: -2.2$ $A_3^2: 0.06$	$A_3^1: -2$ $A_3^2: 0.5$	$A_3^1: -1.1$ $A_3^2: 1.4$	$A_3^1: -0.9$ $A_3^2: 1.1$	$A_3^1: -0.5$ $A_3^2: 1$	$A_3^1: -0.3$ $A_3^2: 1.6$
A_2^2	$A_3^1: -1.4$ $A_3^2: 0.5$	$A_3^1: -1.6$ $A_3^2: 0.7$	$A_3^1: -0.8$ $A_3^2: 0.9$	$A_3^1: -0.5$ $A_3^2: 1.1$	$A_3^1: -0.4$ $A_3^2: 1$	$A_3^1: -0.1$ $A_3^2: 0.9$

The part of the fuzzy universe of discourse is presented in the figure 4.

The discretisation of the input-output representation of the system refers to the Euler approximation [21] and the developed results in [22] is given by (20):

$$y(k+2) = -0.9y(k+1) + 0.1y(k) - Ty^3(k) + 12T\cos(k) + Tu(k) \qquad (20)$$

In order to apply the IMC it is required to develop a synthesis of the inverse fuzzy model. The decomposition of the fuzzy proposed system has 5 fuzzy subsystems set of 5 basic meshes:

$(1,1,1)$, $(2,1,1)$, $(3,1,1)$, $(4,1,1)$, $(5,1,1)$.

Whether $P1$ the vector composed of inputs $e_1 = y(k)$ and $e_2 = y(k+1)$. $e_1 = y(k), e_2 = y(k+1)$ and $e_3 = u(k)$

The output subsystem defined on the fuzzy elementary mesh (i_1,i_2,i_3) is given as follows (21):

$$\begin{aligned} &s(i_1,i_2,i_3) = \sum_{v3\in\{0,1\}} \Theta_{(i_1,i_2,i_3)}(i_3+v_3,P1).\mu_{A_3^{i_3}}(e_3) = \\ &\left(\sum_{v3\in\{0,1\}} \left(\begin{matrix} \sum_{(v_1,v_2)\in\{0,1\}^2} \xi^{(i_1+v_1,i_2+v_2)}(P1). \\ \Theta(i_1+v_1,i_2+v_2,i_3+v_3) \end{matrix} \right)\right).\mu_{A_3^{i_3}}(e_3) \end{aligned} \qquad (21)$$

$$\begin{aligned} &\Theta_{(i_1,i_2,i_3)}(i_3+v_3,P1) = \\ &\sum_{(v_1,v_2)\in} \xi^{(i_1+v_1,i_2+v_2)}(P1).\Theta(i_1+v_1,i_2+v_2,i_3+v_3); \\ &v_3 \in \{0,1\} \end{aligned} \qquad (22)$$

We dispose only 2 rules instead of 2^3. We consider for example the cell $(1,1,1)$, the output of the fuzzy subsystem is expressed by (23):

$$\begin{aligned} &s_{(1,1,1)} = u(k).\begin{bmatrix} 0.036y(k)y(k+1) + 0.093y(k) \\ -0.037y(k+1) - 0.226 \end{bmatrix} + \\ &0.14y(k) - 0.056y(k+1) - 0.054y(k)y(k+1) - 0.34 \end{aligned} \qquad (23)$$

Simulation results of closed-loop system are obtained by figures 6, 7, 8 and 9. We chose, first, as the model of fuzzy subsystem whose entries belong to the mesh $(1,1,1)$ response and evolution of the reference trajectory are presented in figure 6, then, is implanted the five fuzzy subsystems in order to minimize the error between the reference trajectory and the outputs nonlinear models, the simulation results are illustrated in figure 7. A disturbance, equal to a unit step applied, on the outputs of the systems, at the time $t = 10\mathrm{s}$. Simulations results are illustrated by figures 8 and 9.

VI. CONCLUSION

In this paper, we showed that the overall output of a fuzzy system of TSK is equal to the output generated by a subsystem fuzzy set to a fuzzy elementary mesh which facilitates the study of complex systems.The inversion problem of a fuzzy model has been discussed, namely the analytical method was adopted in this work. The various stages are developed subsequently exploited in the development and implementation of F.I.M.C. We also noted the performance tracking performed, figure 6, for fuzzy subsystem of the mesh $(1,1,1)$ compared to the response of the open loop system in figure 5, by the method of regulation adopted. A significant improvement is detected at the behavior of the system in figure 7 explained by the fact that the implementation of the command used with all subsystems minimizes the approximation errors.

The results obtained, figure 7 and figure 8 show the rejection of the disturbance and continued to set the command structure adopted by internal model. The latter proves the robustness of the structure F.I.M.C in improving system performance.

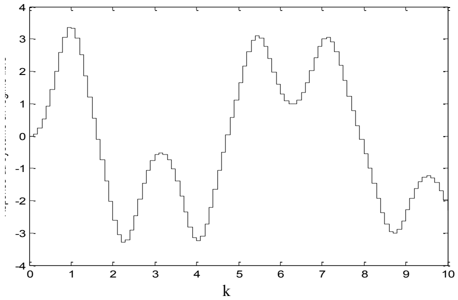

Fig. 5- Response of the System in the Open Loop

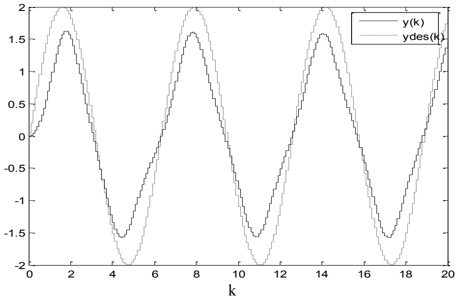

Fig. 6- Reference Trajectory and the System's Output for the Mesh Subsystem $(1,1,1)$

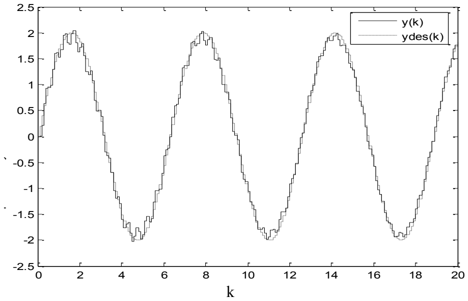

Fig. 7- Reference Trajectory and the System's Output for all Fuzzy Subsystems

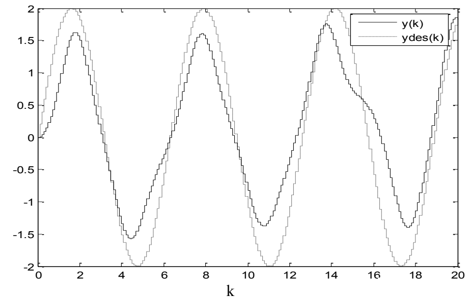

Fig. 8- Reference Trajectory and the System's Output for the Mesh Subsystem $(1,1,1)$ in Presence of Disturbance

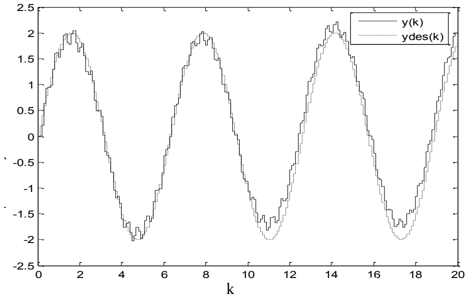

Fig. 9- Reference Trajectory and System's Output for all Fuzzy Subsystems in Presence of Disturbance

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