Design the fuzzy robust controller and PID controller for torsional Auto- pilot system

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Abstract: One of the most important issues in designing the controllers for the nonlinear systems is the parametric and Structural uncertainties and the Penetration of the disturbances and commotions in such systems. Designing the optimal control systems is an important and useful issue in the real systems to overcome the uncertainties and commotions. In this paper, first , the fuzzy systems and PID controllers are introduced and the PID controllers and fuzzy systems with optimal parameters are designed. Finally, fuzzy and PID controllers are compared .
Keywords: fuzzy logic, fuzzy controller, PID controller, missile, Auto- pilot

INTRODUCTION

The word of " fuzzy" is defined as a " Vague, Genk, inaccurate, confusing, confused, tangled and uncertain " in terminology. First time, Electronics, computer science professor at the University of California, Berkeley, Dr Lotfi Zade introduced Fuzzy logic in 1960. Classical logic shows anything based on a binary system (false or true, 0 or 1 , black or white), but fuzzy logic shows the correctness of anything by a number between 0 and 1 . When engineering scientists explored methods to overcome a more difficult problem, Dr Lotfi Zade introduced the fuzzy system theory that created a type of modeling the systems [2].

Fuzzy system is a system with an accurate definition. Fuzzy control is an especial type of nonlinear control that is defined clearly. This is similar to linear systems and linear controls. The word of " linear" is a technical adjective that specifies the state and the situation of the control system. Such description is also true for the word " fuzzy". Basically, fuzzy systems describe the uncertain and unclear phenomena, but the fuzzy system is an accurate method. Fuzzy systems are used to formulate the human knowledge. When the fuzzy systems are used as the controller, they called as fuzzy controllers. If fuzzy systems are used in order to model the process and controllers are designed based on this model, then these controllers called fuzzy controllers, too. Then, fuzzy controllers are same the fuzzy systems that are nonlinear controllers with an especial structure.

One of the industrial controller is PID controller that has been noticed because of their ability to apply to most of control systems. If the mathematical model of the system is not known and we can use the analytic design method, then PID controllers are very useful [7].

Nonlinear control is a common subject with various methods and successful industrial application that attracts the attention of the researchers in various fields such as airplane, spacecraft, robotic control and biomedicine engineering to develop and use the nonlinear control methods. There are various reasons for this attention [3]. The linear control methods are based on the main assumption of performance in a small area for a linear model. When we need a wide performance limit, the linear controller has an unstable and weak performance. Another linear control assumption is that the system model is really able to be Linearized. While there are many nonlinear factors in the control systems that their discontinuous nature doesn't allow the linear approximation. Such nonlinear effects lead to the unfavorable behaviors in the control systems. Also , an appropriate design of the nonlinear control can have a simplier and reacher content than similar linear designs.

Fuzzy systems

Usually, fuzzy systems are divided into three groups: net fuzzy systems, Takagi- Sugeno- Kang fuzzy systems, Mamdani fuzzy systems.

A pure fuzzy system includes a fuzzy rule base that presents a set of rules of if- then and a fuzzy Inference engine that combined these rules to a map of fuzzy sets in the input space to the fuzzy sets [5]. The main problem of the net fuzzy systems is that the output and input of the fuzzy sets. While, in the engineering systems, the input and output are variables with the real values. To solve this problem, Takagi- Sugeno and Kang introduced another type of fuzzy system that its input and output are variables with the real values. In the conclusion part , instead of using a descriptive statement with verbal values, fuzzy system rules of TSK uses a simple mathematical relation [5]. Similar to the net fuzzy systems, TSK fuzzy systems have some problems. Firstly, the conclusion part of the rules is a mathematical formula, then doesn't provide a framework to present the human knowledge. Secondly , applying the different principles of the fuzzy logic is very difficult in this system. Therefore , there are not the flexibility of the fuzzy systems in this structure. To solve this problem, we use the third type of the fuzzy system, namely, Mamdani fuzzy system in this paper. A simple solution is to add a fuzzy- making that converts an input variable with real value into a fuzzy set and a non- fuzzy making that converts a fuzzy set into an output variable with real value . By this method , we can creates a fuzzy system with a fuzzy – making and non fuzzy- making that its main structure is shown in following figure . This system solves the disadvantage of the net fuzzy system and TSK fuzzy system [5].

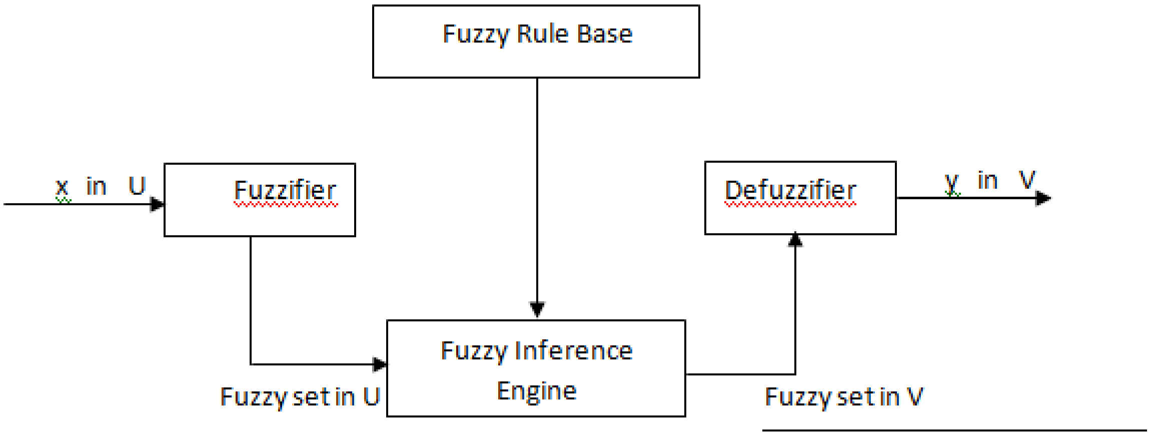

Figure 1. main structure of the Mamdani fuzzy systems

What is ANFIS

ANFIS is the abbreviation of the Adaptive neuro- fuzzy inference system. ANFIS creates an inference system by a set of output- input data and regulates the parameters of the membership functions of the fuzzy systems by using the algorithm of Post-release or combining to the least squares method. This regulating operation allows the fuzzy system to call its structure from the data set.

FIS structure and parameter regulation by using ANFIS

To change the mapping between input and output , we can use a structure similar to the neural networks. In fact , we can use the neural networks to map the input into membership functions and its parameters and then mapping the input membership functions t into output.

Parameters related to the membership functions change during the learning process. Estimation (or regulation) of these parameters is facilitated through a gradient vector by using a toolbox of neural – fuzzy networks of the MATLAB software. This gradient vector provides a measurement for the desirability of modeling the system parameters of the fuzzy inference . After providing the ANFIS gradient vector, we use the estimation of the membership function parameters of the fuzzy sets by Post-release method or combination into the least square method [8].

Auto- pilot

One of the important and specialized issue in the flight the various flying devices (such as airplane, missile, helicopter) is the flight dynamics. An airplane or missile should have three feathers during the flight in all the flight situations (in terms of atmospheric, weight, velocity, center of gravity): controllable, stable, having balance.

These three requirements are the pre- condition of a safe ailplane and a success mission of the missile.

Types of missile from aspect of maneuverability limits

Missiles could be divided into categories from the view of maneuverability limits: a) STT missile , this missile is an especial type of the missile that use the rotation around the z axis for turning. This causes the missile leave out the circular route while other missiles use the rotation around the x axis to turn. But, the turning of the STT missiles by rotation around the x axis leads to turn off the motor and thus falling the missile [22]. b) This missile is controlled by tail and similar to the airplane possesses the ability to rotate and turn, simultaneously. This feature increases the maneuverability ability of this missile.

Translational equations of the missile

Let us consider F is the force of gravity, m is fixed mass of the missile, and $\overline{V}$ is the inertial velocity of the mass center. Then , the translational equation is:

$$F = m\overline{V} \qquad (1)$$

That it can be rewritten as

$$F_x = A_x + W_x = \frac{w}{g}(\dot{a} + qw - rv)$$

$$F_y = A_y + W_y = \frac{w}{g}(\dot{v} + ur - wp) \qquad (2)$$

$$F_z = A_z + W_z = \frac{w}{g}(\dot{w} + pv - qu)$$

Where u, v, w are the total velocity components in x, y, and z directions. F_x , F_y , F_z are the total force components and W_x , W_y , W_z are the weight components. A_x , A_y , A_z are the aerodynamics force components [26].

According to the figure 1, we can write the weight force components of the missile as

$$W_x = -W \sin\theta$$

$$W_y = W \cos\theta \sin\phi \qquad (3)$$

$$W_z = W \cos\theta \sin\phi$$

Where θ is the angle of torsion and ϕ is the rotational angle.

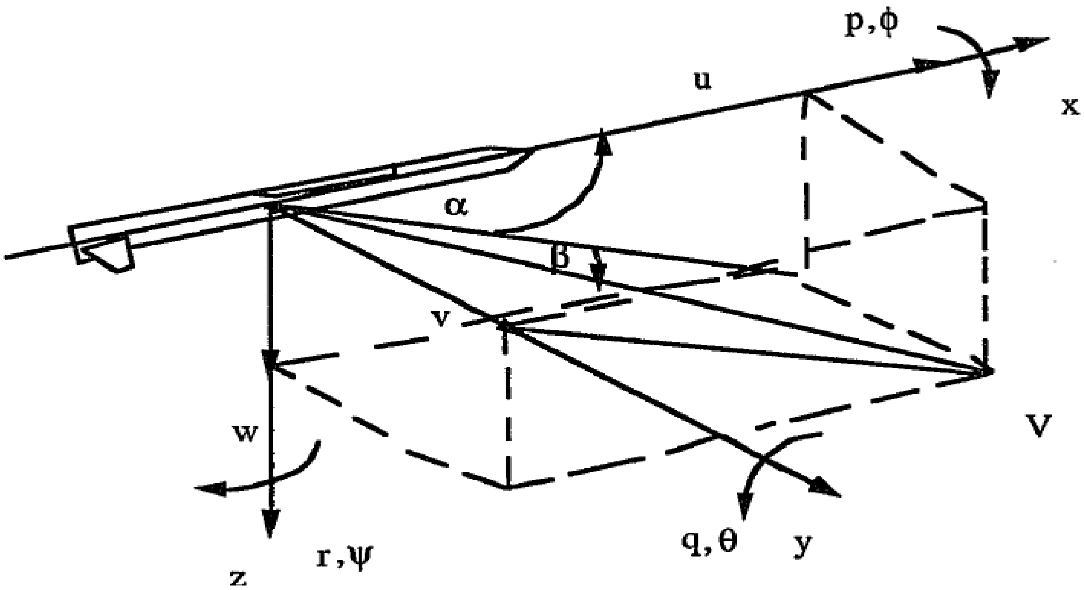

Figure 1. attack angle of slip, rotation, and torsion and weight force components of the missile in the coordinate system of the missile body.

Also, A_x , A_y , A_z can be written as

$$A_y = QS(C_{Y_\beta}\beta + C_{Y_\rho}\rho + C_{Y_r}r + C_{Y_{\delta_\rho}}\delta_\rho + C_{Y_{\delta q}}\delta_q)$$

$$A_z = QS(C_{N_\alpha}\alpha + C_{N_q}q + C_{N_{\delta_q}}\delta_q) \qquad (4)$$

Where Q is dynamic pressure, S is wing area, $C_{a,b}$ is aerodynamic coefficient of the force a due to b and δ_p , δ_q are the deviations of the control surfaces. ρ, q, r are the components of the missile rotational velocity. To simplify, we consider following assumptions:

1- x components of the aerodynamic force applying the body are ignored, namely: A_x=0

2- first order aerodynamic coefficients are constant,, $C_{N\alpha}$=0

3- aerodynamic forces and torques are the linear functions of the state variables and control inputs.

With regard to above equations , we can calculate the time derivative of the velocity components along with the axes. But , because the translational equations of the missile motion is the same equations of the attach angle and slip angle of the missile. Then, we obtain the equations related to the attack and slip angles . for this purpose, we define the attack angle and slip angle as following:

$$\alpha = \tan^{-1}(\frac{w}{u}) \qquad (5)$$

$$\beta = \sin^{-1}(\frac{u}{v}) \qquad (6)$$

Finally, the translational equations of the missile motion are calculated as

$$\dot{\alpha} = q - \tan(\beta)\left[p\ \cos(\alpha) - r\ \sin(\alpha)\right] + \frac{q}{V\ \cos(\beta)}\left[\cos(\alpha)\cos(\varphi)\cos(\theta) + \sin(\alpha)\sin(\theta)\right] +$$

$$\frac{gQs}{WV\ cod(\beta)}\left[C_{N_\alpha}\alpha + C_{N_q}q + C_{N_{\delta_q}}\delta_q\right]\cos(\alpha)$$

$$\dot{\beta} = p\ \sin(\alpha) - r\ \cos(\alpha) + \frac{gQs}{WV}(C_{Y_\beta}\beta + C_{Y_r}r + C_{Y_P}P + C_{Y_{\delta_r}}\delta_r)\cos(\beta) + \frac{g}{v}\cos(\theta)\sin(\varphi)\cos(\beta)$$

(7)

Rotational equations of the missile

Following equation known as the rotational dynamic equation of the missile:

$$\overline{M} = J\overline{\varpi} + \overline{h}(p,q,r) \qquad (8)$$

Where $\overline{M}$ is the torque vector applying on the missile. And $\overline{\varpi} = (p,q,r)$ is the rotational velocity of the missile. Constant matrix J shows the body inertial matrix and $h = (p,q,r)$ is due to use the axes of the body to develop the equations [18,23]. The matrix J can be shown as following:

$$J = \begin{bmatrix} I_{kx} & -I_{xy} & -I_{kj} \\ -I_{xy} & -I_{yy} & -I_{yx} \\ -I_{xz} & -I_{yz} & I_{ZZ} \end{bmatrix} \qquad (9)$$

Where

$$I_{zz} = \int (y^2 + z^2)dm$$

$$I_{xz} = \int (x^2 + z^2)dm$$

$$I_{yy} = \int (x^2 + z^2)dm$$

$$I_{xz} = \int x\,z\,dm$$

$$I_{yz} = \int y\,z\,dm$$

$$I_{xy} = \int x\,y\,dm$$

Also , $h(p,q,r)$, which is due to use the body coordinate system, is:

$$h(p,q,r) = \begin{bmatrix} -(I_{yy} - I_{zz})qr + I_{yz}(r^2 - q^2) - I_{xz}pq + I_{xy}rp \\ -(I_{zz} - I_{xx})rp + I_{XZ}(p^2 - r^2) - I_{zy}qr + I_{yz}pq \\ -(I_{xx} - I_{yy})pq + I_{xy}(q^2 - p^2) - I_{yz}rp + I_{zx}qr \\ \end{bmatrix} \qquad (10)$$

Aerodynamic torque $\overline{M}$ is :

$$\overline{M}=\begin{bmatrix}L\\m\\n\end{bmatrix}=Qsd\begin{bmatrix}C_{L\beta}\beta+C_{Lr}r+C_{L\delta p}\delta p+C_{L\delta r}\delta r\\C_{m\alpha}\alpha+C_{m\dot\alpha}\dot\alpha+C_{mq}q+C_{L\delta q}\delta q\\C_{n\beta}\beta+C_{np}p+C_{nr}r+C_{n\delta p}\delta p+C_{n\delta r}\delta r\end{bmatrix} \qquad (11)$$

Where L, m, n are components of the aerodynamic torque in direction of x, y, z. we can rewrite the equation (8) in terms of time derivative of rotation rate and torsion rate as:

$$\dot\omega=J^{-1}(\overline{M}-h(p,q,r)) \qquad (12)$$

From above equations we can easily find that time derivative of the angle velocity ($\dot\omega$) depends on the attack angle derivative. Then , the rotational equations can be written as :

$$\begin{bmatrix}\dot p\\\dot q\\\dot r\end{bmatrix}=\begin{bmatrix}f_p(x)\\f_q(x)\\f_r(x)\end{bmatrix}+\begin{bmatrix}g_{p\delta p}&g_{p\delta q}&g_{p\delta r}\\g_{q\delta q}&g_{q\delta q}&g_{q\delta q}\\g_{r\delta r}&g_{r\delta r}&g_{r\delta r}\end{bmatrix}\begin{bmatrix}\delta_p\\\delta_q\\\delta_r\end{bmatrix} \qquad (13)$$

Where $g_{ij}(x), f_i(x)$ are obtained from the state equations.

Reference path

A path that missile should trace by using the motion equations and control law, is defined by following relations:

$$\alpha_d=\begin{cases}\alpha_{d_f}\sin\omega t & 0<t<t_f\\\alpha_{d_f} & t\ge t_f\end{cases}$$

$$\dot\alpha_d=\begin{cases}\alpha_{d_f}\cos\omega t & 0<t<t_f\\0 & t\ge t_f\end{cases} \qquad (14)$$

$$\ddot\alpha_d=\begin{cases}\alpha_{d_f}\omega^2 - \alpha_{d_f}\omega^2\sin\omega t & 0<t<t_f\\0 & t\ge t_f\end{cases}$$

Where $t_{f\ min}$ is the minimum time to achieve the stable situation of the system.

Design of torsional Auto- pilot

The aim of the design of torsional Auto- pilot is to achieve a favaroble attack angle so that lateral dynamics are stable. For this purpose, the following conditions should be established: slip angle (β) should be lower than 5^0. Deviations of the control surfaces δ_p, δ_q, δ_r should be less than 45^0. GL commands should be such that the attack angle become more than 20^0 and change rate of the hydrolic axes should be lower than 500^0/sand the lateral dynamics should be stable.

Let us consider the translational equations. Since forces produced by control surfaces are insignificant, then aerodynamic coefficients of the normal force due to the torsional control surface, $C_{N\,\delta q}$ are considered zero and gravity acceleration, g, and slip angle , β, are insignificant. Then, the derivative of the attack angle is :

$$\dot\alpha=q+\tilde{Q}[C_{N_\alpha}\alpha+C_{N_q}q]\cos\alpha \qquad (13)$$

Where $\tilde{Q}=\dfrac{gs}{WV\ \cos\beta}$

But , there are not the control surfaces, then the second derivative of the attack angle to appear the control surfaces.

$$\delta_q=(-(\tilde{f}_{\ddot\alpha}+\tilde{g}_{\ddot\alpha_{\delta p}}\delta_p+\tilde{g}_{\ddot\alpha_{\delta r}}\delta_r)+\ddot\alpha)\Big/\tilde{g}_{\ddot\alpha_{\delta q}} \qquad (14)$$

The right statement includes input and output of the control surfaces. We can consider total relation as a control variable. Namely ,

$$\ddot{\alpha} = u \quad (15)$$

Then , the equation 14 will become:

$$\delta_q = (-(\tilde{f}_{\ddot{\alpha}} + \tilde{g}_{\ddot{\alpha}_{\delta p}} \delta_p + \tilde{g}_{\ddot{\alpha}_{\delta r}} \delta_r) + u) \Big/ \tilde{g}_{\ddot{\alpha}_{\delta q}} \quad (16)$$

If a relation between input and output of the control surfaces is nonlinear, the control variable ,u, is determined by a nonlinear control method.

Modify the zero dynamics of the torsional Auto- pilot

If the second order of the derivative of the attach angle is zero, without rotational inputs we have:

$$\delta_q = (-(\tilde{f}_{\ddot{\alpha}} + \tilde{g}_{\ddot{\alpha}_{\delta p}} \delta_p + \tilde{g}_{\ddot{\alpha}_{\delta r}} \delta_r) + u) \Big/ \tilde{g}_{\ddot{\alpha}_{\delta q}} \quad (17)$$

This reduces the effect of the torsional control inputs and changes the path on the discontinuous null matrix. Without this limitation, zero dynamics are assumed as:

$$\dot{\beta} = -r + \frac{gQs}{wv}(C_{Y_\beta}\beta + C_{Y_r} r + C_{Y_p} p + C_{Y_{\delta_p}} \delta_p + C_{Y_{\delta_r}} \delta_r) \quad (18)$$

$$\dot{p} = \left(f_p(x)_{\alpha,q=0} + g_{p_{\delta_p}} \delta_p + g_{p_{\delta_r}} \delta_r\right) \quad (19)$$

$$\dot{r} = (f_r(x)_{\alpha,q=0} + g_{r_{\delta_q}} \delta_q + g_{r_{\delta_p}} \delta_p + g_{r_{\delta_r}} \delta_r) \quad (20)$$

Torsional control input is defined by equation (20). By altering this statement in torsional control input with zero attack angle and zero torsional velocity , the following equations are obtained [9]:

$$\dot{\eta} = \tilde{f}(\eta) + \tilde{g}(\eta)\begin{pmatrix}\delta_p \\ \delta_r\end{pmatrix} \quad (21)$$

Where $\eta = (\beta \ p \ r)^T$ *and*

$$\tilde{f}(\eta) = \begin{pmatrix} f_\beta(\eta) \\ f_p(\eta) - g_{p\delta_q}\left(\frac{\tilde{f}_{\ddot{\alpha}}}{\tilde{g}_{\ddot{\alpha}\delta_q}}\right) \\ f_r(\eta) - g_{r\delta q}\left(\frac{\tilde{f}_{\ddot{\alpha}}}{\tilde{g}_{\ddot{\alpha}\delta_q}}\right) \end{pmatrix} \quad (22)$$

$$\tilde{g}(\eta) = \begin{pmatrix} g_{\beta\delta_p} & g_{\beta\delta_r} \\ g_{p\delta_p} - g_{p\delta_q}\left(\frac{\tilde{g}_{\ddot{\alpha}_{\delta_p}}}{\tilde{g}_{\ddot{\alpha}_{\delta_q}}}\right) & g_{p\delta_p} - g_{p\delta_q}\left(\frac{\tilde{g}_{\ddot{\alpha}_{\delta_r}}}{\tilde{g}_{\ddot{\alpha}_{\delta_q}}}\right) \\ g_{r\delta_p} - g_{r\delta_q}\left(\frac{\tilde{g}_{\ddot{\alpha}_{\delta_p}}}{\tilde{g}_{\ddot{\alpha}_{\delta_q}}}\right) & g_{r\delta_p} - g_{r\delta_q}\left(\frac{\tilde{g}_{\ddot{\alpha}_{\delta_r}}}{\tilde{g}_{\ddot{\alpha}_{\delta_q}}}\right) \end{pmatrix} \quad \textbf{(23)}$$

Therefore :

$$\dot{\eta} = \frac{\partial}{\partial\eta}\tilde{f}(0)\eta + \frac{\partial}{\partial\eta}\tilde{g}(0)\begin{pmatrix}\delta_p \\ \delta_r\end{pmatrix} \qquad \textbf{(24)}$$

$$\dot{\eta} = A\eta + B\begin{pmatrix}\delta_p \\ \delta_r\end{pmatrix} \qquad \textbf{(25)}$$

Determine the minimum time

Estimation of the minimum time , $f_{t_{\min}}$, is obtained by the command of torsional input to create and observe the system response , rapidly. On the word, the minimum time to achieve the stable situation of the system should be such that the either deviation due to torsional incident command and observing the system response with maximum speed is possible.

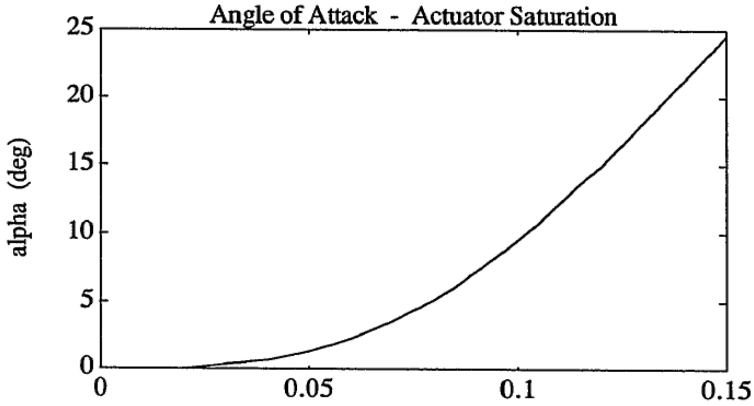

Figure 2. determination of $t_{f_{\min}}$ for a torsional Auto- pilot

Minimum time to achieve the desired attack angle of 20^0 is 0.14 s. In this position , the torsion rate is 312^0/s . It is obvious that $t_{f_{\min}}$ is considered as 0.14s so that the maximum torsion rate is conducted to the Ferrin point upper than the launch point .

$$\alpha_d = \begin{cases} \alpha_{d_f} \sin\omega t & 0 < t < t_f \\ \alpha_{d_f} & t \geq t_f \end{cases} \qquad (26)$$

$$\ddot{\alpha}_d = \begin{cases} \alpha_{d_f}\omega^2 - \alpha_{d_f}\omega^2 \sin\omega t & 0 < t < t_f \\ 0 & t \geq t_f \end{cases}$$

Where $\alpha = 20^0$ and $\omega = \dfrac{\pi}{2tf}$.

On the other hand, since $\ddot{\alpha} = u$, then:

$$\ddot{\alpha}_d - k(t)(\dot{\alpha} - \dot{\alpha}_d) - \lambda(t)\operatorname{sgn}(s) \qquad (27)$$

$$S = k(t)(\alpha - \alpha_d) + (\dot{\alpha} - \dot{\alpha}_d) \qquad (28)$$

Finding the control gain $\lambda(t)$ and control bandwidth $k(t)$ that presente the stable tracking and favor resistance, is difficult.

Now, we design a fuzzy controller and a PID controller and implement them on the torsional Auto- pilot and finally compare the results of the simulation. We will show the pereference of the fuzzy controller than PID controller.

Design the fuzzy controller

The aim of designing the fuzzy controllers is to use the suitable fuzzy system in the control law, which trace the reference path of the missile according to the motion equations of the missile.

$$\alpha_d = \begin{cases} \alpha_{d_f} \sin(\omega(t + t_f)) & t_f < t < 2t_f \\ 0 & t \geq 2t_f \end{cases} \quad (29)$$

$$\dot{\alpha}_d = \begin{cases} \alpha_{d_f} \cos(\omega(t + t_f)) & t_f < t < 2t_f \\ 0 & t \geq 2t_f \end{cases}$$

$$\ddot{\alpha}_d = \begin{cases} \alpha_{d_f} \omega^2 - \alpha_{d_f} \omega^2 \sin \omega t & t_f < t < 2t_f \\ 0 & t \geq 2t_f \end{cases}$$

For this purpose, we consider the control law for the missile motion;

$$u = \frac{1}{g}\left(-f + \alpha^{\cdot\cdot} - k(t)(\alpha - \alpha^{\cdot}) - \lambda(t) sat(s)\right) \quad (30)$$

By using the descent gradient in the control law, we can approximate the functions of f and g and bandwidth of k(t) by the fuzzy system. In all systems we use the 9 fuzzy rules, 6 Guassian functions, non-fuzzy average centers and inference engine. After designing the required fuzzy system to trace the reference path, we adjust the parameters of membership functions of fuzzy sets optimally by nervous- fuzzy networks (ANFIS). Nervous- fuzzy networks (ANFIS) regulates the parameters of the membership functions , automatically , by using the descent gradient method. By embedding these parameters in the membership functions, following results is obtained:

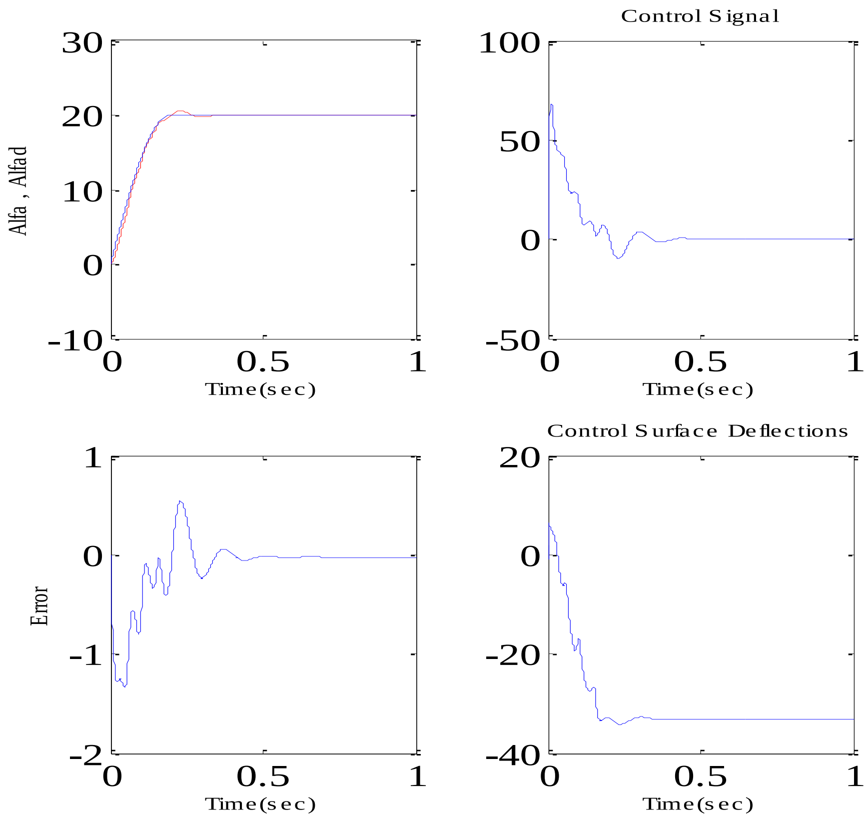

Figure 3. results of simulation by using the fuzzy controllers

Design PID controllers

To design PID controllers, we should define functions f and g and bandwidth k(t) in the control law as follows:

$$G(s) = k_p(1 + \frac{1}{T_i\ s} + T_d\ s) \qquad (26)$$

Then, by using the experimental method , we regular the defined PID controller parameters . The results of simulations are shown in figure 4.

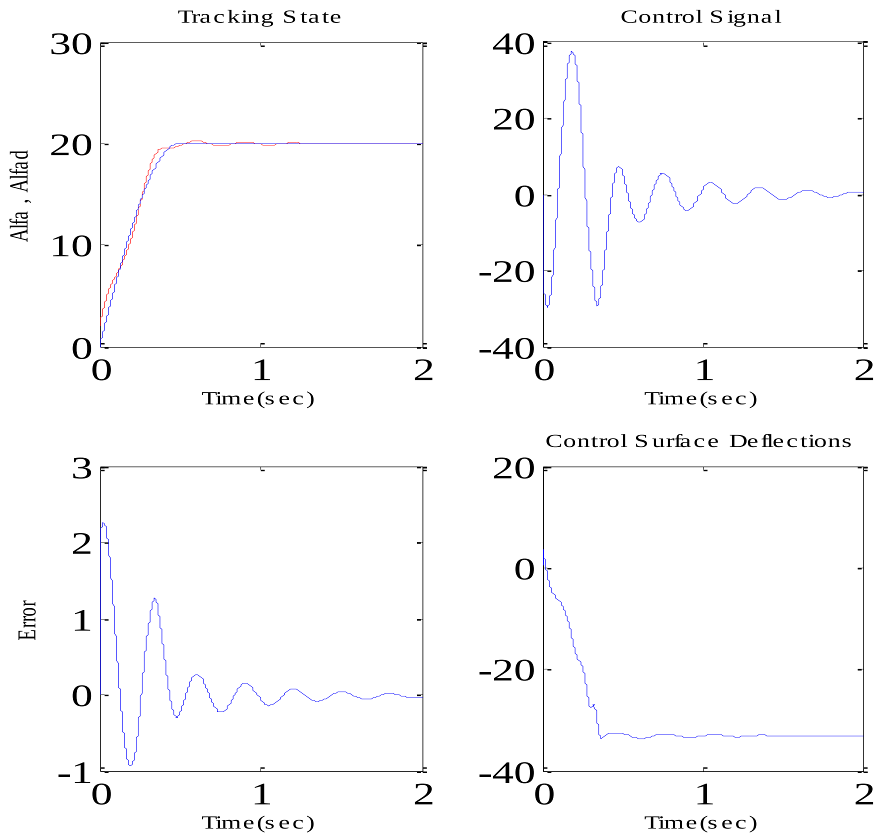

Figure 4. results of simulation by using PID controllers

CONCLUSION

By observing the simulation results, we easily see that the tracking speed of the fuzzy controller in more than PID controller. Also, in fuzzy controller, the oscillation phenomenon doesn't occur for input of torsional control surface δ_q until 0.3 s. While , in PID controller, the oscillation phenomenon doesn't occur for input of torsional control surface δ_q until 1.4 s. On the other hand, we observe in fuzzy controller that the state path diverges to a favorable angle of 20 degrees of the reference path in 0.4 second, approximately and track this path by the end. But , in PID controller, the state path diverges to a favorable angle of 20 degrees of the reference path in 1.6 second, approximately . The error diagrams show this , clearly. In the fuzzy method, the control signal is zero in 0.8 s, approximately . This shows low cost of control in this method, while the control signal constantly oscillates in PID method.based on the mentioned points, we can conclude the preference of the fuzzy controller than PID controller.

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