Eng. &Tech.Journal, Vol. 33,Part (A), No.3, 2015

Aircraft Pitch Control Using Type-2 Fuzzy Logic

Yamama A.Shafeek
Control and System Engineering Department, University of Technology/Baghdad.
Email:yam4bn@gmail.com

Received on:19/8/2014 & Accepted on:5/3/2015

ABSTRACT

Modern aircrafts design is tending to employ automatic control in their every part. In this paper, an autopilot is designed to control the pitch of an aircraft using both PD-like type-1 and type-2 fuzzy logic controllers. The flight system is exposed to atmospheric effects like wind speed, rain, temperature… etc, and noise from the system which affect the response. To test the effectiveness of the two controllers, three different cases are simulated; system without disturbance and system with slow and fast varying disturbances.

Keywords: Pitch control, Autopilot, Type-1 fuzzy logic control, Type-2 fuzzy logic control.

السيطرة على إنحدار الطائرة بإستخدام المنطق المضبب من النوع الثاني

الخلاصة

يميل تصميم الطائرات الحديثة إلى استخدام التحكم الأوتوماتيكي في كل جزء منها. يهدف هذا البحث إلى تصميم طيار آلي للسيطرة على زاوية إنحدار الطائرة باستخدام كل من مسيطر المنطق المضبب الشبيه بالمسيطر التفاضلي التناسبي من النوعين الأول والثاني. ولكون نظام الطيران معرضا للتأثيرات الجوية مثل سرعة الرياح والأمطار ودرجة الحرارة ... الخ بالإضافة إلى الضوضاء من النظام مما يؤثر على الإستجابة, تمت محاكاة ثلاث حالات مختلفة لإختبار فعالية وحدتي التحكم, نظام بدون ضوضاء ونظام بضوضاء تتغير بصورة بطيئة و أخرى سريعة التغير.

INTRODUCTION

A conventional aircraft has the usual control surfaces, namely ailerons, elevator, and rudder. The primary flying controls are part of the flight control system and are defined as the input elements moved directly by a human pilot to cause an operation of the control surfaces [1]. The main primary flying controls are roll, pitch, and yaw controls. They achieve the 3 basic rotations of an aircraft about x, y, and z axes, respectively. Where the origin is the center of mass, the x-axis points toward the front of the aircraft (longitudinal axis), the z-axis points down (vertical axis), and the y-axis is perpendicular to the x – z plane (lateral axis). Basically, the angles of ailerons, elevator, and rudder determine the roll, pitch, and yaw movements, respectively. **Yousif *et al*** (2010) [2] studied and analyzed the aircraft longitudinal and lateral motions.

https://doi.org/10.30684/etj.33.3A.12
2412-0758/University of Technology-Iraq, Baghdad, Iraq

An autopilot is an element within the flight control system; it is a pilot relief mechanism that assists in maintaining an attitude, heading, altitude, or flying to navigation or landing references. Disengagement of the autopilot does not prevent the aircraft from being operated safely [3]. The main purpose of autopilots is to stabilize the aircraft and return it to the desired flight attitude after any disturbance. In general, it may be said that if the period of oscillation inherent in an aircraft is 10 seconds or more, the pilot can adequately control or damp the oscillation, but if the period is 4 seconds or less, the pilot's reaction time is not short enough; thus, such oscillations should be well damped. The so-called "short period" pitch oscillations inherent in all aircraft fall into the category of a 4-second oscillation. However, in almost all jet fighter and jet transport aircraft artificial damping must be provided by an automatic system [4].

Fuzzy systems have been used in a wide variety of applications in engineering, science, business, medicine, and other fields. For instance, in engineering one of the most potential application areas is aircraft/spacecraft (flight control, engine control, avionic systems, failure diagnosis, navigation, and satellite attitude control) [5].

The Fuzzy Logic tool that was introduced in 1965 by Lotfi Zadeh is a mathematical tool for dealing with uncertainty. It provides a technique to deal with imprecision and information granularity. The uncertainty is found to arise from ignorance, from chance and randomness, due to lack of knowledge, from vagueness (unclear), like the fuzziness existing in our natural language. Lotfi Zadeh proposed the set membership idea to make suitable decisions when uncertainty occurs [6]. **Samir (2013) [7]** studied different tuning methods of fuzzy logic control for linear and nonlinear systems by. The tuning methods used are rules (RB), membership functions (DB), and combination of them called by combination of multi-stage (CMS) tuning method. Results showed that CMS-tuning method provides better results than DB or RB tuning methods by improving the steady state characteristics and performance indices of linear or nonlinear control system.

Type-2 fuzzy logic is a generalization of conventional type-1 fuzzy logic in the sense that uncertainty is not only limited to the linguistic variables but also is present in the definition of the membership functions. Type-1 fuzzy systems, whose membership functions are type-1 fuzzy sets, are unable to directly handle such uncertainties [8]. A type-2 fuzzy set is characterized by a fuzzy membership function, i.e., the membership grade for each element of this set is a fuzzy set in [0,1], unlike a type-1 set where the membership grade is a crisp number in [0,1]. Such sets can be used in situations where there is uncertainty about the membership grades themselves, e.g., an uncertainty in the shape of the membership function or in some of its parameters.

Unfortunately, type-2 fuzzy logic controllers (T2FLC) are computationally intensive. **Wu *et al*** (2006) [9] presented a simplified type-2 fuzzy logic controller that is suitable for real-time applications. The key idea was to only replace some critical type-1 fuzzy sets by type-2 sets.

Many researchers implemented fuzzy logic in controlling the pitch angle of aircraft system [10-14], where either proportional integral (PI), proportional derivative (PD), or proportional integral derivative (PID) like type-1 fuzzy logic were successfully used in system control. **Torabi *et al*** (2013) [15] had a comparative assessment between fuzzy and model predictive control (MPC) for a pitch control system of an aircraft system. The results obtained demonstrated that the effect of the disturbances in the system can successfully be handled by predictive controller. The design of

MPC gave acceptable response but less quality than that was given from Fuzzy controller.

In this paper PD-like type-2 fuzzy logic controller (T2FLC) is designed to control the aircraft pitch angle in the presence of disturbances. The system response is compared to that of the analogous PD-like type-1 fuzzy logic controller (T1FLC). The two systems are simulated using Matlab/Simulink R2010a.

Aircraft Pitch Equations

The aircraft equations of motion are derived by applying Newton's laws of motion, which relate the summation of the external forces and moments to the linear and angular accelerations of the system [4] (for detailed equations derivation refer to [1&4]).

Under certain assumptions, the nonlinear coupled differential equations of motion of an aircraft can be decoupled and linearized into the longitudinal and lateral equations. Pitch control is a longitudinal problem [16]. The basic coordinate axes and forces acting on an aircraft are shown in Figure (1):

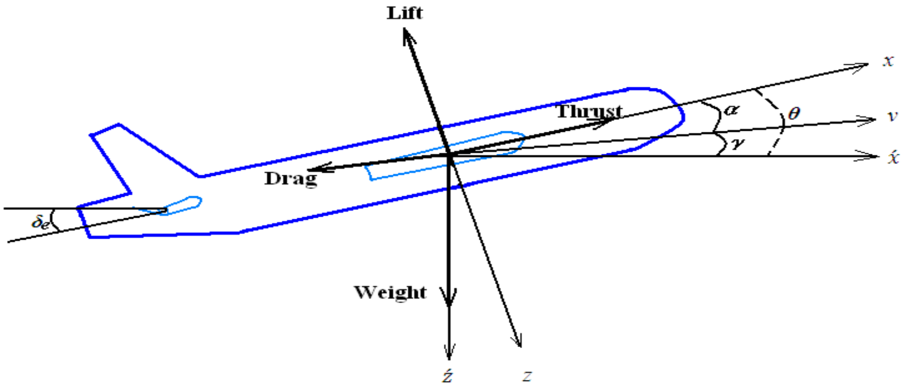


Figure (1) Basic coordinate axes and forces acting on an aircraft

In order to simplify the system equations, it will be assumed that; the aircraft is in steady-cruise at constant altitude and velocity; thus, the thrust and drag cancel out and the lift and weight balance out each other. Also, assume that change in pitch angle does not change the speed of an aircraft under any circumstance. So the longitudinal equations of motion of an aircraft can be written as [16]:

$$\dot{\alpha} = \mu\Omega\sigma\left[-(C_L + C_D)\alpha + \frac{1}{(\mu - C_L)}q - (C_W \sin\gamma)\theta + C_L\right] \qquad \ldots (1)$$

$$\dot{q} = \frac{\mu\Omega}{2i_{yy}}\{[C_M - \eta(C_L + C_D)]\alpha + [C_M + \sigma C_M(1 - \mu C_L)]q + (\eta C_W \sin\gamma)\delta_e\} \ldots (2)$$

$$\dot{\theta} = \Omega q \qquad \ldots (3)$$

Where:
$= \frac{\rho S \bar{c}}{4m}$, $= \frac{2U}{\bar{c}}$, $\sigma = \frac{1}{1 + \mu C_L}$, $\eta = \mu\sigma C_M$, and the other variables are as listed in Table (1).

Table (1) Model Variables

Variable	Meaning
α	Angle of attack
q	Pitch rate
θ	Pitch angle
δ_e	Elevator deflection angle
ρ	Density of air
S	Platform area of the wing
$\bar{c}$	Average chord length
m	Mass of the aircraft
U	Equilibrium flight speed
C_D	Coefficient of drag
C_L	Coefficient of lift
C_W	Coefficient of weight
C_M	Coefficient of pitch moment
γ	Flight path angle
i_{yy}	Normalized moment of inertia

It is required to get a transfer function that describes the model as pitch angle with respect to elevator deflection angle. Inserting data from Boeing's commercial aircraft into (1), (2), and (3), results in the following set of equations [16]:

$$\dot{\alpha} = -0.313\,\alpha + 56.7\,q + 0.232\,\delta_e \qquad \ldots(4)$$

$$\dot{q} = -0.0139\,\alpha - 0.426\,q + 0.0203\,\delta_e \qquad \ldots(5)$$

$$\dot{\theta} = 56.7\,q \qquad \ldots(6)$$

Taking the Laplace transform for (4), (5), and (6), produces the following equations:

$$s\,\alpha(s) = -0.313\,\alpha(s) + 56.7\,q(s) + 0.232\,\delta_e(s) \qquad \ldots(7)$$

$$s\,q(s) = -0.0139\,\alpha(s) - 0.426\,q(s) + 0.0203\,\delta_e(s) \qquad \ldots(8)$$

$$s\,\theta(s) = 56.7\,q(s) \qquad \ldots(9)$$

The transfer function of pitch angle related to the elevator deflection angle can be easily obtained from (7), (8), and (9) as:

$$\frac{\theta(s)}{\delta_e(s)} = \frac{1.151\,s + 0.1774}{s^3 + 0.739\,s^2 + 0.921\,s} \qquad \ldots(10)$$

Distinguishing Type-1 and Interval Type-2 Fuzzy Logic Systems

In classical logic, known as crisp logic, an element either is or is not a member of a set. That is, each element has a membership degree of either 1 or 0 in the set. In a fuzzy set, fuzzy membership values reflect the membership grades of the elements in the set [5]. Fuzzy sets model the properties of imprecision, approximation, or vagueness. The function μ(x) that maps x to [0, 1] is called a *membership function*. This membership function describes the certainty that an element of x, denoted$\tilde{x}$, maybe classified linguistically in the given fuzzy set. Figure (2) shows an example of a type-1 fuzzy membership function (Gaussian function) which is given by:

$$f(x,\sigma,c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \qquad \ldots(11)$$

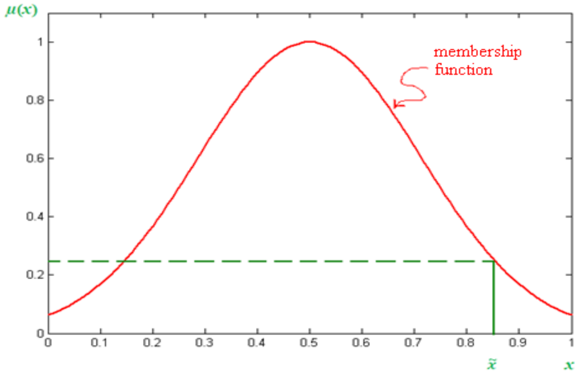


Figure (2) Type-1 fuzzy membership function

Where

x, c, and σ represent the input, center of peak, and standard deviation of the function, respectively. As can be seen in Figure (2), the membership grade of any specific value of x, say $\tilde{x}$ is a crisp number.

The type-1fuzzy logic system (T1FLS) block shown in Figure (3) is composed of [5]; a *rule-base* (a set of If-Then rules) which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control, an *inference mechanism* which emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant, a *fuzzification interface* which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules, and a *defuzzification interface* which converts the conclusions of the inference mechanism into actual inputs for the process.

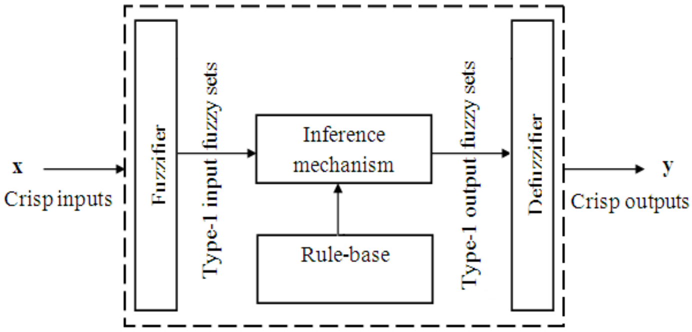


Figure (3) Type-1 fuzzy logic system [5]

Quite often, the knowledge that is used to build fuzzy system rules is uncertain. Such uncertainty leads to rules whose antecedents or consequents are uncertain, which translates into uncertain antecedent or consequent membership functions. T1FLSs, whose membership functions are type-1 fuzzy sets, are unable to directly handle such uncertainties. In interval type-2 fuzzy logic systems (IT2FLS), the antecedent or consequent membership functions are type-2 fuzzy sets. Such sets are fuzzy sets whose membership grades themselves are type-1 fuzzy sets; they are very useful in circumstances where it is difficult to determine an exact membership function for a fuzzy set [8]. The IT2FLS block diagram is shown in Figure (4).

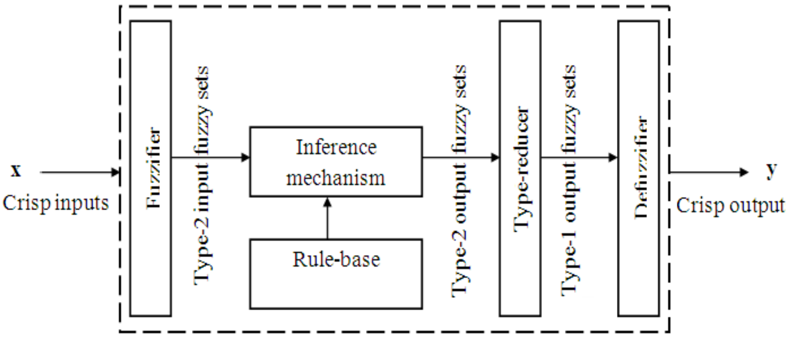


Figure (4) Interval type-2 fuzzy logic system [8]

In T1FLS, where the output sets are type-1 fuzzy sets, defuzzification is performed in order to get a number, which is in some sense a crisp (type-0) representative of the combined output sets. In the type-2 case, the output sets are type-2; so extended versions of type-1 defuzzification methods must be used. Since type-1 defuzzification gives a crisp number at the output of the fuzzy system, the extended defuzzification operation in the type-2 case gives a type-1 fuzzy set at the output. Since this operation takes us from the type-2 output sets of the fuzzy system to a type-1 set, this operation can be called *type reduction* and the type-1 fuzzy set so obtained is called a *type-reduced set*. The type-reduced fuzzy set may then be defuzzified to obtain a single crisp number [8].

Figure (5) shows an example of an interval type-2 fuzzy membership function. Here there are upper and lower membership functions given by:

$$f_{upper}(x,\sigma,m_1,m_2)=\begin{cases} e^{\frac{-(x-m_1)^2}{2\sigma^2}} & if\ x<m_1 \\ 1 & if\ m_1\le x\le m_2 \\ e^{\frac{-(x-m_2)^2}{2\sigma^2}} & if\ x>m_2 \end{cases} \qquad \ldots(12)$$

$$f_{lower}(x,\sigma,m_1,m_2)=\begin{cases} e^{\frac{-(x-m_2)^2}{2\sigma^2}} & if\ x\le \frac{m_1+m_2}{2} \\ e^{\frac{-(x-m_1)^2}{2\sigma^2}} & if\ x> \frac{m_1+m_2}{2} \end{cases} \qquad \ldots(13)$$

Where

$m_1,\ m_2$ are as indicated in Figure (5) and σ represents the standard deviation of the function.

Uncertainty in the primary memberships of a type-2 fuzzy set consists of a bounded region that is called the *footprint of uncertainty* (FOU). Mathematically, it is the union of all primary membership functions. This footprint of uncertainty can be obtained by projecting in two dimensions the three-dimensional view of the type-2 Gaussian membership function. Here, the membership grade of any specific value of x, say $\tilde{x}$ is not a crisp number; it is a fuzzy set [8]. **Ozek *et al*** [17] introduced an IT2FLS toolbox written in MATLAB programming language, the toolbox is very useful and used in the simulations of the control systems in this paper.

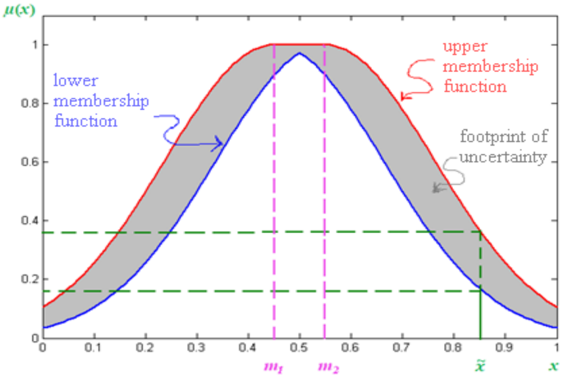


Figure (5) Interval type-2 fuzzy membership function

Controllers Development

The general aircraft pitch control system is shown in Figure (6), where disturbance is considered at plant input. PD-like fuzzy controller is a controller which takes the error and its derivative as inputs to the fuzzy system. In the following, a Mamdani type PD-like T1FLC, and Mamdani type PD-like T2FLC, are developed.

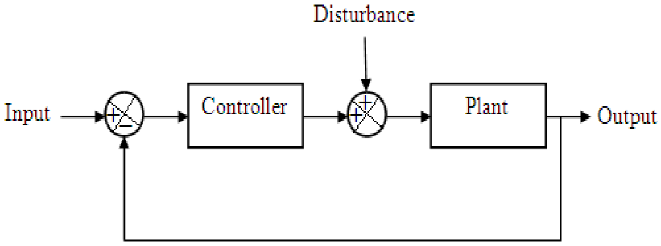


Figure (6) Control system

PD-like Type-1 Fuzzy Logic Controller

The PD-like fuzzy controller takes two inputs, error e(t) and derivative of error $\frac{d}{dt}$e(t) and has one output control action u(t), these inputs and output are called linguistic variables. The fuzzy sets of each input are represented by seven Gaussian membership functions (equ. 11) which are; Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). While the fuzzy sets of output are represented by three Gaussian membership functions which are; Negative (N), Zero (Z), and Positive (P). The range of values of the inputs that can be quantified with the fuzzy sets (universe of discourse) is [-1, 1] and of output is [-10, 10]. The membership functions of all linguistic variables are shown in Figure (7).

Minimum operator is used to represent the AND in rules premises and the implication and centroid method for defuzzification,

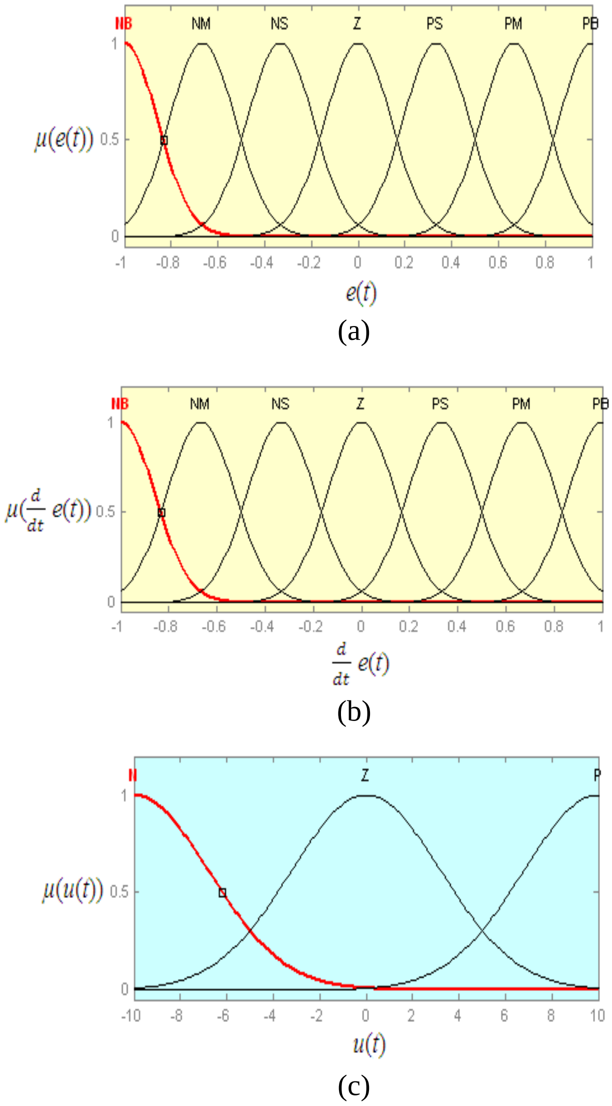


Figure (7) PD-like T1FLC membership functions for
(a) error (b) change of error (c) control action

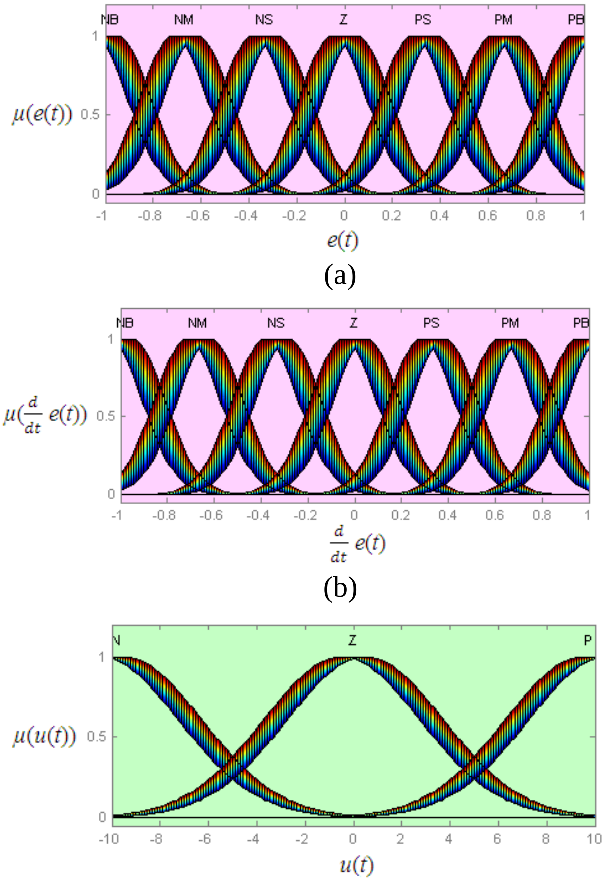
Conventionally, the number of rules = (number of fuzzy membership functions)$^{\text{number of fuzzy inputs}}$. Since the fuzzy system has two inputs each one with 7 membership functions then there will be 7^2 = 49 rule listed in Table (2). But since any input has some contribution in all of the fuzzy sets and will circle around the main diagonal of the fuzzy rule table and settle in the center of this table, recent researches [18] propose to use only the diagonal rules. So, the developed controller uses only the 7 diagonal fuzzy rules (highlighted with yellow color in Table (2)) to simplify the controller and reduce complex computations.

Table (2) Fuzzy rules table

$\frac{d}{dt}e(t)$ \ e(t)	NB	NM	NS	Z	PS	PM	PB
NB	N	N	N	N	N	N	Z
NM	N	N	N	N	N	Z	P
NS	N	N	N	N	Z	P	P
Z	N	N	N	Z	P	P	P
PS	N	N	Z	P	P	P	P
PM	N	Z	P	P	P	P	P
PB	Z	P	P	P	P	P	P

PD-like Type-2 Fuzzy Logic Controller

The T2FLC is to have the same specifications of the type-1 except that the membership functions are type-2 Gaussian functions (equ. 12 & equ. 13) as shown in Figure (8). Center of sets method is used for type reduction.



(c)

Figure (8) PD-like T2FLC membership functions for (a) error (b) change of error (c) control action

Simulation

The two developed controllers are simulated using Matlab/Simulink as in the block diagram in Figure (9). The reference input is a step of 0.2 rad desired pitch angle$\theta_d(s)$to simulate the change in pitch angle. The error $e(s)$ and its derivative $s\ e(s)$ are computed then multiplied by the gains K_p = 35 and K_d = 2.5, respectively which were tuned for the best response. The saturations are used to limit the fuzzy system inputs' minimum and maximum values to the range of their corresponding universe of discourse. The fuzzy controller decides the proper elevator deflection angle $\delta_e\ (s)$ to achieve the desired pitch angle$\theta_d(s)$. The response for disturbance free case (Figure (10)) shows that both controllers performs well and that the values of time response specifications for T2FLC are better than that of type-1 (faster and less overshoot and steady state error).

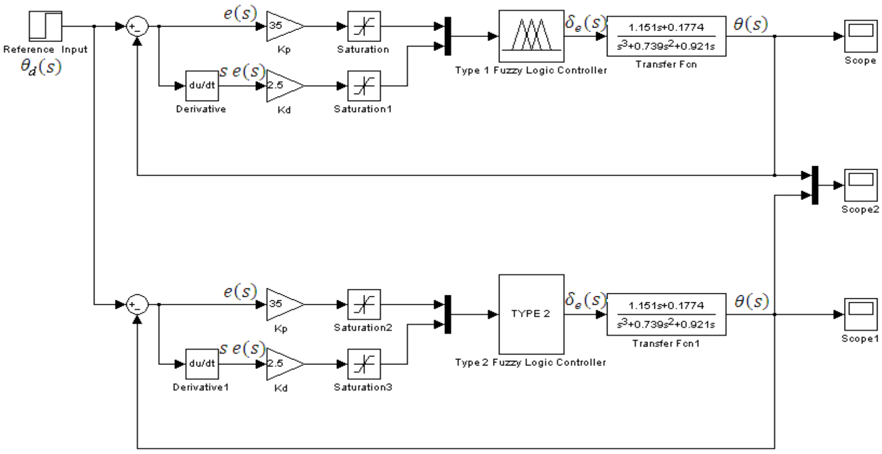


Figure (9) Block diagram of T1FLC and T2FLC system

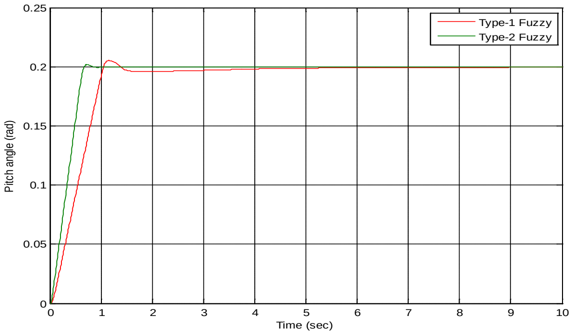


Figure (10) System response of T1FLC and T2FLC

To test controllers robustness for the model with disturbance applied at its input, two cases are considered; first a step disturbance which represent the disturbances that are of slow varying type (Figure (11)), second a random disturbance which represent the disturbances that are of fast change rate.

The response of the system with disturbance step (Figure (12)) equal to the input (0.2) at t=3 second is shown in Figure (13). The exact disturbance is applied to the two systems. In this case, T2FLC overcomes the applied disturbance with steady-state error e_{ss} = 0.0005 while the effect of disturbance in T1FLC response is obvious with e_{ss} = 0.0056. Table (3) summarizes all performance specifications of the system response of the two controllers for all the tested cases. The percentage overshoot M_p% in this case of T1FLC equals 0 as in the Table. This is because in calculations the final steady-state value θ_{ss} = 0.2053 (affected by disturbance) equals the peak valueθ_{max}, while in T2FLC response θ_{max} = 0.202 (less than that of type-1). This is clearly seen in Figure (13).

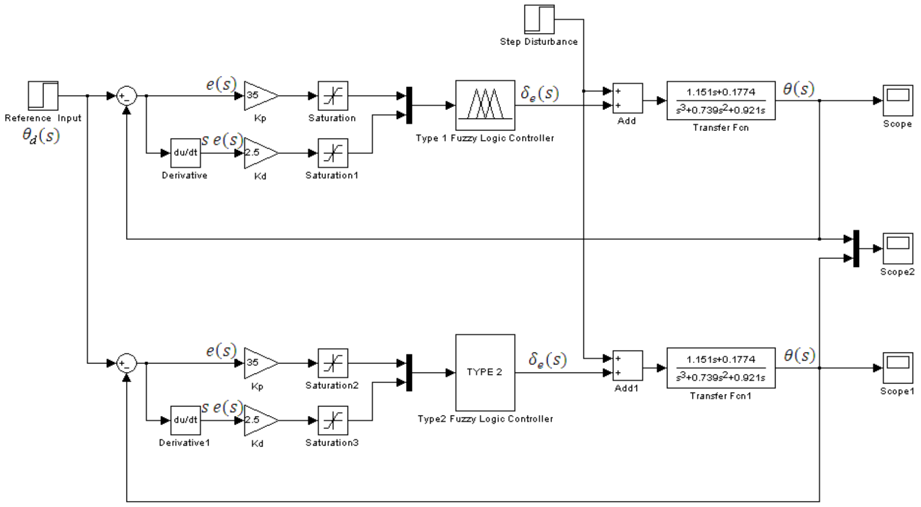


Figure (11)Block diagram of T1FLC and T2FLC system with step disturbance

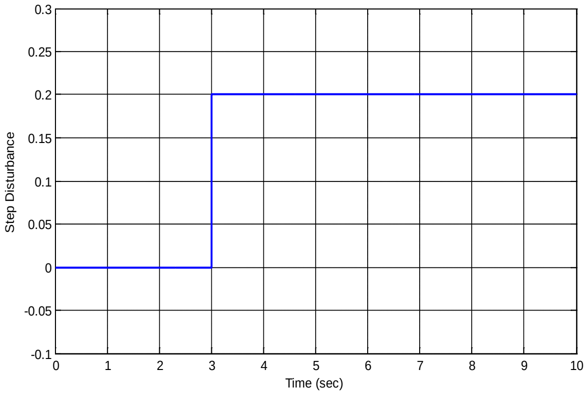


Figure (12) Applied step disturbance

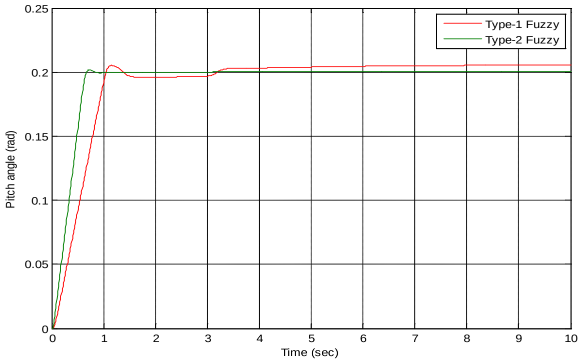


Figure (13) System response of T1FLC and T2FLC with step disturbance

The block diagram of the system with random noise is the same as in Figure (11) except that the step disturbance is replaced with a random signal within the range ±0.5 (Figure (14)). The response for the system with disturbance random is shown in Figure (15). Again, type-2 fuzzy system performs better than type-1 by faster, smoother, and less affected by random disturbance response.

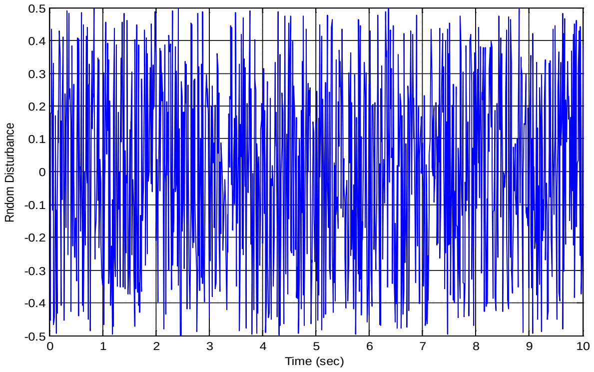


Figure (14) Applied random disturbance

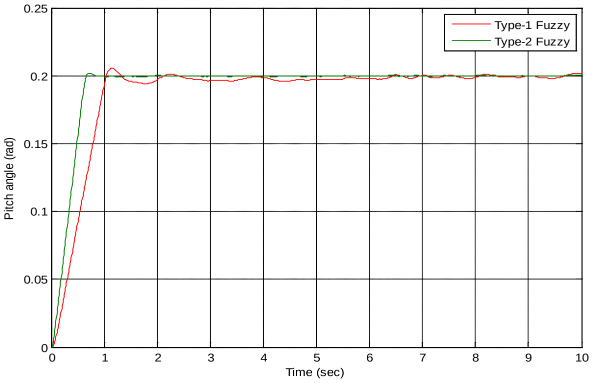


Figure (15) System response of T1FLC and T2FLC with random disturbance

Further examination of the results in Table (3) shows that the response speed (indicated by peak time t_p, delay time t_d, rise time t_r, and steady-state time t_s) is not much affected by disturbances.

CONCLUSIONS

In this paper, PD-like T1FLC and T2FLC were developed to control the pitch angle of aircraft. Each fuzzy system has only 7 rules (diagonal rules of conventional fuzzy system) instead of 49 to reduce computations in rule firing and defuzzification. To test systems' robustness, three cases were tested; the nominal system with no disturbance, step disturbance added to the model input, and random disturbance with different value. The time responses of T2FLC in all cases were better than that of type-1 in terms of steady-state error, maximum overshoot, rise time, settling time… etc. this is natural due to the presence of foot print of uncertainty in the membership functions of IT2FLS. Further step would be to use particle swarm optimization method (PSO) to determine the best values for membership functions' parameters (m_1, m_2, and σ) for the T2FLC.

Table (3) Time domain performance specifications for the response of the two controllers in three test cases

Performance Specific-ations / **Test Cases**		**Percentage overshoot M_p%**	**Peak time ts**	**Delay time ts**	**Rise time ts**	**Settling time t_s**	**Steady state errore_{ss}**
Disturbance Free	T1FLC	2.85	1.15	0.545	0.78	1.77	0.0004
	T2FLC	1.05	0.72	0.335	0.48	0.9	0.0001
Disturbance Step	T1FLC	0	1.16	0.56	0.8	1.77	0.0056
	T2FLC	0.74	0.72	0.34	0.48	0.9	0.0005
Disturbance Random	T1FLC	1.93	1.15	0.55	0.78	2.64	0.0017
	T2FLC	0.849	0.72	0.335	0.485	0.97	0.0002

REFERENCES

[1] Mclean, D., Automatic Flight Control Systems, Prentice Hall International Series in Systems and Control Engineering, 1990.

[2] Yousif, A. H., and U. S. Kazem., "Simulation of aircraft control using bond graph techniques and Matlab/Simulink software," Eng. & tech. Journal, vol. 28, no. 13, 2622-2637, 2010.

[3] Redling, T. J., "Integrated flight control systems: A new paradigm for an old art," IEEE Aerospace and Electronic Systems Society (AESS) Systems Magazine, 17-22, 2001.

[4] Blakelock, J. H., Automatic Control of Aircraft and Missiles, John Wiley & Sons, Inc., 1991.

[5] Passino, K. M. and S. Yurkovich Fuzzy Control, Addison-Wesley Longman, Inc., 1998.

[6] Sivanandam, S. N. S. Sumathi, and S. N. Deepa, Introduction to Fuzzy Logic using MATLAB, Springer-Verlag Berlin Heidelberg, 2007.

[7] Samir, A. G., “Multi-stages for tuning fuzzy logic controller (FLC) using genetic algorithm (GA),” Eng. & Tech. Journal, vol. 31, part (A), no. 6, 1166-1181, 2013.

[8] Castillo, O. and P. Melin, Type-2 Fuzzy Logic: Theory and Applications, Springer-Verlag Berlin Heidelberg, 2008.

[9] Wu, D. and W. W. Tan, “A simplified type-2 fuzzy logic controller for real-time control,” ISA Transactions, vol. 45, no. 4, 503–516, 2006.

[10] Narenathreyas, K., “Fuzzy logic control for aircraft longitudinal motion,” Master Thesis, Faculty of Electrical Engineering/ Department of Control Engineering/ Czech Technical University, 2013.

[11] Wahid, N. N. Hassan, M. F. Rahmat, and S. Mansor, “Application of intelligent controller in feedback control loop for aircraft pitch control,” Australian Journal of Basic and Applied Sciences, vol. 5, no. 12, 1065-1074, 2011.

[12] Deepa, S.N. and Sudha G, “Longitudinal control of an aircraft using artificial intelligence,” International Journal of Engineering and Technology, vol. 5, no. 6, 4752-4760, 2014.

[13] Torabi, A. A. A. Ahari, A. Karsaz, and S. H. Kazemi, “Intelligent pitch controller identification and design,” Journal of Mathematics and Computer Science, vol. 8, 113-127, 2014.

[14] Berenji, H. R. S. Saraf, P. Chang, and S. R. Swanson, “Pitch control of the space shuttle training aircraft,” IEEE Transactions on Control Systems Technology, vol. 9, no. 3, 542-551, 2001.

[15] Torabi, A. S. Salehi, A. Karsaz, and E. Tarsayi, “Predictive controller for pitch controller missile,” Journal of American Science, vol. 9, no. 7, 247-253, 2013.

[16] Control Tutorials for Matlab and Simulink, in web page, http://ctms.engin.umich.edu/CTMS/index.php?example=AircraftPitch&section=SystemModeling

[17] Ozek, M. B. and Z. H. Akpolat, “A software tool: Type-2 fuzzy logic toolbox,” Computer Application in Engineering Education, vol. 16, no. 2, 137-146, 2008.

[18] Al-Faiz, M. Z. and S. A. Sadeq, “Particle swarm optimization based fuzzy-neural like PID Controller for TCP/AQM router,” Intelligent Control and Automation, vol. 3, no. 1, 71-77, 2012.