Predictive Controller for Pitch Controller Aircraft

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Abstract: This paper exhibits a comparative assessment based on time response specification performance between fuzzy and Model predictive control (MPC) for a pitch control system of an aircraft system. The dynamic modeling of pitch control system is considered on the design an autopilot that controls the pitch angle. It starts with a derivation of suitable mathematical model to describe the dynamics of an aircraft. For get close to actual conditions. The white noise disturbance applied to the system. The performances of pitch control systems are investigated and analyzed based on common criteria of step's response in order to identify which control strategy delivers better performance with respect to the desired pitch angle. The design of MPC gave response less quality than that was given from Fuzzy controller but acceptable responses. Finally, it is found from simulation, predictive controller proposed gives the best performance compared to fuzzy controller.
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1. Introduction

Today's aircraft designs rely heavily on automatic control system to monitor and control many of aircraft's subsystem. The development of automatic control system has played an important role in the growth of civil and military aviation. Modern aircraft include a variety of automatic control system that aids the flight crew in navigation, flight management and augmenting the stability characteristic of the airplane.

To reduce the complexity of analysis, the aircraft is usually assumed as a rigid body and aircraft's motion consist of a small deviation from it is equilibrium flight condition [2].The pitch of aircraft is control by elevator which usually situated at the rear of the airplane running parallel to the wing that houses the ailerons. Pitch control is a longitudinal problem, and this work Gives on design an autopilot that controls the pitch of an aircraft. Autopilot is a pilot relief mechanism that assists in maintaining an attitude, heading, altitude or flying to navigation or landing references [3].

The combination of nonlinear dynamics, modeling uncertainties and parameter variation in characterizing an aircraft and its operating environment are the one major problem of flight control system. This work is attempted to Survey the control strategies required to address the complex longitudinal dynamic characteristics of such aircraft. Many the research works has been done in [4], [5], [6], [7] and [8], to control the pitch or longitudinal dynamic of an aircraft for the purpose of flight stability. This research is still remains an open issue in the present and future efforts [9].

In this paper used predictive controller to improve performance system.in the past paper, Disturbance effect haven't apply to system but in this paper it applied. The simulation results shown that the dynamic characteristics of control systems can be improved by this method.

Problem Statement

Control of dynamic systems with present day sophistication and complexities has often been an important research area due to the difficulties in modeling, nonlinearities, and uncertainties, particularly when there is a constant change in system dynamics. It is also known that the response of a dynamic nonlinear plant cannot be tracked into a desired pattern with a linear controller. Thus, a changing dynamic controller is important to control such a plant. [10]

Pitch is defined as a rotation around the lateral or transverse axis, which is parallel to the wings, and is measured as the angle between the direction of speed in a vertical plan and the horizontal line.

Changes of pitch are caused by the deflection of the elevator, which rises or lowers the nose and tail of the aircraft. When the elevator is raised (defined as negative value), the force of the airflow will push the tail down. Hence, the nose of the aircraft will rise and the altitude of the aircraft will increase. One of the targets of a pitch control system is to control or help a pilot to control an aircraft to keep the pitch attitude constant, that is, make the aircraft return to desired attitude in a reasonable length of time after a disturbance of the pitch angle, or make the pitch follow a given command as quickly as possible [11].

Modeling of a Pitch Control

This section provides a brief description on the modeling of pitch control longitudinal equation of aircraft, as a basis of a simulation environment for development and performance evaluation of the proposed controller techniques. The system of longitudinal dynamics is considered in this investigation and derived in the transfer function and states pace forms. The pitch control system considered in this work is shown in Figure 1 where X_b,Y_b and Z_b represent the aerodynamics force components. θ, Φ and $\delta_e$represent the orientation of aircraft (pitch angle) in the earth-axis system and elevator deflection angle.

The equations governing the motion of an aircraft are a very complicated set of six nonlinear coupled differential equations. Although, under certain assumptions, they can be decoupled and linearized into longitudinal and lateral equations. Aircraft pitch is governed by the longitudinal dynamics. In this example we will design an autopilot that controls the pitch of an aircraft. The basic coordinate axes and forces acting on an aircraft are shown in the figure given below.

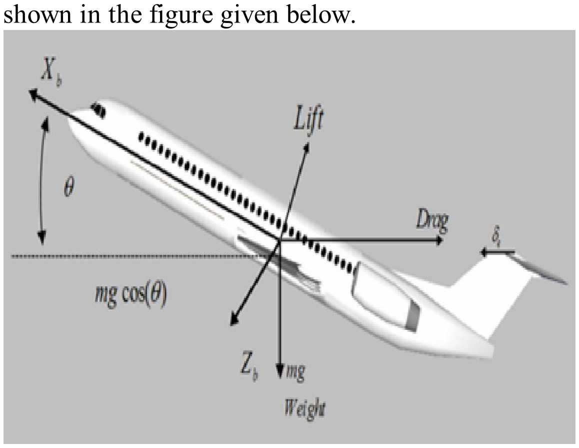

Figure 1. Description of pitch control system.

Figure 2 shows the forces, moments and velocity components in the body fixed coordinate of aircraft system. The aerodynamics moment components forroll, pitch and yaw axis are represent as L, M and N. The term p, q, r represent the angular rates about roll, pitch and yaw axis while term u, v, w represent the velocity components of roll, pitch and yaw axis. α and β are represents as the angle of attack and sideslip.

A few assumption need to be considered before continuing with the modeling process. First, the aircraft is steady state cruise at constant altitude and velocity, thus the thrust and drag are cancel out and the lift and weight balance out each other. Second, the change in pitch angle does not change the speed of an aircraft under any circumstance.

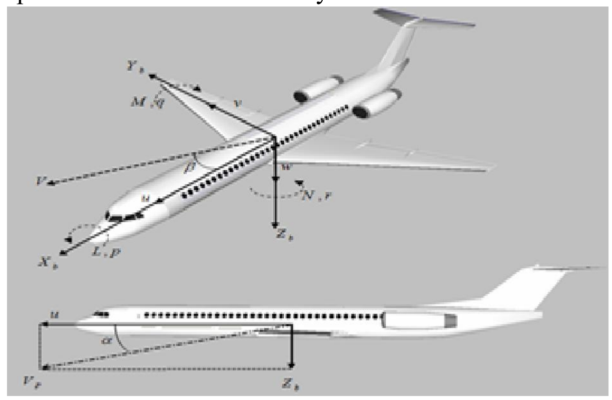

Figure 2: Definition of force, moments and velocity in body fixed coordinate.

Referring to the Figure 1 and Figure 2, the following dynamic equations include force andmoment equations are determined as shown in equation (1), (2) and (3). Referring to the Figure 1 and Figure 2, the following dynamic equations include force and moment equations are determined. The longitudinal stability derivatives parameter used are denoted in Table 1 [1].

Table1.Longitudinal Derivative Stability Parameters

	Components		
	Dynamics Pressure and Dimensional Derivative $Q = 36.8 lb/ft^2$,QS= 6771lb, QS c = 38596ft.lb, (c / $2u_0$) = 0.016s		
	Z-Force, (F^{-1})	Pitching Moment, (FT^{-1})	Pitching Moment, (FT^{-1})
Rolling velocities	$X_u = -0.045$	$Z_u = -0.369$	$M_u = -0.369$
Yawing velocities	$X_W = 0.036$ $X_{\dot{W}} = 0$	$Z_W = -2.02$ $X_{\dot{W}} = 0$	$M_W = -0.05$ $M_{\dot{W}} = 0$
Angle of attack	$X_\alpha = 0$ $X_{\dot{\alpha}} = 0$	$Z_\alpha = -355.42$ $Z_{\dot{\alpha}} = 0$	$M_\alpha = -8.8$ $M_{\dot{\alpha}} = -0.8976$
Pitching rate	$X_a = 0$	$Z_a = 0$	$M_a = -2.05$
Elevator deflection	$X_{\delta_e} = 0$	$Z_{\delta_e} = -28.15$	$M_{\delta_e} = -11.874$

$$X - mgs_\theta = m(\dot{u} + qv - rv) \quad (1)$$

$$Z + mgC_\theta C_\varphi = m(\dot{w} + pv - qv) \quad (2)$$

$$M = I_y\dot{q} + rq(I_X - I_Z) + I_{XZ}(p^2 - r^2) \quad (3)$$

It is required to completely solved the aircraft problem with considering the following assumption: (1) rolling rate $\rho = \dot{\Phi} - \dot{\psi}S_\theta$, (2) yawing rate,q= $\dot{\theta}C_\Phi + \dot{\psi}C_\theta S_\Phi$,(3)pitching rate, r= $\dot{\psi}C_\theta C_\Phi - \dot{\theta}S_\Phi$, (4) Pitch Angle, $\dot{\theta} = qC_\Phi - rS_\Phi$, (5) roll Angle, $\dot{\Phi} = p + qS_\Phi T_\theta + rC_\Phi T_\theta$ and (6) Yaw Angle,$\dot{\psi} = (qS_\Phi + r_\Phi)sec\theta$.

Equation (1), (2) and (3) should be linearized using small disturbance theory. The equations are replaced by a variable or reference value plus a perturbation or disturbance, as shown below.

$u = u_0 + \Delta u \qquad v = v_0 + \Delta u \qquad w = w_0 + \Delta w$

$p = p_0 + \Delta p \qquad q = q_0 + \Delta q \qquad r = r_0 + \Delta r$

$X = X_0 + \Delta X \qquad M = M_0 + MY \qquad Z = Z_0 + \Delta Z$

$\delta = \delta_0 + \Delta\delta$

For convenience, the reference flight condition is assumed to be symmetric and the propulsive forces are assumed to remain constant. This implies that, $v_0 = p_0 = q_0 = r_0 = \varphi_0 = w_0 = 0$. After linearization the (4), (5) and (6) are obtained.

$$\left(\frac{d}{dt} - X_u\right)\Delta u - X_w \Delta w + (g\cos\theta_0)\Delta\theta = X\delta_e \Delta\delta_e \quad (4)$$

$$-Z_u \Delta u + \left[(1 - Z_u)\frac{d}{dt} - Z_w\right]\Delta w - \left[(u_0 - Z_q)\frac{d}{dt} - \sin\theta_0\right]\Delta\theta = Z_{\delta e}\Delta\delta_e \quad (5)$$

$$-M_u \Delta u - \left(M_{\dot{w}}\frac{d}{dt} + M_w\right)\Delta w + \left(\frac{d^2}{d^2 t} - M_q \frac{d}{dt}\right)\Delta\theta = M_{\delta e}\Delta\delta_e \quad (6)$$

By manipulating the (4), (5), (6) and substituting the parameters values of the longitudinal stability derivatives, the following transfer function for the change in the pitch change in the pitch rate to the change in elevator deflection angle is shown as (7) obtained.

$$\frac{\Delta q(s)}{\Delta\delta_e(s)} = \frac{-(M_{\delta e} + M_{\dot{\alpha}} Z_{\delta e}/u_0)s - (M_\alpha Z_{\delta e}/u_0 - M_\alpha Z_\alpha/u_0)}{s^2 - (M_q + M_{\dot{\alpha}} + Z_\alpha/u_0)s + (Z_\alpha M_\alpha/u_0 - M_\alpha)} \quad (7)$$

The transfer function of the change in pitch angle to the change in elevator angle can be obtained from the change in pitch rates to the change in elevator angle in the following way.

$$\Delta q = \Delta\dot{\theta} \quad (8)$$

$$\Delta q(s) = s\Delta\theta(s) \quad (9)$$

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s}.\frac{\Delta q(s)}{\Delta\theta(s)} \quad (10)$$

Therefore the transfer function of the pitch control system is obtained in (11) and (12) respectively.

$$\frac{\Delta q(s)}{\Delta\delta_e(s)} = \frac{1}{s}.\frac{-(M_{\delta e} + M_{\dot{\alpha}} Z_{\delta e}/u_0)s - (M_\alpha Z_{\delta e}/u_0 - M_\alpha Z_\alpha/u_0)}{s^2 - (M_q + M_{\dot{\alpha}} + Z_\alpha/u_0)s + (Z_\alpha M_\alpha/u_0 - M_\alpha)} \quad (11)$$

Transfer function

To find the transfer function of the above system, we need to take the Laplace transform of the above modeling equations. Recall that when finding a transfer function, zero initial conditions should be assumed. The Laplace transform of the above equations are shown below. [20]

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1.151s + 0.1774}{s^3 + 0.739s^2 + 0.921s} \quad (9)$$

These values are taken from the data from one of Boeing's commercial aircraft.

The Design of Fuzzy Controller

Fuzzy control is based on the artificial experience. Therefore, for those control problems which can't be resolved by traditional methods can often be resolved by the fuzzy control technology. By the fuzzy control technology, it does not know the mathematical model of the plant and easy to control uncertain systems or nonlinear control systems and can restrain the strong disturbance.

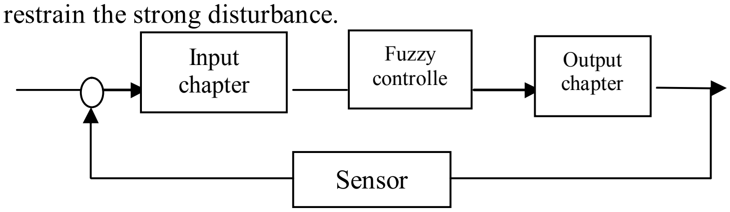

Figure 3. The basic structure of fuzzy control system [16]

The only difference is to control the device by fuzzy controller to achieve the desired performance. Fuzzy self-tuning PID controller is a conventional PID regulator based on the fuzzy set theory, under the absolute control error and deviation change and the absolute value of the rate, on-line automatically adjusting the proportional coefficient KP, integral coefficient of KI and differential factor KD of the fuzzy controller. Fuzzy controller is a nonlinear control device, using fuzzy reasoning algorithm. The sample data of the controlled process are taken as the clear amount of input to the controller, and then after input quantization factor calculation, are transferred into fuzzy values, so they can be used for fuzzy reasoning by fuzzy language and rules.

To the other part of process, the reasoning results are firstly transferred into clear values by anti-fuzzy inference and thus derive the control output with quantified factor calculation used as the control value for the controlled process. Based on the MATLAB fuzzy logic toolbox, the above control algorithm can be easily implemented [17].

Design of nominal fuzzy controller

In order to design the PID parameters based-on fuzzy controller, at first the simplest structure of two-input single output nominal fuzzy controller is given. At any given time instance n with a sampling time Ts, the two input variables of fuzzy controller, error state variable and error change are defined as

$e(n) = y(n) - r(n) \quad (12)$

$\Delta e(n) = e(n) - e(n-1). \quad (13)$

And its output variable u(n) is the control signal of process. Without loss the generality, the system is assumed to have r inputs denoted by the r-dimensional vector $U(KT)=[u_1(KT)......u_r(KT)]^T$ and s outputs denoted by the s-dimensional vector $y(KT)=[y_1(KT)-y_s(KT)]^T$. Most often the inputs to the fuzzy controller are generated by some function of the plant output y(KT)and reference input yr(kT). The inputs to the fuzzy controller are the error $e(KT)=[e_1(KT)-e_s(KT)]^T$ and changes in error $C(KT)=[C_1(KT)-C_s(KT)]^T$ defined as

$$e(kT) = y_r(kT) - y(kT) \quad (14)$$

$$c\,(kT) = \frac{yr\,(kT)\; - y\,(kT)}{T} \quad (15)$$

Where $e(kT) = y_r(kT) - y(kT)$ denotes the desired plant output is sample period.

For greater flexibility in fuzzy controller implementation, the universes of discourse for each plant input are normalized to the interval $[-1 \quad 1]$ by means of constant scaling factors. The gains g_e, g_c and g_u were employed to normalize the universe of discourse for the error e(kT) and changes in error c(kT), and controlleroutput u(kT) respectively.

With the plant input is generated from IF-THEN control rules of the form

If $\tilde{e}$ is $\tilde{E}_i$ and $\tilde{c}$ is $\tilde{C}_j$ then $\tilde{u}$ is $\bar{U}_l$

Where $\tilde{e}$ and $\tilde{c}$ denote the linguistic variables associated with controller inputs e and c respectively. $\tilde{u}$ denotes the linguistic variable associated with the controller output u, $\tilde{E}_i$ and $\tilde{C}_j$ denote the linguistic values respectively and $\tilde{U}_j$ denotes the consequent linguistic value[$i \in [1,m]$ $j \in [1,n]$ $l \in [1, m \times n]$.These are 49 rules that have been utilized as a closed-loop component in designing the FLC for maintaining pitch angle of aircraft system as defined in Table 2 [18].

Table2. Fuzzy control rules

e / Δe	NL	NM	NS	ZR	PS	PM	PL
PL	NS	ZR	PS	PM	PL	PL	PL
PS	NM	NS	ZR	PS	PM	PL	PL
ZR	NL	NM	NS	ZR	PS	PM	PL
NS	NL	NL	NM	NS	ZR	PS	PM
NM	NL	NL	NL	NM	NS	ZR	PS
NL	NL	NL	NL	NL	NM	NS	ZR

Implementation and results

In this section, the proposed of control schemes are implemented and the corresponding results are. The membership functions for error and control surface of fuzzy are shown as fig.7and8 respectively

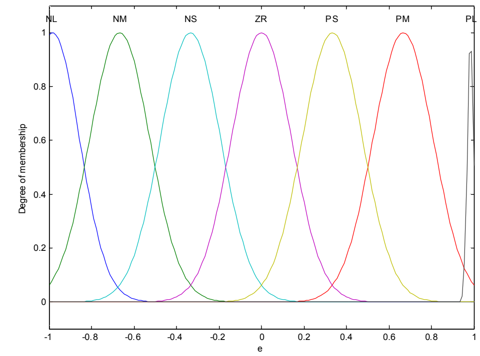

Figure 4. Membership function of input e and Δe.

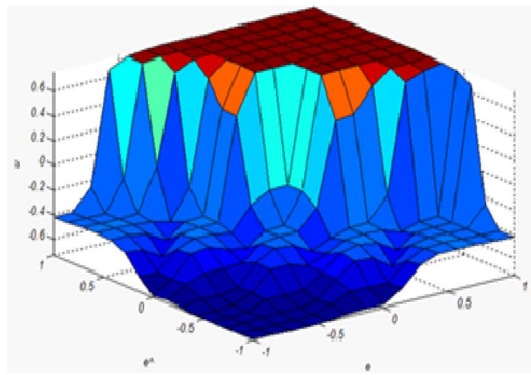

Figure 5. Control surface of fuzzy logic controller proposed.

2- Generalized Predictive Control Theory for Nonlinear Systems

The generalized predictive control approach gives an analytic solution for tracking problems of multivariable nonlinear systems in terms of a generalized predictive control performance index. A novel guidance law is developed in the following section by employing this algorithm. The generalized predictive control gives the approximation of the tracking error in the receding horizon by its Taylor-series expansion to any specified order. A closed-form optimal predictive controller is obtained by minimizing a quadratic performance index with integral action. On-line optimization is not required and stability of the closed-loop system is guaranteed. For more detail, the reader is referred to Refs. [11,12].Consider the nonlinear system

$$\begin{cases} \dot{x}(t) = f(x(t)) + g(x(t))u(t) \\ \qquad y(t) = h(x(t)) \end{cases} \quad (16)$$

Where $\in \Re^n$, $u \in \Re^m$ and $y \in \Re^m$ are the state, control and output vectors, respectively. It is assumed that each of the system output $y(t)$ has the same well-defined relative degree ρ, the output $y(t)$ and the reference trajectory $w(t)$ are sufficiently many times continuously differentiable with respect to *t* and the control order is chose to be *r*. The future output $y(t+\tau)$ is approximately predicted by its Taylor-series expansion up to order $\rho + r$, given by

$$y(t+\tau) \approx T(\tau)Y(t) \qquad (17)$$

$$\tau = diag\{\tau, \dots, \tau\} \qquad (18)$$

$$T(\tau) = \begin{bmatrix} I_{m\times m} & \tau & \cdots & \frac{\tau^{(\rho+r)}}{(\rho+r)!} \end{bmatrix} \qquad (19)$$

$$Y(t)=\begin{bmatrix} y \\ \dot{y} \\ \vdots \\ y^{(\rho)} \\ y^{(\rho+1)} \\ \vdots \\ y^{(\rho+r)} \end{bmatrix} - \begin{bmatrix} h \\ L_f h \\ \vdots \\ L_f^{\rho} h \\ L_f^{(\rho+1)} h \\ \vdots \\ L_f^{(\rho+1)} h \end{bmatrix} + \begin{bmatrix} 0_{m\times 1} \\ 0_{m\times 1} \\ \vdots \\ L_g L_f^{\rho} h.u \\ L_g L_f^{\rho} h.\dot{u} + p_1(u,x) \\ \vdots \\ L_g L_f^{\rho} h.u^{[r]} \\ +p_r(u,\dot{u},\cdots,u^{[r-1]},x) \end{bmatrix} \qquad (20)$$

Where L_f^{*}, L_g^{*} represent the Lie derivative with respect to *f* and *g*, P_i *is nonlinear in both* $u(t),\dots,u^{i+1}(t)$ *and* $x(t)$ *for* $i=1,\dots,r$.

In the moving time frame, the reference trajectory $w(t+\tau)$ is also approximated by the Taylor expansion of $w(t)$ up to $(\rho + r)$ th order, given by

$$w(t+\tau) \approx T(\tau)w(t) \qquad (21)$$

$$w(t)= \begin{bmatrix} w(t)^T & \dot{w}(t)^T & \cdots & w^{[\rho+1]}(t)^T \end{bmatrix}^T \qquad (22)$$

The receding-horizon performance index with built-in integral action is given by

$$J = \frac{1}{2}\int_0^T \big(y(t+\tau) - w(t+\tau)\big)^T \big(y(t+\tau) - w(t+\tau)\big) d\tau \qquad (23)$$

Where *T* is the predictive period. The actual control input *u(t)* given by the initial value of the optimal control input $u(t+\tau)$, $0 \le \tau \le T$, which minimizes the performance index by setting $\frac{\partial J}{\partial u} = 0$,is described as

$$u(t) = -\left(L_g L_f^{\rho-1} h(x)\right)^{-1}\left(KM_p + L_f^{\rho} h(x) - w^{[\rho]}(t)\right) \qquad (24)$$

Where $M_p \in R^{mp}$ is given by

$$M_p = \begin{bmatrix} h(x) - w(t) \\ L_f h(x) - \dot{w}(t) \\ \vdots \\ L_f^{\rho-1} h(x) - w^{[\rho-1]}(t) \end{bmatrix} \qquad (25)$$

K$\in R^{m\times mp}$ is the first rows of matrix $T_{rr}^{-1}T_{pr}$ which are the submatrices of $T(\tau)$, given by

$$T(\tau) = \begin{bmatrix} T_{\rho\rho} & T_{\rho r} \\ T_{\rho r} & T_{rr} \end{bmatrix} \qquad (26)$$

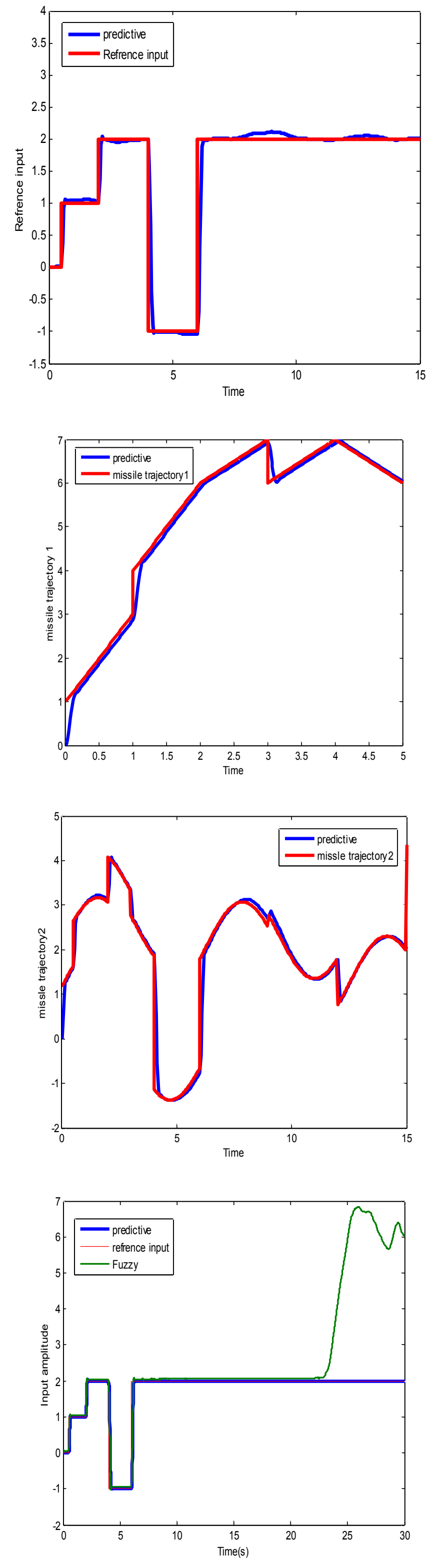

Figure 6: comparing between predictive controller with reference input, two missile trajectory and fuzzy controller

As we can see, the optimal predictive control law (26) is a nonlinear time invariant state feedback law. The control gain K is constant, which only depends on the predictive time T, the control order *r, and the relative degree* ρ.

Simulation

The proposed control schemes have been implemented within simulation environment in Matlab and Simulink. In the previous section, the controllers were introduced which used to control the processes. As expected, controller fuzzy in compare with other controllers despite the severe disturbance on pitch system (caused by severe storms, rainy weather, etc .) had the desirable step response. Severe disturbances (means high amplitude disturbance) to proof the robustness of the fuzzy controller has been applying on pitch system. Performance of the control schemes has been evaluated in term of time domain specification.

Conclusion

A new control approach to pitch-rate command tracking off lighter aircraft has been proposed in this paper. Modeling is done on an aircraft pitch control and predictive controller is proposed successfully. The proposed control schemes have been implemented within simulation environment in Matlab and Simulink. Performance of the control schemes has been evaluated in term of time domain specification. The results obtained, demonstrate that the effect of the disturbances in the system can successfully be handled by predictive controller. MPC controller with constraints will be developed and able to compensate for constraints that represent physical limits of actuators in pitch angle. The design of MPC gave response less quality than that was given from Fuzzy controller but acceptable responses.

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