AIAA Guidance, Navigation, and Control Conference and Exhibit
5-8 August 2002, Monterey, California

AIAA 2002-4646

AIAA-2002-4646

PID and Fuzzy Logic Pitch Attitude Hold Systems for a Fighter Jet

Dr. DAVID E. BOSSERT, Lt Col, USAF*
US Air Force Academy

Dr. KELLY COHEN, Lt Col, Israeli Ministry of Defense %
Visiting Researcher, US Air Force Academy

Abstract

This paper describes the design of fuzzy logic pitch attitude hold systems for an F-4 fighter jet under a variety of performance conditions that include approach, subsonic cruise and supersonic cruise. It expands the work from a previous paper on the same subject by adding more diverse plant cases, PID controller comparison, and an improved fuzzy logic design. The response is compared to both a conventional gain designed through classical root-locus techniques as well as to PID control. In addition, the design is tested for an F-4 in the approach condition, then with a 50% reduction in both longitudinal stability and pitch damping, and finally subsonic and supersonic cruise conditions. The different cases allow analysis of the off-design performance characteristics, or fault-tolerant capabilities, for the fuzzy logic and proportional gain controllers. Results show that a 25-rule fuzzy logic controller outperforms the conventional controllers in terms of settling time, peak value, and steady state error for a step response in all cases. However, the conventional controllers have a slightly faster rise time in all cases. The effectiveness of a fuzzy logic controller shows potential for application to other autopilot control modes in lieu of conventional gains. One fuzzy logic controller can be used for the entire flight envelope, including some moderate aircraft degradation conditions.

* Assoc Prof of Aeronautics, US Air Force Academy; Member AIAA
% Visiting Researcher, US Air Force Academy

Introduction

Many modern aircraft such as the F-22 possess fly-by-wire flight control systems, which allows for implementation of not only stability augmentation for dynamic performance but also implementation of autopilot modes. In addition, with the proliferation of autonomous unmanned aerial vehicles (UAVs), autopilot modes have become very important. Modern control laws allow for the design of robust controllers which have the potential to be effective for multiple flight conditions, including degraded performance due to partial aircraft failure.

There has been some research on modern control for aircraft and UAVs. Atkins at the University of Michigan has done work on developing a fixed wing autonomous UAV called the Solus with a focus toward fault detection, isolation, and recovery [1]. In addition, Ozimina at the Naval Research Lab has implemented a variable proportional and rate feedback scheme for small unmanned aircraft [2]. Snell at the University of California has investigated robust longitudinal control design using Quantitative Feedback Theory (QFT) [3] and Bossert at the US Air Force Academy has examined QFT for pitch attitude hold systems [4]. Also, Steinberg did an excellent comparison of intelligent, adaptive and non-linear flight control laws [9].

Other work by Fujimoro at Shizuoka University analyzed gain-scheduled control using fuzzy logic based on linear matrix inequalities to implement a full-order observer-based flight control [5]. Another example for modern flight control is the design of automatic landing systems using mixed H_2/Hinf control [6]. Other modern control techniques applied to flight control are nonlinear control [7] and neural networks [8]. Steinberg [9] compares in

Table 1- Plant Cases

Flight Condition	Transfer Function
Approach	3361 s^2 + 1357 s + 102.2 -- 230.6 s^5 + 2508 s^4 + 2161 s^3 + 1406 s^2 + 63.04 s + 32.01
Approach, 50% Deg Cma, Cmq	3361 s^2 + 1372 s + 105 -- 230.6 s^5 + 2472 s^4 + 1731 s^3 + 744.8 s^2 + 36.92 s + 16
F4 Subsonic Cruise	9.99e004 s^2 + 5.105e004 s + 623.4 --- 877.6 s^5 + 9884 s^4 + 1.82e004 s^3 + 7.114e004 s^2 - 61.19 s - 114.1
F4 Supersonic Cruise	1.3e005 s^2 + 2.183e004 s - 31.29 --- - 1742 s^5 + 1.83e004 s^4 + 3.553e004 s^3 + 2.677e005 s^2 + 1247 s + 123.9

simulation six different nonlinear control laws for multi-axis control of a high performance aircraft and reported that the fuzzy logic control system had remarkably stable performance across the envelope for a fixed controller, though it was rarely the best performer due to its slow convergence to zero steady-state error.

In this paper, we develop a fuzzy logic based control strategy that overcomes the above problem by providing rapid convergence to steady-state error without compromising on stability and performance robustness for a wide range of flight conditions. The layout of this paper is to define the F-4 plant models, and then the pitch attitude hold control scheme. Next, the root locus and PID designs for the baseline case of an F-4 on approach are presented. Next, the design of the fuzzy logic controller is presented and compared to the root-locus design. Finally, design observations and conclusions are presented.

PLANT MODELS

An F-4 fighter jet in the approach condition is chosen for its challenging dynamics. The baseline approach condition is sea level and Mach = 0.26. All plant models include actuator dynamics modeled as 10/(s+10), or an actuator with a time constant of 0.1 seconds. To investigate fault tolerance, several degraded variants of this basic flight condition were examined as well [10]. Specifically, a 50% reduction in the following derivatives: static longitudinal stability derivative, $C_{m\alpha}$, and the pitch damping derivative, C_{mq}. In addition two more flight conditions are considered, namely, subsonic and supersonic cruise. This plant set consists of marginally stable and unstable cases, and presents an interesting control challenge. The plant transfer functions are summarized in Table 1.

To show the variation of the plant dynamics, the four plant cases are plotted in Figure 1.

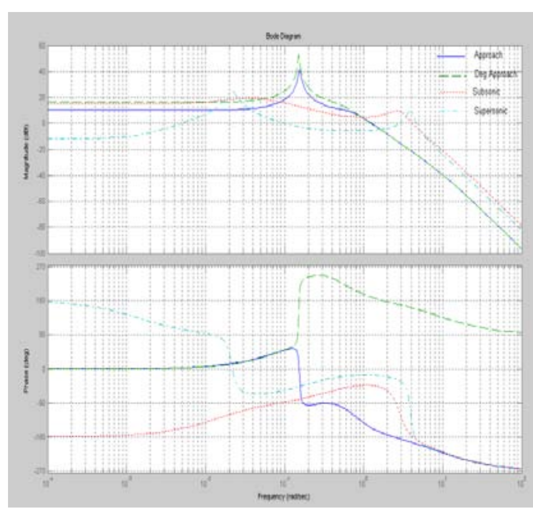

Figure 1 - Bode Plots for the Four Plant Cases

Note the variation in plant dynamics and the unstable plant for the case where both C_{mq} and $C_{m\alpha}$ are degraded. For a classical control feel, the pole-zero map for the different plant cases is shown in Figure 2.

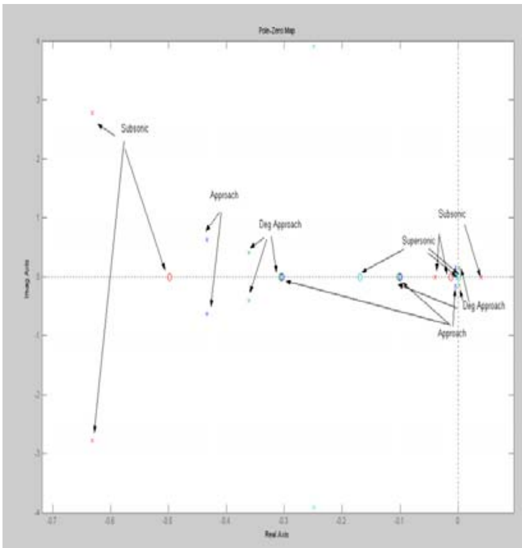

Figure 2 – Pole Zero Map for four Plant Cases

The plant characteristic which makes closed loop design difficult is the location of a zero close to the origin (-0.1) along the real axis coupled with a complex pair of poles near the imaginary axis. One of the poles will invariable be drawn to the zero close to the origin, which results in a slow mode. The subsonic cruise is for an F-4 at 35,000 feet at M=0.9, while the supersonic cruise occurs at 55,000 feet at M=1.8. These represent most of the flight envelope for an F-4, as well as cases when there is moderate degradation in the aircraft dynamics.

PITCH ATTITUDE HOLD CONTROL SCHEME

The simplest way to implement a pitch attitude hold control system is to use the setup of Figure 3 where the pitch angle is simply fed back to the reference command and the error signal fed to the elevator through a controller [11]. Additionally, an inner loop which feeds back pitch rate is added for the PID and fuzzy controllers to increase the damping of the poles closest to the origin before closing the outer loop. Furthermore, for the PID controller an inner integrator is also added

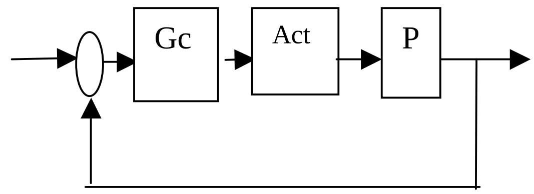

Figure 3 – Basic Pitch Attitude Hold System

BASIC ROOT-LOCUS AND PID DESIGN

Root-locus design is a classical design technique uses a single gain chosen by closing the feedback loop, as shown in Figure 3. The design is accomplished using the MATLAB root-locus tool which allows analysis of closed loop response as the gain varies [13]. The gain was varied until the "best" response to a step input was achieved. The definition of "best" in this case was lowest steady-state error, fastest rise time, and fastest settling time. For the single loop case, a gain of 0.5 is chosen. The PID design was based on the following gains:
$K_P = 5.80$; $K_I = 0.47$; $K_D = 2.85$

The gain for the root locus design was obtained by using the MATLAB root locus tool. The gain was varied and the time response examined for the design plant case iteratively until an acceptable balance between rise time, settling time, overshoot, and steady state error was achieved. The PID gains were tuned starting from the best root locus gain, and then the 3 gains were iteratively changed after looking at the time response for the design plant case. When the "best" response as described in the previous paragraph was obtained, the PID tuning was complete.

FUZZY LOGIC DESIGN

The pitch attitude hold systems for an F-4 fighter jet comprises a lightly damped second-order system. Cohen, Weller and Ben-Asher [14] propose an effective means of controlling such systems by introducing a variable damping strategy, which is realized by a fuzzy logic algorithm. The main advantages of using a fuzzy approach are the relative ease and simplicity of implementation and the robustness characteristics. The parameters of the fuzzy controller may be adapted to provide fairly fast control for large deviations, of the measured state of the plant from the desired state, and a minor amount of control for small deviations.

The successful implementation of a fuzzy logic controller depends, among other design aspects, on the heuristic rule base from which control actions are derived. In order to obtain the required heuristic physically-based insight, a single DOF system based on optimal control theory was analytically examined, to observe the characteristics of a minimum time solution [14]. Based on this analysis, Cohen, Weller and Ben-Asher [14] introduced a fuzzy logic non-linear mapping function, which has the potential of being a universal approximator to emulate the above minimum time solution. The resulting rule base is the core of the control law that is applied to all the current application.

This approach has been applied to vibration suppression of flexible structures [15] and for active suppression of aircraft cabin noise that is induced by structure borne vibration [16]. Furthermore, the above method has been demonstrated experimentally on smart structures at the Technion [17]. The Fuzzy Logic design was accomplished using MATLAB [18]. A typical layout of a fuzzy logic controller is shown in Figure 4.

POSITIVE, SMALL POSITIVE, ZERO, SMALL NEGATIVE and NEGATIVE. The respective membership functions for the inputs / output parameters are obtained after a tuning process. The fuzzy adaptation strategy is based on rules of the form "if...then..." that convert inputs to a single output, i.e. conversion of one fuzzy set into another.

Heuristic rules based on previous experience [14-17] are coupled with fuzzy reasoning whereby *large* values of the inputs require a *lightly* damped system, which would provide quick rise times. However, when the plant state is in the vicinity of the desired state, the damping factor is *large* to reduce the overshoot and steady state error. The Rule-Base, presented in Table 2, describes a set of 25 rules. A typical rule may be read as: If theta_error is **Negative** *and* theta_rate is **Positive**, then elevator deflection is SMALL NEGATIVE.

In the next step, all the output values, obtained by clipping or scaling, are then brought together to form the final output membership function. After evaluation of the propositions, the output values represented are unified to produce a fuzzy set incorporating the solution variable. This unification of outputs of each rule,

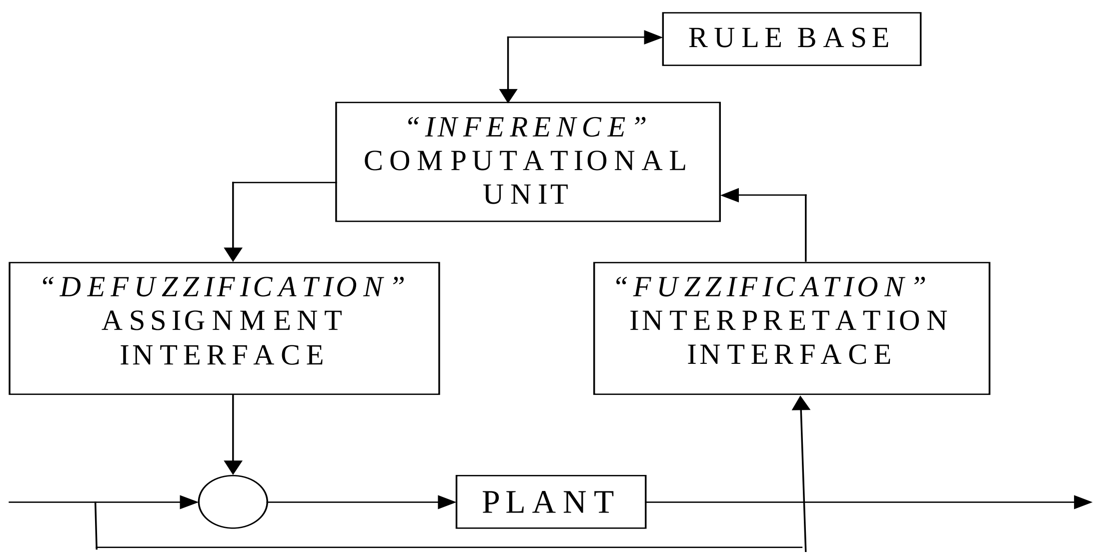

Figure 4 - Typical Fuzzy Logic Controller

The fuzzy controller is implemented as a 25-rule Mamdani Fuzzy system with 2 inputs and 1 output. The two inputs are theta_error and theta_rate, and the output is elevator deflection. Five membership functions are used to describe each of the input and output parameters, namely,

referred to as *aggregation*, occurs only once for each output variable. The aggregation process is always comprised of a commutative method. In this effort, the method applied is the *Bounded*

Table 2 - Fuzzy Logic Rule Base

	theta_error **Negative**	theta_error **Negative Small**	theta_error **Zero**	theta_error **Positive Small**	theta_error **Positive**
Theta_rate **Positive**	SMALL NEGATIVE	SMALL NEGATIVE	NEGATIVE	NEGATIVE	NEGATIVE
Theta_rate **Positive Small**	SMALL POSITIVE	SMALL NEGATIVE	SMALL NEGATIVE	SMALL NEGATIVE	NEGATIVE
theta_rate **Zero**	POSITIVE	SMALL POSITIVE	ZERO	SMALL NEGATIVE	NEGATIVE
Theta_rate **Negative Small**	POSITIVE	SMALL POSITIVE	SMALL POSITIVE	SMALL POSITIVE	SMALL NEGATIVE
Theta_rate **Negative**	POSITIVE	POSITIVE	POSITIVE	SMALL POSITIVE	SMALL POSITIVE

SUM (simply the sum of each rule's output set having an upper bound of 1). Applying the *sum* to the rule base given Table 2, the union of the fuzzy sets for the same output variable is taken to reach the respective aggregation of the output.

Finally, in order to reach a practical controller a control action comprising of a single numerical value is required. Therefore, the space of the fuzzy damping factor, obtained using the method described in the previous section, is mapped into a non-fuzzy space (crisp) in a process known as defuzzification. There are various strategies aimed at producing a crisp value. Herein, the center of area (COA) scheme is adapted.

The response of the fuzzy logic pitch attitude hold system, the PID controller and the root-locus gain to a step input for an F-4 in the approach condition is shown in Figure 5. In all of the following plots, the fuzzy controller is a solid line, the PID control is a dot-dash line, and the root-locus gain controller is a solid line with "+" marks. The performance of all controllers for all plant cases is summarized in Table 3. This is the design condition, and when compared to the root-locus design, the other two controllers have a lower settling time, lower peak value, and less steady state error. The fuzzy controller does have a slightly slower rise time, though. It is important to note that additional further fine-tuning of the fuzzy logic controller may further improve the closed-loop performance. The response of the three controllers for the case where both pitch damping and static longitudinal stability are decreased by 50% is tested. The open loop plant is unstable in this case. Table 3 shows the same trends with the fuzzy and PID controller showing robustness characteristics. Next, the three controllers are tested for the case where the aircraft at subsonic cruise. Figure 6 shows that same trends for the design condition, except that the settling time is drastically improved for the fuzzy logic controller. Next, the response of the controllers to the supersonic cruise condition is shown in Figure 7. Once again, the same trends of lower settling time, lower peak value, and lower steady state error are present.

Table 3 – Time Response Summary

Case	Ts (s)	Tr (s)	Tp (s)	Mp (Deg)	FV (Deg)
Root Locus F4 Approach (Design Condition)	23.6	1.09	3.14	1.09	.62
PID F4 Approach (Design Condition)	7.08	1.27	4.98	1.023	1.00
Fuzzy F4 Approach (Design Condition)	1.65	1.68	1.74	1.013	1.00
Root Locus 50% Red in Cmα and Cmq	25.8	1.16	3.57	1.42	.77
PID 50% Red in Cmα and Cmq	8.0	1.03	1.35	1.045	1.01
Fuzzy 50% Red in Cmα and Cmq	1.66	1.69	1.75	1.014	1.00

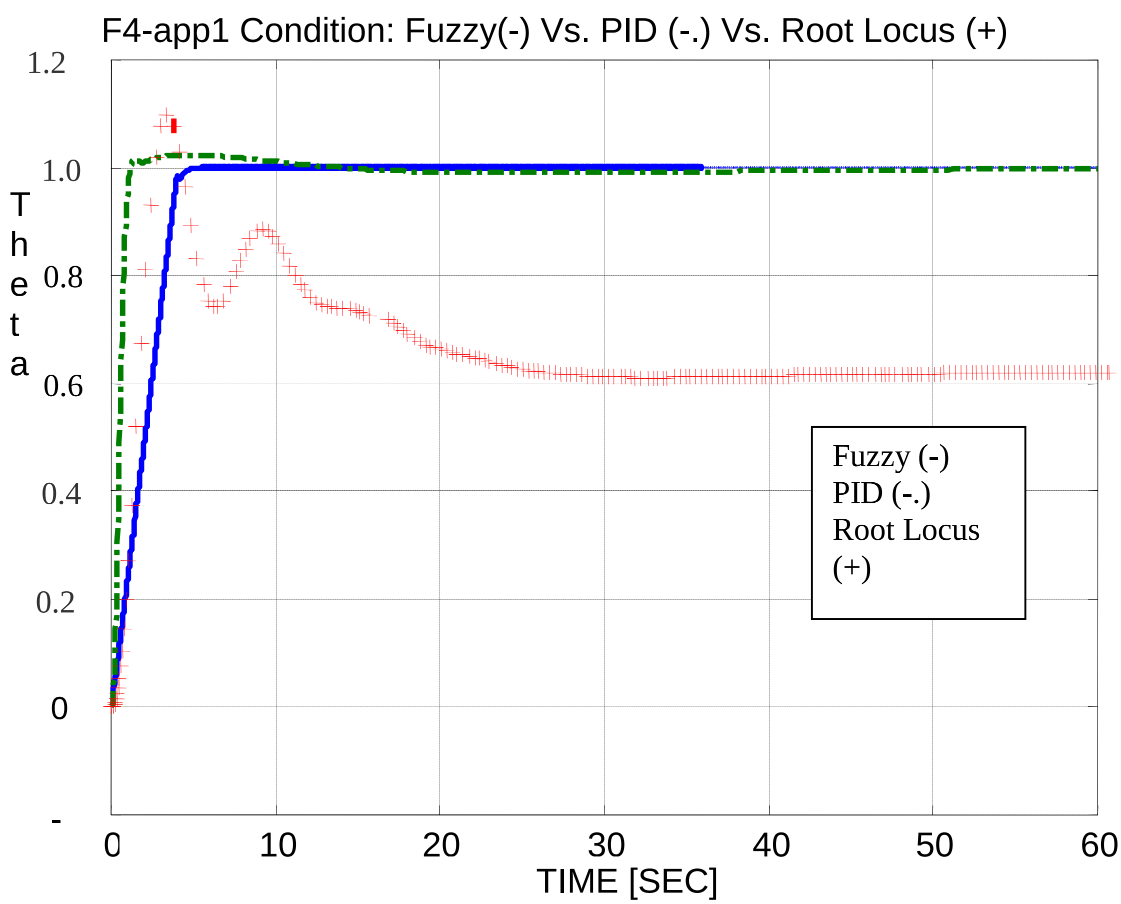

Figure 5 – F-4 Approach (Design condition)

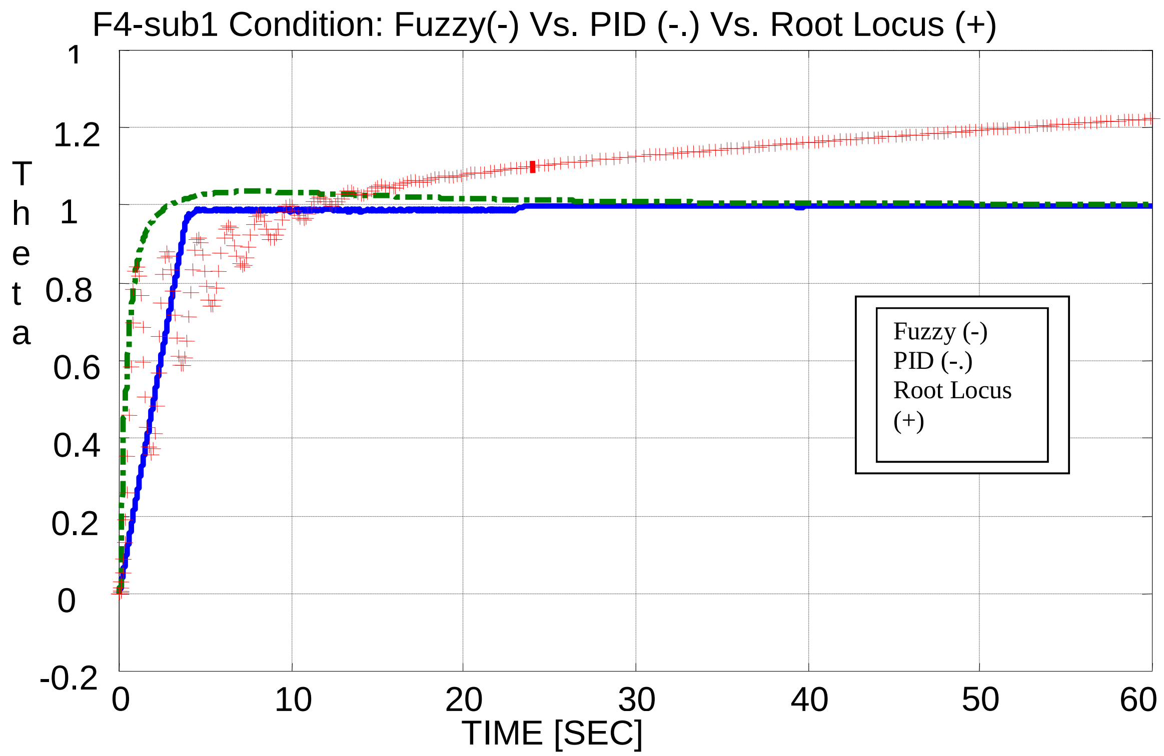

Figure 6 – F-4 Subsonic Cruise

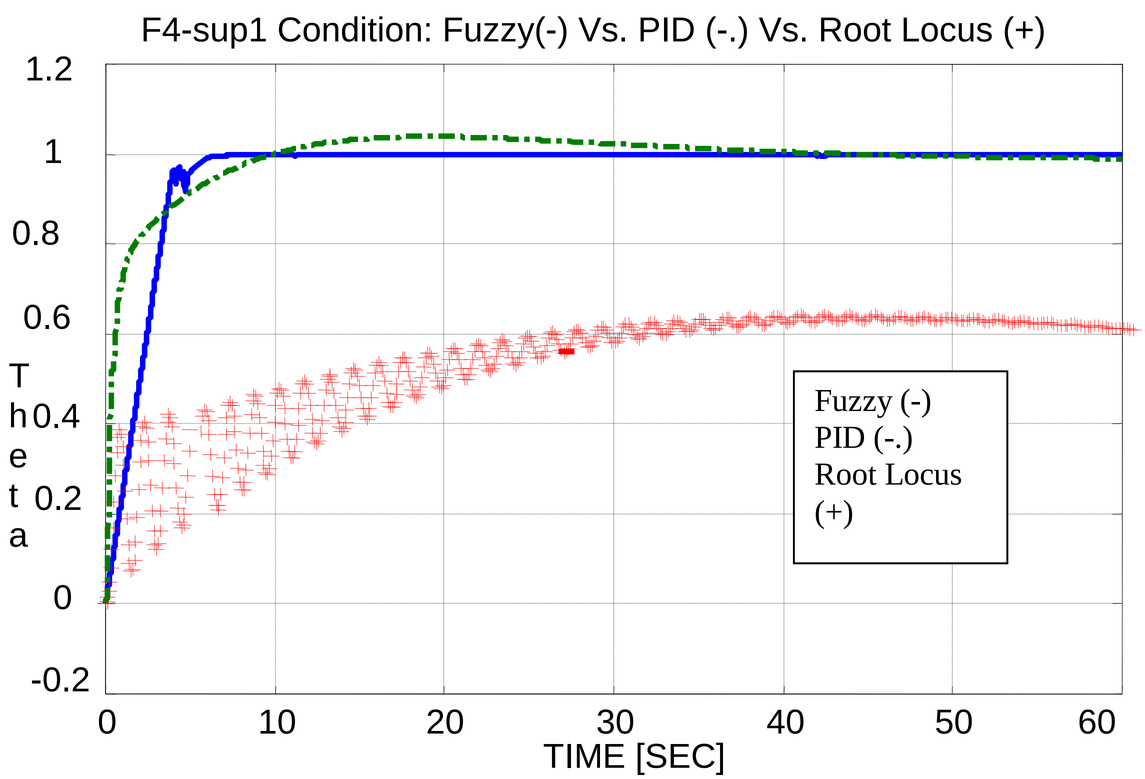

Figure 7 – F-4 Supersonic Cruise

DESIGN OBSERVATIONS

One of the key objectives of this series of articles on comparison of flight control techniques is to provide observations on the design process as well as the performance. The amount of time taken to design the root-locus constant gain controller and the PID controller was less (a couple of hours as opposed to a couple of days) than the fuzzy logic controller. In terms of implementation complexity, the constant gain controllers would be easier to implement. However, the PID control requires integration for the Integral part which is not needed for the fuzzy controller making it more computationally efficient. The results have shown that the fuzzy approach has provided rapid convergence of the steady-state error as opposed to the findings of Steinberg [9].

CONCLUSIONS

Pitch attitude hold systems were designed using a constant gain approach (PID as well as Root Locus) as opposed to a variable gain approach based on fuzzy logic control. The controllers were tested for robustness for very different conditions i.e. Subsonic cruise and Supersonic cruise. The fuzzy logic controller provided better performance than the PID controller by having a lower settling time and a lower peak value. However, the PID controller offers quicker rise times. The Root Locus design was by far the more inferior. This effort shows that fuzzy logic controllers may be an attractive alternative for pitch attitude hold systems.

Future work will examine higher order robust controllers implementing pitch attitude hold systems. Also, fuzzy controllers for other autopilot applications will be examined. Eventually, all the controllers will be compared against each other by implementation on an engineering flight simulator at the US Air Force Academy.

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