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Longitudinal Stability Augmentation using a Fuzzy Logic based PID Controller

Andrew Vick and Kelly Cohen – *Department of Aerospace Engineering, University of Cincinnati, P.O. Box 0070, Cincinnati, Ohio 45221*

Abstract— **We develop a PID based fuzzy logic pitch attitude hold system for a typical fighter jet under a variety of performance conditions that include approach, subsonic cruise and supersonic cruise. In this approach, the gains found in a classic PID controller are replaced with fuzzy systems, still contributing the overall effects of a proportional, integral, and derivative controller. The response is compared to conventional 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 for all flight conditions, the fuzzy PID controller was able to perform comparably to the conventional controller, while exhibiting faster rise times.**

Keywords-fuzzy logic control; stability augmentation system; pitch attitude hold system; robust control

I. Introduction

Many modern fighter aircraft are designed with no or little inherent stability and when coupled with a fly-by-wire flight control system enable enhanced maneuverability most essential in combat. A stability augmentation system (SAS) is a control system coupled to pilot handling which brings about an improvement in the inherent aircraft handling qualities in light of the above mentioned marginal/unstable aircraft. Moreover, there is a growing demand for 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. Wang and Stengel apply stochastic robust nonlinear control approach to a highly nonlinear complex, the high-incidence research aircraft model [1]. In addition, Ozimina implemented a variable proportional and rate feedback scheme for small unmanned aircraft [2]. Snell investigated robust longitudinal control design using Quantitative Feedback Theory (QFT) [3] and Bossert examined QFT for pitch attitude hold systems [4]. Fujimoro 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 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. Bossert and Cohen have examined Fuzzy Logic Pitch Attitude Hold systems for fighter jets as well [10, 11].

The main contribution of this research effort is to apply a fuzzy logic PID controller, as described by Chen and Pham [12] as well as an indigenous alternative approach, in handling steady-state error based on just error and rate of error measurements for an F-4 attitude hold system. The layout of this paper is to define the F-4 plant models, and then the pitch attitude hold control scheme. Then, the design of the fuzzy logic controller is presented and compared to the conventional PID design. Finally, design observations and conclusions are presented.

II. 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}. This plant set consists of marginally stable and unstable cases, and presents an interesting control challenge. In addition, two more flight conditions are considered for robustness testing, namely, subsonic and supersonic cruise [11]. Note the variation in plant dynamics and the unstable plant for the case where both C_{mq} and $C_{m\alpha}$ are degraded. 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. The plant characteristics for the robustness testing are provided in Table 1.

III. FUZZY LOGIC PID CONTROL DESIGN

A basic layout of this type of fuzzy logic controller is illustrated in Figure 1. As shown, the fuzzy logic controller uses the error signal as well as the error rate as inputs, and generates an appropriate gain for the current conditions. This type of approach shows some potential advantages over a classic PID controller, where the gains are fixed for all operating conditions.

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

Table 1. Plant Cases for Robustness Testing

The fuzzy logic based approach allows for the flexibility to decrease the derivative controller gain for large error inputs, providing a fast response, and increase the contribution to reduce overshoot and add damping when the error signal is low in magnitude. Similar logic can be applied to the other two components, tuning them depending on the given input conditions for selective performance improvements.

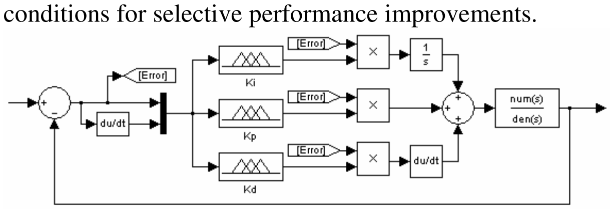

Figure 1. Basic Layout of Fuzzy PID Controller

In order for this type of approach to be implemented, a fuzzy rule base needs to be selected. To begin, the rule bases proposed by Chen and Pham [12] for a stable second-order plant were utilized for the system under consideration here. Tables 2, 3, and 4 illustrate the rule bases in tabular format for the proportional (Kp), integral (Ki), and derivative (Kd) controller gains respectively.

ė e	NB	NS	ZE	PS	PB
NB	VB	VB	VB	VB	VB
NS	B	B	B	MB	MB
ZE	ZE	ZE	MS	S	S
PS	B	B	B	MB	VB
PB	VB	VB	VB	VB	VB

Table 2. Rule Base For Proportional Gain

ė e	NB	NS	ZE	PS	PB
NB	M	M	M	M	M
NS	S	S	S	S	S
ZE	MS	MS	ZE	MS	MS
PS	S	S	S	S	S
PB	M	M	M	M	M

Table 3. Rule Base For Integral Gain

ė e	NB	NS	ZE	PS	PB
NB	ZE	S	MB	MB	VB
NS	S	B	MB	VB	VB
ZE	M	MB	MB	VB	VB
PS	B	VB	VB	VB	VB
PB	VB	VB	VB	VB	VB

Table 4. Rule Base For Derivative Gain

With the rule bases established, the membership functions for the output gains of the individual fuzzy controllers can be adjusted until acceptable performance is realized. As a starting point for the membership functions, the gains found for the classic PID controller, described in [12], were contained within the span of the output membership range, as this was a known stable point for all flight conditions. From the previous study into fuzzy logic for this application [12], one point that was noted was even though the fuzzy system provided lower settling time and lower peak values; it was still inferior in terms of rise time as compared to the PID controller. Therefore, a focus of this study was to try to obtain comparable or improved rise times over the classic PID controller using a fuzzy approach. The membership functions were modified through repetitive testing to meet this goal.

IV. RESULTS AND DISCUSSION

The step response for the approach flight condition is illustrated below in Figure 2. Notice the quick rise time in the fuzzy PID system for this condition, slight faster than the conventional PID system. While the overshoot is slightly higher and settling time longer for the fuzzy PID system, with some additional membership function tweaking the performance could be further improved. This case was merely meant to serve as a proof-of-concept for the fuzzy PID system achieving rise times comparable to a conventional system.

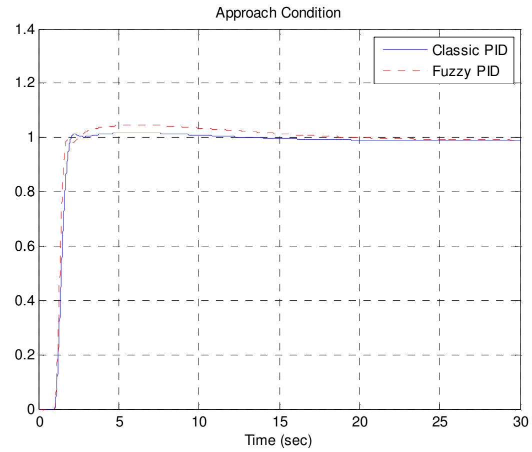

Figure 2. Step Response for Approach Condition

The step responses to the other flight conditions are shown in figures 3 - 5. For these cases, note the fuzzy PID controller still provides for a stable response, while maintaining the quick rise time that was focal to the design.

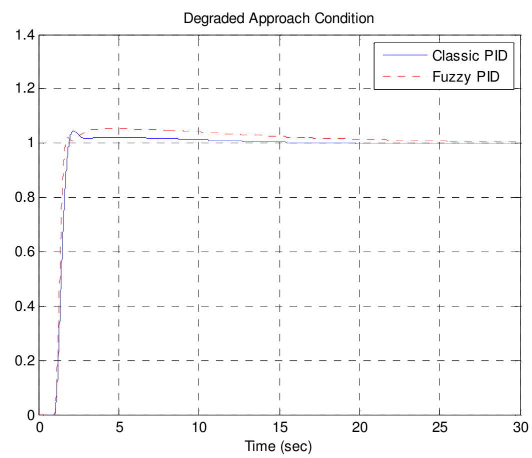

Figure 3. Step Response for Degraded Approach Condition

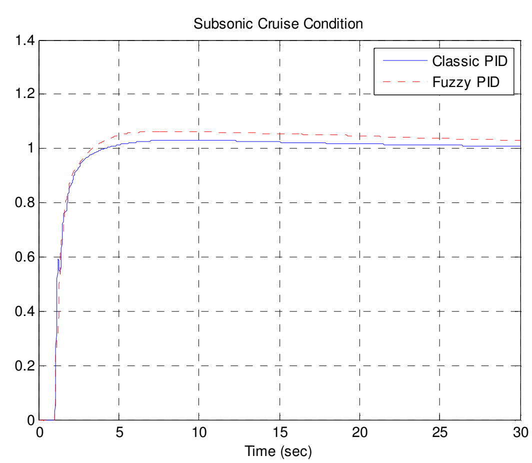

Figure 4. Step Response for Subsonic Cruise Condition

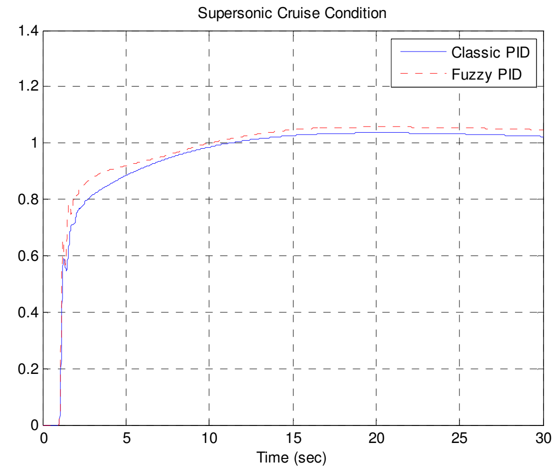

Figure 5. Step Response for Supersonic Cruise Condition

At this point, it pays to make a special note on the fuzzy rule bases used to obtain these results. Looking at the rule bases proposed by Chen and Pham [12] in Tables 2-4, it could easily be seen that these rule bases are non-symmetric. The corresponding output fuzzy set for certain positive conditions would not be the same for the corresponding negative condition. Therefore, the system will exhibit different behavior in response to negative step inputs, even though the transfer function characterizing the plant is the same. Figures 6 - 9 illustrate the step response for the four flight conditions for a negative step input. The approach and degraded approach conditions now have significantly larger overshoots, and undesirable oscillations in the cruise conditions.

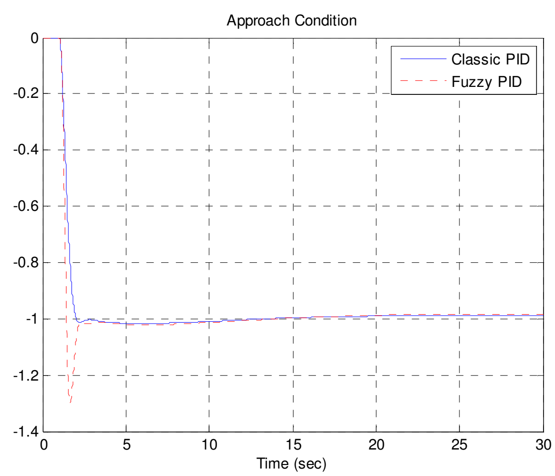

Figure 6. Negative Step Response for Approach Condition

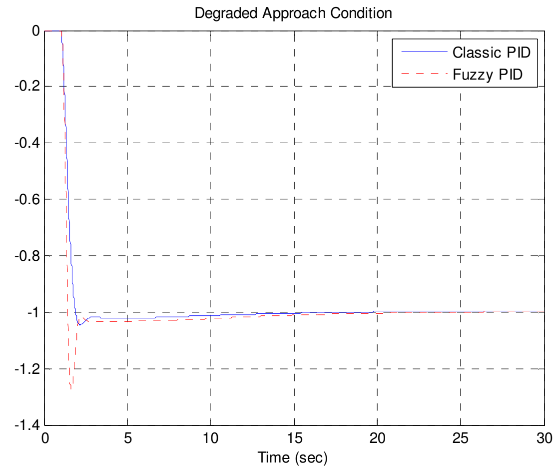

Figure 7. Neg. Step Response for Deg. Approach Condition

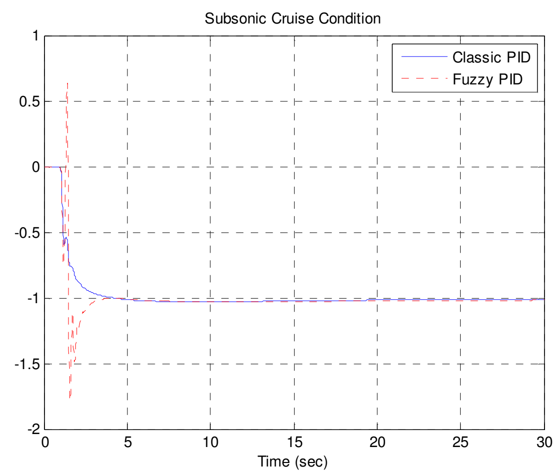

Figure 8. Neg. Step Response for Subsonic Cruise Condition

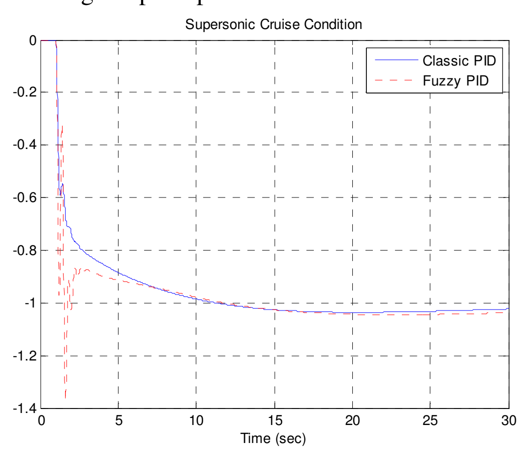

Figure 9. Neg. Step Response for Supersonic Cruise Condition

It goes without saying that this type of behavior would not be appreciated by pilots, who would basically have to learn two sets of handling characteristics for the aircraft. In fact, this point can be generalized to operators in many different scenarios, who would expect and even demand similar performance characteristics in different directions when the plant is governed by the same transfer functions. Therefore, while these rule bases may yield satisfactory results for the simple second-order case examined in the text, it cannot be generalized for higher-order, more complex applications.

In order to avoid this scenario, the solution is simple; implement a symmetric rule base. A system that would yield the same outputs for both negative and positive input conditions would provide similar system responses, only differing in sign. For this study, only the proportional and derivative gain rule bases were updated; it was deemed updates to the integral rule base would have marginal improvements compared to the other cases. For a proportional controller, it is desired to have a large gain when the error is large, to reduce the error as quickly as possible. At lower error readings, the gain can be tapered, helping to reduce the resulting overshoot. For the derivative controller, the opposite is true: the gain should be largest when the error is small, working to reduce the overshoot and drive the oscillations out of the response. Using these basic principles, the rule bases shown in Tables 5 and 6 were developed. Notice these rule bases are inverted from each other, sharing similar structure while meeting the demands of the system.

ė e	NB	NS	ZE	PS	PB
NB	VB	MB	B	MB	VB
NS	MB	S	MS	S	MB
ZE	B	MS	ZE	MS	B
PS	MB	S	MS	S	MB
PB	VB	MB	B	MB	VB

Table 5. Symmetric Rule Base For Proportional Gain

ė e	NB	NS	ZE	PS	PB
NB	ZE	MS	S	MS	ZE
NS	MS	B	MB	B	MS
ZE	S	MB	VB	MB	S
PS	MS	B	MB	B	MS
PB	ZE	MS	S	MS	ZE

Table 6. Symmetric Rule Base For Derivative Gain

With these rule bases in place, the membership functions can be tuned again to provide acceptable responses to inputs in each of the flight conditions. The step responses for each of the flight conditions are illustrated in Figures 10 - 13.

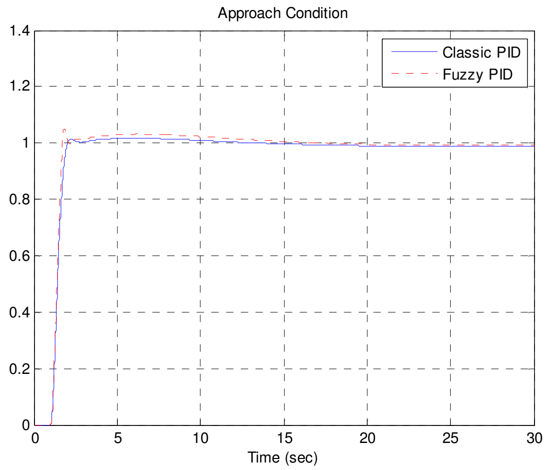

Figure 10. Step Response for Approach Condition

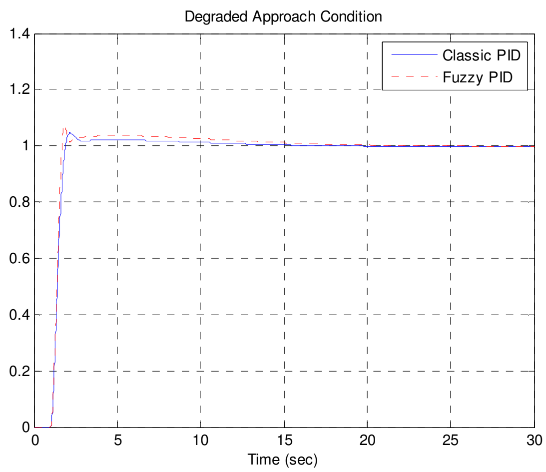

Figure 11. Step Response for Degraded Approach Condition

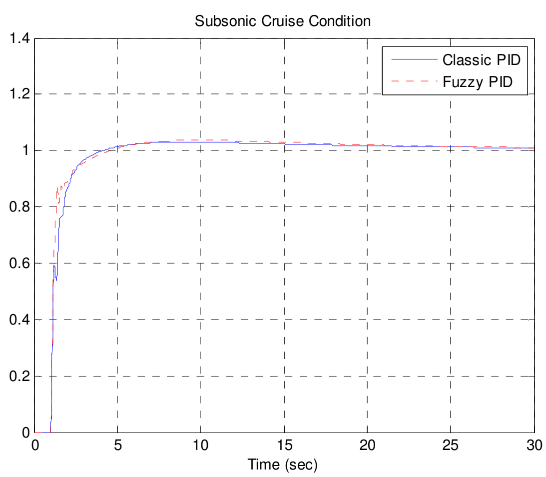

Figure 12. Step Response for Subsonic Cruise Condition

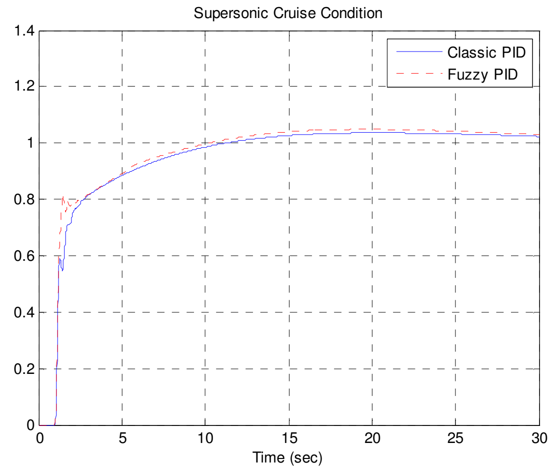

Figure 13. Step Response for Supersonic Cruise Condition

By transitioning to a symmetric rule base, consistent behavior to bidirectional inputs can be realized while still meeting the high performance objectives for the control, achieving responses comparable to the classical PID system with higher rise times. Further membership function tweaking may improve the response even further, but this illustrates the potential for control systems to be designed using fuzzy logic techniques even when stringent rise time requirements are imposed on the designer.

V. CONCLUSIONS AND RECOMMENDATIONS

Pitch attitude hold systems were designed using a constant gain approach (conventional PID) as opposed to a variable gain approach based on a PID fuzzy logic control using both a suggested asymmetric rules-base [12] as well as an indigenous symmetric rule base as well. The controllers were tested for robustness for very different conditions, i.e. Subsonic cruise and Supersonic cruise. The fuzzy logic controllers provided quicker rise times while maintaining other performance measures at comparable levels, such as overshoot and settling time. This illustrates the potential for fuzzy systems to be implemented in the face of high rise time requirements, as the previous study into a fuzzy logic controller in this application showed slower rise times than the classic PID controller.

Future work will examine application of derivatives of the fuzzy PID approach for control of gas turbine engines. Studies will be performed to determine the possible benefits this approach may yield in place of conventional PID controllers for hardware loop control on a military turbojet engine. Strict requirements are placed on the control in this application, and it will be an interesting challenge for the fuzzy PID control to meet them and provide performance improvements in various regions of the flight envelope.

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