A COMPARISON OF NONLINEAR ALGORITHMS TO PREVENT PILOT-INDUCED OSCILLATIONS CAUSED BY ACTUATOR RATE LIMITING

THESIS

James G. Hanley, Major, USAF

AFIT/GAE/ENY/03-4

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GAE/ENY/03-4

A Comparison of Nonlinear Algorithms to Prevent Pilot-Induced Oscillations Caused by Actuator Rate Limiting

THESIS

Presented to the Faculty of the Graduate School of Engineering and Management
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Aeronautical Engineering

James G. Hanley, B.S. U.S. Air Force Academy
Major, USAF

March, 2003

AFIT/GAE/ENY/03-4

A Comparison of Nonlinear Algorithms to Prevent Pilot-Induced Oscillations Caused by Actuator Rate Limiting

James G. Hanley, B.S. U.S. Air Force Academy

Major, USAF

Approved:

/signed/	
Dr Bradley S. Liebst Ph.D. Thesis Advisor	Date
/signed/	
Lt Col David R. Jacques Ph.D. Committee Member	Date
/signed/	
Lt Col John M. Phillips Ph.D. Committee Member	Date

Preface

This study was conducted under a joint program between the Air Force Institute of Technology and the U.S. Air Force Test Pilot School. I would like to thank several individuals who made this study possible. To my primary advisor, Dr. Brad Liebst, who proposed the comparison and offered valuable insights. To Lt. Col. Mike Phillips, who provided guidance and encouragement during the flight test portion of this study. To Mr. Curtis Clark and Mr. Jeff Slutz, for their endless hours preparing the LAMARS simulator. To Mr. Andy Markofski, Mr. Jeff Peer, and all the members of the VISTA maintenance team for the preparation and effort during the flight test.

I'd especially like to thank the members of the HAVE PREVENT test team who made the flight test a reality: Lt. Col. Stefan Ritter (Luftwaffe), Major John Gloystein, Major Hank Griffiths, Capt. Joel Luker, Capt. Michael Young, and Lt. Fabio Mellone (Italian AF). It was a privilege to work with gentlemen of your knowledge, ability, and professionalism. Most importantly, I would like to thank my wife for her support, love, and advice she gave me during these last two years.

James G. Hanley

Table of Contents

Page

List of Figures

Figure		Page

List of Tables

Table Page

List of Abbreviations

AFIT/GAE/ENY/03-4

Abstract

Actuator rate limiting has contributed to Pilot-Induced Oscillations (PIO) on almost every new fly-by-wire aircraft. Actuator rate limiting affected aircraft handling qualities in two ways: it exposed the aircraft's unaugmented flight dynamics and shifted the phase between the pilot input and actuator output. Phase shifting was the primary cause of PIO due to rate limiting. Two proposed solutions both placed a flight control system filter between the pilot command and actuator input. The first, referred to as Feedback-with-Bypass (FWB) and developed by Dr. Lars Rundqwist of SAAB Aircraft, used a low-pass filter to add phase lead to the pilot command. The second, referred to as Derivative-Switching (DS) and developed by Dr. Brad Liebst and Capt. Mike Chapa of AFIT, used the first and second derivatives of the pilot's command to reverse the actuator output in phase with the pilot input during actuator rate limiting. The objective of this study was to compare the ability of these two flight control system filters to prevent PIO during actuator rate limiting, and the filters' effects on aircraft handling qualities.

This comparison was conducted in three steps: computer simulation, ground simulation in the Large Amplitude Multimode Aerospace Research Simulator (LAMARS), and flight tests conducted in the Variable Stability In-flight Simulator Test Aircraft (VISTA). Pilot PIO and Cooper-Harper ratings were used for the comparison during the last two steps.

During computer simulation, the FWB filter better reduced the phase lag and prevented sustained or divergent oscillations during the closed-loop analysis. During both ground simulation and flight tests, the FWB filter was more effective at preventing divergent PIO and improving handling qualities. This was primarily due to the ability of the FWB filter to reduce phase lag better than the DS filter. However, PIO could not be prevented by either filter for configurations with poor aircraft dynamics and low actuator rate limits. Overall the FWB filter performed better during all tests.

A Comparison of Nonlinear Algorithms to Prevent Pilot-Induced Oscillations Caused by Actuator Rate Limiting

I. Introduction

Pilot-induced oscillations (PIO) are a complex dynamic interaction between the pilot and the aircraft, ranging from annoying overshoots to dangerous life-threatening gyrations [2]. PIO events have been around since the Wright brothers first aircraft [9]. More recently, the crashes of two modern developmental fighters, the YF-22 and the JAS-39, were directly attributed to PIO caused by actuator rate limiting. According to a report from the National Research Council, almost all new fly-by-wire (FBW) aircraft have exhibited PIO events at some time during development [10]. Most severe PIO events are characterized by rate limiting of the control surface actuators. An Air Force funded study on PIO concluded there was an "urgent need" for further research into PIO events caused by rate limiting and for well-developed and understood solutions [6].

Actuator rate limiting affects aircraft handling qualities in two ways: it exposes the aircraft's unaugmented dynamics and shifts the phase between the pilot input and actuator output. Modern aircraft, like the F-22, C-17, JAS-39, and Boeing 777, all use feedback control to improve their handling qualities. To save weight and reduce their radar cross-section, these newer aircraft use smaller stabilizers, which make the aircraft less inherently stable. Feedback control with FBW technology is often used to improve aircraft stability. However, the Air Force funded study found a "ubiquitous connection" between FBW aircraft and PIO caused by actuator rate limiting [6]. When the unaugmented, or bare airframe, dynamics are exposed, and phase lag is introduced, PIO are the result.

Several studies have found that placing an algorithm, or filter, in the flight control system circuitry between the pilot commanded input and the rate limited actuator (Figure 1.1) was an effective means of preventing this type of PIO [1]. The purpose of this study was to compare two recent examples. The first, referred to in this study as Feedback-with-Bypass (FWB) was designed by Dr. Lars Rundqwist of SAAB Aircraft [16]. The second, referred to as Derivative-Switching (DS), was designed by Dr. Brad Liebst and Captain Mike Chapa of the Air Force Institute of Technology (AFIT) [11]. The ability of these filters to prevent PIO could provide an essential tool to aircraft flight control system designers.

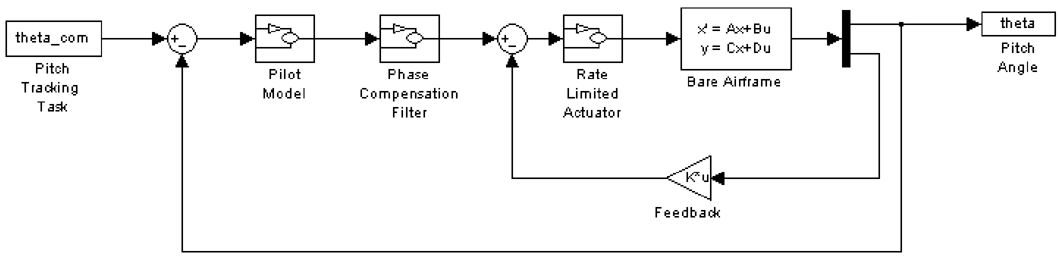

Figure 1.1 Aircraft Pitch Tracking Model with Phase Compensation Filter

1.1 Pilot Induced Oscillation Theory

MIL-STD-1797A [15] defines PIO as

> . . . sustained or uncontrollable oscillations resulting from the efforts of the pilot to control the aircraft.

An important aspect of this definition is that the oscillations result from the interaction of the pilot and the aircraft dynamics. For PIO to occur, the pilot must aggressively maneuver the aircraft during a precision tracking task. Although it is termed pilot-induced, it is the problem of the aircraft designer to create vehicle dynamics that are not prone to PIO.

PIO events are generally classified into three categories [6]. Category I covers linear pilot-vehicle system (PVS) oscillations. These types of PIO events, usually associated with older aircraft, are caused by excessive lag in the aircraft's linear dynamics. This type of oscillation is common when the pilot is learning a new aircraft or new task. Category II covers quasi-linear PVS oscillations with position or rate limiting of the actuators. These are the most common of the severe PIO events. They are dominated by the nonlinear effects of position or rate limits on the control surfaces. Category II PIO events have occurred in almost every new FBW aircraft during development [10]. Category III covers nonlinear

PVS oscillations with nonlinear transitions in either aircraft or pilot behavioral dynamics. Following the triggering event, events in this Category usually resemble a Category II PIO.

Category I PIO events can be corrected by improving the linear dynamics of the aircraft, either by increasing the unaugmented aircraft stability or through feedback control. Category III PIO events can be corrected by examining the mode shifts in the aircraft's Flight Control System, and ensuring these shifts are not large or unexpected. To prevent the most common PIO events, Category II, requires the aircraft to have good handling qualities during actuator rate limiting. Two possible solutions to this category of PIO are compared in this study.

1.2 What is Rate Limiting?

In modern aircraft, control surfaces (e.g. the elevator, ailerons, or rudder) are moved by hydraulic actuators. These actuators pump hydraulic fluid which in turn moves the control surface. The rate at which the control surface can move is limited by how much fluid the actuator can pump. This "rate limit" can only be increased by installing a larger pump. Unfortunately, the size of the pump is limited either by cost or by the small confines of the aircraft. Rate limiting occurs when the pilot commanded input to the actuator exceeds the pump capacity.

Actuator rate limiting affects aircraft handling qualities in two ways: it exposes the aircraft's unaugmented dynamics and shifts the phase between pilot input and actuator output. Phase shifting is the primary cause of pilot-induced oscillations (PIO) due to rate limiting. Consider a sine wave input (Figure 1.2). If the commanded deflection rate is greater than the rate limit, several things occur. First, the output resembles a sawtooth pattern. Second, the output is reduced in magnitude. Finally, the phase is shifted. The phase shift is of particular importance. Current FBW aircraft have approximately 45 degrees of phase margin. This margin can be quickly exceeded by rate-limiting-induced phase lag. For example, during the YF-22 accident, the phase lag started at 180 degrees and evolved to 234 degrees [3]. Phase lag adds a time delay to the aircraft dynamics, in addition to other delays inherent to the aircraft design. When the total time delay becomes too large, PIO can develop. As an example, analysis of the second SAAB JAS-39

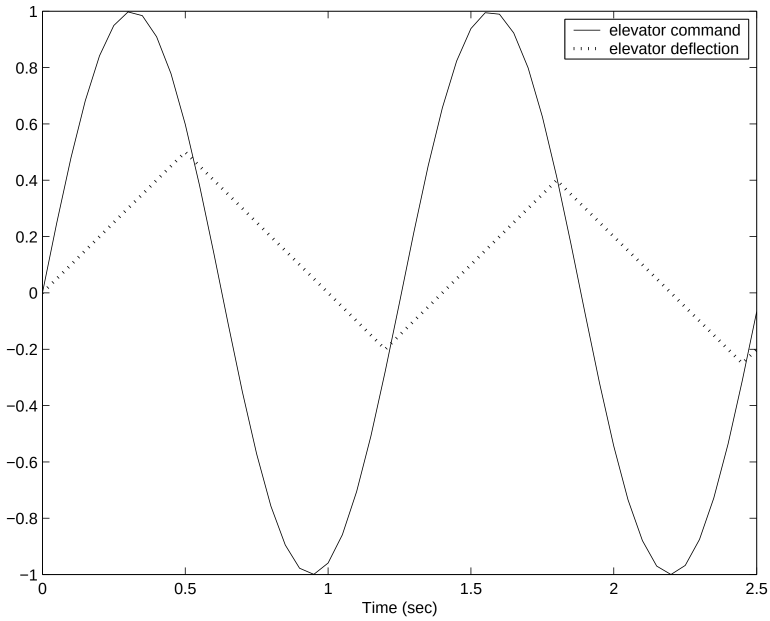

Figure 1.2 Effect of Rate Limiting on a Sine Wave Input

Gripen accident showed the effective time delay increased from less than 100 milliseconds to around 800 milliseconds [7].

Modern fighter aircraft, like the Gripen, are typically designed with an unstable bare airframe [16]. The benefit of this type of design is smaller control surface size. This smaller control surface reduces the aircraft weight and radar cross section [8]. These aircraft rely on feedback control to keep the aircraft stable. As the aircraft bare airframe becomes more unstable, the required feedback to make the aircraft easily controllable increases. However, using feedback control takes up the capability of the actuator, both in position and rate. When a pilot commands a large input the actuator must use its full pumping capacity to accommodate the pilot's request. This leaves nothing for the feedback controllers, and can cause the aircraft to effectively return to its unaugmented, unstable state. There are three ways to correct this. First, the size of the control surfaces could be increased, so that the bare airframe becomes more stable. This would also increase the aircraft weight and radar signature. Second, the size of the hydraulic pump could be increased. Because of size and cost restrictions, this could be prohibitive. Finally, flight control system software modifications to reduce the phase lag introduced by rate limiting could be used. The third solution was the focus of this study.

1.3 Background

Pilot-induced oscillations made headlines during the development of the USAF YF-22 and the SAAB JAS- 39 Gripen. During testing of the YF-22, the aircraft performed a low altitude go-around with afterburner. Raising the gear caused an unexpected increase in the stick gain as well as engagement of the thrust-vectoring nozzles. The resulting severe oscillations, characterized by both the horizontal tail and thrust-vectoring nozzles performing at their respective rate limits, caused the aircraft to impact the runway with the gear up [3]. The JAS-39 was involved in two accidents due to rate limiting PIO [10]. The first occurred during landing. While trying to control the aircraft in gusty winds, the pilot commanded the actuators to move at their rate limit at low altitude, which triggered PIO and destroyed the aircraft. The second accident occurred during an airshow. The pilot aggressively rolled out of a turn, again commanded the actuators to move at their rate limit, causing the aircraft to become uncontrollable, and was forced to eject 5.9 seconds after rolling out [7]. All these events had a common root cause—rate limiting of the actuators. The publicity following these incidents led to an increased focus on the prevention of this type of PIO.

Pilot-induced oscillations have been the focus of several recent studies. In 1985, HAVE PIO examined the capability of Ralph Smith's longitudinal criteria and Roger Hoh's bandwidth method in predicting PIO tendencies and a PIO rating [4]. It found that Smith's criteria could perform only with a correctly tuned pilot model, while Hoh's method performed well without a pilot model. However, this study only examined the linear causes of PIO. In 1997, HAVE LIMITS gathered data on PIO due to rate limiting in the cruise phase [5]. It determined the sum of sines tracking task to be an effective tool in exposing phase lag during PIO tests. The study also highlighted the drastic changes in handling qualities when the actuators reach their rate limit. The prevention of PIO due to actuator rate limiting was attacked in two important studies. In 1996, Dr. Rundqwist presented his research efforts in designing a phase compensation filter in the SAAB JAS-39

Gripen [16]. He found that the filter significantly reduced the phase lag caused by rate limiting. In 1999, HAVE FILTER studied the capabilities of a rate limiter pre-filter along with a software rate limiter to prevent PIO caused by rate limiting [11]. This study found a combination of the pre-filter and software rate limiter was successful in reducing phase lag and preventing this type of PIO. These two methods of reducing phase lag, published by Dr. Rundqwist and Capt. Chapa, were the subjects for comparison in this study.

1.4 Objectives

The objective of this project was to compare the ability of two flight control system filters in the prevention of pilot-induced oscillations (PIO) during actuator rate limiting, and the filters' effects on aircraft handling qualities. The specific objectives were:

1) Compare the FWB and DS filters in the prevention of pilot-induced oscillations caused by actuator rate limiting

2) Compare the aircraft handling qualities achieved using each filter during rate-limited and non-rate-limited tasks.

Both objectives were met.

1.5 Approach

The study was divided into the following steps:

1. Using the program Simulink [1], compare the No-Filter, FWB filter, and DS filter performance in preventing PIO, using both open and closed loop analysis.

2. Compare the PIO prevention capabilities and handling qualities effects of each filter on a motion-based flight simulator, using the Large Amplitude Multimode Aerospace Research Simulator (LAMARS).

3. Compare the PIO prevention capabilities and handling qualities effects of each filter during actual flight tests, using the Variable-stability In-flight Simulator Test Aircraft (VISTA)NF-16D.

[1] Simulink is a registered trademark of Mathworks.

The Air Force Flight Test Center (AFFTC) five-point general-purpose scale [20] was used to compare the performance of each filter configuration. The five ratings assigned were: Much Better, Better, About the Same, Worse and Much Worse.

1.6 Scope

This study was very limited in scope. The major limitations were:

1) Only the pitch axis was evaluated.

2) Simulator time was limited to 14 hours over two days.

3) Flight time was limited to 27.3 hours.

II. Theory

2.1 Filter 1: Feedback with Bypass

The Feedback-with-Bypass (FWB) filter was designed in response to the loss of two JAS-39 Gripen aircraft. The SAAB JAS-39 Gripen (JAS stands for the Swedish words for fighter, attack, and reconnaissance [12]) was developed in the 1980s and 1990s to replace SAAB's current fleet of Viggens and Drakens. The aircraft was designed with negative static longitudinal stability and full time feedback control for improved performance [12]. During testing, two prototype aircraft were destroyed in major accidents. The first accident occurred during landing, the second during a public demonstration at the Stockholm Water Festival [7]. The contributing factor during both accidents was PIO caused by actuator rate limiting [7]. After losing the second aircraft, SAAB commissioned Dr. Lars Rundqwist to develop a preventative filter for the aircraft flight control system of this FBW aircraft. The resulting algorithm, Figure 2.1, was published and patented in 1996 [16] (U.S. patent 5,528,119).

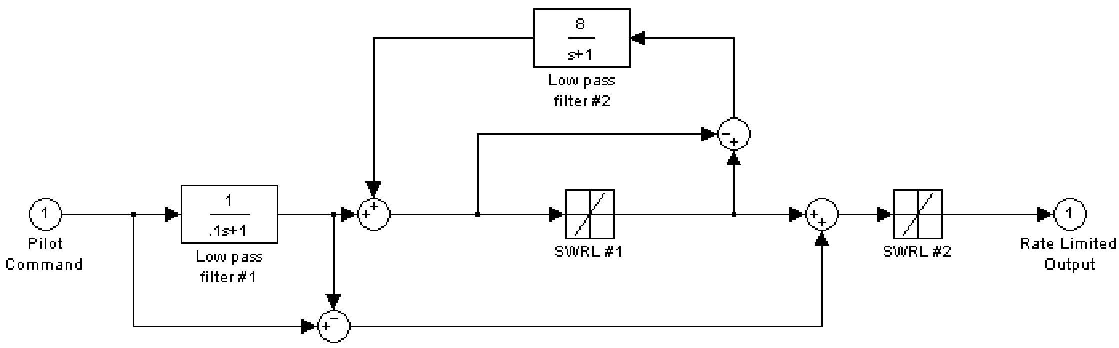

Figure 2.1 Feedback-with-Bypass Filter

A pilot command, composed of both high and low frequency components, enters a low pass filter. High frequency components, greater than 10 rad/sec, bypass the majority of the filter. The low frequency components pass through a software rate limiter (SWRL) set to the same value as the actuator rate limit. During rate limiting, the input signal to the SWRL is greater than the output. When this occurs, the difference between the output and input passes through a second low pass filter. Because this difference signal has a negative sign, its phase is shifted 180 degrees from the pilot command. When this signal passes through the low-pass filter and feeds back to the low frequency input, phase lead is added to the system. The result is a rate-limited signal with significantly less phase lag.

The variables in this filter are the cutoff frequencies in the two low pass filters and the gain in low pass filter 2. For all Simulink analysis these values were set to those in Figure 2.1.

2.2 Filter 2: Derivative Switching

The Derivative-Switching (DS) filter was designed for the project HAVE FILTER, a research effort between the U.S. Air Force Test Pilot School (USAF TPS) and AFIT, to prevent PIO due to actuator rate limiting[11]. Figure 2.2 is a Simulink diagram of the filter.

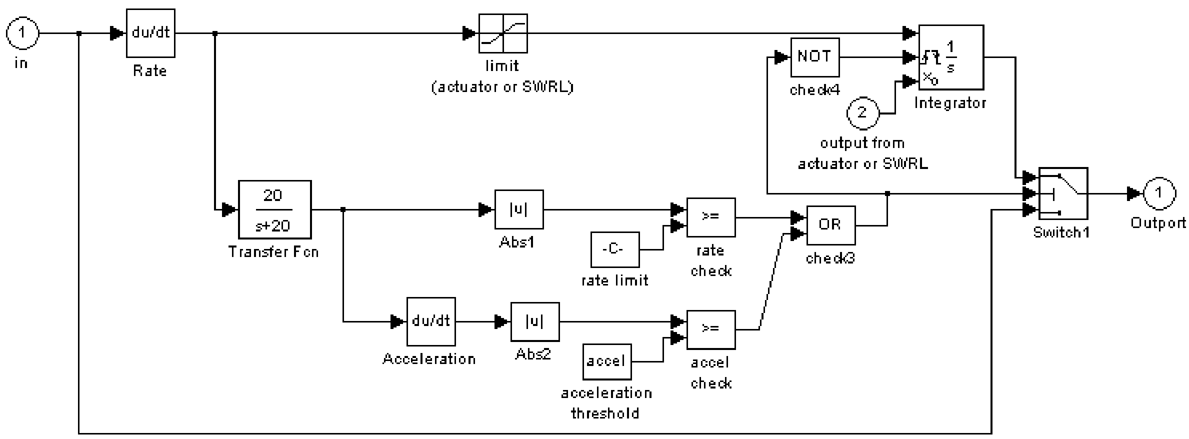

Figure 2.2 Derivative-Switching Filter

This filter has three main segments. The upper segment uses an algorithm that differentiates, limits, and integrates (Figure 2.3) to keep the output in phase with a low frequency, symmetrical input. A reset integrator is used to correct the bias inherent in an unsymmetrical input. The middle segment provides the switching logic. First, high frequency noise is filtered from the signal. The rate and acceleration of the filtered signal are checked against preset values. If either derivative exceeds their respective limit, the upper segment is activated. Otherwise, the lower segment is active, and the signal passes through the filter cleanly.

The only variable in this filter is the acceleration threshold. This value was adjusted for optimum performance in each test.

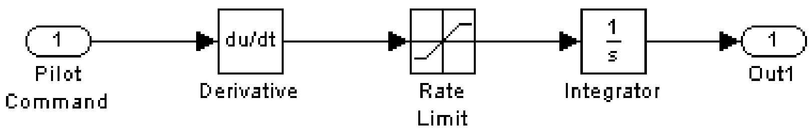

Figure 2.3 Simple Differentiate-Limit-Integrate filter

2.3 Handling Qualities

In an effort to correlate an aircraft's stability and control characteristics with pilot opinion, MIL-STD-1797A [15] defines the three levels of handling qualities shown in Table 2.1

Level 1	Satisfactory	Flying qualities clearly adequate for the mission flight phase. Desired performance is achievable with no more than minimal pilot compensation
Level 2	Acceptable	Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.
Level 3	Controllable	Flying qualities such that the aircraft can be controlled in the context of the mission flight phase, even though pilot workload is excessive or mission effectiveness is inadequate, or both.

Table 2.1 MIL-STD-1797A Definitions of Handling Qualities Levels

The goal of every aircraft designer is Level 1 handling qualities. Level 2 is acceptable with an aircraft system failure. Level 3 handling qualities could occur with multiple aircraft failures or during severe turbulence.

2.4 Rating Scales

Two rating scales were used during the ground simulation and flight test porion of this study. To express PIO susceptibility, the PIO rating scale in Figure A.1 was used. This scale, taken from the Test Pilot School curriculum [17] was selected because of its familiarity and ease of use. A rating of 1 to 3 reported no PIO were encountered. A 4 rating indicated a PIO with bounded oscillations. A 5 rating was given if divergent oscillations were present. A rating of 6 meant that divergent oscillations were encountered during gentle maneuvering. The Cooper-Harper rating (CHR) scale in Figure A.2 was used to define the configuration's handling qualities. This scale, devised by George E. Harper and Robert P. Cooper in 1969, was selected because it is the most widely used handling qualities scale in the world [17]. A rating of 1 to 3 indicated Level 1 handling qualities. A 4 to 6 rating meant the aircraft handling qualities were Level 2. A 7 to 9 rating was given for Level 3 handling qualities. A rating of 10 was given if the aircraft was found uncontrollable.

III. Computer Simulation

The Simulink study began with open loop analysis of each filter alone. Aircraft and actuator dynamics were added, and the closed loop response was analyzed using a Nichols diagram. Finally, a Neal-Smith pilot model was added and the aircraft dynamics were modified to include handling qualities Levels 1, 2, and 3, and unstable dynamics with angle of attack (α) and pitch rate (q) feedback. All analysis was performed at a solution rate of 60 Hz, identical to both LAMARS and VISTA processing rates.

3.1 Open Loop Analysis

Rate limiting is mathematically nonlinear. A commonly used technique to study systems with nonlinearities is the describing function analysis [18]. In this type of examination, a sinusoidal input was sent through a nonlinear component. A Fourier Series approximation of the output was constructed, however only the fundamental frequency was considered, and the response was assumed symmetrical about the origin [18]. Therefore only the Fourier coefficients a_1 and b_1 were calculated. The describing function was dependent on the amplitude C and frequency ω of the input. The describing function $Y_N(C,\omega)$ for a nonlinearity N with input $u = Csin(\omega t)$ and output $y(t)$ [16] was

$$Y_N(C,\omega) = \frac{b_1 + ia_1}{C} \tag{3.1}$$

$$a_1 = \frac{\omega}{\pi}\int_0^{\frac{2\pi}{\omega}} y(t)cos(\omega t)dt \tag{3.2}$$

$$b_1 = \frac{\omega}{\pi}\int_0^{\frac{2\pi}{\omega}} y(t)sin(\omega t)dt \tag{3.3}$$

or

$$Y_N(C,\omega) = \frac{c_1 * e^{i\phi}}{C} \tag{3.4}$$

$$c_1 = \sqrt{(a_1)^2 + (b_1)^2} \tag{3.5}$$

$$\phi = tan^{-1}(\frac{a_1}{b_1}) \tag{3.6}$$

This technique is especially useful in “the prediction of limit cycles in nonlinear systems” [18]. The sine wave response in Figure 1.2 shows this to be a reasonable approximation for rate limiting cases.

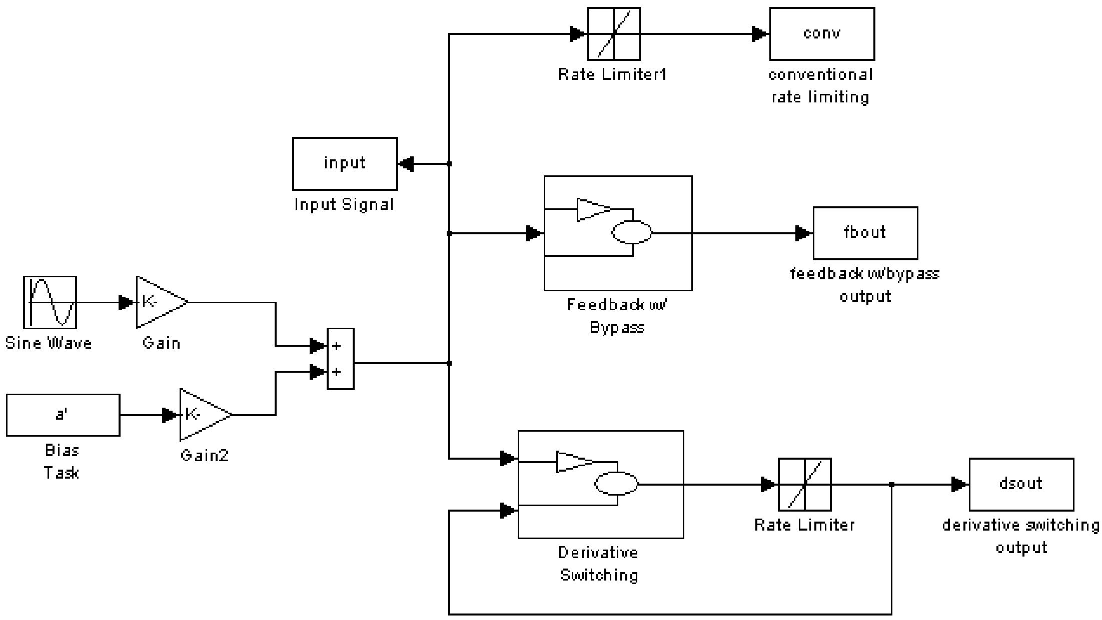

Figure 3.1 Simulink Diagram of Open Loop System

The following analysis examined the response of no filter, the FWB filter, and the DS filter to sine wave inputs of varying frequencies (Figure 3.1). Only the frequencies of concern to the pilot, between 0.1 and 10 rad/sec, were studied [15]. Above 10 rad/sec, even a 180 degree phase lag would result in a delay of less than 0.3 seconds. Below 0.1 radians, the period is long enough that the pilot can make intermediate corrections. All rate limits were set to ± 1 rad/sec. The coefficients were calculated numerically, using the trapezoid rule.

Figure 3.2 shows the rate-limited response of each configuration to a sine wave. The DS filter shows the almost no phase lag. The FWB filter shows improved phase lag over the

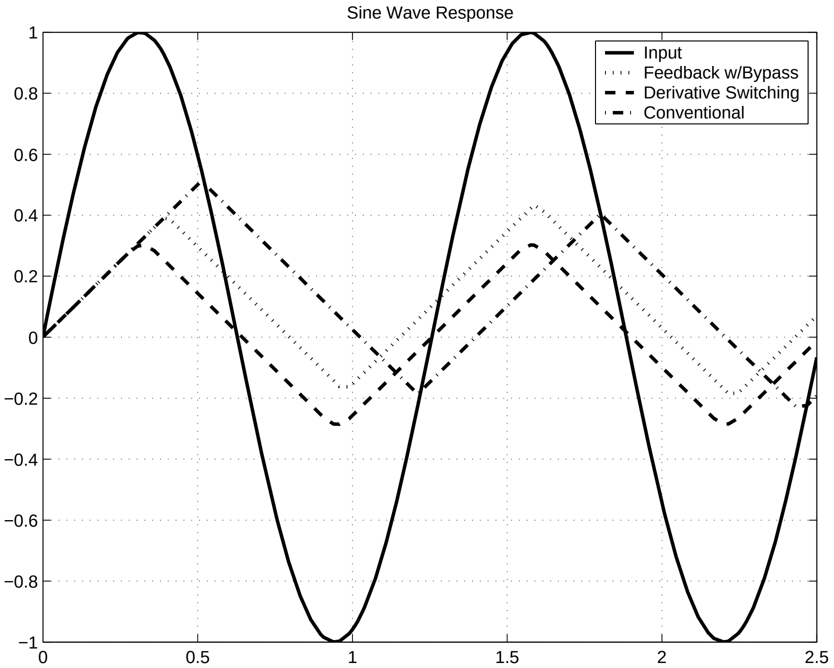

Figure 3.2 Filter Response to sin(5t)

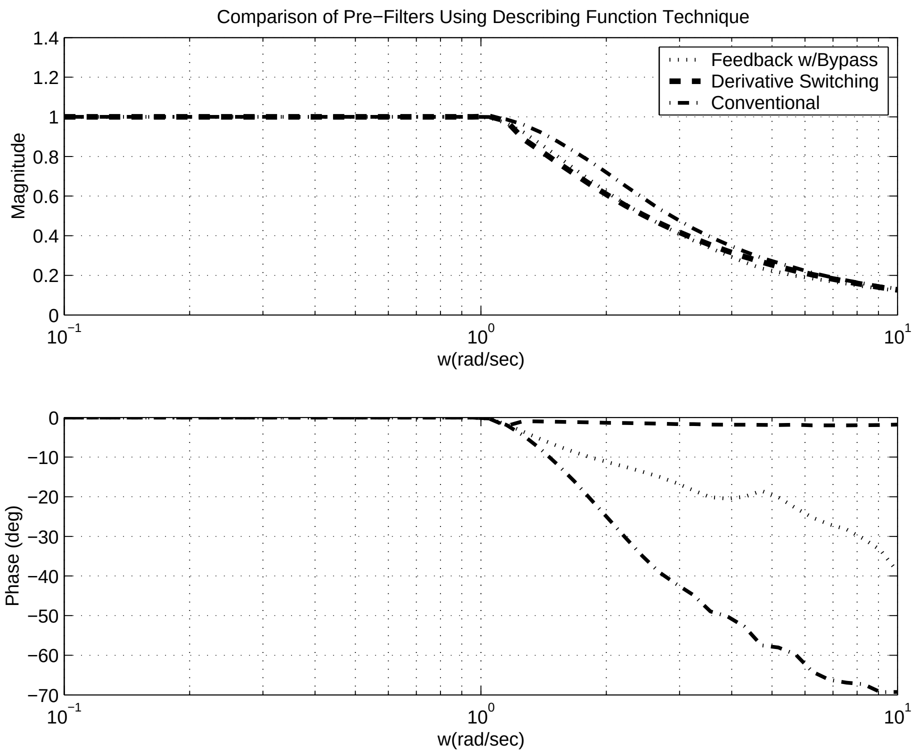

Figure 3.3 Magnitude and Phase of Describing Functions

No-Filter case. Figure 3.3 shows the same trend was found in the frequencies of interest. Rate limiting began after 1 rad/sec. After that, the DS filter continued to show almost no phase lag, the FWB filter showed improved but significant phase lag, and the No-Filter case performed the worst.

The next task was to look at bias removal. If the input is not symmetric, a steady state error, or bias, can result. This can be very confusing to the pilot, and will result in a lower handling qualities rating. Figure 3.4 examines each filter's ability to remove bias after an asymmetric input.

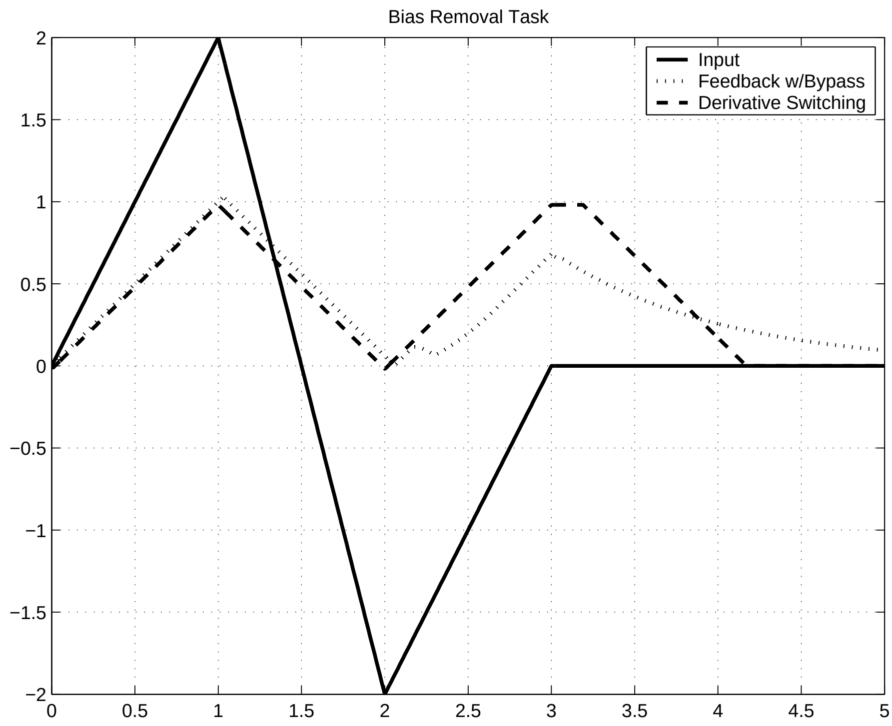

Figure 3.4 FWB and DS Bias Removal

Both filters effectively removed the bias. The DS filter removed the bias at the rate limit. The FWB filter removed it at an exponential rate.

During the open loop analysis, the DS filter performed better than both the FWB and No-Filter configurations in reducing phase lag. The FWB filter performed better than no filter in phase lag reduction. The FWB and DS filters performed about the same at effectively eliminating bias.

3.2 Closed Loop Analysis

3.2.1 Phase Lag Reduction Comparison. To determine the phase properties for each filter, a basic aircraft control system was modelled. Using reference [19], a pitch dynamics model of the F-16 was developed. A state feedback controller using angle of attack (α), pitch angle (θ), and pitch rate (q) was designed for 200 km/h (124 mph) and 1000 m (3280 ft) altitude.

The response of the system was analyzed for the four configurations shown in Figure 3.5. The first configuration was the ideal linear response of the system with no rate limit. The second included only the effects of conventional rate limiting. The third configuration used the FWB filter. The fourth used the DS filter. All rate limits were set at 1 rad/sec, and the acceleration threshold for the derivative switching filter was set at its optimum value, 2 rad/sec^2.

Given the sine wave input, $u(t) = Asin(\omega t)$, the output shown in Figure 3.6 was estimated as another sine wave with phase shift, $y(t) = Bsin(\omega t+\phi)$. The transfer function of the nonlinear portion of the system was Y_N, the linear portion (i.e. the actuator, aircraft dynamics, and feedback) was G, and defining the sensitivity function $S = (1 + Y_N G)^{-1}$, and the equation for the open loop transfer function $Y_N G$ was found by looking at the output node in Figure 3.5.

$$y(t) = u(t) - Y_N * G * y(t) \quad (3.7)$$

$$S = \frac{y(t)}{u(t)} \quad (3.8)$$

$$S = \frac{Bsin(\omega t + \phi)}{Asin(\omega t)} \quad (3.9)$$

The magnitude and phase of the sensitivity function was then calculated.

$$|S| = \frac{|B|}{|A|} \quad (3.10)$$

$$\angle S = \phi \quad (3.11)$$

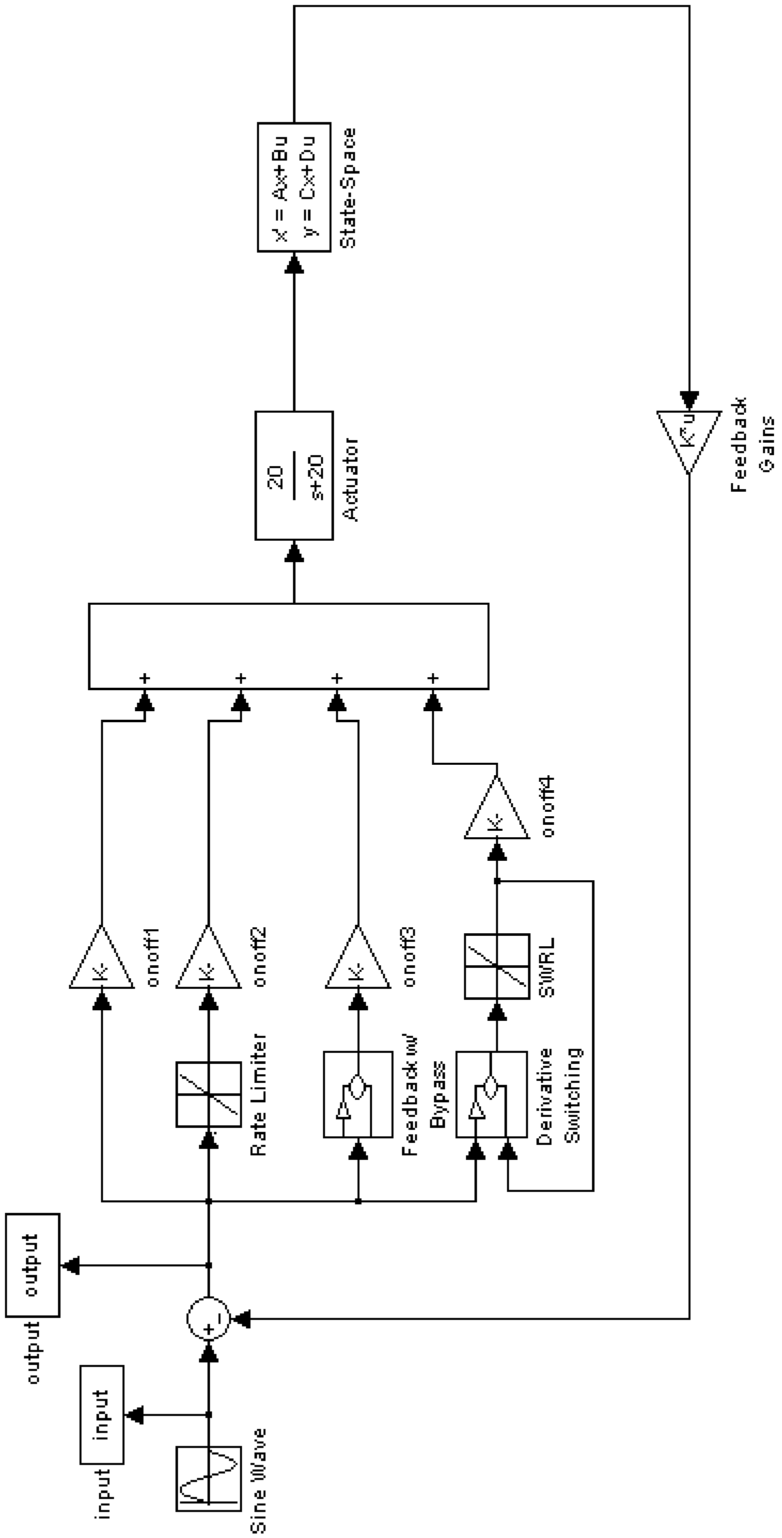

Figure 3.5 Simulink Diagram of F-16 Dynamics

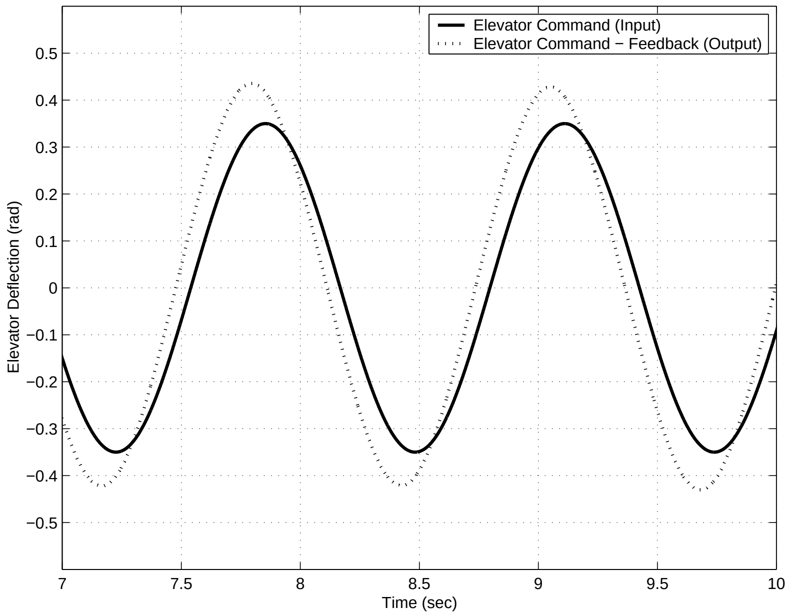

Figure 3.6 Example of Input and Output from Figure 3.5, $\omega = 5$

The open loop transfer function $Y_N G$ was finally determined.

$$S = \frac{|B|}{|A|} e^{j\phi} \tag{3.12}$$

$$Y_N G = (\frac{|A|}{|B|} cos(\phi) - 1) - j \frac{|A|}{|B|} sin(\phi) \tag{3.13}$$

The magnitude and phase of $Y_N G$ were plotted in Figure 3.7 (a Nichols diagram) to calculate the closed loop phase shift.

The differences between the three rate limited cases and the linear transfer function indicate the phase lag in the closed loop system. The closed loop phase lag can be determined by examining the Nichols diagram at identical input frequencies. Before rate limiting occurred, all four plots coincide, indicating no phase lag. As input frequency increased, and rate limiting began to dominate, several interesting trends appeared. As expected, conventional rate limiting with no protection was the worst performer. The FWB filter remained closer in phase than the DS filter. The result was the FWB filter performed better than both the DS and No-Filter configurations.

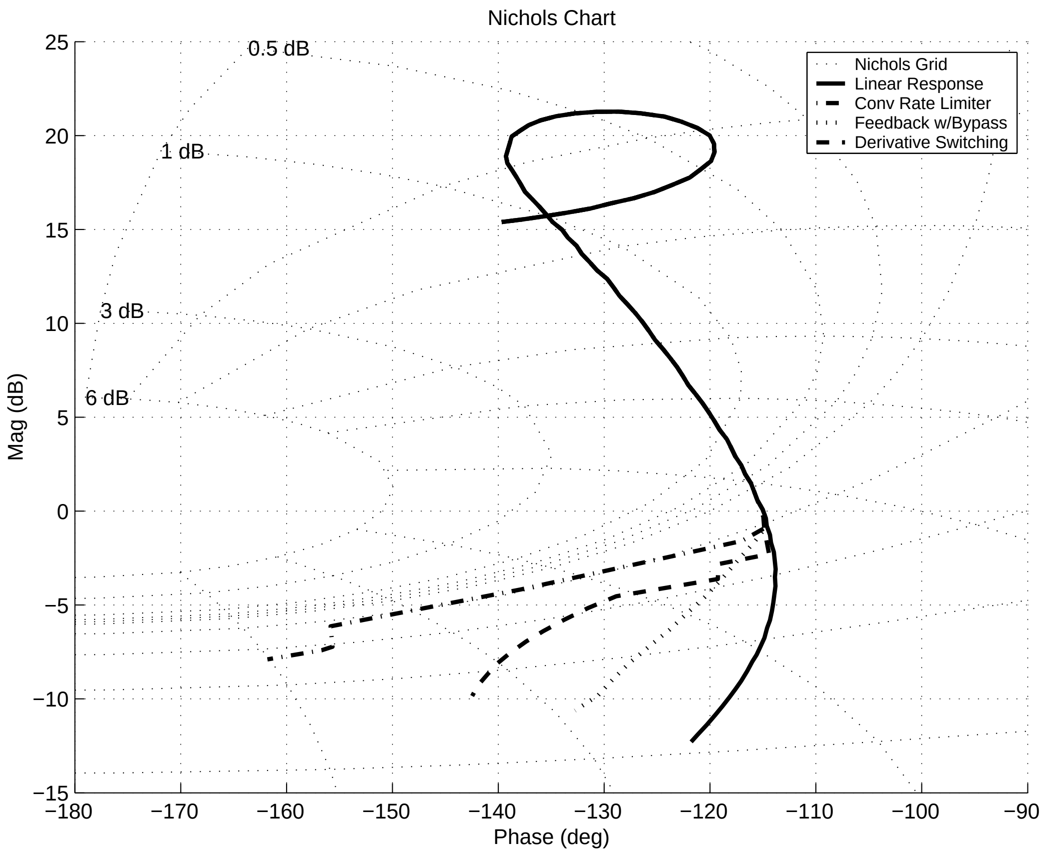

Figure 3.7 Nichols Diagram of F-16 Model from Figure 3.5

3.2.2 Adding Pilot and Aircraft Closed Loop Dynamics. The final portion of computer analysis incorporated all aspects of aircraft-pilot coupling. This included four separate aircraft models, a Neal-Smith pilot model, rate and position limited actuator dynamics, and options for no filter, the FWB filter, or the DS filter. The performance during pulse, and sum of sines pitch tracking tasks were examined. Figure 3.8 shows the Simulink diagram used for this analysis.

3.2.2.1 Aircraft Models. This study examined four different aircraft models, labelled Cases A,B,C, and D, taken from reference [8]. The second-order longitudinal dynamic approximations associated with these models as well as their respective short-period natural frequencies (ω_{nsp})and short-period damping ratios (ζ_{sp}) are summarized in Table 3.1. The Case A aircraft had no stability augmentation. This configuration had bare airframe dynamics that displayed good handling qualities and was therefore considered Level 1 in accordance with MIL-HDBK 1797A [15]. Case B had bare airframe dynamics that were acceptable (Level 2) with only a small amount of stability augmentation needed to achieve Level 1 closed-loop handling qualities. Case C had poor (Level 3) bare airframe dynamics with significant stability augmentation required to bring it to Level 1 handling qualities. The Case C short period poles were close to the jω axis, making the open-loop response very oscillatory. Case D had unstable bare airframe dynamics with a time to double amplitude (T_2) of 2.31 seconds, requiring a significant amount of stability augmentation to achieve Level 1 handling qualities. Each consecutive bare airframe (from Case A to D) exhibited decreasing stability. However, the stability augmentation system was designed to provide nearly identical closed-loop dynamics for all four configurations if the commanded actuator rate was under its limit.

Table 3.1 contains bare airframe and closed-loop pole coordinates. These bare airframe poles became important when the aircraft model reached a nonlinear saturation. The configurations with little or no augmentation feedback were less prone to PIO due to their more-stable bare airframe dynamics. Conversely, Cases C and D were more prone to PIO if rate limiting was encountered. Case D would have a tendency to go unstable in the event of rate limiting. Case D was very similar to the Gripen, which had a time to double

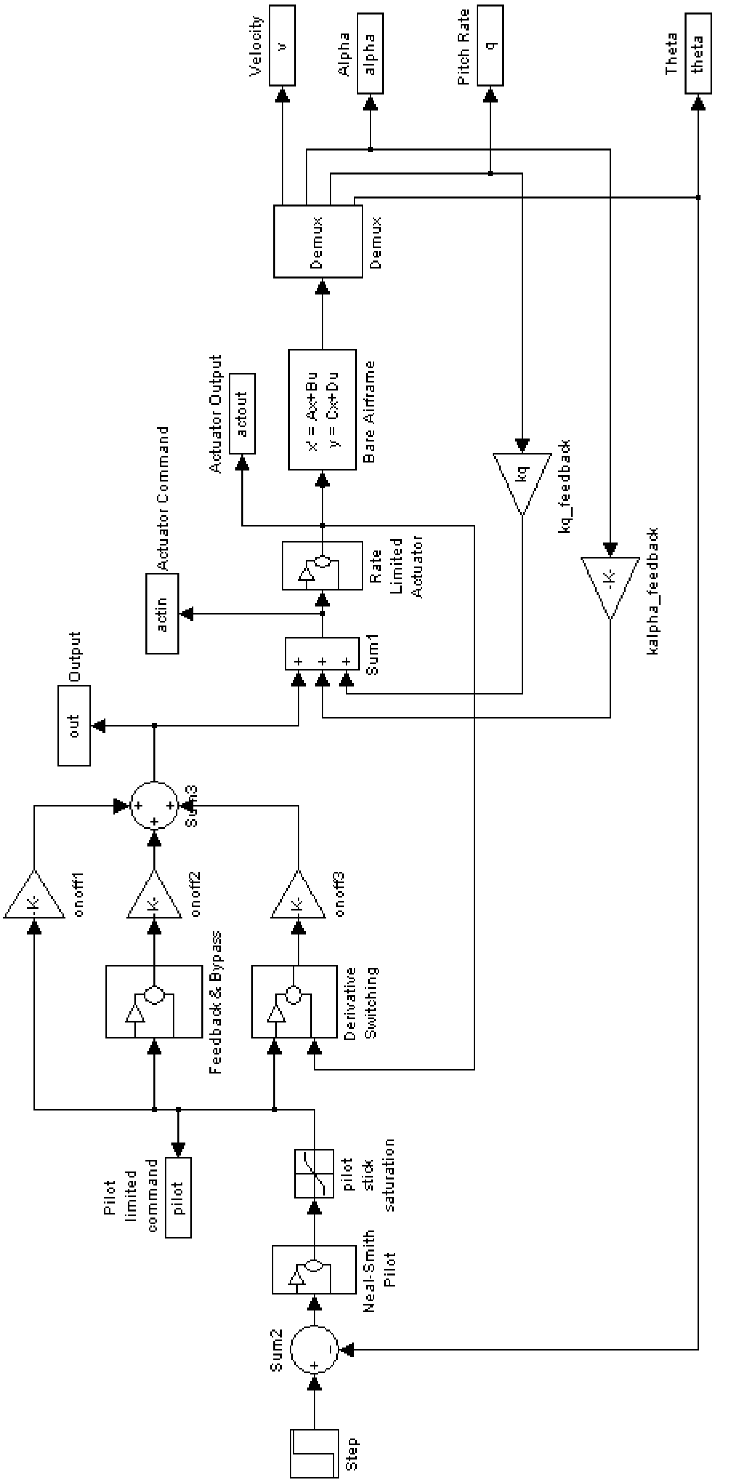

Figure 3.8 Simulink Diagram of Aircraft Model

Case	Bare Airfame Poles	ω_{nsp} (rad/sec)	ζ_{sp}	Kq	Kα	A/C Poles with Stability Augmentation
A	-.017 ± j.074 -2.20 ± j2.22	3.12	0.70	0	0	-.017 ± j.074 -2.20 ± j2.22
B	-.016 ± j.079 -1.42 ± j1.86	2.34	0.61	.14	.21	as above
C	-.009 ± j.097 -0.86 ± j.084	0.86	0.995	.24	.51	as above
D	-.017 ± j.033 1.07, -1.67		$T_2 = 2.31sec$	.34	.61	as above

Table 3.1 Aircraft Configurations

of 0.4 seconds [12]. However, the testing emphasized the Case C configuration, as it was more likely to enter sustained oscillations.

Figure 3.9, taken from reference [13], shows the relationship between ω_{nsp}, ζ_{sp}, and handling qualities. In Figure 3.9, "Good" represents handling qualities Level 1, "Acceptable" and "Poor" represent Level 2, and "Unacceptable" represents Level 3.

3.2.2.2 Pilot Model. Although no mathematical model can truly represent the complexities of a human pilot, the commonly used Neal-Smith model was chosen for this research. This model accounts for the effects of: adjustable gain dependent on task, a time delay for the pilot to process his instrument readings, a lead compensator to anticipate commands, and a lag compensator to smooth inputs [15]. For the linear analysis (i.e. without rate limiting and filters turned off), the four aircraft models used in this study have identical transfer functions.

$$\frac{\theta(s)}{\delta_e(s)} = \frac{-11.09(s+1.26)(s+0.038)}{(s^2+4.4s+9.68)(s^2+0.034s+0.0058)} \tag{3.14}$$

The pilot model [$Y_p(s)$] that satisfied the MIL-HDBK 1797A conditions for Level 1 handling qualities [15] is

$$Y_p(s) = -0.145e^{-0.25s} * \frac{5s+1}{s} * \frac{0.3s+1}{0.01s+1} \tag{3.15}$$

3.2.2.3 Actuator Dynamics. The actuator was modelled with both rate and position limits. The rate limit was set to 60 deg/sec for most of the computer analysis. The

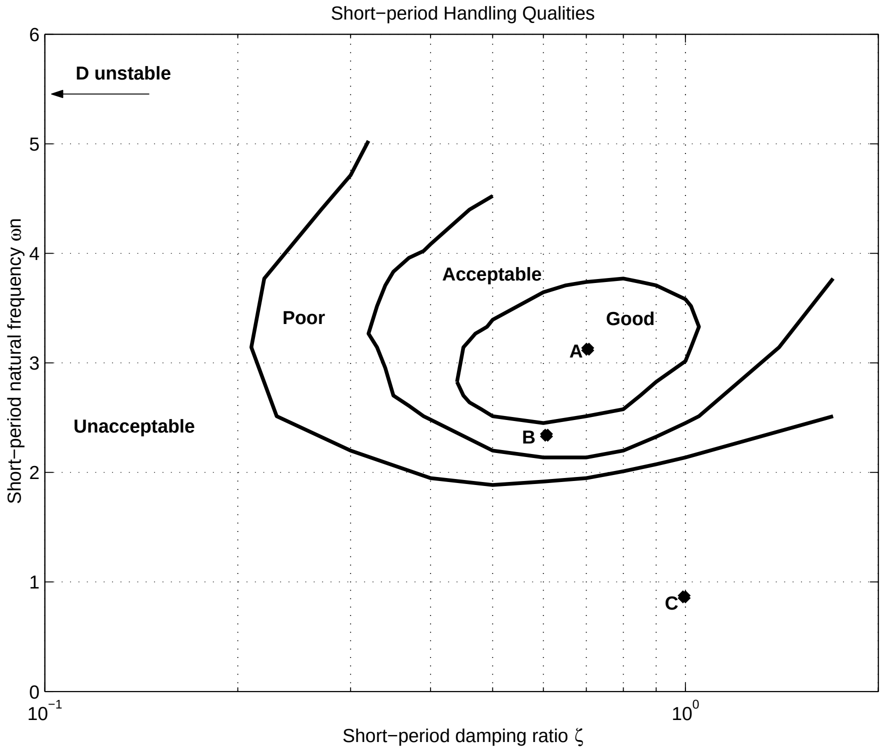

Figure 3.9 Short-period Flying Qualities

position limit was set at ±35 degrees. These values are similar to F-16 settings. Figure 3.10 shows the schematic for modelling actuator dynamics

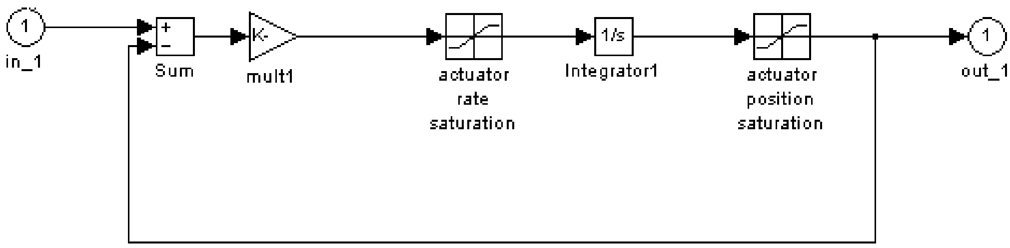

Figure 3.10 Actuator Dynamics

3.2.3 Task 1: Pulse Input. For this test, the tracking task was a 0.5 second pulse. Table 3.2 shows the pulse amplitude for each of the four cases. The target amplitude was adjusted so that each case experienced rate limiting during the task. The goal was to see the result of rate limiting for each aircraft model. From Chapter 1, if the pilot demanded a maximum rate from the actuator, the feedback controller was inoperative and the aircraft would return to bare airframe tendencies.

Case	Pulse Amplitude (degrees)
A	60
B	60
C	28
D	18

Table 3.2 Amplitude of 0.5 Pulse for Each Aircraft Configuration

Figure 3.11 shows the results with no filter, i.e. conventional rate limiting, on the Case A aircraft. The pilot command, the actuator command (i.e. the pilot plus feedback commands), and the rate-limited actuator output were plotted. This configuration had very few overshoots, with the aircraft returning to steady state after approximately 5 seconds. Rate limiting can be seen in the sawtooth pattern of the actuator displacement. Since this case had zero feedback, the pilot and actuator commands overlay. The phase lag is visible during the first two seconds in the time difference between the pilot command and the actuator output, but disappeared after. No PIO were encountered.

Figure 3.12 shows the Case B results. This configuration had slightly more overshoots, with the aircraft returning to steady state after approximately 7 seconds. Rate limiting was present during the first 3 seconds. The phase lag was slightly larger than Case A, but also disappears after several seconds. Because of the increased number of overshoots, this configuration would rate lower during a handling qualities evaluation, but no PIO were encountered.

For Case C, Figure 3.13, a Category II PIO developed after a few seconds. In 3 seconds, stop-to-stop pilot commands began and the actuator displacement resembled a sawtooth pattern. The time delay between the pilot command and the actuator output increased as the task progressed, showing increasing phase lag. As a result of the increasing phase lag, the commanded actuator displacement shows the aircraft entering divergent oscillations. In this case, the pilot is demanding full actuator capacity, leaving no authority for the stability augmentation, and exposing the marginally stable unaugmented dynamics

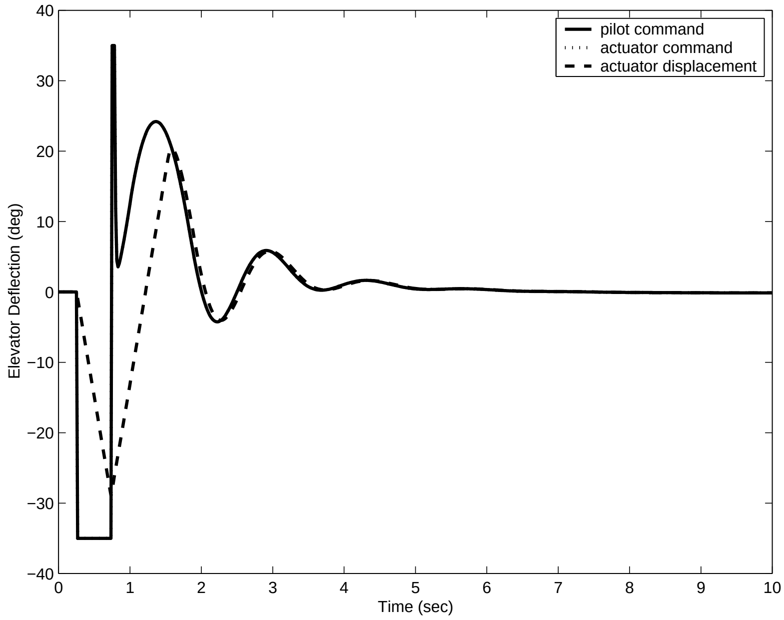

Figure 3.11 Response of Case A Aircraft to Pulse Tracking Task, No Filter

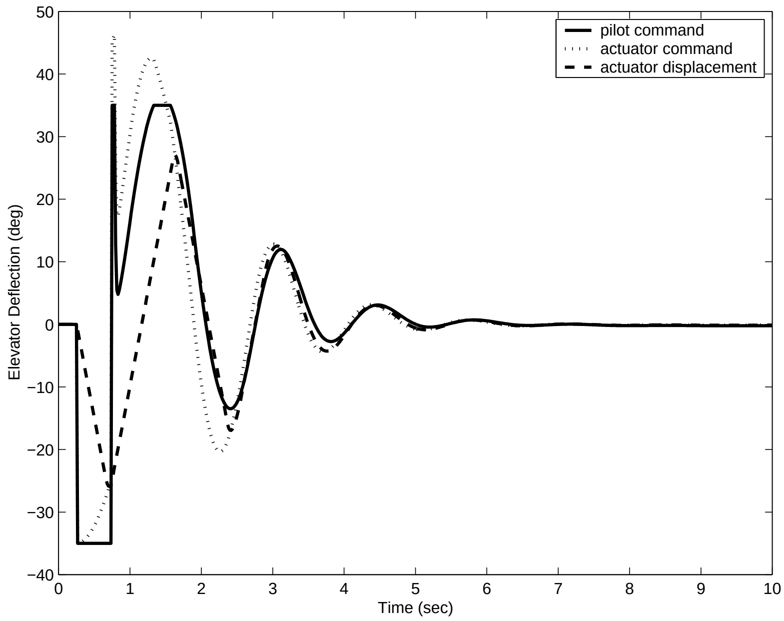

Figure 3.12 Response of Case B Aircraft to Pulse Tracking Task, No Filter

of the aircraft. The tendency to enter sustained oscillations made Case C the most closely examined case.

For Case D, Figure 3.14, the pilot quickly demanded maximum elevator performance again, and the aircraft departed after 5 seconds. This was an example of uncontrollable bare airframe dynamics. Although the phase lag was minimal in this test, the unaugmented dynamics of this case made it very susceptible to departure.

The analysis was repeated with the FWB filter on. This filter improved the performance in all four cases (Figure B.1). All aircraft oscillations settled after 5 seconds. The two cases of interest, Cases C and D, are shown in Figures 3.15 and 3.16. The phase lag, the difference between pilot command and actuator output was eliminated with the FWB filter. In fact the filter caused the aircraft to anticipate the pilot reversals, actually demonstrating phase lead.

The third analysis was performed with the DS filter on and the acceleration threshold set to 250 deg/sec^2. This also improved the performance all four cases (Figure B.2). The two cases of interest, Cases C and D, are shown in Figures 3.17 and 3.18. Phase lag again was eliminated, with a small amount of phase lead present.

Filter robustness was then checked. The pulse task amplitude for Cases C and D was increased to 60 and 30 degrees respectively. Both filters were able to eliminate PIO during the Case C investigation (Figures 3.19 and 3.20). During Case D testing, the DS filter returned to a rate limited PIO, while the FWB filter still responded well, preventing both PIO and departure (Figures 3.21 and 3.22). With the DS filter on, the phase lead seen in earlier tests disappeared. Because this case had unstable bare airframe dynamics even the slightest amount of phase lag caused this aircraft to depart.

3.2.4 Task 2: Discrete Tracking. For the next Simulink test, a discrete pitch tracking task (Figure 3.23), taken from page 108o of MIL-STD-1797A, was used.

The No-Filter configurations were tested first. To keep the task pitch angles at a reasonable level, the actuator rate limit was set to 30 deg/sec. The maximum amplitude of the tracking task was adjusted to enter sustained oscillations after the large jump at 42

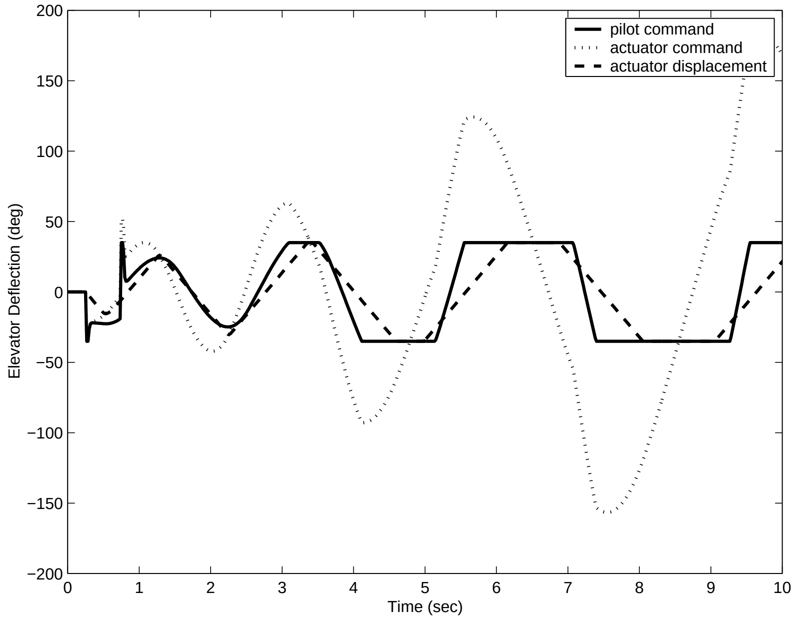

Figure 3.13 Response of Case C Aircraft to Pulse Tracking Task, No Filter

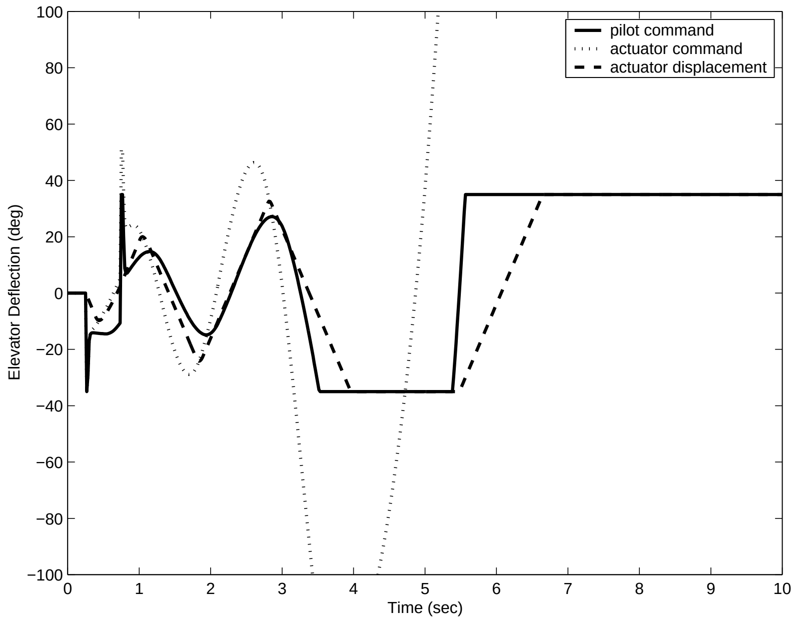

Figure 3.14 Response of Case D Aircraft to Pulse Tracking Task, No Filter

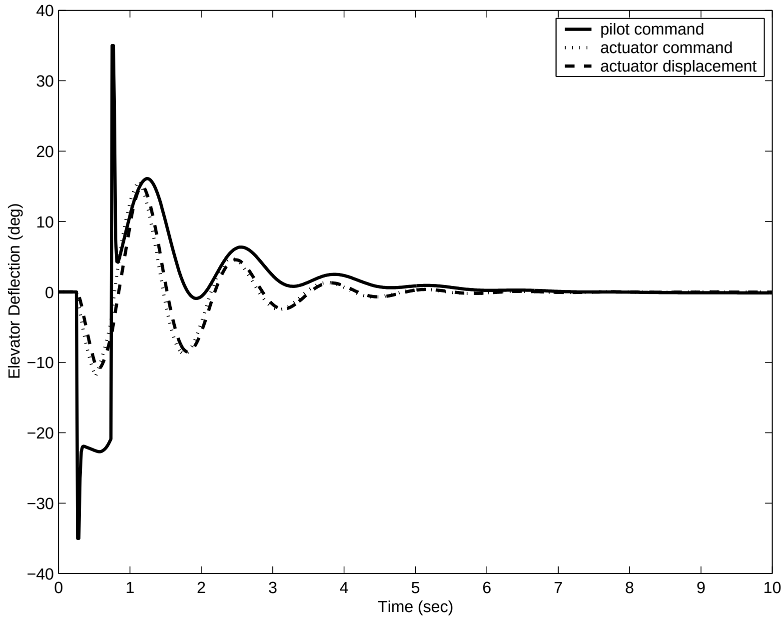

Figure 3.15 Response of Case C Aircraft to Pulse Tracking Task, FWB On

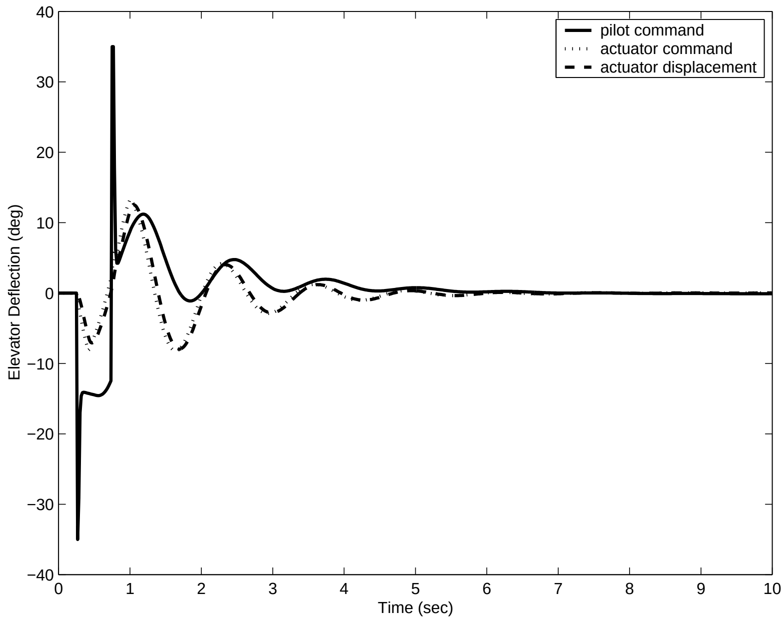

Figure 3.16 Response of Case D Aircraft to Pulse Tracking Task, FWB On

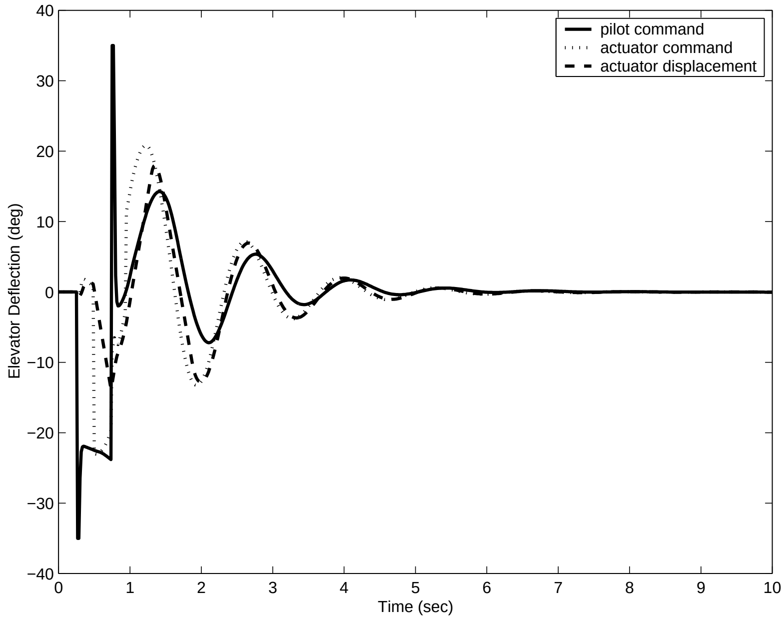

Figure 3.17 Response of Case C Aircraft to Pulse Tracking Task, DS On

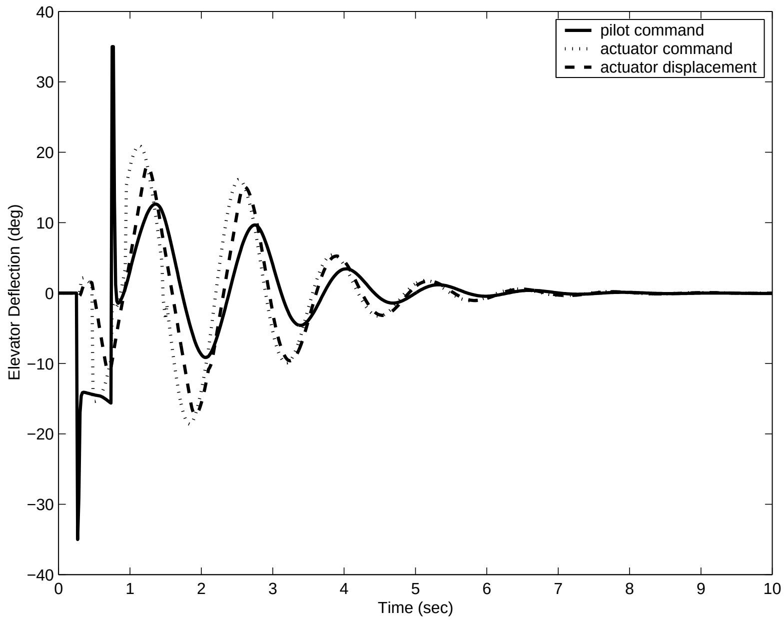

Figure 3.18 Response of Case D Aircraft to Pulse Tracking Task, DS On

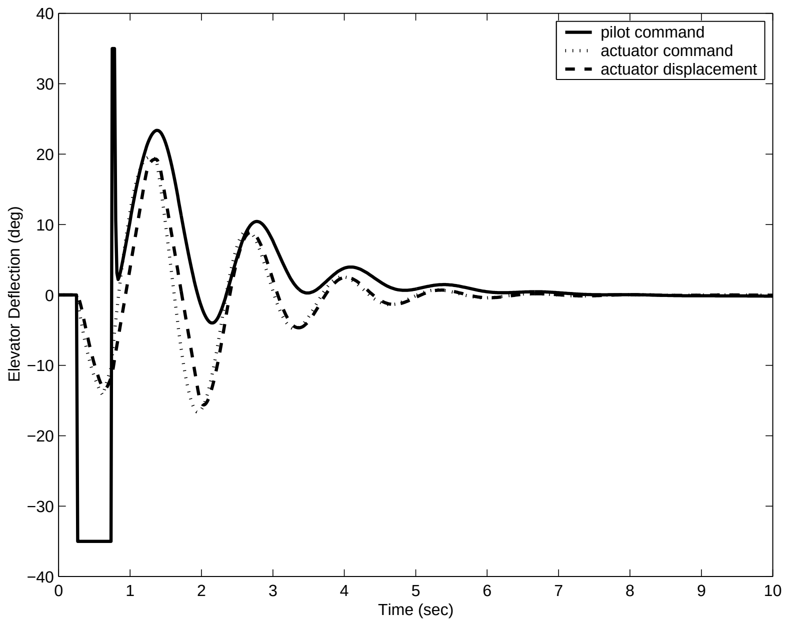

Figure 3.19 60 Degree Pulse Response, Case C, FWB

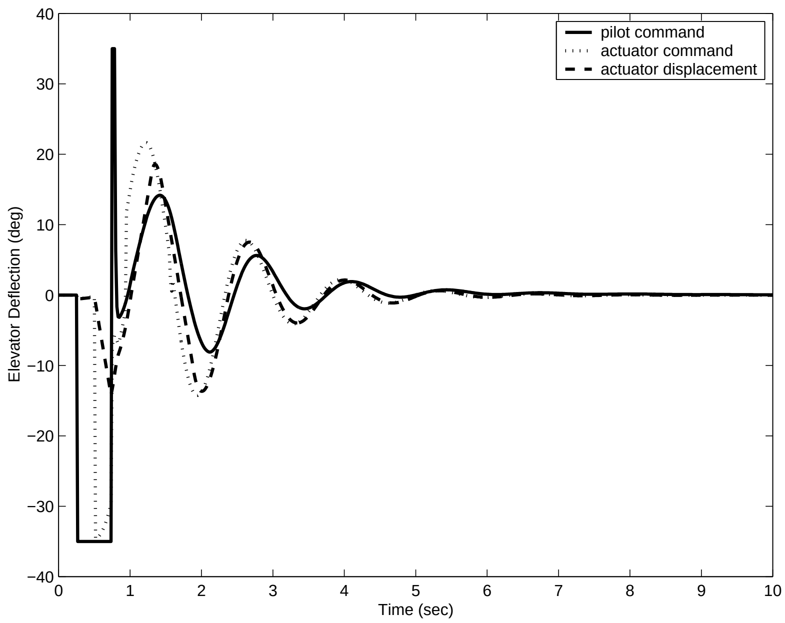

Figure 3.20 60 Degree Pulse Response, Case C, DS

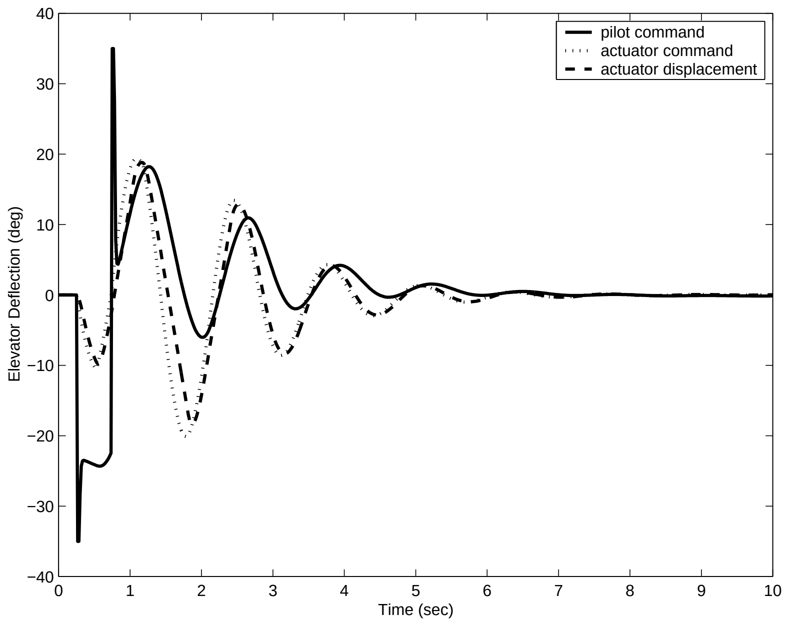

Figure 3.21   30 Degree Pulse Response, Case D, FWB

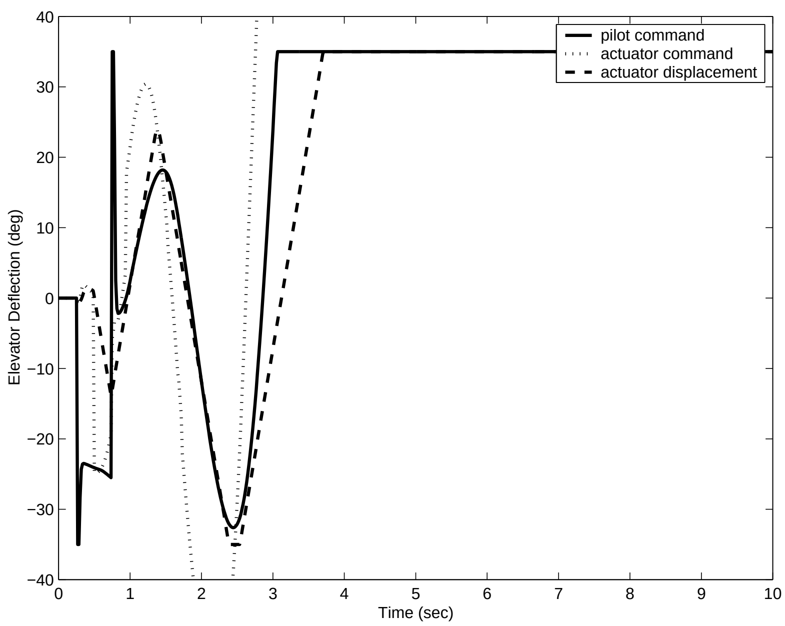

Figure 3.22   30 Degree Pulse Response, Case D, DS

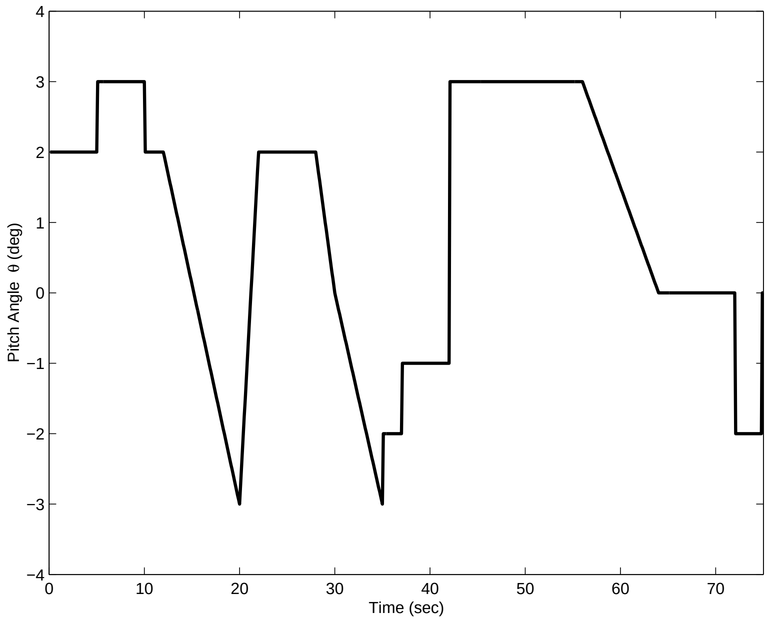

Figure 3.23 Discrete Pitch Tracking Task from MIL-STD-1797, page 108o

seconds with the Case C, No-Filter configuration. Figures 3.24 and 3.25 show that Case C entered divergent oscillations and Case D departed 43 seconds into the task with no filter.

The Case C, No-Filter aircraft oscillations were a result of increasing phase lag, as seen in Figure 3.26. The delay between the pilot command and the actuator output increases with each successive overshoot. The goal of adding each filter was to reduce or eliminate this phase lag.

Turning the FWB filter on prevented the aircraft from both the divergent oscillations and departure for aircraft Cases C and D (Figures 3.27 and 3.28). The FWB filter eliminated the phase lag associated with large pitch jumps (Figure 3.29). In addition, the magnitude of the pilot input was lower, implying that the pilot was not drawn into larger inputs.

With the DS filter on, the acceleration threshold was adjusted to optimize its performance. However, even by varying this threshold between 100 and 5000 deg/sec^2 the filter could not prevent a PIO in Case C or departure in Case D (Figures 3.30 and 3.31). In fact, if the maximum amplitude was lowered slightly, a PIO would result with the DS filter turned on but not with the filter off.

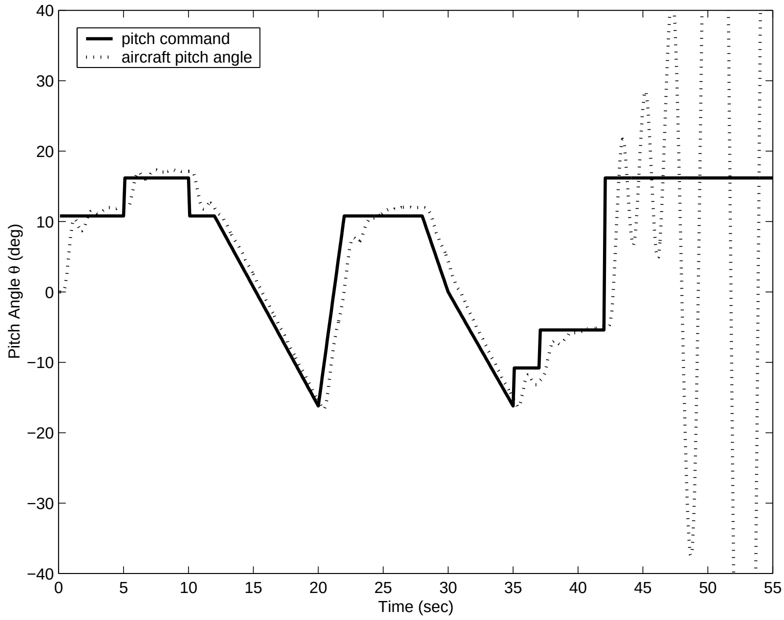

Figure 3.24 Aircraft Response during Discrete Tracking Task, Case C, No Filter

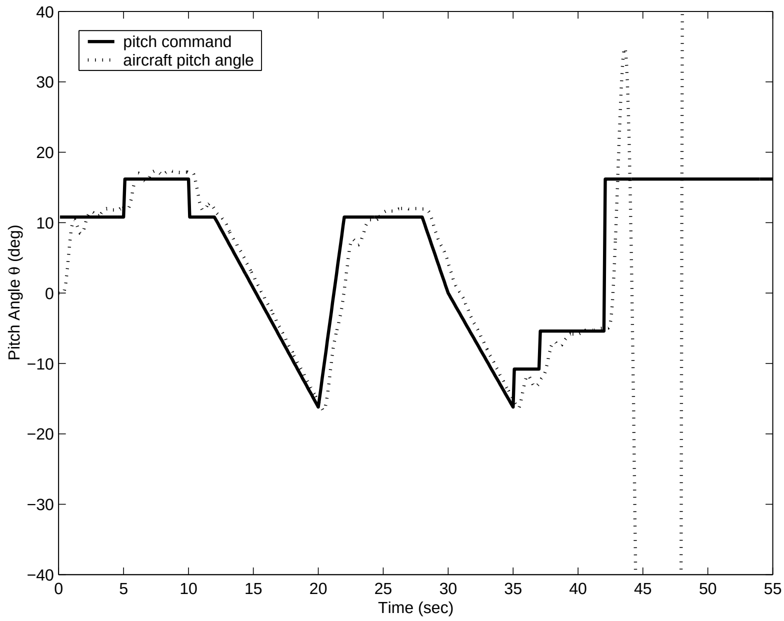

Figure 3.25 Aircraft Response during Discrete Tracking Task, Case D, No Filter

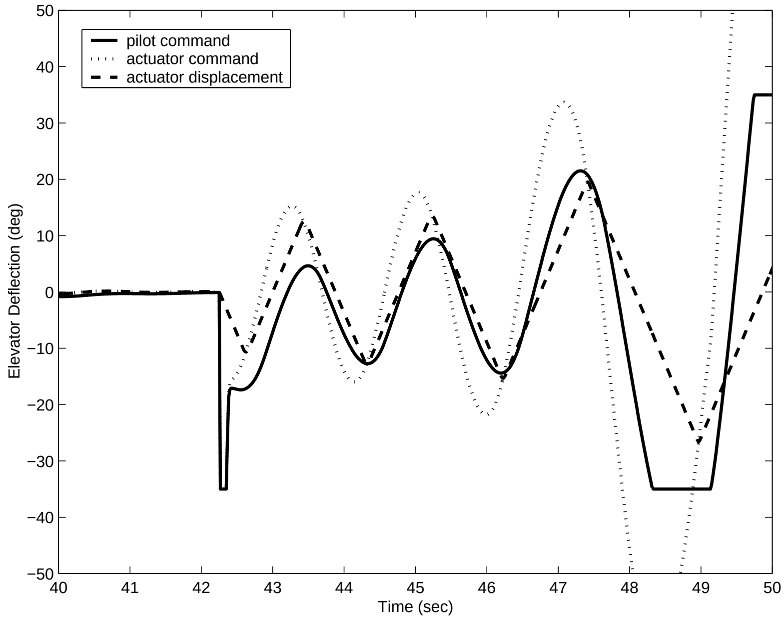

Figure 3.26 Increasing Phase Lag during Discrete Task, Case C, No Filter

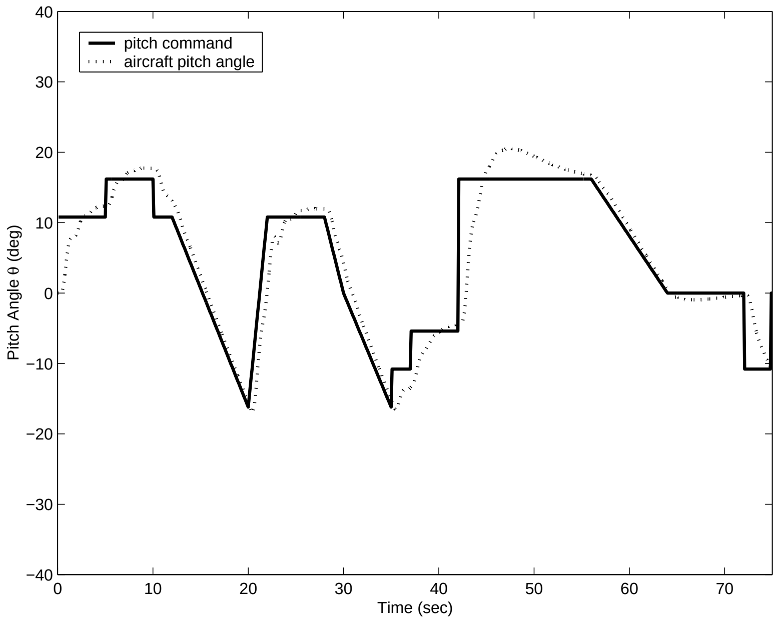

Figure 3.27 Aircraft Response during Discrete Tracking Task, Case C, FWB

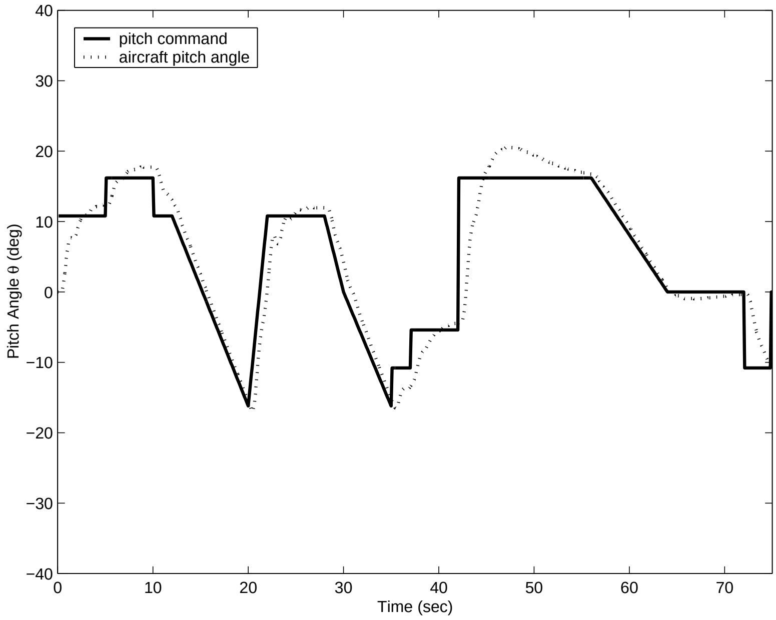

Figure 3.28 Aircraft Response during Discrete Tracking Task, Case D, FWB

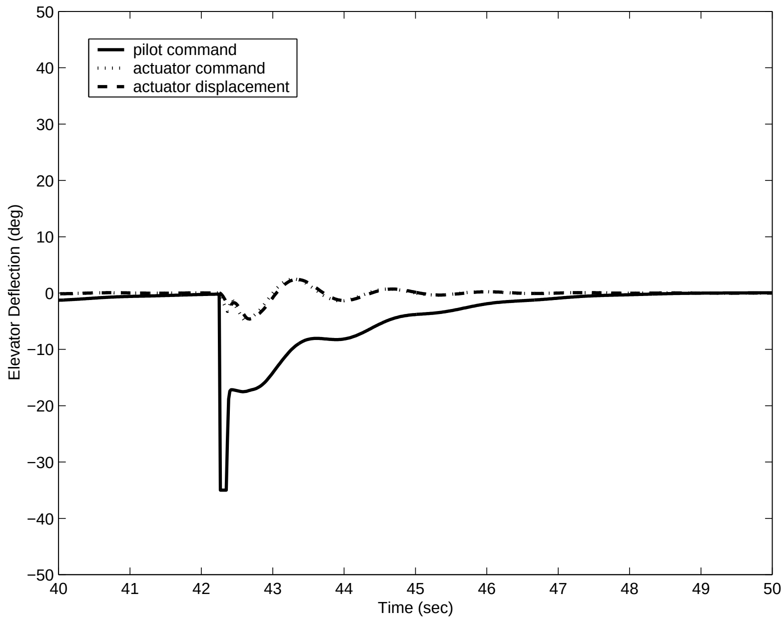

Figure 3.29 Reduced Phase Lag during Discrete Task, Case C, FWB

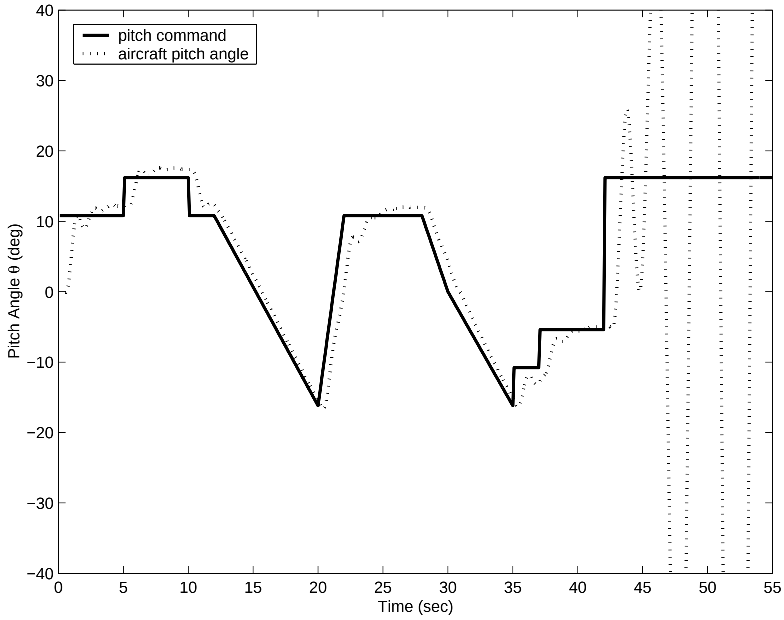

Figure 3.30 Aircraft Response during Discrete Tracking Task, Case C, DS

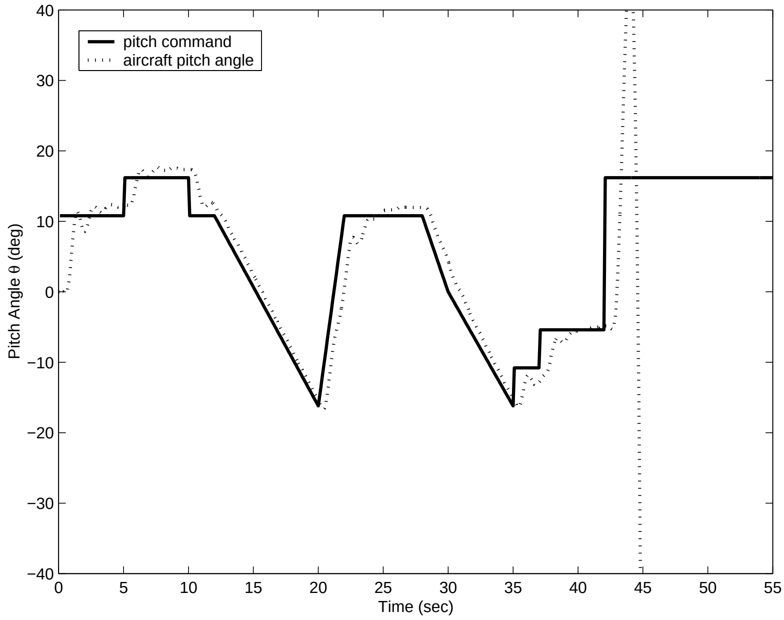

Figure 3.31 Aircraft Response during Discrete Tracking Task, Case D, DS

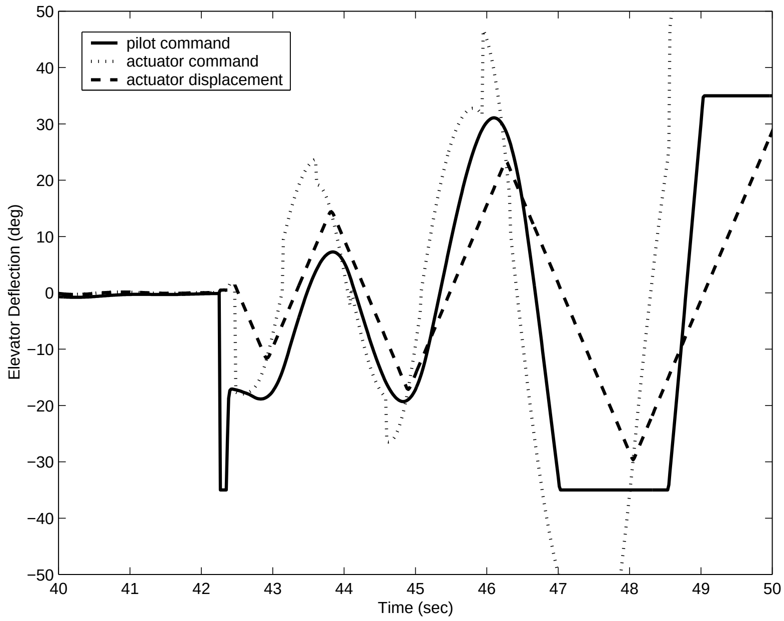

Figure 3.32 Increasing Phase Lag during Discrete Task, Case C, DS

The DS filter added an additional time delay of approximately 0.2 sec during the large pilot input at 42 seconds (Figure 3.32). The large pilot input triggers both the acceleration and rate thresholds, but the filter did not react, commanding a small input in the opposite direction. This added delay degraded performance below the No-Filter configuration.

3.2.5 Task 3: Sum of Sines. The sum of sines task, developed by Hoh Aeronautics [5], was used for the final tracking task (Figure 3.33. The primary benefit of this task was its ability to expose phase lag. The task was generated from the following equations:

$$\theta_{command} = \sum A_i sin(\omega_i t) \quad (3.16)$$

$$\omega_i = 2\pi \frac{N_i}{63} \quad (3.17)$$

Table 3.3 lists the values for A_i, ω_i, and N_i.

The purpose of this task was to expose the phase lag. The easiest way for the pilot to detect this phase lag was to compare the task to the aircraft pitch angle. The maximum amplitude of the task was set similarly to the discrete task: with both filters off the Case C aircraft entered into oscillations and the Case D aircraft departed (Figure B.6). The results

i	A_i	N_i	ω_i
1	-1.0	2	0.1995
2	1.0	5	0.4987
3	1.0	9	0.8976
4	0.5	14	1.396
5	-0.2	24	2.394
6	0.2	42	4.189
7	-0.08	90	8.976

Table 3.3 Sum of Sines Parameters

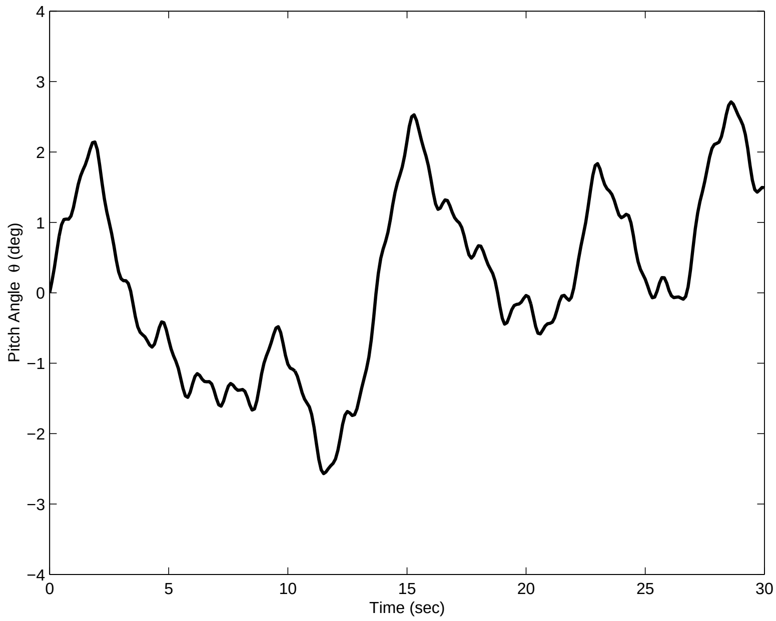

Figure 3.33 Sum of Sines Pitch Tracking Task

were identical to the discrete task (Figures B.7 and B.8). Figure 3.34 gives insight to the success of the FWB filter and to the failure of the DS filter. The DS filter configuration phase lag clearly increases with time compared to the FWB filter. This result can be linked with Figure 3.7 which showed the closed loop phase lag of the DS filter was greater than the FWB filter.

3.3 Simulink Analysis Results

The DS filter performed better than both the No-Filter and FWB configurations during the open loop analysis. The DS filter was better able to prevent phase lag using the

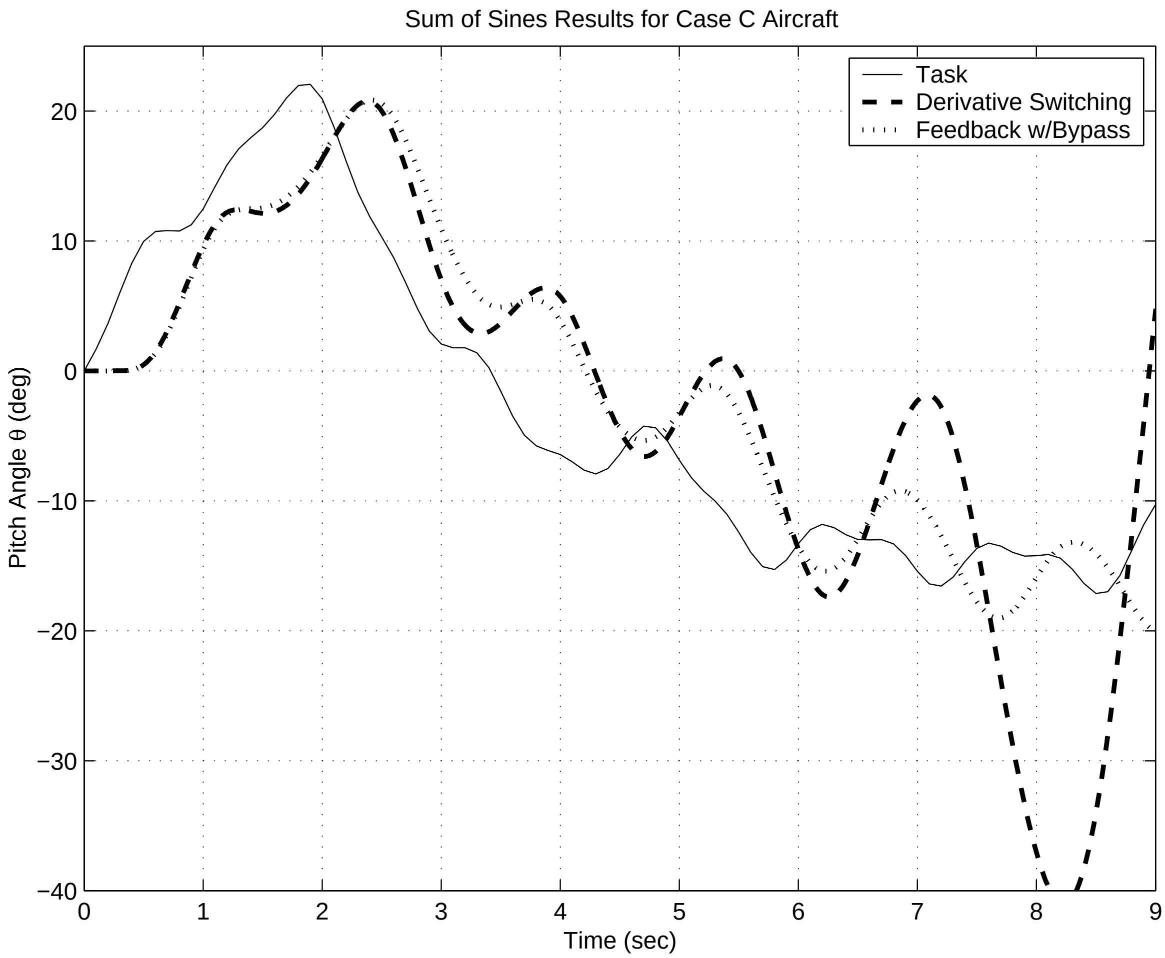

Figure 3.34 A Comparison of Phase Lag of Each Filter

describing function analysis and also removed bias effectively. The FWB filter prevented phase lag better better than the No-Filter configuration and was also able to effectively remove bias.

The FWB filter performed much better than the DS and No-Filter configurations during all closed loop tasks. The FWB configuration remained closer in phase in both the Nichols diagram analysis and the sum of sines tracking task. It could handle larger pulse inputs and eliminated PIO and departure in every pitch tracking task. The DS filter performed better than the No-Filter on the Nichols diargram, but worse on the discrete tracking task. While the FWB filter appeared to reduce pilot inputs, the DS and No-Filter configurations appeared to draw the pilot into larger inputs until Category II PIO developed.

IV. Ground Simulation

The second step of this study was to compare the FWB and DS filters in a motion-based simulator. The purpose this step was to gather data for the study and to prepare the test team for flight test. The objectives were to compare the ability of the two flight control system filters to prevent PIO during actuator rate limiting, and the filters' effects on aircraft handling qualities. All simulator testing was performed during 14 sessions on 26 and 27 September 2002.

4.1 Simulator Description

The Large Amplitude Multimode Aerospace Research Simulator (LAMARS) was a five degree of freedom motion simulator located inside a 20 foot dome. For visual imagery, the simulator had two side projectors and a center projector with a total field of view of 135 degrees [14]. An F-15 type center stick was installed. A single throttle was installed, but not used. To decrease pilot workload during the test, the simulator was programmed to hold constant airspeed.

LAMARS was capable of simulating any set of aircraft dynamics, flight control system, and actuator rate limit, which made it ideal for this study. The simulator was programmed with the four short period dynamics with feedback (Cases A, B, C, and D) used in the computer simulation. The flight control system used in Figure 3.8, with pitch rate and angle of attack feedback, was incorporated. In addition, four selectable rate limits (15, 30, 45, and 60 deg/sec) were used.

4.2 Test Points

Each aircraft case, rate limit, and filter configuration was assigned a priority, shown in Table 4.1. Case C configurations were given the highest priority because of their susceptibility to PIO. Case D configurations were also important because of their tendency to depart controlled flight. Cases A and B were used to keep the pilot unbiased. If a pilot were given nothing but poor aircraft configurations, he would alter his control strategy during the test. Therefore, Case A (Level 1 handling qualities) and Case B (Level 2) configurations were incorporated into each mission to give the pilot both good and bad handling test points.

Case	Priority	Rate Limit	Filter	Test Point
A	2	60	No-Filter	1
			FWB	2
			DS	3
		45	No-Filter	4
			FWB	5
			DS	6
	5	30	No-Filter	7
			FWB	8
			DS	9
		15	No-Filter	10
			FWB	11
			DS	12
B	3	60	No-Filter	13
			FWB	14
			DS	15
		45	No-Filter	16
			FWB	17
			DS	18
	5	30	No-Filter	19
			FWB	20
			DS	21
		15	No-Filter	22
			FWB	23
			DS	24

Case	Priority	Rate Limit	Filter	Test Point
C	1	60	No-Filter	25
			FWB	26
			DS	27
		45	No-Filter	28
			FWB	29
			DS	30
		30	No-Filter	31
			FWB	32
			DS	33
		15	No-Filter	34
			FWB	35
			DS	36
D	3	60	No-Filter	37
			FWB	38
			DS	39
		45	No-Filter	40
			FWB	41
			DS	42
	4	30	No-Filter	43
			FWB	44
			DS	45
		15	No-Filter	46
			FWB	47
			DS	48

Table 4.1 Test Condition Matrix

4.3 Test Procedures

The evaluator pilot (EP) performed a handling qualities investigation for each combination of airframe dynamics, actuator rate limit, and filter. The EP was blind as to the exact test point configuration. All testing was performed at simulated conditions of 15,000 ft and 350 knots indicated airspeed (KIAS). Each investigation was divided into three parts: Phases 1, 2, and 3 [17].

The Phase 1 investigation consisted of open loop and gentle tracking maneuvers to evaluate low (pilot) gain, low bandwidth handling qualities. Some example maneuvers

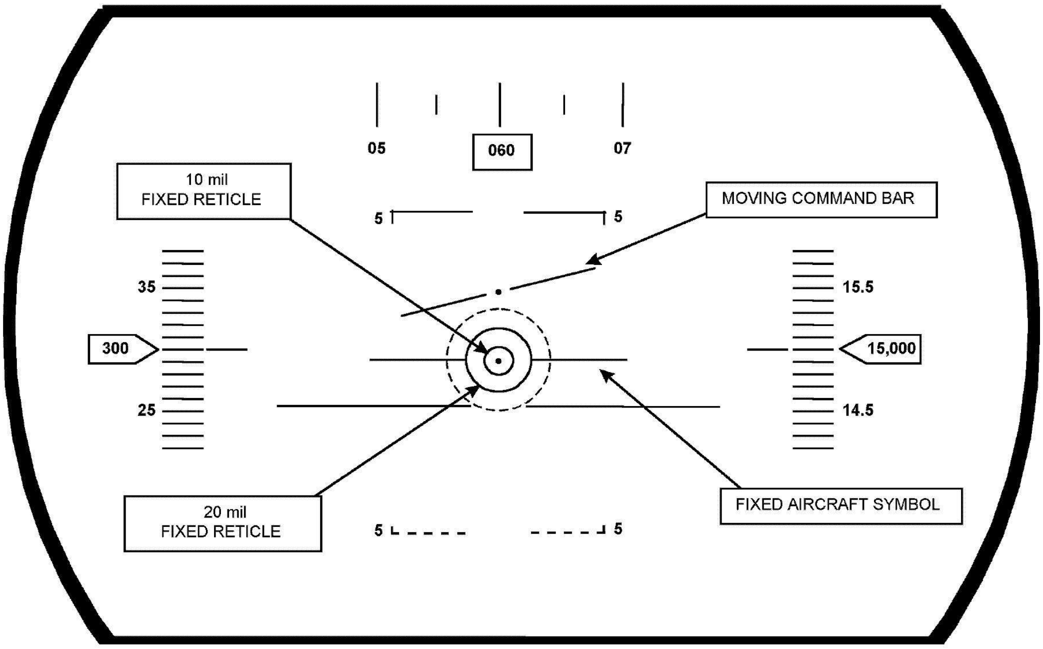

Figure 4.1 Sample HUD Symbology

included doublets, step inputs, and pitch angle captures. The Phase 1 maneuvers familiarized the EP with the feel of the aircraft and often revealed how the aircraft would perform during the Phase 2 and 3 tasks.

Phase 2 testing was an evaluation of high gain, high bandwidth handling qualities. It used a specialized technique, called Handling Qualities During Tracking (HQDT), requiring the pilot to "track a precision aim point on a target as aggressively and assiduously as possible, always striving to correct even the smallest tracking errors as rapidly as possible."[17] Pilot gain and frequency of inputs were increased during the task to evaluate PIO tendencies. HQDT was the most reliable method of finding PIO susceptibility. For this phase, the heads-up display (HUD) shown in Figure 4.1 was used. The moving command bar, or target, followed the sum of sines tracking task in pitch only. During or immediately following the task, pilot comments were recorded and a PIO rating (PIOR) was assigned using the scale shown in Figure A.1.

During Phase 3 testing, the EP performed an operational evaluation of the aircraft's handling qualities and PIO susceptibility. Two separate tracking tasks were used — a discrete HUD tracking task with a synthetic target generated in the HUD, and tracking of

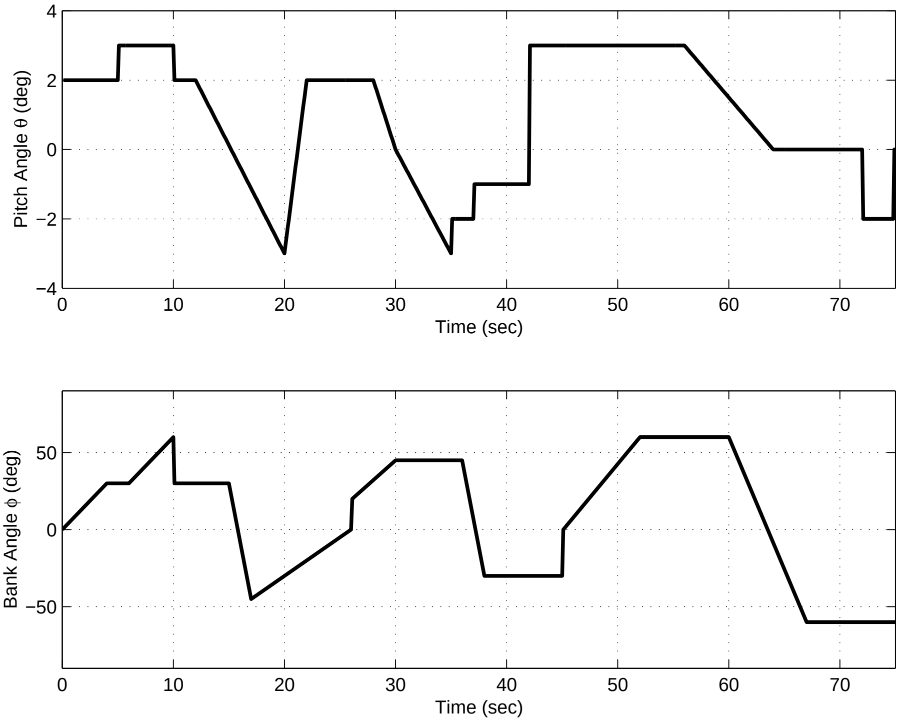

Figure 4.2 Pitch and Bank Commands for HUD Discrete Tracking Task

a target aircraft. The synthetic target followed the discrete pitch and bank profile described in MIL-HDBK 1797A (Figure 4.2). The discrete task lasted 75 seconds. When tracking a target aircraft, the target was set up approximately 2500 feet in front of the test aircraft and flew 3G turns, reversing every 20 seconds.

The tracking technique used with each task was to aggressively acquire the target, actively stabilize on it and fine track in a way to quickly correct every motion away from the target. This aggressive technique was designed to stress the actuator rate limiter and minimize the track error. The pilot tracked the target using 10- and 20-mil radius reticles.

Task performance and pilot workload were used to obtain a Cooper Harper Rating (CHR) from Figure A.2. Performance criteria used to assign a CHR for the HUD tracking task were:

- Desired - 75% of the track time, have the target within the 10-mil reticle
- Adequate - 75% of the track time, have the target within the 20-mil reticle

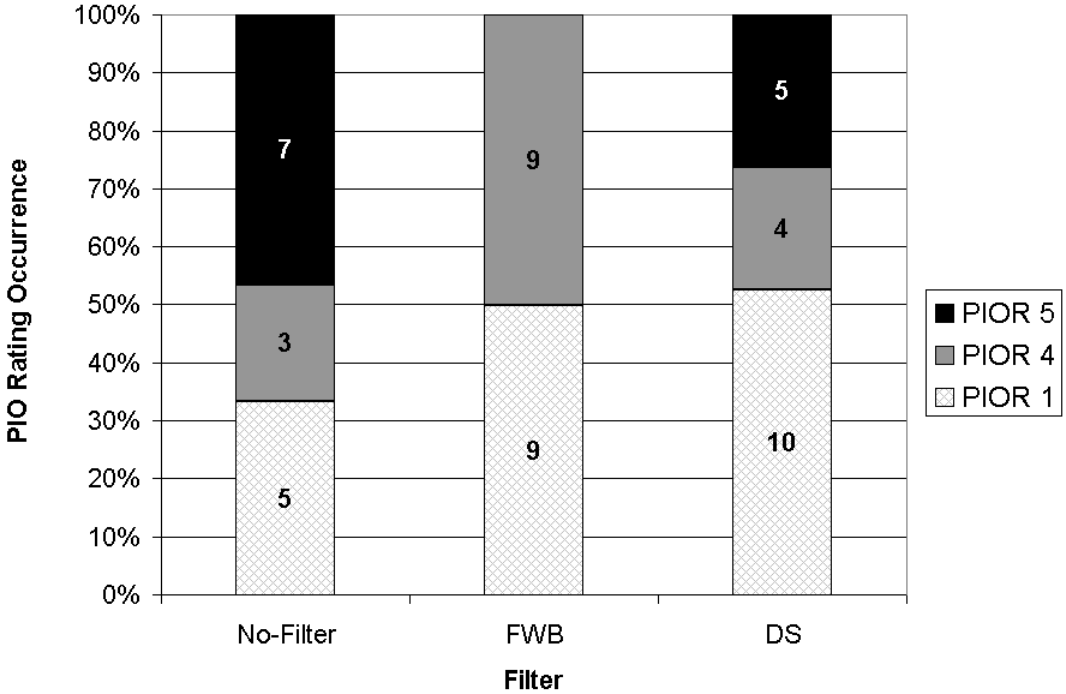

Figure 4.3 Simulator PIO Rating Comparison - Case C (60, 45, 30 deg/sec)

During or immediately following the Phase 3 task, pilot comments were recorded and a CHR was assigned.

4.4 Simulator PIO Results

For each Phase 2 task, occurrence of actuator rate limiting, a PIO rating and pilot comments were recorded. The data were restricted to test cases where rate limiting was achieved. This occurred during 96 of the 97 test points. The rate of PIO occurrence and whether the PIO was divergent or bounded were examined. Only configurations with at least three rate-limited test points per filter choice were analyzed. This included Case C and D configurations with actuator rate limits at or above 30 deg/sec. The Five-Point General Purpose Scale was used to describe which filter configuration better prevented PIO for each case.

4.4.1 Case C. Rate limiting occurred on the Phase 2 task during 52 Case C test points with actuator rate limits at or above 30 deg/sec. Figure 4.3 shows the results of the investigation. The FWB and DS filter performed about the same in reducing the number of PIO encountered. Both reduced PIO occurrence from 67% to approximately 50%. However, the FWB filter was able to completely prevent divergent PIO (PIO rating 5) from occurring, while the DS filter encountered a divergent PIO approximately 25% of the time. A divergent PIO is much more dangerous, as it almost always leads to aircraft departure. Therefore, while the DS filter and No-Filter performed about the same, the FWB filter was much better than both the DS and No-Filter configurations in preventing divergent PIO.

For Case C, each actuator rate limit was examined more closely to determine filter performance (Figure 4.4). The likelihood of PIO increased as actuator rate limit decreased, except with the FWB filter. Its performance was independent of rate limit.

4.4.2 Case C, 60 deg/sec. The FWB filter had the highest occurence of PIO. However, all PIO encountered with the FWB filter were bounded (Figure 4.4). The DS filter was about the same as the No-Filter configuration at reducing the occurrence of PIO, and both experienced divergent PIO. The FWB filter was better than both the No-Filter and DS configurations because it always prevented divergent PIO.

4.4.3 Case C, 45 deg/sec. All three configurations prevented PIO about the same (Figure 4.4). However, all PIO with the FWB filter were bounded. The FWB filter was better than the DS and No-Filter configurations because of it's ability to bound PIO. The DS filter was about the same as with no filter in preventing PIO.

4.4.4 Case C, 30 deg/sec. The DS filter was able to prevent PIO only once, making its performance about the same as with no filter (Figure 4.4). The FWB filter configuration was much better than the No-Filter and DS configurations at reducing the occurrence of PIO and keeping the oscillations bounded.

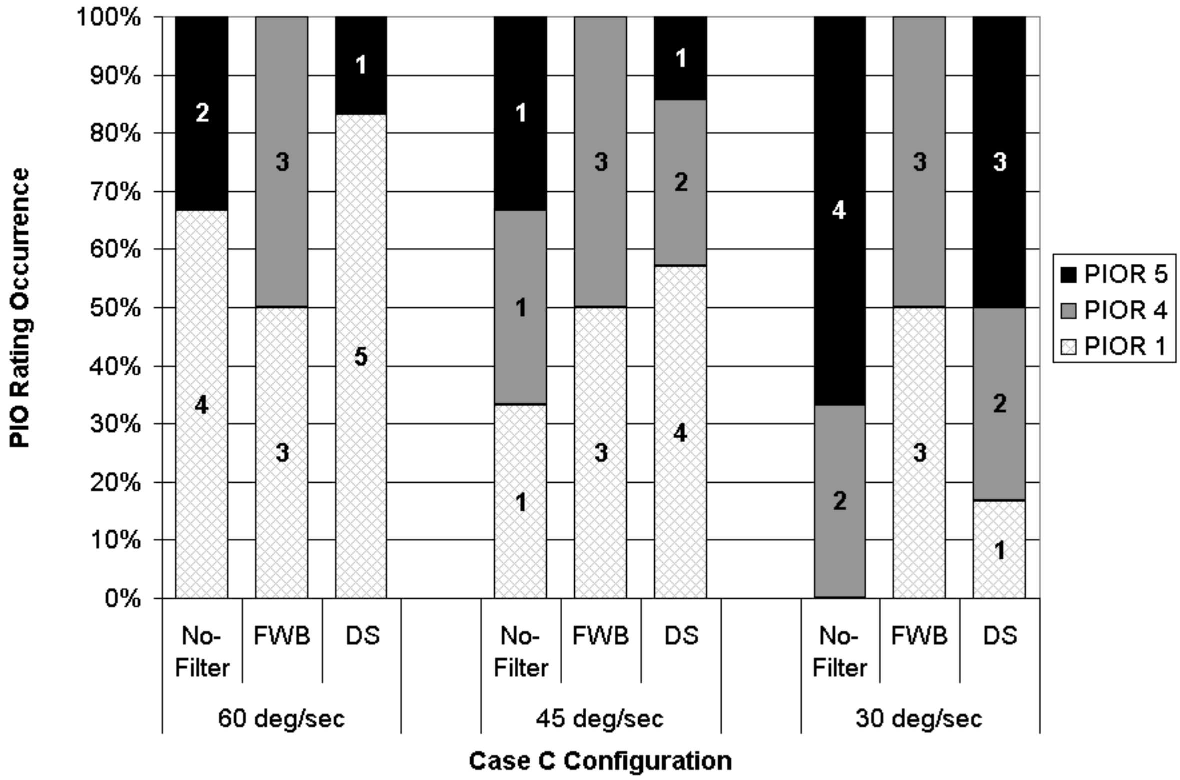

Figure 4.4 Simulator PIO Rating Comparison by Rate Limit - Case C

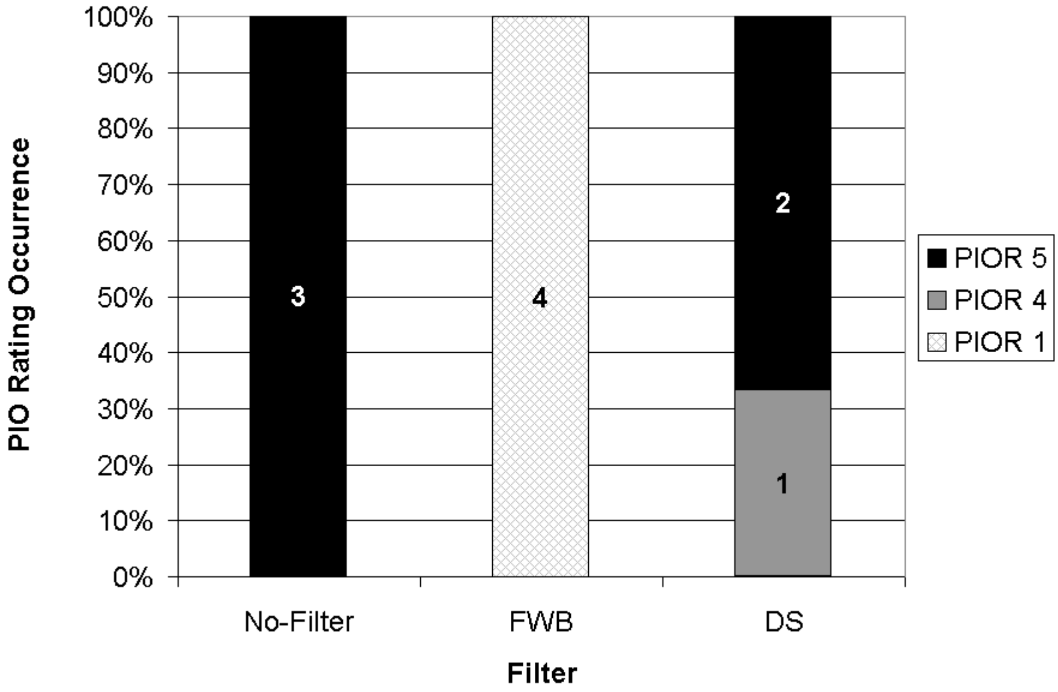

Figure 4.5 Simulator PIO Rating Comparison - Case D - 60,45,30 deg/sec

4.4.5 Case D. Rate limiting occurred on the Phase 2 task during 10 Case D test points with actuator actuator rate limits at or above 30 deg/sec (Figure 4.5). The FWB filter was able to prevent both bounded and divergent PIO every time while the DS filter was never able to prevent PIO. The advantage of the FWB filter was clear. The FWB filter was designed for an aircraft with unstable unaugmented dynamics, the Gripen, and was well suited for Case D. The FWB performed much better than both the DS and No-filter configurations. The DS filter performed about the same as with no filter.

4.4.6 Overall Simulator PIO Results. Table 4.2 summarizes the simulator PIO results. The best configuration for all rate-limited simulator test cases was the FWB filter. Although it was not capable of reducing the total number of PIO occurrences for all test cases, it was capable of keeping the oscillations bounded. The FWB filter performance was also independent of rate limit. The DS filter reduced the number of times PIO occurred, but as with no filter, the majority of oscillations were still divergent. The DS filter performed about the same as the No-Filter configuration.

Aircraft Case	Rate Limit	FWB vs No-Filter	DS vs No-Filter	FWB vs DS	Best Performer
C	All	Much Better	About the Same	Much Better	FWB
	60 deg/sec	Better	About the Same	Better	FWB
	45 deg/sec	Better	About the Same	Better	FWB
	30 deg/sec	Much Better	About the Same	Much Better	FWB
D	All	Much Better	About the Same	Much Better	FWB

Table 4.2 PIO Comparision Summary - Simulator

4.5 Filter Effect on Handling Qualities

For each Phase 3 task, occurrence of actuator rate limiting, a CHR, and pilot comments were recorded. Only test points where rate limiting was achieved sometime during the task were compared. This occurred during 88 of the 97 points. Pilot comments and handling qualities (HQ) levels were compared for each configuration. Only configurations with at least three rate-limited test points per filter choice were analyzed. This included Case C and D configurations with actuator rate limits at or above 30 deg/sec. The combination of pilot ratings and comments determined which was better. The Five-Point General Purpose Scale was used to describe which filter configuration had the best handling qualities for each case.

4.5.1 Case C. Rate limiting occurred on the Phase 3 tasks during 50 Case C test points. Figure 4.6 shows the results of the investigation. The FWB filter was able to increase the number of Level 1 HQ ratings from the No-Filter configuration. During rate limiting, the FWB filter did not draw the pilot into larger inputs, keeping the aircraft steady and predictable. Pilots commented that compensation was minimal or moderate to control any oscillations. In contrast, the DS filter caused the aircraft to become uncontrollable 15% of the time. Pilots reported having to relax or release the controls with this filter. Figures 4.7 and 4.8 show the difference in number and magnitude of oscillations with these two filters. The FWB filter performed better than No-Filter, and much better than the DS filter. Adding the DS filter made HQ much worse.

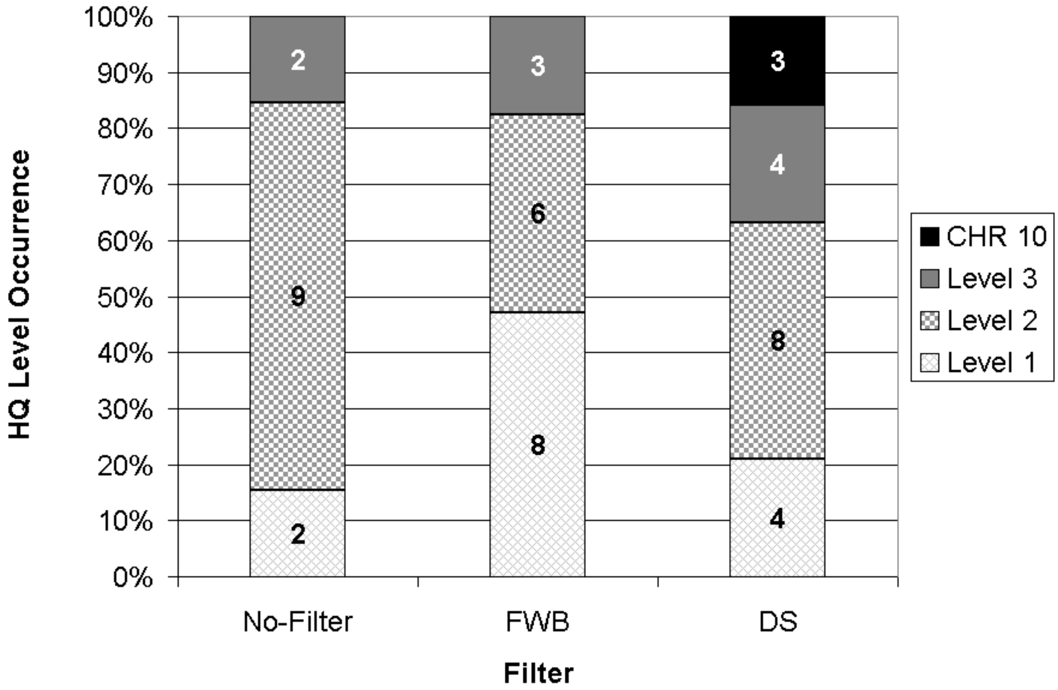

Figure 4.6 Simulator Cooper-Harper Ratings - Case C

For Case C, each actuator rate limit was examined more closely to determine filter performance (Figure 4.9). As expected, handling qualities degraded as actuator rate limit decreased.

4.5.2 Case C, 60 deg/sec. The size of oscillations was the pilot's primary concern at this rate limit. When tracking aggressively with the No-Filter configuration, large oscillations about the target were easily induced. These oscillations led to predominantly Level 2 CHR (Figure 4.9). The FWB filter tended to decrease oscillations around the target in all cases. The reduced oscillations led to better HQ ratings than any other configuration. With the DS filter, oscillations about the target were generally decreased compared to the No-Filter configuration but were still present due to a perceived time delay by the pilots, observed as a difference between stick input and aircraft movement. The delay generated a Level 3 rating from one pilot due to a PIO, the only one encountered at this rate limit. Based upon CHR and pilot comments, the FWB configuration was better

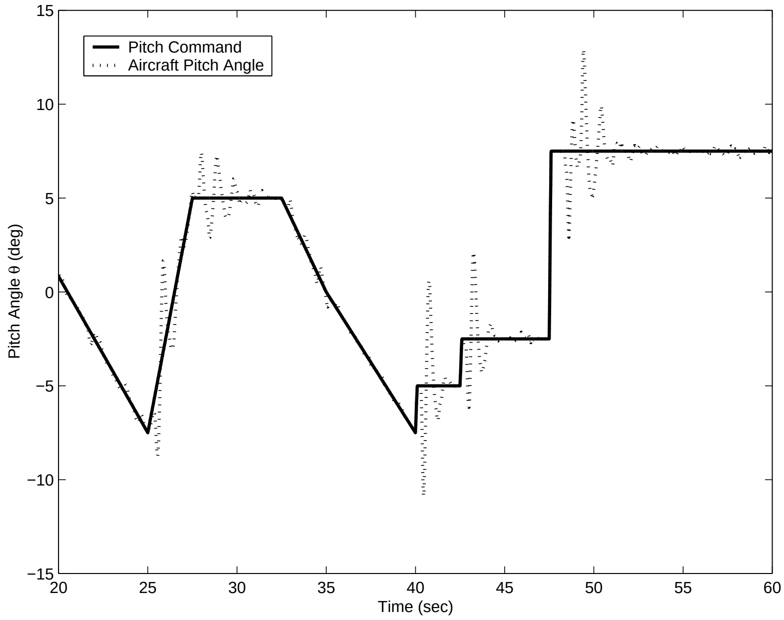

Figure 4.7 Simulator Performance during Discrete Tracking Task - FWB Filter, Case C

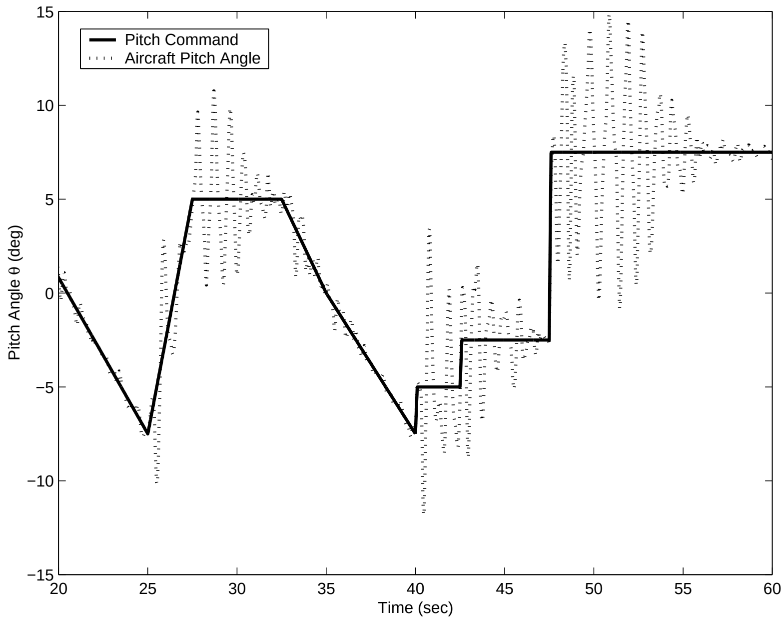

Figure 4.8 Simulator Performance during Discrete Tracking Task - DS Filter, Case C

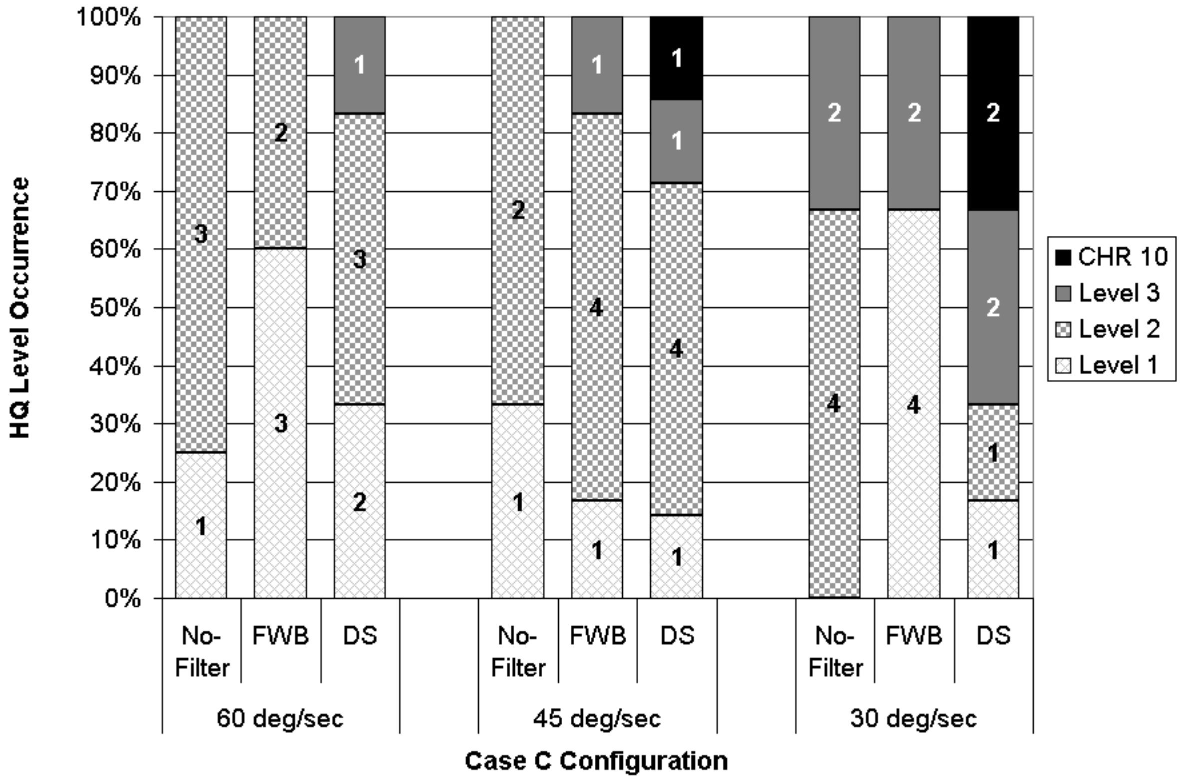

Figure 4.9 Simulator Cooper-Harper Ratings by Rate Limit - Case C

than the No-Filter configuration, while the DS configuration was worse than having no filter.

4.5.3 Case C, 45 deg/sec. The effects of rate limiting were more visible during these test points. The majority of these cases were rated with Level 2 HQ (Figure 4.9), but there was a wide spectrum of ratings. Controlling oscillations during large pitch captures was the primary concern of the pilots. With the No-Filter configuration, there were small oscillations around the target that could be controlled easily. With the FWB filter, the oscillations about the target could be controlled through pilot technique. There were fewer oscillations than the No-Filter configuration, and the oscillations were also smaller in amplitude. With the DS filter, the oscillations around the target were the hardest to control, which generally led to worse ratings and caused one pilot to PIO and release the controls. Level 3 and uncontrollable ratings were given 2 of 7 times with the DS filter configuration. Based upon pilot rating and comments, the FWB filter and No-Filter configurations were about the same, while both were much better than the DS filter.

4.5.4 Case C, 30 deg/sec. Aircraft controllability became an issue at this rate limit. The No-Filter configuration produced only Level 2 and Level 3 ratings (Figure 4.9). Control during task execution was never lost in any test run. Considerable compensation was necessary to dampen oscillations near the target. This compensation detracted from overall performance and caused considerable to intolerable overall workload for the pilot. The FWB filter configuration produced significantly more Level 1 ratings than the others. More importantly, task execution was never uncontrollable. The oscillations around the target were never divergent. The DS filter was the worst of the three configurations. During 2 of the 5 test points PIO were encountered, forcing the pilots to release the stick to recover. With aggressive inputs, the large phase lag present in the system drew pilots into larger and larger inputs. Control was only achievable using small inputs. There was a large variation in the ratings for this point, which may have been due to different pilot techniques to dampen out the oscillations. However, Level 3 ratings or worse were given 3 of 5 times. The pilots who were able to complete the task had to reduce their gains to eliminate the oscillations. The ratings and comments showed that FWB had better

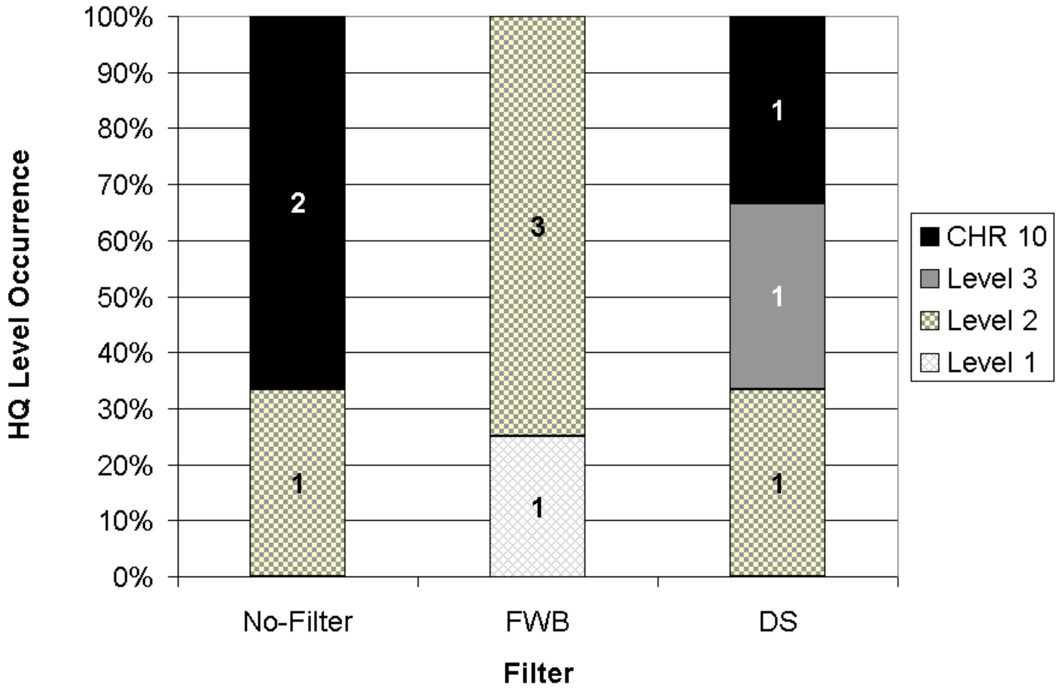

Figure 4.10 Simulator Cooper-Harper Ratings - Case D

handling qualities for the task than either the DS or No-Filter configurations. The DS configuration degraded handling qualities, making it much worse than with no filter.

4.5.5 Case D. Rate limiting occurred on the Phase 3 tasks during 10 Case D test points. As expected, with no filter the aircraft exhibited uncontrollable HQ most of the time. The Level 2 rating was a result of under-aggressive pilot technique, which did not stress the actuators enough to expose the bare aircraft dynamics. The FWB filter performed exceptionally well for Case D. Only Level 1 and 2 ratings were given (Figure 4.10). Pilots commented that this configuration had only small oscillations, with a low workload for aircraft control. In contrast, pilots flying with the DS filter commented that considerable compensation was required to keep the aircraft controllable. Figures 4.11 and 4.12 show the difference in size and number of oscillations that the pilots encountered with each filter. Controlling the larger oscillations seen in Figure 4.12 greatly increased pilot workload, leading to lower HQ ratings. These figures demonstrate the clear advantage of

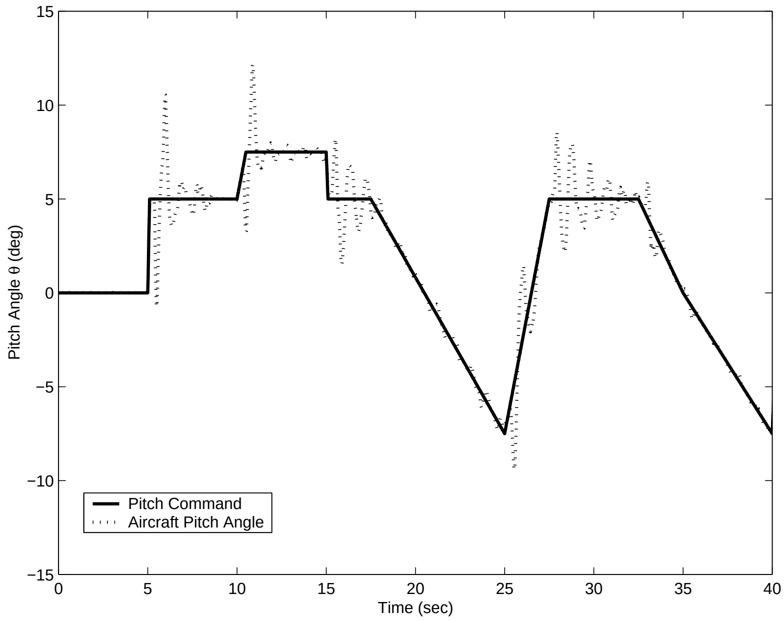

Figure 4.11 Simulator Performance during Discrete Tracking Task - FWB, Case D

the FWB filter during Case D. The FWB performed much better than both the DS and No-Filter configurations. The DS filter performed about the same as with no filter.

4.5.6 Overall Simulator Handling Qualities Results. The goal of these two filters was to reduce phase lag during actuator rate limiting. During an operational evaluation, configurations with either filter should not interfere with aircraft HQ, but make the aircraft easier to control during large oscillations. The FWB filter was able to accomplish this goal, while the DS filter generally degraded HQ. Control was lost twice as often (4 vs. 2) when using the DS filter versus no filter at all. The DS filter caused divergent PIO, leading to these uncontrollable HQ ratings. Control during task execution was never lost while using the FWB filter. The FWB filter had the same or better handling qualities for all rate limit cases (Table 4.3), and its performance was especially good with unstable bare airframe dynamics (Case D).

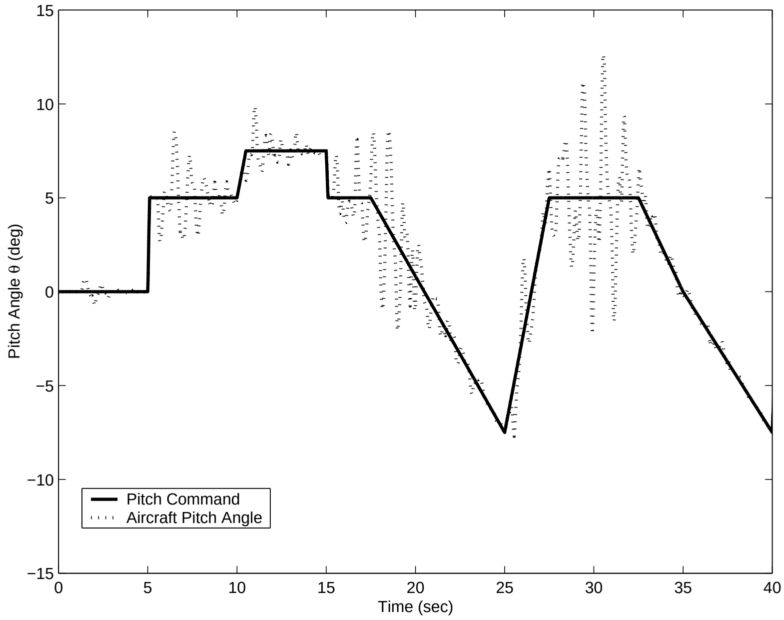

Figure 4.12 Simulator Performance during Discrete Tracking Task - DS, Case D

Aircraft Case	Rate Limit	FWB vs No-Filter	DS vs No-Filter	FWB vs DS	Best Performer
C	All	Better	Much Worse	Much Better	FWB
	60 deg/sec	Better	Worse	Better	FWB
	45 deg/sec	About the Same	Much Worse	Better	FWB
	30 deg/sec	Better	Much Worse	Better	FWB
D	All	Much Better	About the Same	Much Better	FWB

Table 4.3 HQ Comparision Summary - Simulator

V. Flight Test Results

The third and final step of this study was to compare the FWB and DS filters in flight. The objectives of the flight tests were to compare the ability of two flight control system filters to prevent PIO during actuator rate limiting, and the filters' effects on aircraft handling qualities. Test flights were conducted at Edwards AFB, CA, from 16 to 23 October 2002. Thirteen test sorties, 21.0 total flight hours, were accomplished in the Variable Stability In-flight Simulator Test Aircraft (VISTA) NF-16D.

5.1 Aircraft Description

The NF-16D VISTA was a modified F-16D aircraft with a digital flight control system. To allow the pilot in command/safety pilot (SP) to fly from the rear cockpit, all essential controls were moved from the front to the rear cockpit. The rear cockpit had conventional F-16 controls except that the throttle was driven by a servo, which followed the electrical commands of the front cockpit when the VISTA Simulation System (VSS) was engaged. Primary system engagement and VSS controls and displays were located in the rear cockpit. The front cockpit included the VSS control panel needed for the EP to engage the variable feel center stick. Other modifications to the aircraft included a high flow rate hydraulic system with increased capacity pumps and higher rate actuators. The maximum actuator rate was approximately 69 deg/sec.

The VSS was modified with the flight control system from Figure 3.8. The short period dynamics of Cases A, B, C, and D aircraft dynamics were matched in the VSS at 300 KIAS and 15,000 ft. Four separate actuator rate limits (60, 45, 30, and 15 deg/sec) were available. The SP could select any combination of aircraft dynamics, rate limit and filter from the test matrix (Table 4.1).

5.2 Test Procedures

Test points, shown in Table 4.1, were identical to those used in ground simulation. All testing was conducted at 15,000 ft and 300 KIAS. The SP selected the test point combination of airframe dynamics, actuator rate limit, and filter. The EP, blind to the exact configuration, then performed a HQ investigation. The investigation was divided into three parts: Phases 1, 2, and 3 [17].

Tracking tasks used during the Phase 2 and 3 investigation were identical to those used in LAMARS. However, during aircraft calibration the test team realized that the HUD reticles used in the simulator were too large. The reticles were set to 10 and 20 mil radius instead of diameter. This increased target tracking scores above the intended level. To lower tracking scores to an acceptable range, the smaller reticle size was used and the discrete tracking task performance criteria were changed to:

- Desired - 45% of the track time, have the target within the 10-mil reticle
- Adequate - 45% of the track time, have the target within the 20-mil reticle

All other test procedures were identical to those used in the ground simulator.

5.3 Flight Test PIO Results

For each Phase 2 task, occurrence of actuator rate limiting, a PIO rating and pilot comments were recorded. The data were restricted to test cases where rate limiting was achieved. This occurred during 109 of the 130 test points. The rate of PIO occurrence and whether the PIO were divergent or bounded were examined. Only configurations with at least three rate-limited test points per filter choice were analyzed. This included all Case C configurations and Case D configurations with actuator rate limits at or above 45 deg/sec. The Five-Point General Purpose Scale was used to describe which filter configuration better prevented PIO for each test case.

The Phase 2 flight tests were affected by an apparent non-linearity in the VISTA center stick dynamics. Pilot comments indicated that, for high-frequency inputs, stick force increased suddenly and slowed down the pilot's inputs. As a result, the stick dynamics may have prevented rate limiting for some of the higher rate limit configurations. However, this bias was constant across all three filter types for any given aircraft configuration, so the stick dynamics' effect on the comparison was not an issue.

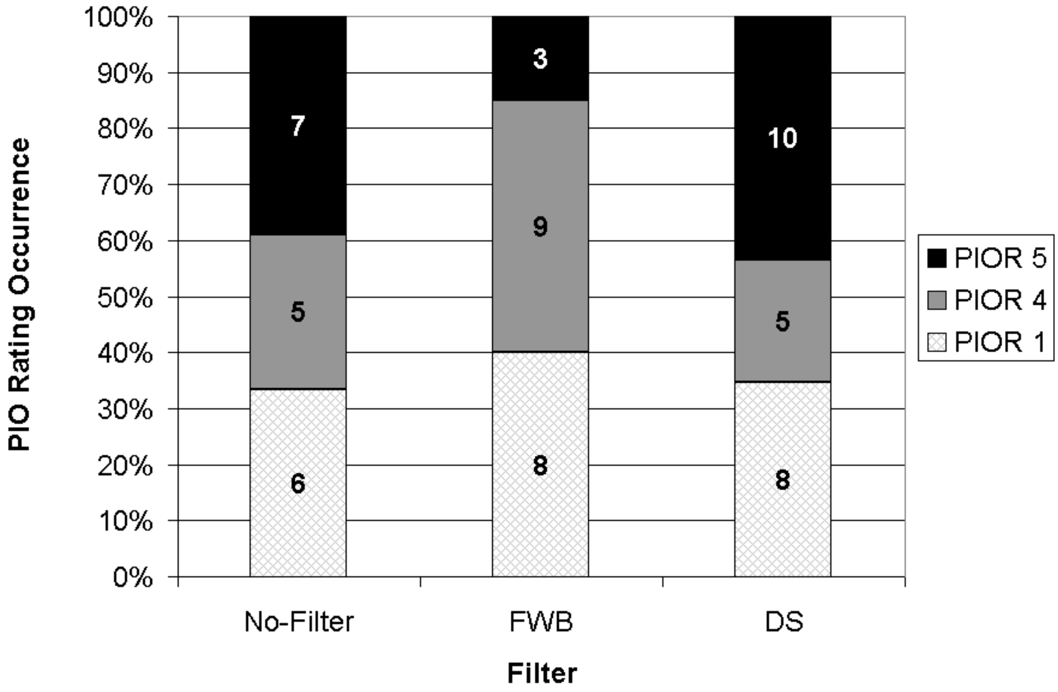

Figure 5.1 Flight Test PIO Rating Comparison - Case C

5.3.1 Case C. Rate limiting occurred on the Phase 2 task during 52 Case C test points. Figure 5.1 shows the results of the investigation. The FWB and DS filter both only marginally reduced the occurrence of PIO. However, the FWB filter was able to reduce divergent PIO (PIO rating 5) from occurring, while the DS filter encountered a divergent PIO as often as with no filter. Therefore, the FWB filter performed better than both the DS filter and No-Filter configurations in preventing divergent PIO. The performance of the DS filter was about the same as with no filter.

For Case C, each actuator rate limit was examined more closely to determine filter performance (Figure 5.2). As expected, the likelihood of PIO increased as actuator rate limit decreased.

5.3.2 Case C, 60 deg/sec. Neither the No-Filter nor the FWB configurations experienced PIO at this rate limit. However, the DS filter encountered PIO 33% of the time. Figures 5.3 and 5.4 show the difference in phase lag with each of the two filters.

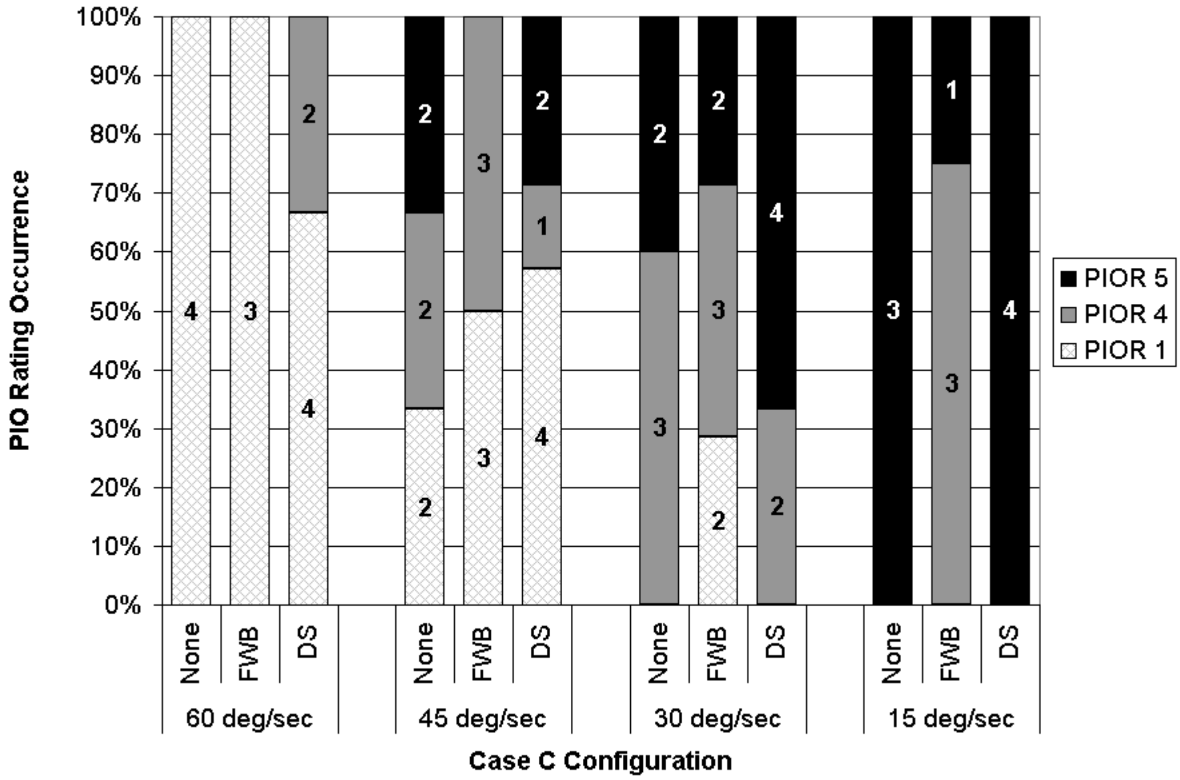

Figure 5.2 Flight Test PIO Rating Comparison by Rate Limit - Case C

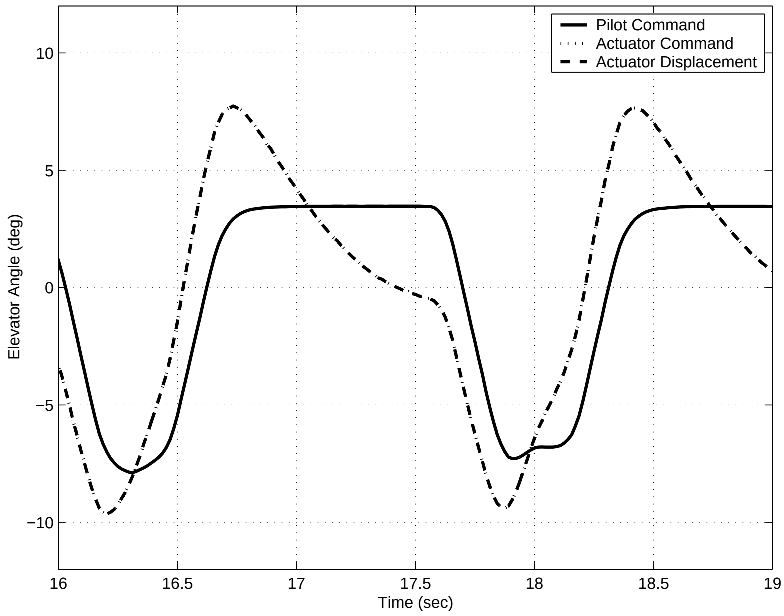

Figure 5.3 Example of Minimal Phase Lag with FWB Filter - Case C, 60 deg/sec

With the FWB filter (Figure 5.3) the elevator displacement remained closely in phase with the pilot command. With the DS filter (Figure 5.4), there was a significant time delay between pilot command and elevator response. The larger time delay led to more PIO with the DS filter. Also, although each filter configuration was tested 6 times, only the DS filter encountered rate limiting every time. Even when the pilots tried to rate limit, it only occurred 50% of the time with the FWB filter and 67% with no filter. The No-Filter and FWB filter configurations performed about the same, and both performed better than the DS filter configuration.

5.3.3 Case C, 45 deg/sec. The FWB filter was the only configuration without divergent PIO. While the DS filter was able to reduce the occurrence of PIO, the rate of divergent PIO remained the same. Preventing this dangerous type of PIO is critical to the success of either filter, and only the FWB filter could accomplish this. The FWB filter performed better than the DS and No-Filter configurations, which performed about the same.

5.3.4 Case C, 30 deg/sec. The FWB filter reduced the number of PIO, but could not prevent divergent PIO at this low rate limit. The DS and No-Filter configurations experienced PIO every time, with the DS filter encountering divergent PIO twice as often. The FWB filter controlled the magnitude of the oscillations about the same as with no filter, with 2 test points being divergent on each. However, the FWB filter was able to prevent PIO almost 30% of the time. The FWB filter performed better than the No-Filter configuration, and both performed better than the DS filter configuration.

5.3.5 Case C, 15 deg/sec. All three filter configurations experienced PIO every time. The No-Filter and DS configurations always experienced divergent oscillations, while the FWB filter kept the oscillations bounded 3 out of 4 times. The FWB filter configuration performed better than the No-Filter and DS filter configurations, which performed about the same.

5.3.6 Case D. Rate limiting occurred on the Phase 2 task during 15 Case D test points with actuator rate limits at or above 45 deg/sec (Figure 5.5). Below this rate limit, the filters had no effect and all PIO were divergent.

The FWB filter was able to prevent divergent PIO every time. A bounded PIO was only experienced on 1 of 7 test points. The DS filter was able to prevent PIO only once, and encountered divergent PIO 50% of the time. Figures 5.6 and 5.7 explain these results. With the FWB filter, almost no phase lag was present. With the DS filter, the Phase lag was more pronounced and grew larger with each succeeding oscillation. The advantage of the FWB filter was clear. As in the simulator, the FWB filter was well suited for Case D. The FWB performed much better than both the DS and No-Filter configurations. The DS filter performed about the same as with no filter.

5.3.7 Overall Flight Test Results on PIO Prevention. The FWB filter was the best configuration in preventing divergent PIO. Divergent PIO were only encountered with a combination of poor unaugmented aircraft dynamics and low actuator rate limits. At rate limits at or above 45 deg/sec, similar to those of operational aircraft, PIO were only encountered on 25% of the test points with the FWB filter, and all PIO were bounded. In

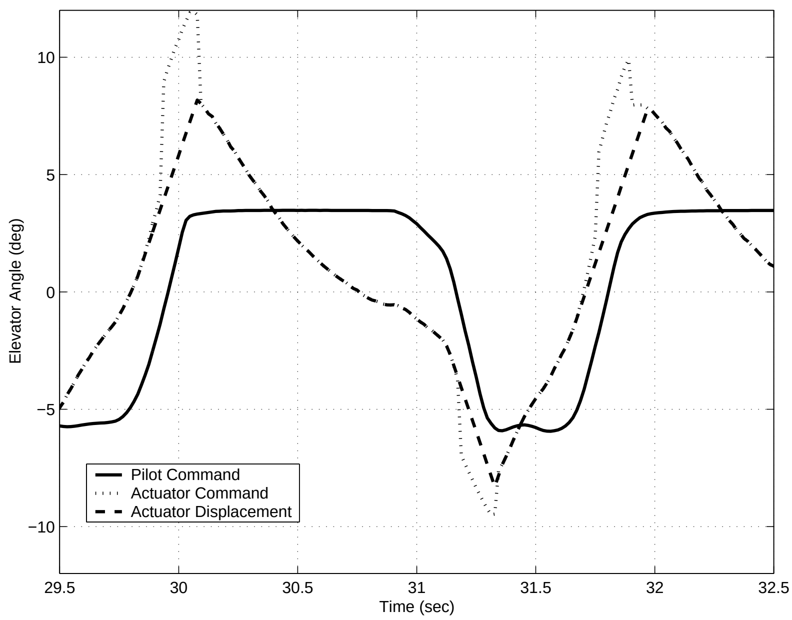

Figure 5.4 Example of Increased Phase Lag with DS Filter - Case C, 60 deg/sec

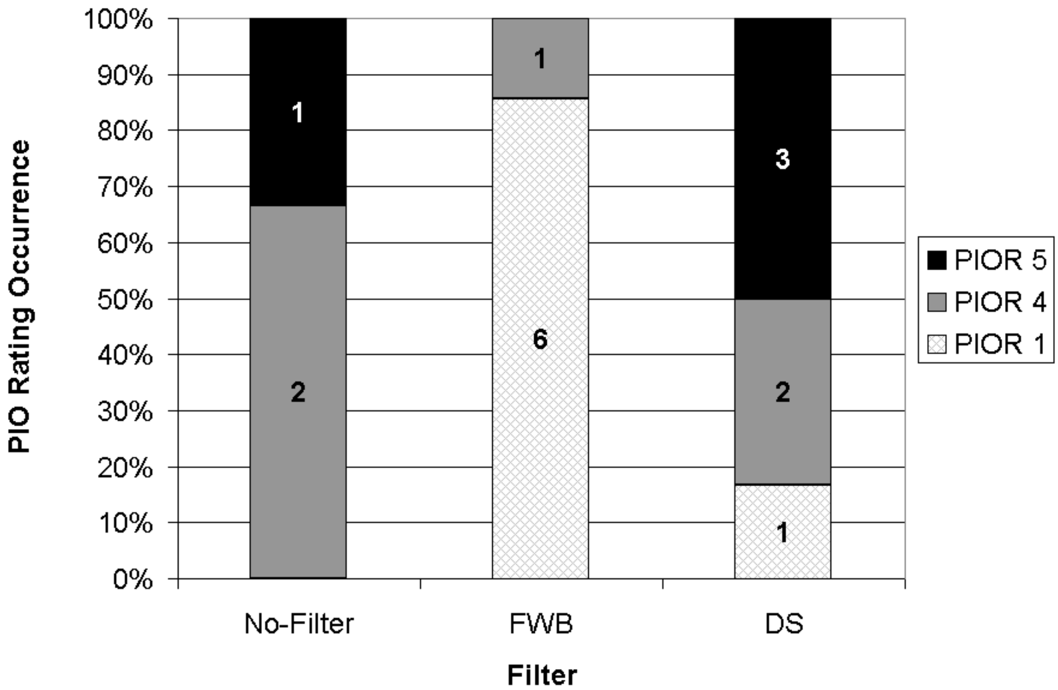

Figure 5.5 Flight Test PIO Rating Comparison - Case D - 60 and 45 deg/sec

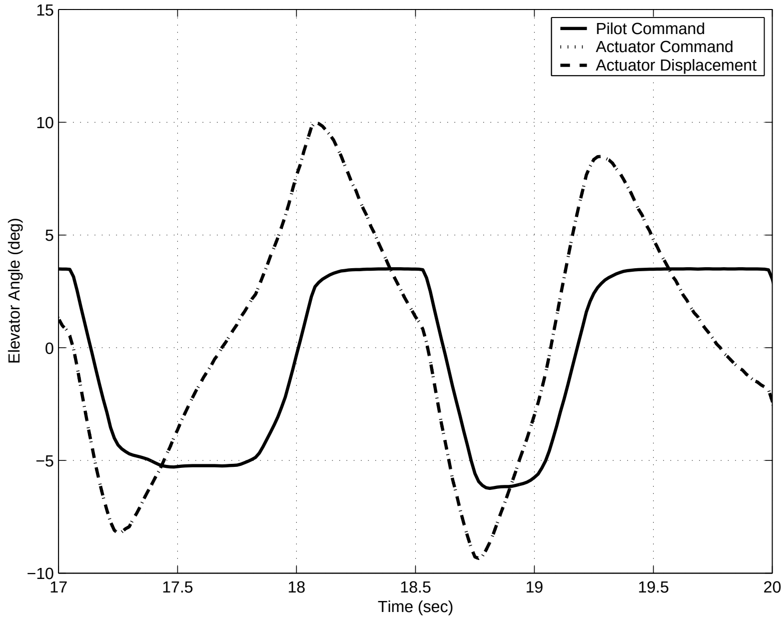

Figure 5.6 Example of Minimal Phase Lag with FWB Filter - Case D, 60 deg/sec

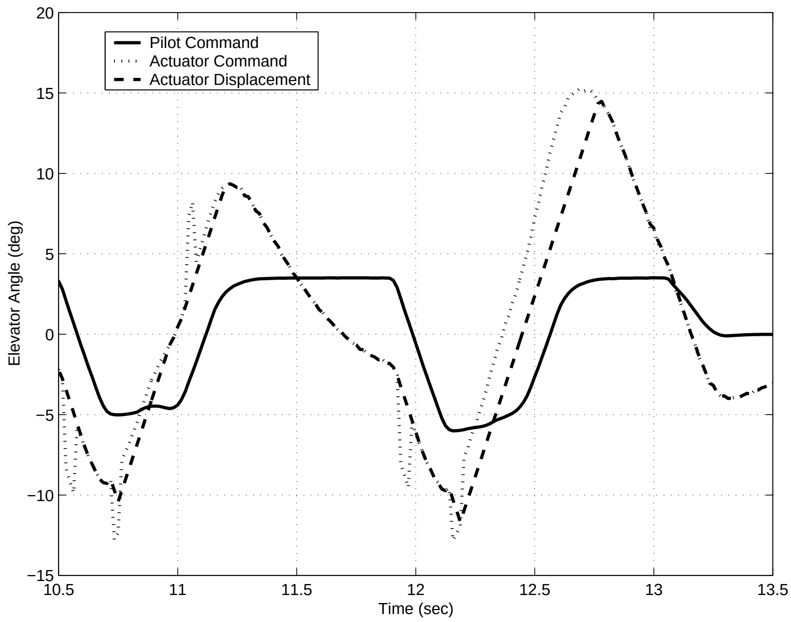

Figure 5.7 Example of Increased Phase Lag with DS Filter - Case D, 45 deg/sec

contrast, the DS filter experienced PIO over 50% of the time for these higher rate limits, and half of the occurrences were divergent. The FWB filter performance was better than with no filter at every condition examined but Case C, 60 deg/sec, where no PIO were experienced. The VISTA stick dynamics could have been a factor at this rate limit. The DS filter performed about the same or worse than with no filter at every condition.

Aircraft Case	Rate Limit	FWB vs No-Filter	DS vs No-Filter	FWB vs DS	Best Performer
C	All	Better	About the Same	Better	FWB
	60 deg/sec	About the Same	Worse	Better	FWB
	45 deg/sec	Better	About the Same	Better	FWB
	30 deg/sec	Better	Worse	Better	FWB
	15 deg/sec	Better	About the Same	Better	FWB
D	All	Much Better	About the Same	Much Better	FWB

Table 5.1 PIO Comparision Summary - Flight

5.4 Filter Effect on Handling Qualities

5.4.1 Flight Test Results on Handling Qualities. For each Phase 3 task, occurrence of actuator rate limiting, a CHR, and pilot comments were recorded. Only the tasks where rate limiting was achieved sometime during the task were compared. This occurred during 94 of the 130 points. Configurations with at least three rate-limited test points per filter choice were analyzed. Pilot comments and CHR levels were compared for all Case C configurations and Case D configurations at or above 45 deg/sec. The combination of pilot ratings and comments were compared for each configuration. The Five-Point General Purpose Scale was used to describe which filter configuration resulted in the best handling qualities for each case.

5.4.2 Case C. Rate limiting occurred during the Phase 3 tasks on 56 Case C test points. Figure 5.8 shows the results of the investigation. As expected, pilots commented that the No-Filter configuration was very oscillatory, with several PIO encounters during aggressive tracking. The FWB filter was able to eliminate the uncontrollable rating seen once in the No-Filter configuration. With the FWB filter, pilots commented about the oscillations, but rated them as easy to control. In contrast, the DS filter caused the

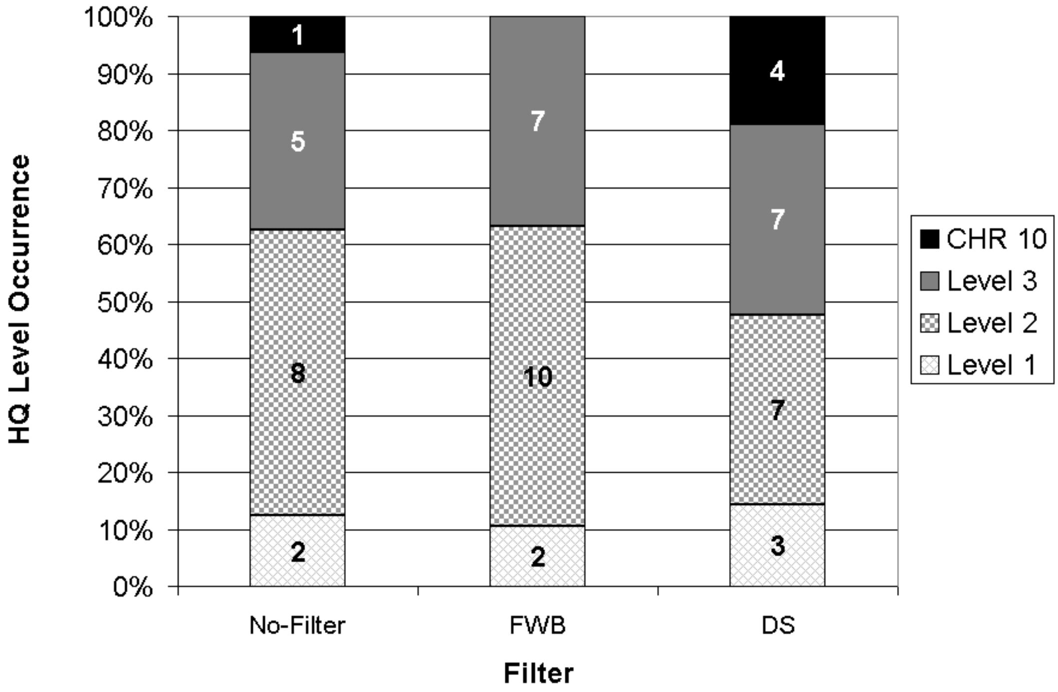

Figure 5.8 Flight Test Cooper-Harper Ratings - Case C

aircraft to become uncontrollable approximately 20% of the time. This configuration was rated as barely controllable, with several divergent PIO encountered. Figure 5.9 shows the easily controlled response of the FWB filter compared to the nearly uncontrollable performance with the DS filter in 5.10. The FWB filter performed better than No-Filter, and much better than the DS filter. Adding the DS filter made HQ much worse.

For Case C, each actuator rate limit was examined more closely to determine filter performance (Figure 5.11). As expected, handling qualities degraded as actuator rate limit decreased.

5.4.3 Case C, 60 deg/sec. Rate limiting was difficult to achieve in the No-Filter and FWB configurations, while it was reached 5 out of 6 times with DS filter. Six attempts were made for all configurations. The No-Filter configuration produced no undesirable handling qualities. Pilots reported the aircraft responded well, even to aggressive inputs. Pilot comments were similar for the FWB configurations. The DS filter gave the

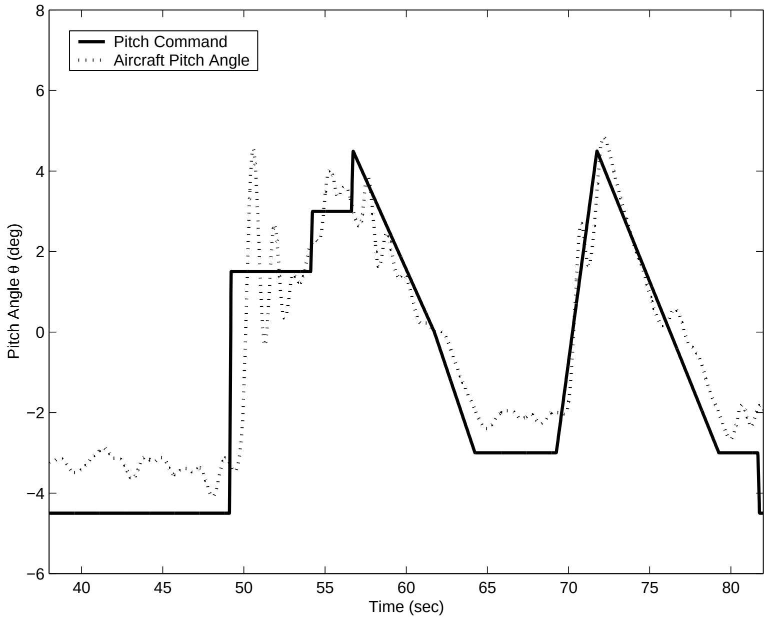

Figure 5.9 Aircraft Performance during Flight Discrete Tracking Task with FWB Filter - Case C, 30 deg/sec

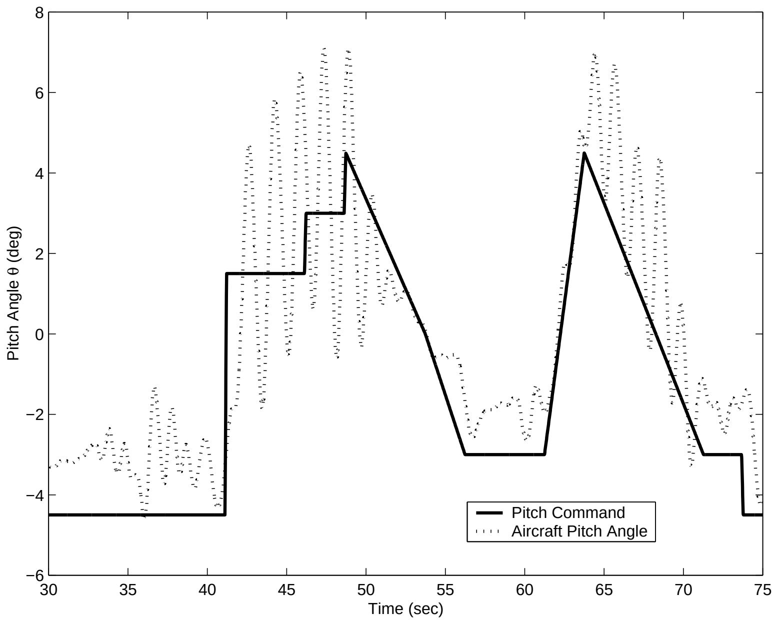

Figure 5.10 Aircraft Performance during Flight Discrete Tracking Task with DS Filter - Case C, 30 deg/sec

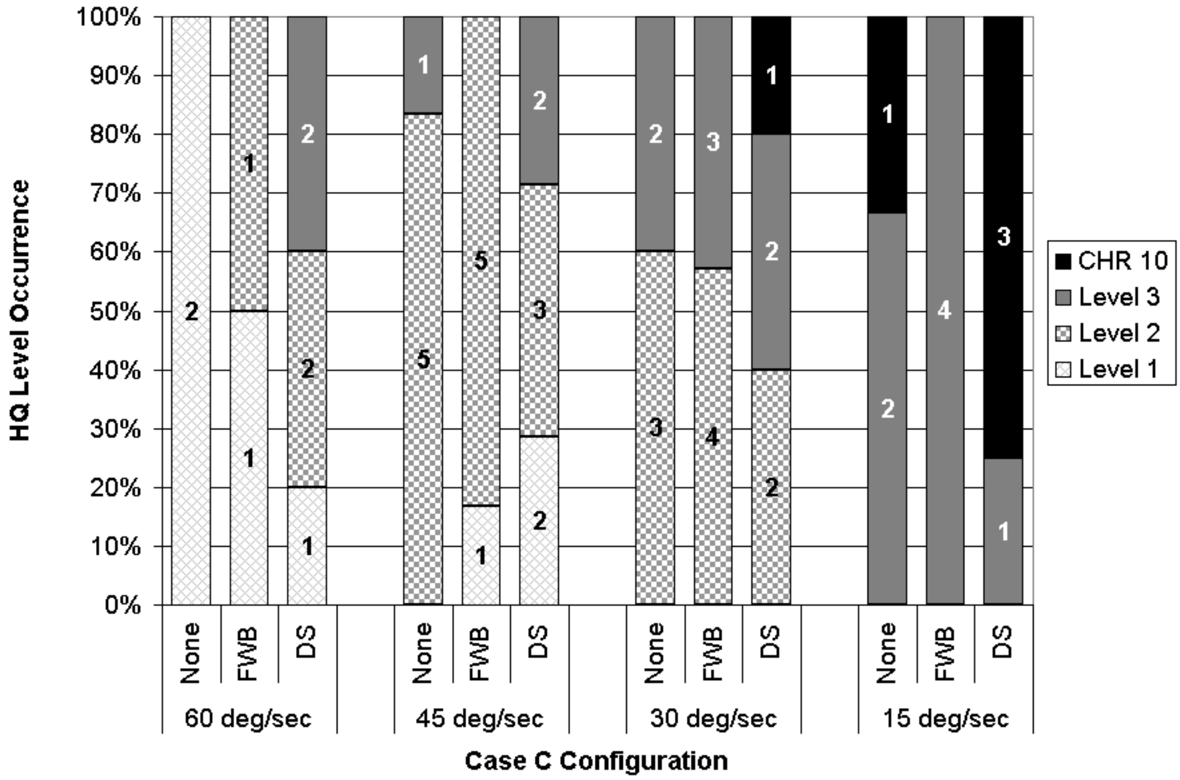

Figure 5.11 Flight Test Cooper-Harper Ratings by Rate Limit - Case C

worst performance and produced several bounded PIO. Pilots commented that they had to sacrifice the task to control oscillations with the DS filter. Because of the limited number of rate-limited test points, no comparison could be made. However with the DS filter, rate limiting occurred more often and aircraft HQ were much worse.

5.4.4 Case C, 45 deg/sec. PIO became more present during the Phase 3 tasks at this rate limit. With no filter, large oscillations were encountered every time the pilot tried to aggressively track the target, generating one Level 3 rating due to PIO and five Level 2 ratings (Figure 5.11). The FWB filter prevented PIO in all of the Phase 3 tasks. Small oscillations were encountered as the pilots tracked the target, producing Level 2 ratings. The DS filter produced both bounded and divergent PIO. One was divergent. Although the DS filter configuration produced Level 1 ratings 2 of 7 times, it also encountered PIO more often than any other configuration. The FWB filter was better than with no filter configuration, and much better than the DS filter configuration. The DS filter was about the same as with no filter.

5.4.5 Case C, 30 deg/sec. Controllability was the key issue at this rate limit. The No-Filter and FWB configurations both produced approximately 60% Level 2 and 40% Level 3 Cooper-Harper ratings (Figure 5.11). The aircraft was never uncontrollable, and oscillations around the target were never divergent. The DS filter was the worst of the three configurations. During 4 of 5 test points, PIO were reported and the pilots had to either freeze the stick or reduce their gains to recover. With aggressive inputs, the large phase lag present in the system drew pilots into larger inputs. Control was only achievable using small inputs. One pilot rated the aircraft as uncontrollable. The pilots who were able to complete the task described how they had to reduce their gains to eliminate the oscillations. The FWB and No-Filter configurations were about the same, while the DS filter configuration was worse than both.

5.4.6 Case C, 15 deg/sec. As expected, this rate limit had the poorest HQ. The No-Filter configuration led to the pilot losing control 1 of 3 times. Intense compensation was required to maintain aircraft control during task execution, and divergent oscillations

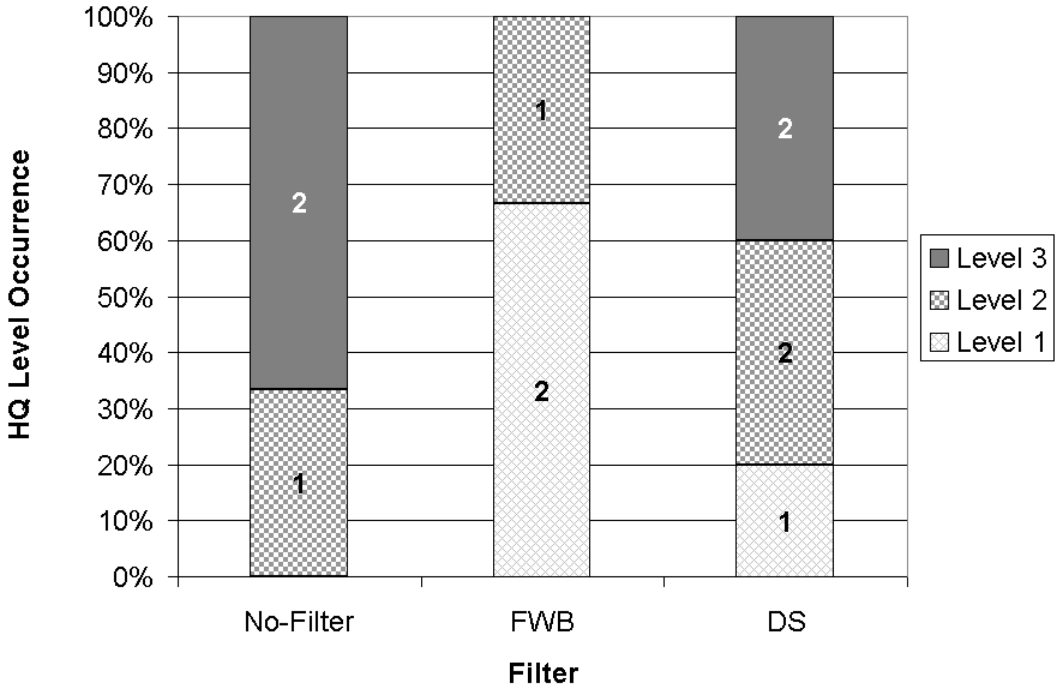

Figure 5.12 Flight Test Cooper-Harper Ratings - Case D

were encountered. The FWB filter never made task execution uncontrollable and produced Level 3 ratings every time (Figure 5.11). This configuration was the only one to allow the pilot to stay in the tracking loop the entire time. Oscillations about the target detracted from overall task performance but control could always be maintained. The DS filter produced loss of control at the beginning of any tracking, and the pilots had no chance to stay in control. The aircraft would have departed controlled flight every time if not for the safety features of the VISTA. The FWB filter had better handling qualities than both the No-Filter and DS filter configurations. The DS filter was the worst of the three.

5.4.7 Case D. Rate limiting occurred during the Phase 3 tasks on 10 Case D test points. The FWB filter performed exceptionally well for Case D. Only Level 1 and 2 ratings were given (Figure 5.12). Pilots commented this configuration had some oscillations around the target, but the oscillations could be controlled with minimal pilot compensation. In contrast, pilots flying with the DS filter commented that aircraft was very oscillatory with large overshoots and several PIO occurring. Similar comments were

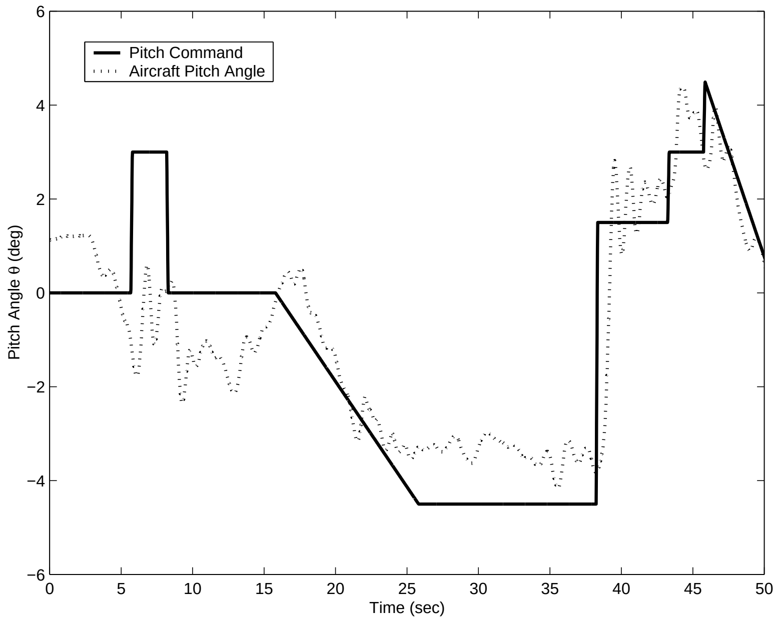

Figure 5.13 Aircraft Performance during Flight Discrete Tracking Task with FWB Filter - Case D, 60 deg/sec

given to the No-Filter configuration. Figures 5.13 and 5.14 show the controlled response of the FWB filter compared with the wildly oscillatory performance of the DS filter. The FWB performed much better than both the DS and No-Filter configurations. The DS filter performed about the same as with no filter.

5.4.8 Overall Flight Test Results on Handling Qualities. The purpose of this investigation was to prove that implementing either filter did not degrade HQ. By controlling the phase lag, each filter should have improved HQ during the rate-limited portion of the task. However, the FWB filter alone was able to accomplish this goal. The FWB filter configuration was the best overall. It consistently reduced the magnitude and number of oscillations around the target. The DS filter made HQ worse for all Case C configurations, and performed about the same as with no filter for Case D. The FWB filter was the best of the three in every aircraft case and rate limit.

Aircraft Case	Rate Limit	FWB vs No-Filter	DS vs No-Filter	FWB vs DS	Best Performer
C	All	Better	Worse	Much Better	FWB
	45 deg/sec	Better	About the Same	Much Better	FWB
	30 deg/sec	About the Same	Worse	Better	FWB
	15 deg/sec	Better	Worse	Better	FWB
D	All	Much Better	About the Same	Much Better	FWB

Table 5.2 HQ Comparision Summary - Flight

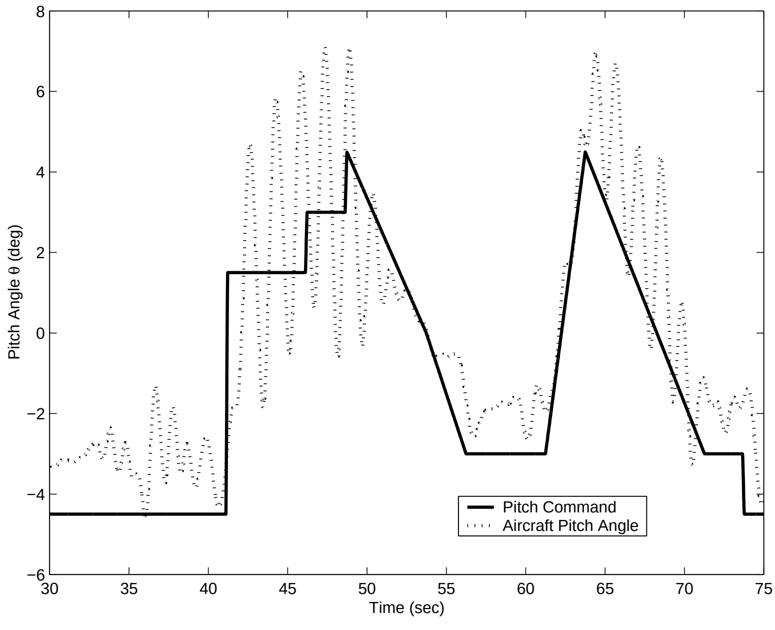

Figure 5.14 Aircraft Performance during Flight Discrete Tracking Task with DS Filter - Case D, 45 deg/sec

VI. *Performance of the Derivative-Switching Filter during Flight Test*

Following the flight test, an examination of the poor performance of the DS filter was performed. The DS filter's performance did not match the results seen during either ground simulator testing or previous flight test results [11]. During simulator testing, adding the DS filter reduced PIO susceptibility for Case C configurations. Chapa also reported during his flight test of the DS filter that adding the filter reduced PIO susceptibility [11]. However during the flight test for this study, adding the DS filter had almost no effect on preventing PIO.

The key difference between these three tests was the way the filter was implemented into the flight control system. For LAMARS testing, the Simulink diagram was converted to FORTRAN code. During Chapa's original flight test, the VISTA was also programmed in FORTRAN. During this study, the VISTA was programmed using Simulink. The derivative and integral subroutines used by Simulink were the source of the inconsistency. The flight test performed in this study was the only test that used these subroutines.

An example of the unstable performance of the Simulink derivative and integral subroutines was seen during the computer simulation (Chapter 3). During the discrete tracking task with Case C, the pilot commanded a sharp, full deflection input at 42 seconds (Figure 6.1). Instead of following the command at the actuator rate limit, the filter initially commanded the elevator to move in the opposite direction, which added a 0.2 sec time delay. This delay degraded the overall performance and resulted in a divergent PIO (Figure 6.2). This delay is due to an error in the Simulink subroutines. When the derivative subroutines in the DS filter (Figure 2.2) were replaced with the following transfer function [$G_{der}(s)$], which emulated a derivative function for frequencies below 20 rad/sec:

$$G_{der}(s) = \frac{400s}{(s+20)^2} \tag{6.1}$$

the results were much different. Both the delay and the divergent PIO were eliminated (Figures 6.3 and 6.4). $G_{der}(s)$ was the transfer function coded into VISTA during Chapa's flight tests.

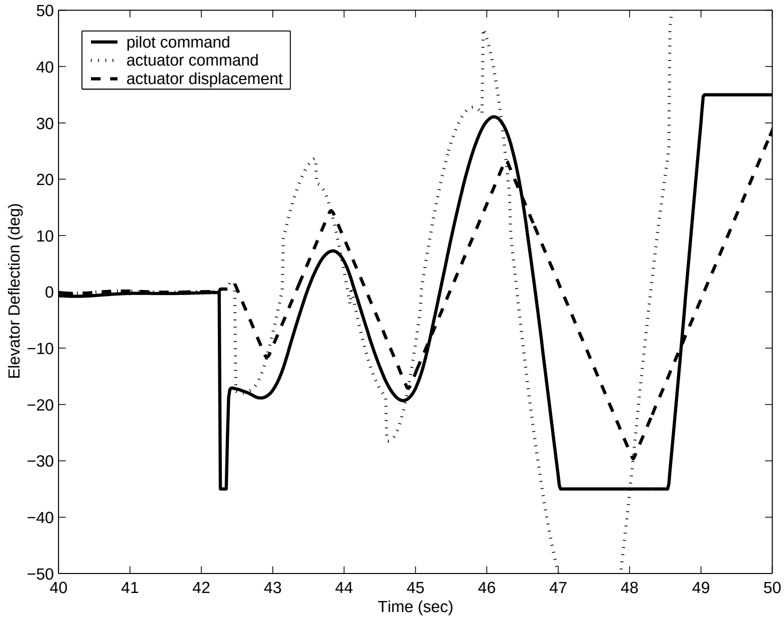

Figure 6.1 Time Delay with Original Simulink System during Discrete Task, Case C, DS

The additional time delay from the Simulink derivative and integral subroutines were the cause of the poor DS filter performance during the flight test. The flight test from this study was the only test to find no improvement in PIO susceptibility. However, all three studies found that adding the DS filter degraded handling qualities [11]. Therefore, while repeating the flight test with a modified DS filter might better prevent PIO, there is no indication that its performance would approach that of the FWB filter.

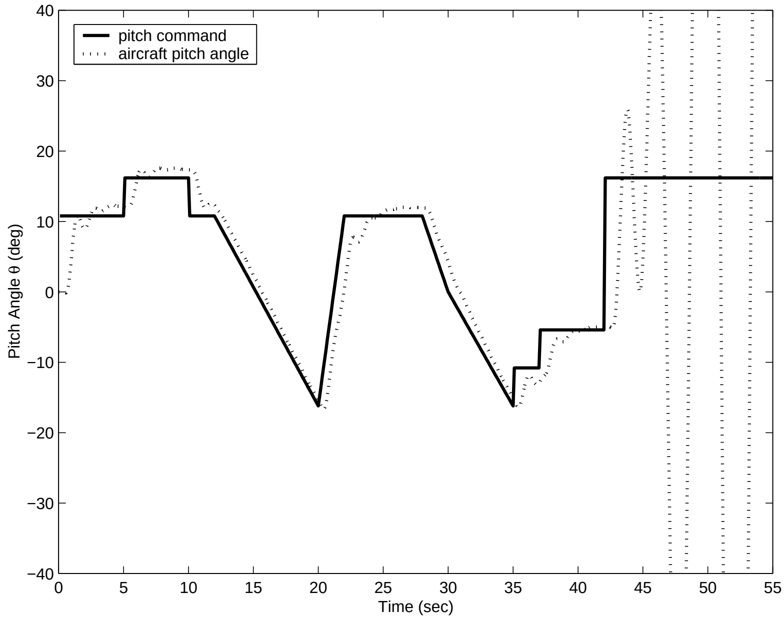

Figure 6.2 Original Simulink Results during Discrete Task, Case C, DS

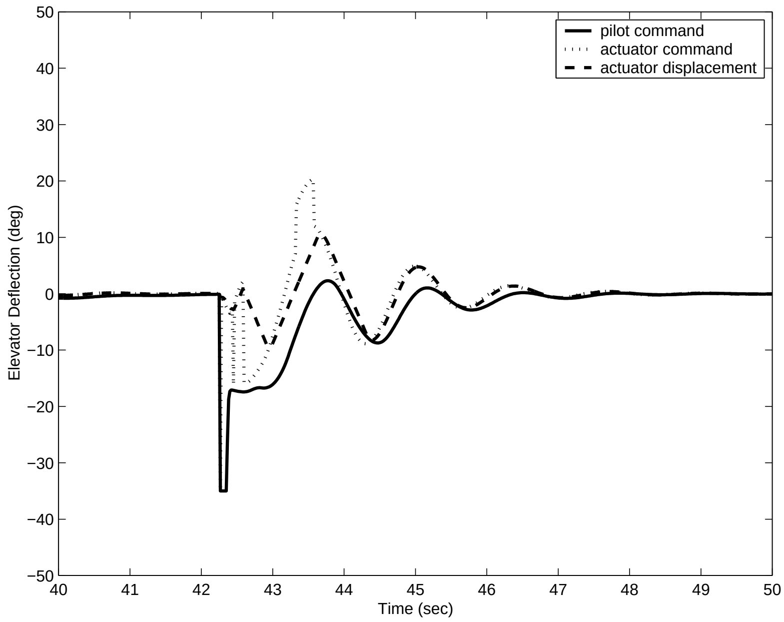

Figure 6.3 No Time Delay with Modified Simulink System during Discrete Task, Case C, DS

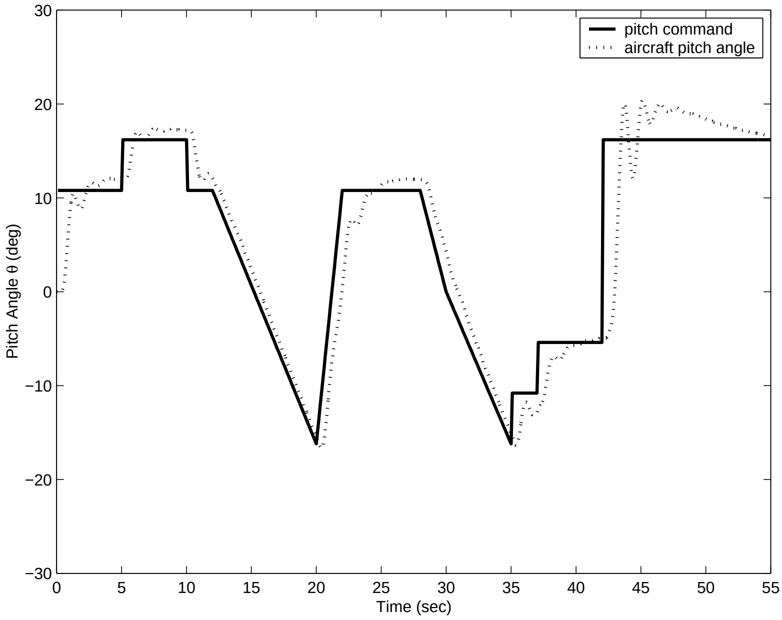

Figure 6.4 Modified Simulink Results during Discrete Task, Case C, DS

VII. Conclusions

A comparison of two flight control system filters, designed to reduce phase lag encountered during actuator rate limiting, was presented in this study. The two filters, labelled Feedback-with-Bypass (FWB) and Derivative-Switching (DS), were tested in their ability to prevent pilot-induced oscillations (PIO) and their affect on aircraft handling qualities. The study was performed in three steps: computer modelling, ground simulation, and flight test. During all three steps the FWB filter performed better than the DS filter.

During the computer simulation, the FWB filter performed better during all closed-loop tests. These tests, performed using Simulink analysis, were an excellent predictor of flight results. During analysis of phase lag, the FWB filter remained closer in phase to the pilot command than the DS filter. The FWB filter was able to prevent PIO during simulation of the discrete tracking task used in both ground simulation and flight test. In contrast, the DS filter could not prevent PIO during the discrete tracking task and actually increased the phase lag. While the FWB filter appeared to reduce pilot inputs, the DS filter appeared to draw the pilot into larger inputs until PIO developed.

Ground simulator testing performed on the Large Amplitude Multimode Simulator (LAMARS) in Wright Patterson AFB showed similar results. The FWB filter was able to reduce the phase lag and prevent PIO more often than the DS filter. While the FWB filter did not prevent PIO in all cases, it was more effective than the DS filter at preventing divergent PIO. The DS filter performance improved as the rate limit increased, but did not prevent either bounded or divergent PIO better than the FWB filter. The ability of the FWB filter to prevent divergent oscillations was the deciding factor in improving PIO susceptibility.

Handling qualities found in LAMARS were better with FWB filter than with either the DS or no filter. By reducing the phase lag, the FWB filter was able to reduce the magnitude and number of oscillations during large pitch captures. This in turn lowered the pilot's workload and improved the handling qualities rating. The DS filter generally degraded aircraft handling qualities.

Flight testing was performed in the Variable-stability In-flight Simulator Test Aircraft (VISTA) NF-16D. Again, the FWB filter was better at preventing divergent PIO for the cases of interest. Because it could effectively reduce phase lag, it was able to limit the number of PIO experienced or keep the PIO bounded. However, it could not prevent divergent PIO every time. With poor aircraft dynamics and low actuator rate limits, the effectiveness of the FWB filter was limited. In contrast, the DS filter was about the same as with no filter at preventing either bounded or divergent PIO.

The FWB filter was rated with the best handling qualities. In many cases, the handling qualities were worse with the DS filter than with no filter. Control was not lost for the configurations of interest with the FWB, but was lost more often with the DS filter compared to no filter. The goal of these filters was to improve handling qualities by reducing phase lag during actuator rate limiting, and to go unnoticed during all other flight phases. This goal was achieved by the FWB filter.

Following the flight test an examination of the failure of the DS filter to prevent PIO was conducted. Simulator results and previous flight tests conducted by Capt. Chapa found the DS filter to be effective in reducing PIO susceptibility. The Simulink derivative and integral subroutines were found to be the culprit. By replacing the derivative subroutine with the transfer function used during the Chapa flight test, the DS filter performance was improved. However, those earlier flight tests found that adding the DS filter degraded handling qualities. Therefore, while repeating the flight test with a modified DS filter might better prevent PIO, there is no indication that its performance would approach that of the FWB filter.

The FWB filter can be a useful flight control system design tool. With a reasonable actuator rate, this filter can prevent divergent PIO and improve aircraft handling qualities even with unstable bare airframe dynamics.

PIO RATING SCALE

Did I experience a PIO?
- No
  - Did I experience undesirable motion?
    - .... No 1
    - Yes
      - Did undesirable motion *tend to occur?* 2
      - Was undesirable motion *easily induced?* 3
- Yes
  - While attempting maneuvers or tight control?
    - Was the PIO *bounded*?.................... 4
    - Was the PIO *divergent*? 5
  - While exercising normal control?.............. 6

DESCRIPTION	NUMERICAL RATING
No tendency for pilot to induce undesirable motions.	1
Undesirable motions end to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.	2
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.	3
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.	4
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by relasing or freezing the stick.	5
Disturbance or normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.	6

Figure A.1 PIO Rating Scale

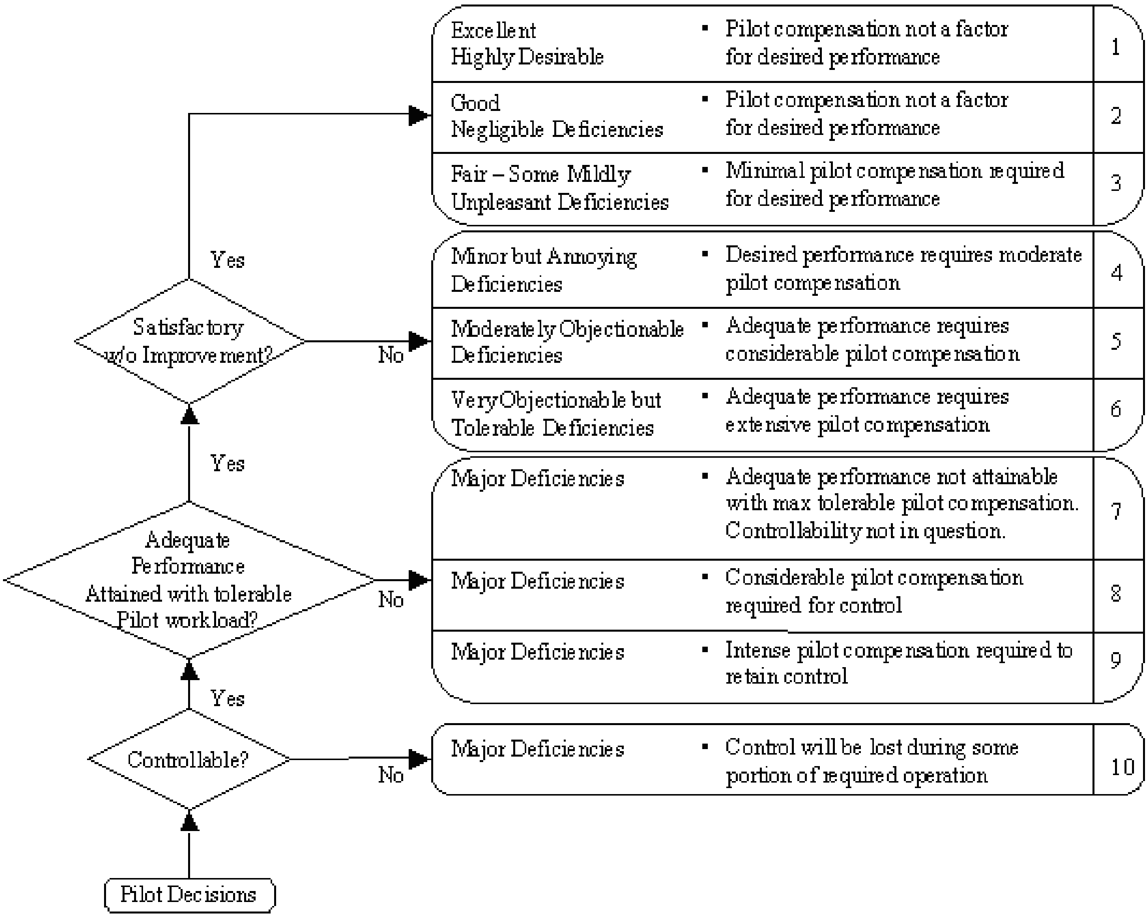

Figure A.2 Cooper-Harper Rating Scale

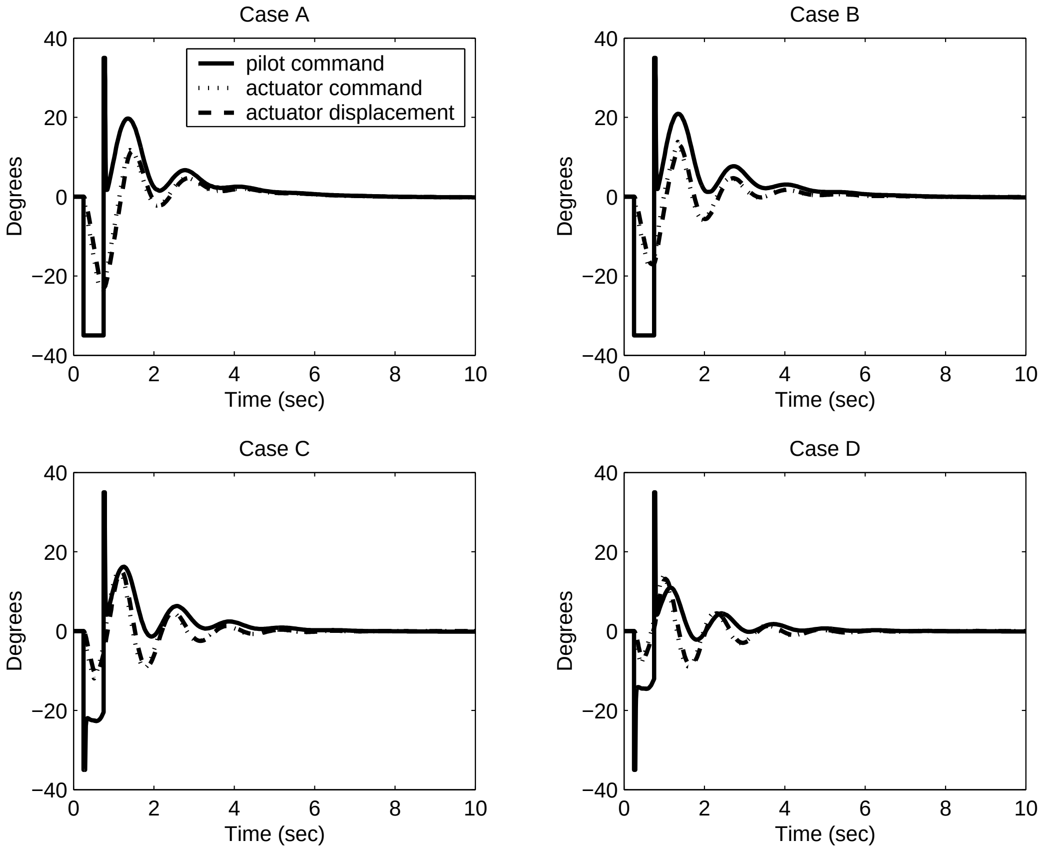

Figure B.1 Response of Aircraft to Pulse Task, FWB Filter On

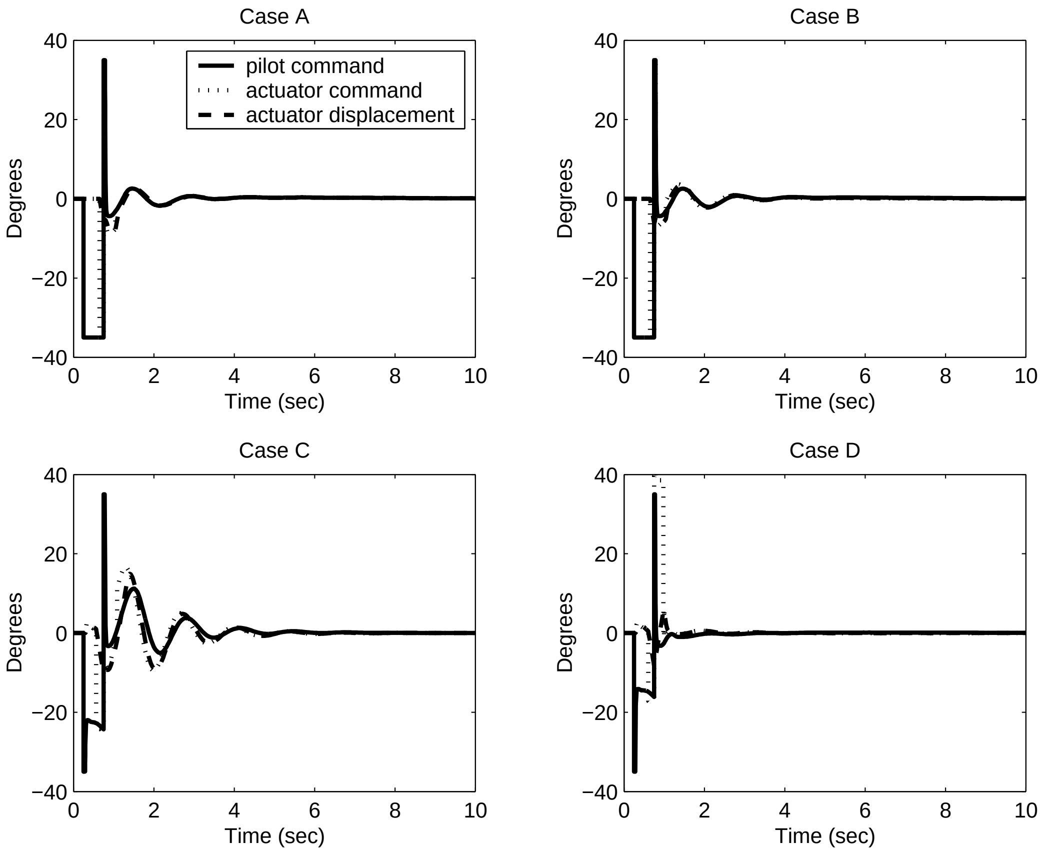

Figure B.2 Response of Aircraft to Pulse task, DS Filter On

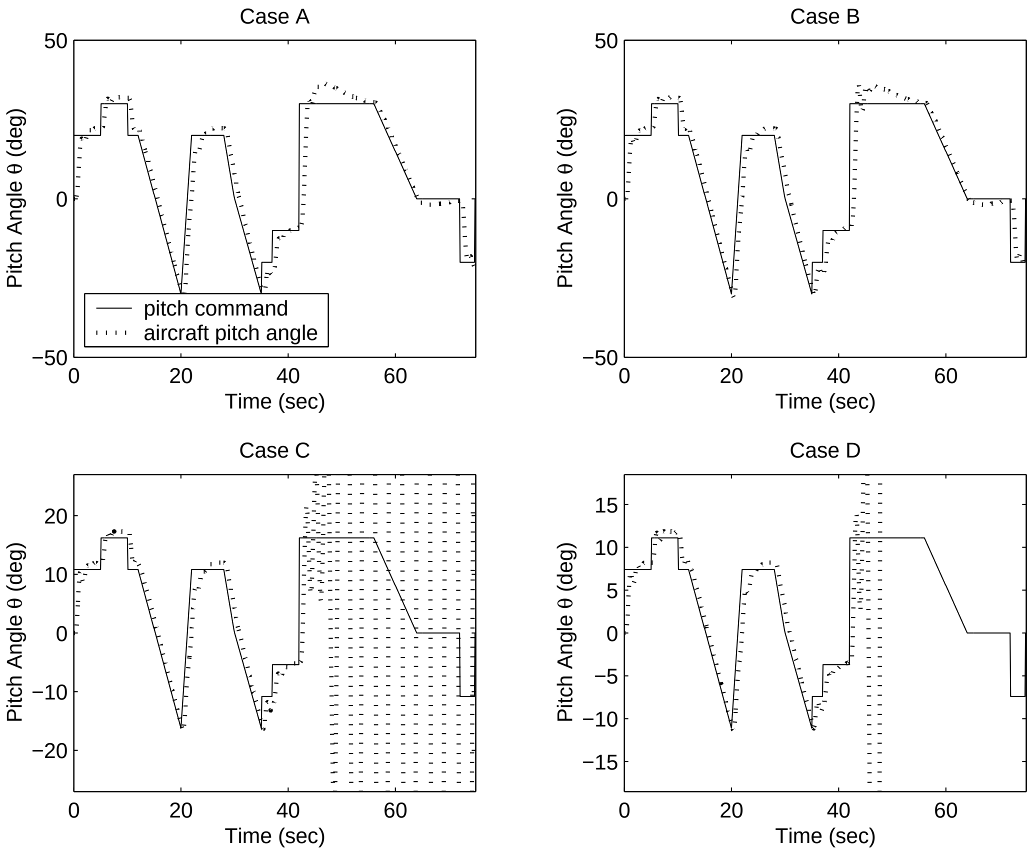

Figure B.3 Response of Aircraft Cases to Discrete Task, No-Filter

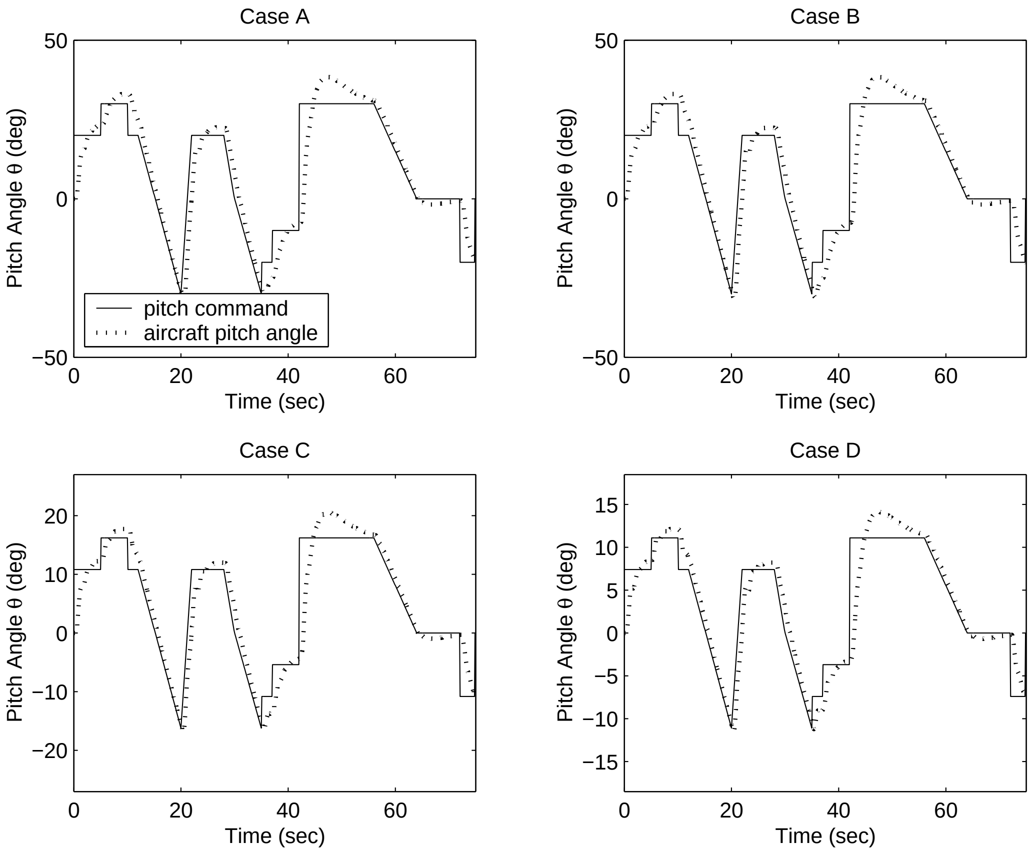

Figure B.4 Response of Aircraft Cases to Discrete Task, FWB Filter On

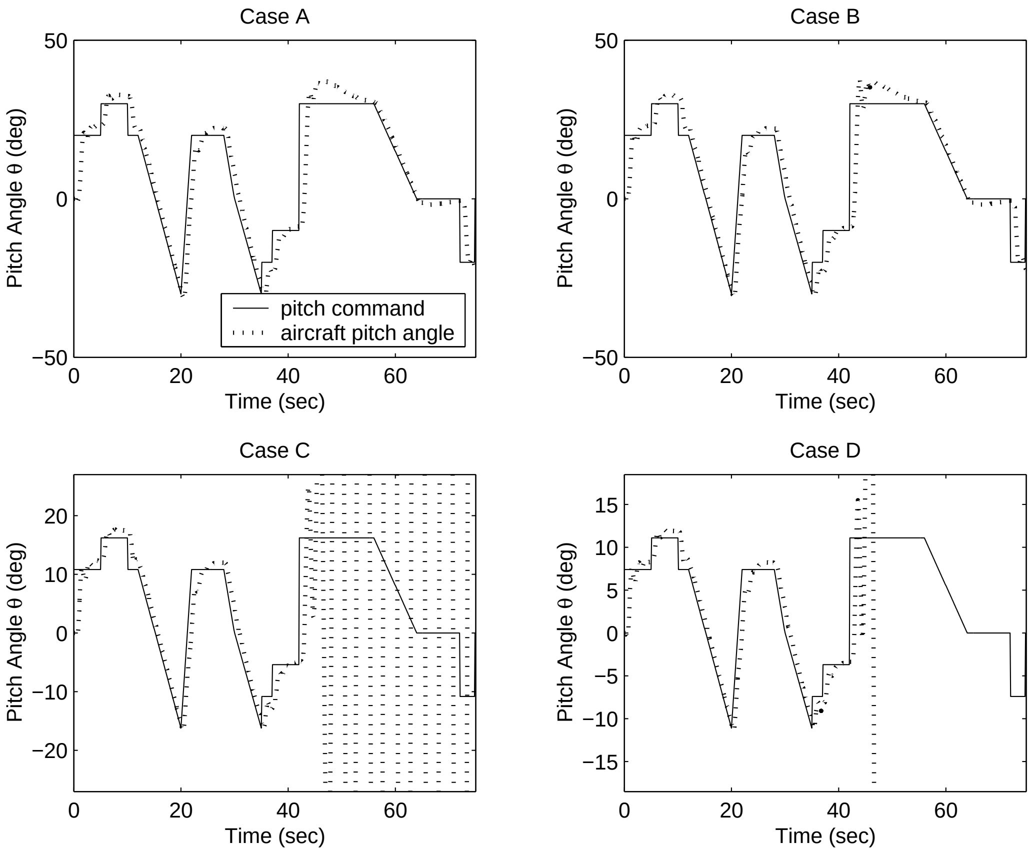

Figure B.5 Response of Aircraft Cases to Discrete Task, DS Filter On

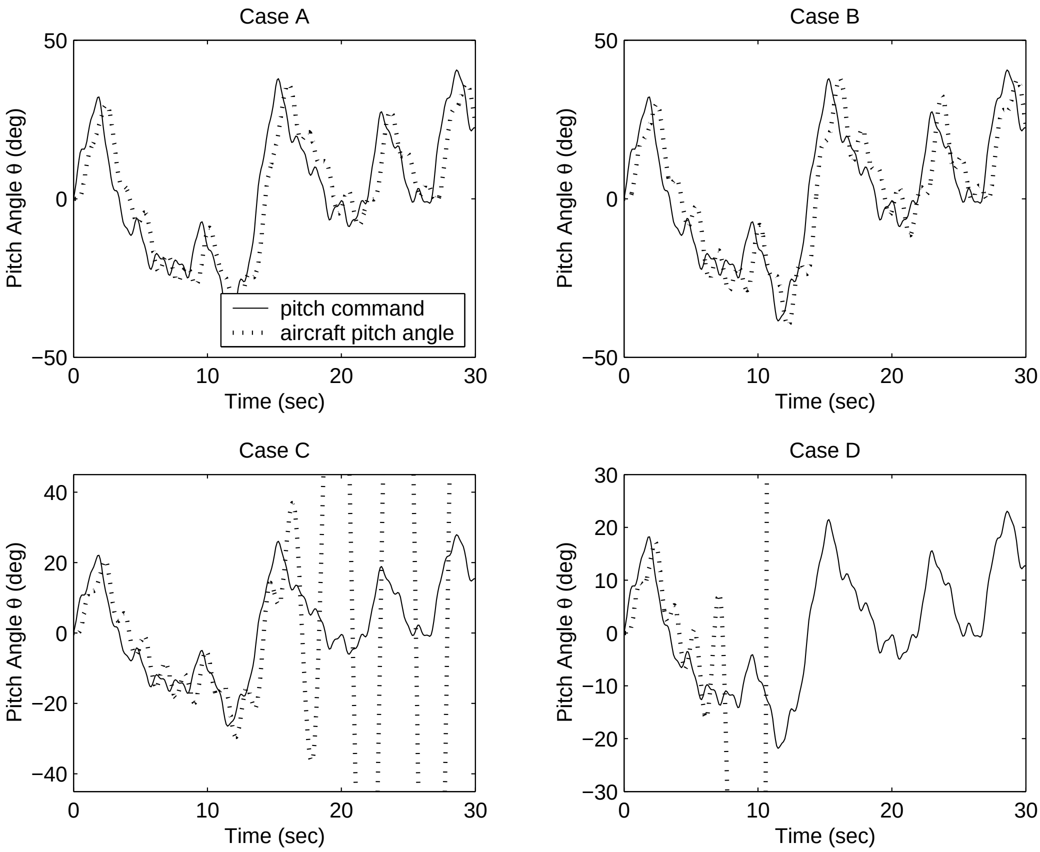

Figure B.6 Response of Aircraft Cases to Sum of Sines Task, No-Filter

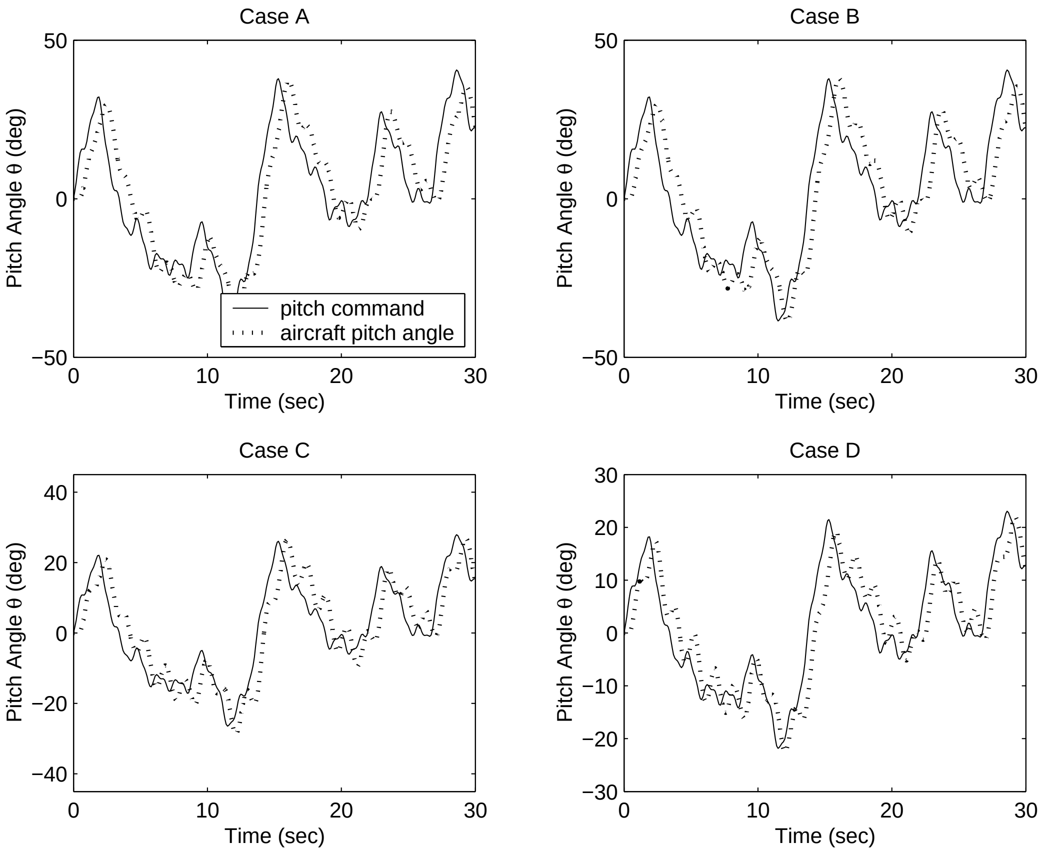

Figure B.7 Response of Aircraft Cases to Sum of Sines Task, FWB Filter On

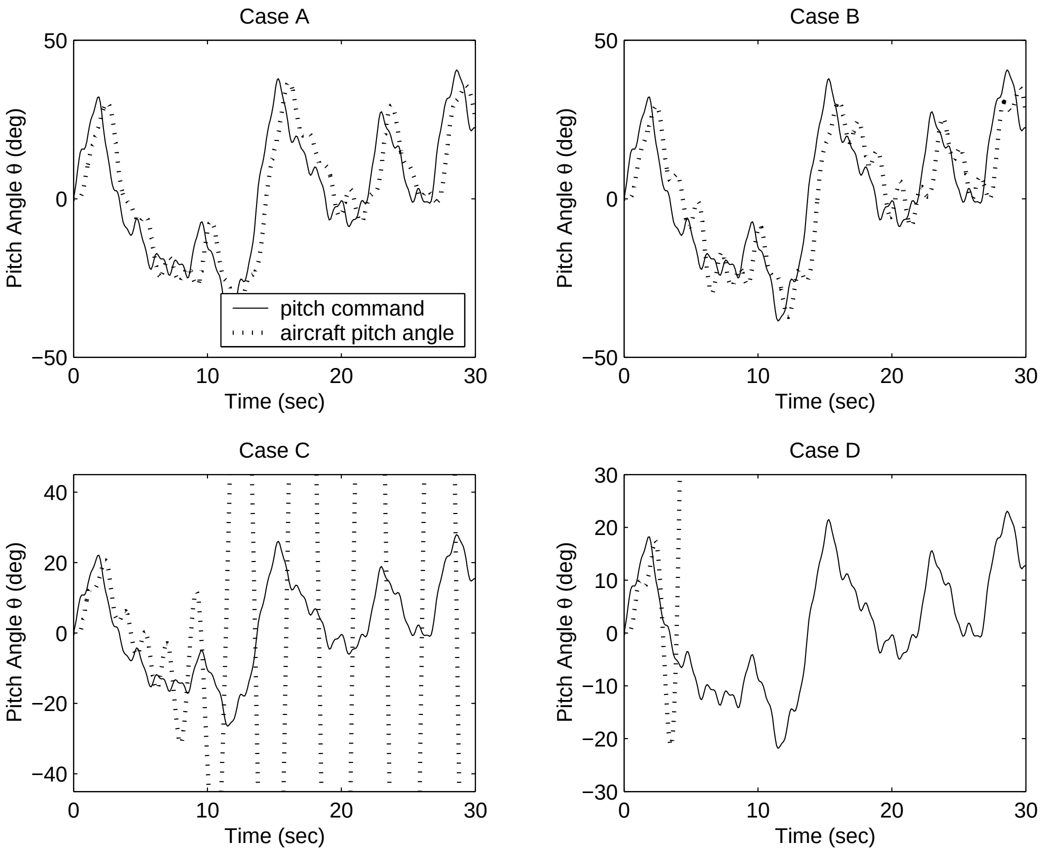

Figure B.8 Response of Aircraft Cases to Sum of Sines Task, DS Filter On

Bibliography

1. A'Harrah, Ralph C. "An Alternate Control Scheme for Alleviating Aircraft Pilot Coupling," *AIAA Guidance, Navigation and Control Conference*, *3*:1194–1201 (1994).

2. Anderson, Mark R. and Anthony B. Page. "Multivariable Analysis of Pilot-in-the-Loop Oscillations," *AIAA Guidance, Navigation and Control Conference*, *3*:278–287 (1995).

3. Dornheim, M.A. "Report Pinpoints Factors Leading to YF-22 Crash," *Aviation Week and Space Technology*, 53–54 (Nov. 9, 1992).

4. Eileen A. Bjorkman, Captain, USAF. *Flight Test Evaluation of Techniques to Predict Pilot Induced Oscillations*. Air Force Institute of Technology, 1986.

5. Kish, Brian. *A Limited Flight Test Investigation of Pilot-Induced Oscillation due to Elevator Rate Limits (HAVE LIMITS)*. Technical Report, Air Force Flight Test Center, Edwards AFB, CA, 1997.

6. Klyde, David H., et al. *Unified Pilot-Induced Oscillation Theory Volume I: PIO Analysis with Linear and Nonlinear Effective Vehicle Characteristics, Including Rate Limiting*. Wright Laboratory, DTC ADA 307580, December 1995.

7. Kullberg, E. and Per-Olov Elgerona. "SAAB Experience with PIO,"

8. Liebst, Brad S. "Pilot-Induced Oscillations (PIO):Causes and Corrections," *The Japan Society for Aeronautical and Space Sciences 13th International Sessions in 37th Aircraft Symposiom*, 601–608 (October 13-15, 1999).

9. McKay, Keith. "Flight Vegicle Integration Panel Workshop on Pilot Induced Oscillation," *Advisor Group for Aerospace Research and Development*, *12*:214–219 (1980).

10. McRuer, Duane T. and others. *Aviation Safety and Pilot Control, Understanding and Preventing Unfavorable Pilot-Vehicle Interactions*. Washington D.C.: National Academy Press, 1997.

11. Michael J. Chapa, Captain, USAF. *A Nonlinear Pre-filter to Prevent Departure and/or Pilot Induced Oscillations (PIO) due to Actuator Rate Limiting*. Air Force Institute of Technology, 1999.

12. Mobarg, Milton and Lowell Lykken. *JAS 39 Gripen Flight Control System Status Report*. Technical Report, SAAB Aircraft Division and Lear Astronics Corporation, 1991.

13. Nelson, Robert C. *Flight Stability and Automatic Control*. American Institute of Aeronautics and Astronautics, Inc., 1999.

14. Nguyen, Ba T., et al. *Comparisons of Flight to Ground-Based Pilot-Induced Oscillations Evaluation Methods*. Technical Report, Air Force Research Laboratory, 1998.

15. of Defense, Department. *MIL STD 1797A, Flying Qualities of Piloted Aircraft*. ASD/ENES, Wright Patterson AFB OH, 28 June 1985.

16. Rundqwist, Lars and Robert Hillgren. "Phase Compensation of Rate Limiters in JAS 39 Gripen," *AIAA Atmospheric Flight Mechanics Conference*, 69–79 (1996).

17. School, U.S. Air Force Test Pilot. *Flying Qualities Testing, Part IV*. Edwards AFB, CA, 2002.

18. Slotine, J.E. and W. Li. *Applied Nonlinear Control*. Prentice Hall, 1991.

19. Stevens, Brian L. and Frank L. Lewis. *Aircraft Control and Simulation* (2nd Edition). Boston, Massachusetts: John Wiley and Sons, Inc., 1998.

20. Weisenseel, Annette W. *The Author's Guide to Writing Air Force Flight Test Center Technical Reports*. Technical Report, Air Force Flight Test Center, 2001.

Vita

Major James G. Hanley was born in Del Rio, Texas. He graduated from Rochester Adams High School, just outside of Detroit, Michigan, in 1987. He went on to earn a Bachelor of Science Degree in Aeronautical Engineering and a commission as a Second Lieutenant from the U.S. Air Force Academy in 1991.

After graduation, James entered Undergraduate Pilot Training at Columbus AFB, Mississippi in August 1991. He received his pilot rating one year later and went on to fly the KC-135 at Altus AFB, Oklahoma and McConnell AFB, Kansas. After nearly 2,000 hours of flight time in the KC-135, James moved on to be an instructor pilot in the T-1A, teaching future "heavy" pilots at Specialized Undergraduate Pilot Training in Columbus AFB, Mississippi.

Major Hanley was selected for the joint AFIT/TPS program in February 2000 and began classes at AFIT in September. After graduation from AFIT/TPS, James will test the C-17 at Edwards AFB, California.

James is a graduate of the U.S.A.F. Test Pilot School, Class 02A, and has over 3,000 of flight experience, mostly in heavy aircraft.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
03-2003	Master's Thesis	04/2001 - 01/2003

4. TITLE AND SUBTITLE

A COMPARISON OF NONLINEAR ALGORITHMS TO PREVENT PILOT-INDUCED OSCILLATIONS CAUSED BY ACTUATOR RATE LIMITING

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Hanley, James G. Maj, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 P Street, Building 640
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GAE/ENY/03-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

USAF TPS
220 Wolfe St
Edwards CA 93524

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The objective of this study was to compare the ability of the Feedback-with-Bypass (FWB) and the Derivative-Switching (DS) flight control system filters to prevent PIO during actuator rate limiting, and the filters' effects on aircraft handling qualities. This comparison was conducted in three steps: computer simulation, ground simulation in the Large Amplitude Multimode Aerospace Research Simulator (LAMARS), and flight tests conducted in the Variable Stability In-flight Simulator Test Aircraft (VISTA). During computer simulation, the FWB filter better reduced the phase lag and prevented sustained or divergent oscillations during the closed-loop analysis. During both ground simulation and flight tests, the FWB filter was more effective at preventing divergent PIO and improving handling qualities. Overall the FWB filter performed better during all tests.

15. SUBJECT TERMS

Pilot-Induced Oscillations, Handling Qualities

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	107	Dr. Bradley S. Liebst, ENY
					19b. TELEPHONE NUMBER *(Include area code)* (937) 255-3636 x4636