AFFTC-TIM-02-07

A COMPARISON OF NONLINEAR ALGORITHMS IN THE PREVENTION OF PILOT-INDUCED OSCILLATIONS CAUSED BY ACTUATOR RATE LIMITING (Project HAVE PREVENT)

AD INEXPLORATA

USAF TPS

James Hanley, Maj, USAF
Project Manager / Project Test Pilot

Stefan Ritter, Lt Col, Luftwaffe
Project Test Pilot

George Griffiths Jr., Maj, USAF
Project Test Pilot

John Gloystein III, Maj, USAF
Project Test Pilot

Joel Luker, Capt, USAF
Project Flight Test Engineer

Michael Young, Capt, USAF
Project Flight Test Engineer

Fabio Mellone, Lt, ItAF
Project Flight Test Engineer

FINAL REPORT

Dec 02

USAF TEST PILOT SCHOOL
AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

This Technical Information Memorandum (AFFTC-TIM-02-07), A Comparison of Nonlinear Algorithms in the Prevention of Pilot-Induced Oscillations Caused by Actuator Rate Limiting, was submitted under job order number (JON) M02C1300 by the Commandant, US Air Force Test Pilot School (USAFTPS), Edwards Air Force Base, CA 93524-6485.

Prepared by:

JAMES HANLEY
Major, USAF
Project Manager

STEFAN RITTER
Lieutenant Colonel, Luftwaffe
Project Test Pilot

GEORGE GRIFFITHS JR
Major, USAF
Project Test Pilot

JOHN GLOYSTEIN III
Major, USAF
Project Test Pilot

JOEL LUKER
Captain, USAF
Project Flight Test Engineer

MICHAEL YOUNG
Captain, USAF
Project Flight Test Engineer

FABIO MELLONE
Lieutenant, ItAF
Project Flight Test Engineer

Reviewed by:

RICK PALO
Major, USAF
Staff Monitor

CHRIS HAMILTON
Major, USAF
Chief, Test Management Division

This Technical Information Memorandum has been approved for publication:

GEORGE KAILIWAI III
Colonel, USAF
USAF TPS/CC

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
12-12-2002

2. REPORT TYPE
Final Technical Information Memorandum

3. DATES COVERED *(From - To)*
16 to 23 October 2002

4. TITLE AND SUBTITLE
A Comparison of Nonlinear Algorithms in the Prevention of Pilot-Induced Oscillation Caused by Actuator Rate Limiting
(Project HAVE PREVENT)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Hanley, James, Major, USAF
Ritter, Stefan, Lieutenant Colonel, Luftwaffe
Gloystein, John III, Major, USAF
Griffiths, George Jr., Major, USAF
Luker, Joel, Captain, USAF
Young, Michael, Captain, USAF
Mellone, Fabio, Lieutenant, ItAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
Air Force Flight Test Center
412th Test Wing
USAF Test Pilot School
220 South Wolfe Ave
Edwards AFB CA 93524-6485

8. PERFORMING ORGANIZATION REPORT NUMBER
AFFTC-TIM-02-07

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAF Test Pilot School
220 South Wolfe Ave
Edwards AFB CA 93524-6485

10. SPONSOR/MONITOR'S ACRONYM(S)

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

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release, December 2002. Requests for this document shall be referred to USAF TPS/EDT, Edwards AFB, California 93524-6485.

13. SUPPLEMENTARY NOTES
CA: Air Force Flight Test Center Edwards AFB CA CC: 012100

14. ABSTRACT
This report presents the results of Project HAVE PREVENT, a comparison of nonlinear algorithms in the prevention of pilot-induced oscillations (PIO) caused by actuator rate limiting. The overall test objective was to compare the ability of two flight control system filters in the prevention of PIO during actuator rate limiting. The Air Force Institute of Technology, Engineering Department (AFIT/ENY) requested this testing. The USAF Test Pilot School (TPS), Class 02A, conducted 13 flight tests totaling 21.0 hours at Edwards AFB, California, from 16 to 23 October 2002.

15. SUBJECT TERMS
handling qualities pilot-induced oscillation rate limiting Gripen PIO prevention flight controls

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Maj James Hanley
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT	58	**19b. TELEPHONE NUMBER** *(include area code)* 661-277-3000

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PREFACE

This technical information memorandum presents the evaluation procedures, concepts, and results from the HAVE PREVENT test project. The United States Air Force Test Pilot School (USAF TPS) HAVE PREVENT Test Team conducted tests at Wright Patterson Air Force Base, Ohio and the Air Force Flight Test Center, Edwards Air Force Base, California. Both the USAF TPS and the Air Force Institute of Technology (AFIT) sponsored this project.

The HAVE PREVENT Test Team would like to thank Mr. Andy Markofski and Mr. Jeff Peer of Veridian Flight Research for their outstanding contributions. Additionally, we would like to thank Mr. Curtis Clark and Mr. Jeff Slutz of the Air Force Research Laboratory for their diligent work in preparing the ground simulation, and Mr. Bob Lamb of the Air Force Flight Test Center for providing technical guidance.

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EXECUTIVE SUMMARY

This Technical Information Memorandum (TIM) presents evaluation procedures, concepts, and results from the HAVE PREVENT test project. 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 responsible test organization (RTO) was the 412th Test Wing. Ground simulation tests were conducted in the Large Amplitude Multimode Aerospace Research Simulator (LAMARS), Wright Patterson AFB, OH, on 26 and 27 September 2002. Test flights were conducted at the Air Force Flight Test Center (AFFTC), Edwards AFB, CA, from 16 to 23 October 2002. Thirteen flight test sorties, 21.0 total hours, were flown in the Variable Stability In-flight Simulator Test Aircraft (VISTA) NF-16D. This project was part of the curriculum for both the US Air Force Test Pilot School and the Air Force Institute of Technology (AFIT).

Actuator rate limiting affected aircraft handling qualities in two ways: it exposed the aircraft's unaugmented dynamics and shifted the phase between pilot input and actuator output. Phase shifting was the primary cause of pilot-induced oscillations (PIO) due to rate limiting. Two proposed solutions both placed a flight control system (FCS) 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. This project compared the aircraft longitudinal response with these two filters using both ground and in-flight simulation.

The overall test objective was to compare the ability of the FWB and DS filters in the prevention of PIO during actuator rate limiting. The specific objectives were: 1) compare the FWB and DS filters in the prevention of pilot-induced oscillations caused by actuator rate limiting, and 2) compare the aircraft handling qualities achieved using each filter during rate-limited and non-rate-limited tasks. The evaluation was limited to the longitudinal axis only. Both test objectives were met.

The test team used PIO and Cooper-Harper rating scales along with pilot comments to compare the two filters. A PIO rating of 4 was considered a bounded PIO; a rating of 5 was a divergent PIO. Cooper-Harper Ratings were compared using two tracking tasks, one on a Head-Up Display (HUD) generated target and one tracking a T-38.

The FWB filter performed better during the comparison based on PIO ratings, Cooper-Harper ratings and pilot comments. While it did not prevent PIO in all cases, the FWB filter.was more effective in preventing divergent PIO. The DS filter performed better as the rate limit increased, but overall did not limit PIO or improve aircraft handling qualities.

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INTRODUCTION

General

Two flight control system (FCS) filters designed to prevent pilot-induced oscillations (PIO) were compared using the Large Amplitude Multimode Aerospace Research Simulator (LAMARS) and the NF-16D Variable Stability In-Flight Simulator Test Aircraft (VISTA). The HAVE PREVENT Test Team from the United Stated Air Force Test Pilot School (USAF TPS) performed ground simulator testing at Wright Patterson AFB, Ohio, on 26-27 September 2002, and flight testing at the USAF Flight Test Center (AFFTC) at Edwards AFB, California, on 16-23 October 2002.

USAF TPS and the Air Force Institute of Technology (AFIT) sponsored this test project as part of a joint curriculum program in support of a Master's degree thesis. All testing was conducted under job order number (JON) M02C1300. The Responsible Test Organization (RTO) was the 412th Test Wing. Ground simulation included 14 1-hour LAMARS sorties over 2 days. The flight test portion consisted of 3 calibration sorties, 13 test sorties in the VISTA NF-16D, and 5 target sorties. Total flight time was 31.1 hours.

This project was conducted under the authority of the Commandant, USAF TPS. Additional guidance and technical requirements were provided by AFIT.

Background

Almost every new fly-by-wire (FBW) aircraft has exhibited PIO during development (Reference 1). Most severe PIO have been attributed to the nonlinear effects of actuator rate limiting. Actuator rate limiting affects aircraft handling qualities in two ways: it exposes the aircraft unaugmented dynamics and shifts the phase between the pilot input and actuator output. Phase shifting is the primary cause of PIO due to rate limiting (Reference 1). Two proposed solutions to the phase lag problem both placed a flight control system (FCS) filter between the pilot command and the 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 pilot inputs to reverse the output during actuator rate limiting to reduce phase lag. This project compared these two filters using both ground simulation and in-flight testing.

Filter 1: Feedback with Bypass

The Feedback-with-Bypass (FWB) filter was designed in response to the loss of two JAS-39 Gripen aircraft (Reference 2). Both aircraft were destroyed as a result of PIO due to actuator rate limiting. A Simulink® diagram of the filter is found in Figure 6, Appendix A. A pilot command, composed of both high and low frequency components, entered the filter. The high frequency components (greater than 10 radians/second) bypassed the main portion of the filter. The low frequency components passed 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 was greater than the output. When this occurred, the difference between the output and input passed through a second low-pass filter. Because this difference signal had a negative sign, its phase was shifted 180 degrees from the pilot command. When this signal passed through the low-pass filter and was fed back to the low frequency input, phase lead was added to the system. The result was a rate-limited signal with significantly less phase lag. Figure 1 demonstrates this reduced phase lag for a rate-limited input.

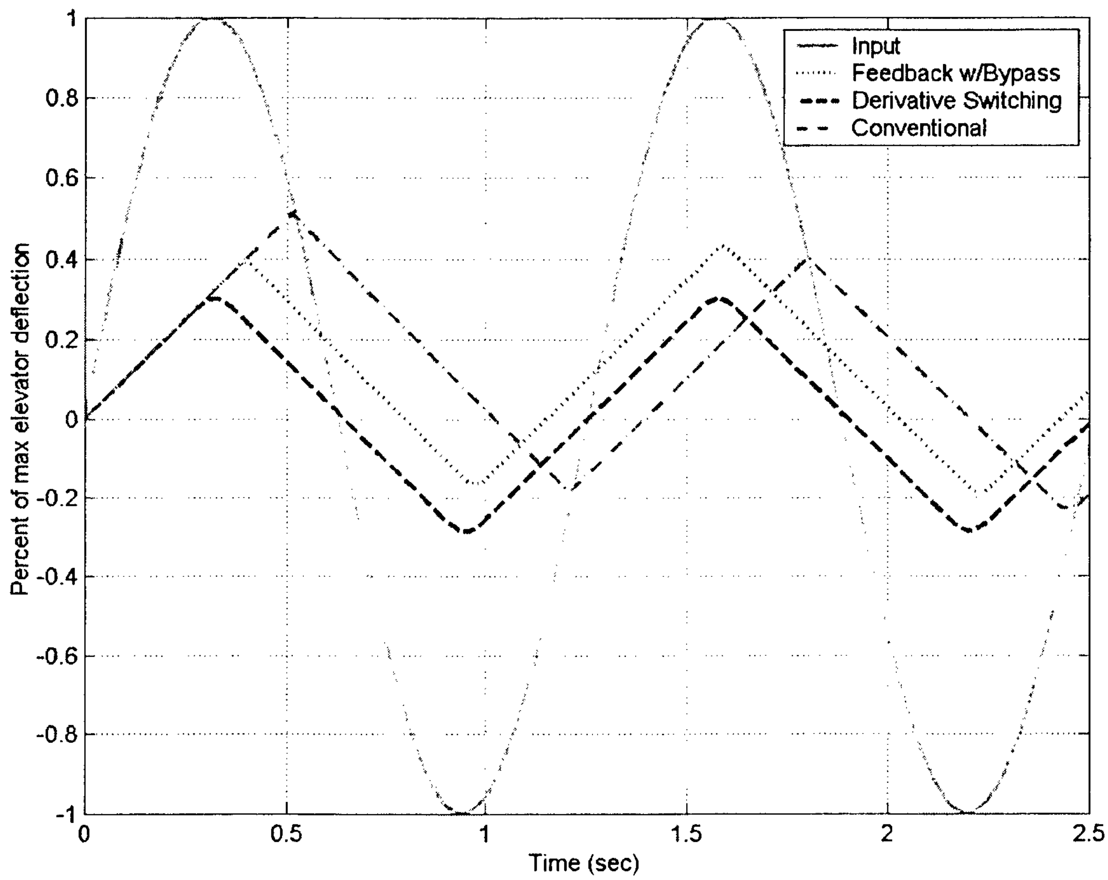

Figure 1: Rate Limited Response of FWB and DS Filters

Filter 2: Derivative Switching

The Derivative-Switching (DS) filter was designed for the USAF TPS/AFIT project HAVE FILTER to prevent PIO due to actuator rate limiting (References 3, 4). A Simulink® diagram of the filter is in Figure 7, Appendix A. This filter had three main segments. The upper segment used an algorithm that differentiated, limited, and integrated to keep the output in phase with a low frequency, symmetrical input. A reset integrator was used to correct the bias inherent in an unsymmetrical input. The middle segment provided the switching logic. First, high frequency noise was filtered from the signal. The rate and acceleration of the filtered signal were checked against preset values. If either derivative exceeded their respective limit, the upper segment was activated. Otherwise, the lower segment was active, and the signal passed through the filter cleanly.

Test Item Description

The FWB and DS filters were the test items for this project. They were compared using four Simulink® aircraft models. The second-order longitudinal dynamic approximations associated with these models are summarized in Table 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 (Reference 7). 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 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 (SAS) was designed to provide nearly identical closed-loop dynamics for all four configurations.

Table 1: Aircraft Dynamics/Configurations and Feedback Gains

Case	Bare Airframe Poles (Open Loop)	K_q	K_α	A/C poles with SAS (Closed Loop)	$\omega_{n_{sp}}$ (rad/sec)	ζ_{sp}
A	-2.20 ± 2.22 i -0.017 ± 0.074 i	0	0	-2.20 ± 2.22 i -0.017 ± 0.074 I	3.12	0.70
B	-1.42 ± 1.86 i -0.016 ± 0.079 i	0.14	0.21	-2.20 ± 2.22 i -0.0166 ± 0.0736 i	2.34	0.61
C	-0.86 ± 0.084 i -0.009 ± 0.097 i	0.24	0.51	-2.196 ± 2.227 i -0.0168 ± 0.0737 i	0.86	0.995
D	-1.67 -0.017 ± 0.033 i +1.07	0.34	0.61	-2.20 ± 2.22 i -0.0169 ± 0.0737 i		T_2=2.31sec

Note: K_q and K_α are the feedback gains required to achieve the desired closed loop dynamics (see Appendix A, Figure 5 to Figure 7 for the Simulink® FCS diagrams).

Table 1 contains bare airframe and closed-loop pole coordinates. These bare airframe poles became important when an 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, reducing the amount of data able to be collected for filter comparison. Thus, the testing emphasized the case C configuration for collecting the majority of the data for the filters' effect on rate-limited PIO handling qualities.

Test Objectives

The overall test objective was to compare the Feedback-with-Bypass and Derivative-Switching algorithms in preventing a PIO caused by actuator rate limiting. This was a limited evaluation of PIO prevention in the longitudinal axis of an aircraft with a digital flight control system (DFLCS).

The specific objectives were:

1. Compare the Feedback-with-Bypass and Derivative-Switching flight control system pilot input 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 test objectives were met.

TEST AND EVALUATION

General

Testing was accomplished in two phases. First, ground testing was conducted in the Large Amplitude Multimode Simulator (LAMARS) at Wright-Patterson AFB on 25 and 26 September 2002. Second, flight testing was conducted at Edwards AFB in the Variable In-Flight Stability Testing Aircraft (VISTA) from 16 to 23 October 02.

During both simulator and flight tests, the investigation was divided into three phases. Phase 1, gentle maneuvering, provided the pilots with a "basic feel" for how the aircraft was going to respond to their inputs. Phase 2 used a specialized technique called Handling Qualities During Tracking (HQDT). HQDT required 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." (Reference 5) HQDT was the most reliable method to determine the Pilot-Induced Oscillation (PIO) tendencies of the aircraft during high gain, high bandwidth pilot inputs. (Reference 5) PIO ratings (Appendix E, Figure 22) and pilot comments were then compared to determine which filter (if any) did a better job of preventing PIO. Phase 3 consisted of an operational tracking task used to determine the Cooper-Harper Rating (CHR, see Appendix E, Figure 21) for pilot workload and task performance. Both phase 2 and phase 3 tasks used a HUD-generated target (shown in Figure 2) for the pilot to track; the phase 3 testing also used a T-38 target acquisition and tracking task.

The AFFTC five-point general-purpose scale (Reference 8) was used to compare the CHR and PIO ratings from each filter configuration. The five ratings assigned were: Much Better, Better, About the Same, Worse and Much Worse.

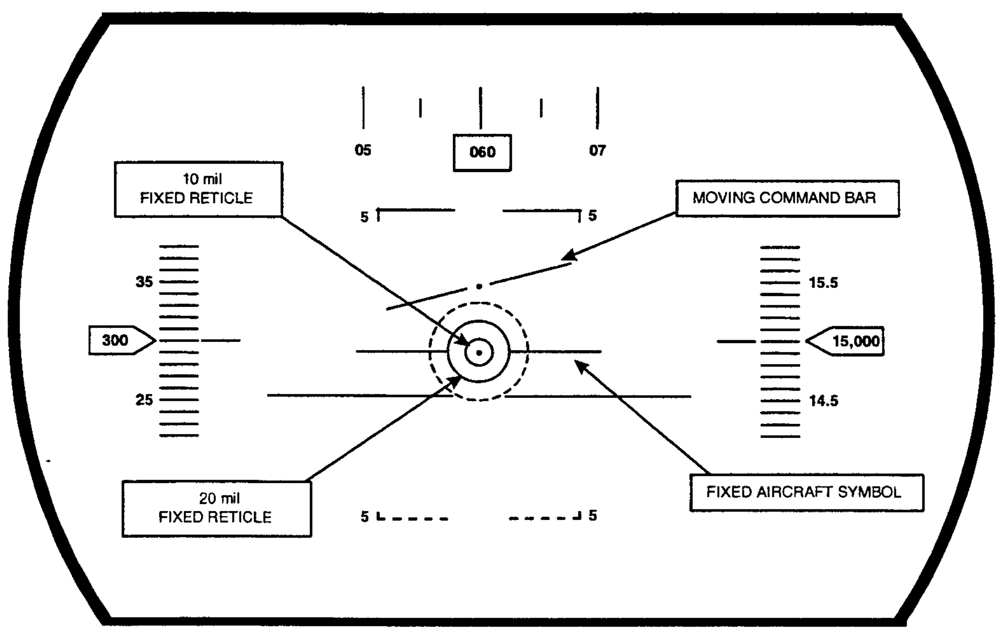

Figure 2: Sample HUD Symbology

Prevention of PIO

Test Procedures

The evaluator pilot (EP) conducted Phase 1 and 2 handling qualities evaluations for each combination of bare airframe dynamics, PIO prevention filter and actuator rate limit shown in the test matrix (see Table 6 in Appendix F). Priority one test points (Case C) were flown by at least three different pilots, with lower-priority points tested as required. These evaluations were performed in both the LAMARS ground simulator and the VISTA NF-16D aircraft.

Phase 1

The EP performed gentle pitch captures and semi-closed loop tracking, progressing from small to large amplitude. Typical maneuvers included doublets, steps, 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

The EP was required to track the Head-Up Display (HUD) target as aggressively and assiduously as possible, striving for zero tracking error. For Phase 2, the HUD target followed the "Sum of Sines" pitch angle path shown in Figure 3. Pilot gain and frequency of inputs were increased during the task to evaluate PIO tendencies. During or immediately following the task, pilot comments were recorded and a PIO rating was assigned using the scale shown in Appendix E, Figure 22.

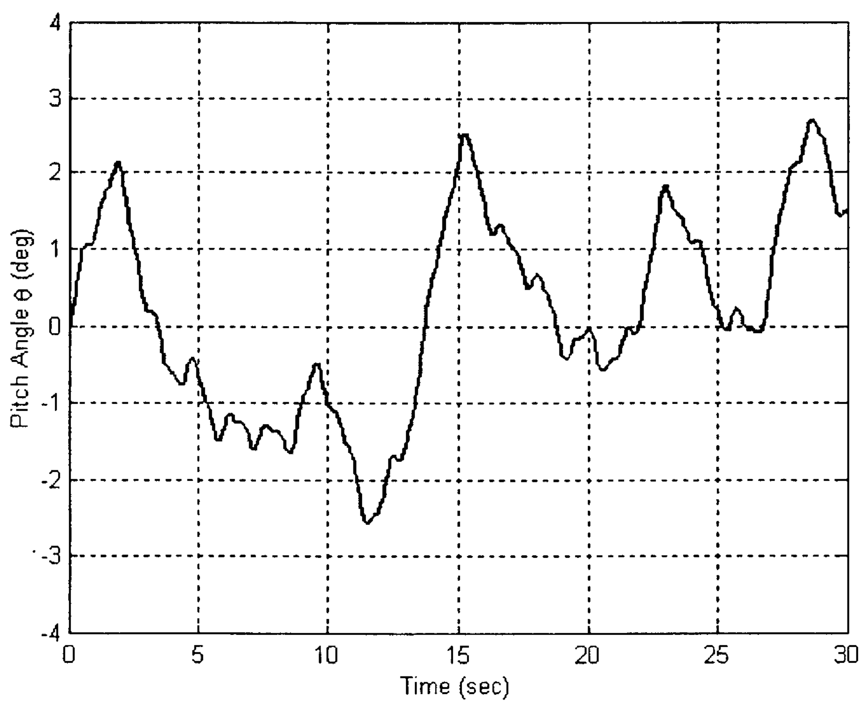

Figure 3: Sum of Sines Pitch Tracking Task

Simulator 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. Due to the limited number of test points collected, the test team only analyzed the Case C configurations. However, both Case C (all four rate limits) and Case D (60 and 45 deg/sec rate limit only) data were included in Appendix B, Figure 8 for later comparison to data collected during flight test.

The test team analyzed the data by looking at the rate of PIO occurrence and whether the PIO was divergent or bounded. The Five-Point General Purpose Scale was used to describe which filter configuration better prevented the occurrence of PIO for each case.

Case C, 60°/sec, Rate-Limited

The no-filter configuration had 6 test points with 2 divergent PIO occurrences. The FWB filter configuration had 6 test points with 3 bounded PIO occurrences. The DS filter configuration had 6 test points with 1 divergent PIO occurrence. The DS filter configuration had the lowest occurrence of PIO, followed by the no-filter configuration and then the FWB filter configuration. However, all PIO encountered with the FWB filter were bounded, and thus more controllable than a divergent PIO.

The DS filter configuration was better than the no-filter configuration at reducing the occurrence of PIO. The FWB filter was better than both the no-filter and DS configurations. Figure 15 and Figure 16 show the increased time delay present with the derivative switching filter compared to the feedback with bypass filter.

Case C, 45°/sec, Rate-Limited

The no-filter configuration had 3 test points with 1 bounded and 1 divergent PIO. The FWB filter configuration had 5 test points with 3 bounded PIO. The DS filter configuration had 6 test points with 1 bounded and 1 divergent PIO. The FWB and no-filter configurations prevented PIO about the same; the DS filter configuration reduced the occurrence of PIO better than the other two. However, all FWB filter configuration PIO were bounded with no occurrence of divergent PIO. Figure 19 shows an example of a divergent PIO seen with the DS filter.

The FWB filter configuration was better than the DS filter configuration because of it's ability to bound PIO, and the DS filter configuration was better than the no-filter configuration.

Case C, 30°/sec, Rate-Limited

The no-filter configuration had 5 test points with 3 divergent and 2 bounded PIO. The FWB filter configuration had 6 test points with 3 bounded PIO. The DS filter configuration had 5 test points with 3 divergent and 1 bounded PIO.

The DS filter configuration was better than the no-filter configuration at reducing the number of PIO occurrences. The FWB filter configuration was much better than the no-filter and DS filter configurations at reducing the occurrence of PIO and keeping the oscillations bounded.

Case C, 15°/sec, Rate-Limited

The no-filter configuration had 3 test points with 3 divergent PIO. The FWB filter configuration had 3 test points with 1 bounded and 1 divergent PIO. The DS filter configuration had 3 test points with 3 divergent PIO. Both the no-filter and DS filter configurations had about the same performance: they experienced divergent PIO for every test point (for example, see Figure 14), where the FWB filter configuration reduced the occurrence of PIO and kept the oscillations bounded half the time.

The FWB filter configuration was much better than the no-filter and DS filter configurations; the DS and no-filter configurations were about the same.

Overall Simulator Results

Table 2 summarizes the simulator PIO results. The best performer for all rate-limited simulator test cases was the FWB filter configuration. 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 rather than divergent. The DS filter configuration was better than the no-filter configuration in reducing PIO occurrence for all test cases except for 15 degrees per second, where they performed about the same.

Comparing all four rate limit cases to one another, the data showed the rate of PIO occurrence for the FWB filter configuration was relatively independent of rate limit, but the DS filter configuration had a marked dependency on the actuator rate limit. The DS filter configuration's ability to prevent PIO improved as actuator rate increased, with a dramatic reduction in PIO occurrence rate being observed when the actuator rate was above 30 degrees per second. However, the *type* of PIO observed for the DS filter (divergent vs bounded) did not follow this correlation. That is, while the DS filter configuration reduced the number of times PIO occurred, the majority of oscillations were still divergent.

Table 2: PIO Comparison Summary – Simulator

Aircraft Case / Rate Limit	FWB vs. No-filter	DS vs. No-filter	FWB vs. DS	Best Performer
C / 60° per sec	Better	Better	Better	FWB
C / 45° per sec	Better	Better	Better	FWB
C / 30° per sec	Much Better	Better	Much Better	FWB
C / 15° per sec	Much Better	About the Same	Much Better	FWB

Flight Test Results

For each Phase 2 task, occurrence of actuator rate limiting, PIO ratings and pilot comments were collected. Data comparisons were limited to only Case C (all rate limits) and

Case D (60 and 45 deg/sec rate limit) configurations where rate limiting was achieved. The test team analyzed the data by looking at the rate of PIO occurrence and whether the PIO was divergent or bounded. The Five-Point General Purpose Scale was used to describe which filter configuration better prevented the occurrence of PIO for each case. Figure 9, Appendix B presents the Flight test PIO ratings.

The flight test Phase 2 results 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. 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.

Case C, 60°/sec, Rate-Limited

The no-filter configuration had 4 test points with no PIO occurrences. The FWB filter configuration had 3 test points with no PIO occurrences. The DS filter configuration had 6 test points with 2 bounded PIO occurrences.

The no-filter and FWB filter configurations performed about the same, and both performed better than the DS filter configuration. Figure X shows an example of a large actuator reversal caused by DS filter effects during a large pitch capture task. These actuator reversals led the pilot to large oscillations not seen in other configurations.

Case C, 45°/sec, Rate-Limited

The no-filter configuration had 6 test points with 2 bounded and 2 divergent PIO occurrences. The FWB filter configuration had 6 test points with 3 bounded PIO occurrences. The DS filter configuration had 7 test points with 1 bounded and 2 divergent PIO occurrences. When ranked by the least number of PIO occurrences, the filter configurations performed in the following order: DS filter, FWB filter and then no-filter configuration. Both the DS filter and the no-filter configuration performed about the same in controlling the oscillations of the aircraft response, with an approximate 50 percent occurrence of an uncontrollable divergent PIO. However, the FWB filter configuration was better than the other two at keeping the oscillations bounded when a PIO did occur.

The FWB filter configuration performed better than the DS filter and no-filter configurations, which performed about the same.

Case C, 30°/sec, Rate-Limited

The no-filter configuration had 6 test points with 3 bounded and 2 divergent PIO occurrences. The FWB filter configuration had 7 test points with 3 bounded and 2 divergent PIO occurrences. The DS filter configuration had 6 test points with 2 bounded and 4 divergent PIO occurrences. The no-filter and the FWB filter configurations performed about the same in reducing the number of PIO, with the DS filter configuration experiencing PIO every time. The FWB filter controlled the oscillations about the same as the no-filter configuration, with about 50 percent of the oscillations (2 out of 7 and 2 out of 6, respectively) being divergent. The DS filter configuration had divergent oscillations occurring 4 out of 6 times.

The no-filter and FWB filter configurations performed about the same, and both performed better than the DS filter configuration.

Case C, 15°/sec, Rate-Limited

The no-filter configuration had 3 test points with 3 divergent PIO occurrences. The FWB filter configuration had 4 test points with 3 bounded and 1 divergent PIO occurrence. The DS filter configuration had 4 test points with 4 divergent PIO occurrences. All three filter configurations experienced PIO every time. The no-filter and DS configurations always experienced divergent oscillations; however, the FWB filter kept the oscillations bounded three out of four times.

The FWB filter configuration performed better than the no-filter and DS filter configurations, which performed about the same.

Case D, 60°/sec, Rate-Limited

The no-filter configuration had 2 test points with 1 divergent PIO occurrence. The FWB filter configuration had 4 test points with 1 bounded PIO occurrence. The DS filter configuration had 3 test points with 2 bounded and 1 divergent PIO occurrence. The FWB filter configuration was better at reducing the occurrence of PIO, followed by the no-filter configuration, and then the DS filter configuration. Both the no-filter and DS filter configurations experienced divergent oscillations. The FWB filter configuration experienced only bounded oscillations.

The FWB filter configuration performed better than the no-filter configuration, and much better than the DS filter configuration. The no-filter configuration performed better than the DS filter configuration.

Case D, 45°/sec, Rate-Limited

The no-filter configuration had 2 test points with 2 divergent PIO occurrences. The FWB filter configuration had 3 test points with zero PIO occurrences. The DS filter configuration had 3 test points with 2 divergent PIO occurrences. Although the no-filter configuration experienced PIO every time, the oscillations were bounded and more controllable than the divergent oscillations that occurred two-thirds of the time with the DS filter configuration.

The no-filter configuration performed better than the DS filter configuration, and the FWB filter configuration performed much better than both of them.

Overall Flight Test Results

The FWB filter configuration was better than the no-filter configuration in preventing the occurrence of PIO for all test cases, and better than DS filter configuration for all test cases but the Case C, 45 deg/sec rate limited test points. However, for that case the FWB filter configuration reduced or eliminated divergent PIO oscillations better than the DS filter and no-filter configurations. In some cases the DS filter configuration increased the probability of PIO occurrence as compared to the no-filter configuration, and the majority of the oscillations that occurred were divergent.

As was seen in the simulator, the performance of the DS filter configuration improved as the actuator rate increased. In addition, comparison of Appendix B, Figures 8 and 9 showed that the simulator predicted the trends seen in flight. The only case where the simulator results for PIO susceptibility did not mirror the flight test results was for the Case C, 60 deg/sec rate limit. The differences could have been due to two things. The simulator motion cues had a hard time replicating the large motions seen when trying to rate limit an actuator that fast. Also, the non-linearities in the VISTA center stick that were described above became more pronounced at the higher rate limits.

Table 3: PIO Comparison Summary – Flight

Aircraft Case / Rate Limit	FWB vs. No-filter	DS vs. No-filter	FWB vs. DS	Best Performer
C / 60° per sec	About the Same	Worse	Better	FWB & No-Filter
C / 45° per sec	Better	About the Same	Better	FWB
C / 30° per sec	About the Same	Worse	Better	FWB & No-Filter
C / 15° per sec	Better	About the Same	Better	FWB
D / 60° per sec	Better	Much Worse	Much Better	FWB
D / 45° per sec	Much Better	About the Same	Much Better	FWB

Filter Effect on Handling Qualities

Test Procedures

Two separate tracking tasks were used in the Phase 3 evaluations – a discrete HUD tracking task with a synthetic target generated in the HUD, and tracking of an actual aircraft. In the simulator the target aircraft was projected on the visual display; for the flight test, a T-38 target was used.

The HUD target was shown in Figure 2. It followed a pitch and bank profile as described in MIL-HDBK 1797A (Reference 7), reproduced below in Figure 4. 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 that were periodically reversed. In the simulator the

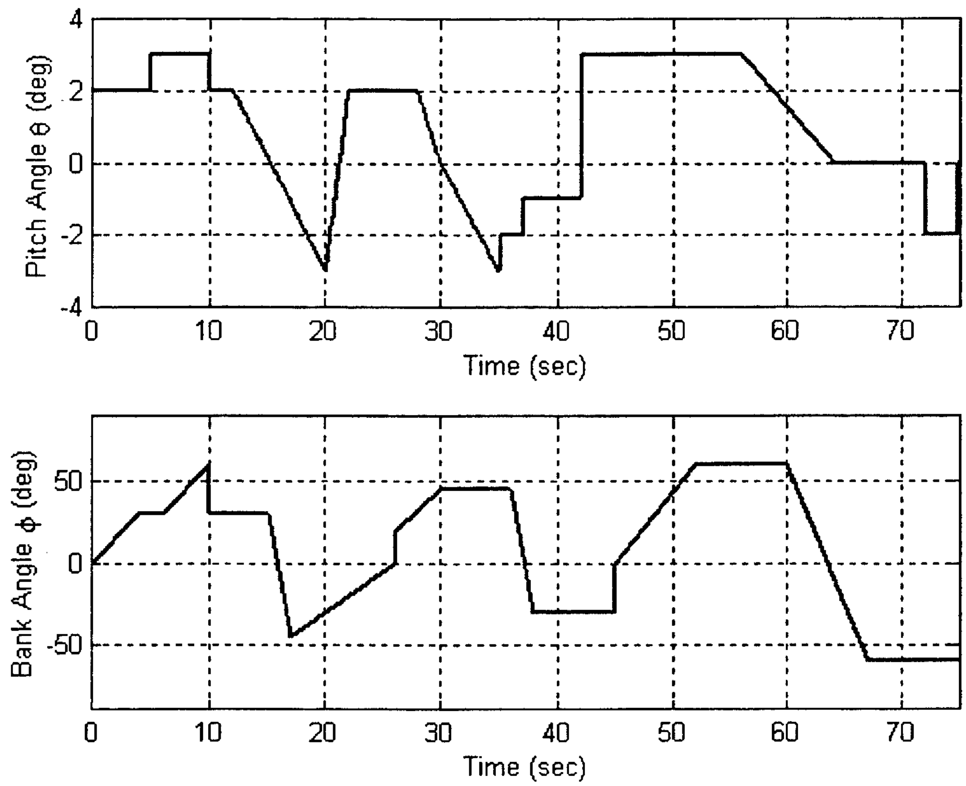

Figure 4: Pitch Command for HUD Discrete Tracking Task

turns were reversed every 20 seconds; in flight, the reversal time was reduced to approximately 15 seconds. The target aircraft tracking task was mainly used to evaluate larger-amplitude aggressive acquisition and transition to fine track.

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 20- and 40-mil diameter reticles.

There were a few test procedures/parameters that differed between the simulator and flight tests. These differences are highlighted in the sections below.

Simulator-Specific Procedures

Performance criteria used to assign a CHR for the HUD tracking task were:

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

Adequate – 75% of the track time, have the target within the 40-mil reticle

Following the testing it was discovered that reticles were set too large. They were supposed to be 10 and 20 mils in diameter, not radius. This was corrected for the flight test.

Flight Test Specific Procedures

The HUD discrete tracking task used for the flight tests was the same task used in the simulator; the only difference was that the task could also be run backwards to prevent the pilots from learning the task. Performance criteria used to assign a CHR for the HUD tracking task were:

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

Adequate – 45% of the track time, have the target in the 20-mil reticle

Simulator Results

For each Phase 3 task, a CHR, rate limiting information and pilot comments were recorded. Only the simulator tasks where rate limiting was achieved were compared. Pilot comments and Cooper-Harper rating levels were compared for each Case C configuration and rate limit combination. The combination of pilot ratings and comments for each configuration determined which was better. Refer to Appendix C, Figure 10, for CHR ratings. Pertinent pilot comments are included in the text below. The Five-Point General Purpose Scale was used to describe which filter configuration had the best handling qualities for each case.

Case C, 60°/sec, Rate-Limited

The no-filter configuration had 3 test points; all 3 produced Level 2 CHR. The FWB configuration had 4 test points; 2 produced Level 1 and 2 produced Level 2 CHR. The DS configuration had 5 test points; 2 produced Level 1, 2 produced Level 2 and 1 produced Level 3 CHR (see Figure 10).

When tracking aggressively with the no-filter configuration, oscillations about the target were easily induced. These oscillations always led to Level 2 CHR.

The FWB filter generated a low-amplitude response that decreased 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 time difference between stick input and actuator output. The delay generated a Level 3 rating from one pilot due to a PIO. This was the only PIO encountered at this rate limiting.

Based upon CHR and pilot comments, the FWB configuration was better than the no-filter configuration, which was better than the DS configuration.

Case C, 45°/sec, Rate-Limited

The no-filter configuration had 3 test points; 1 produced Level 1 and 2 produced Level 2 CHR. The FWB configuration had 6 test points; 1 produced Level 1, 4 produced Level 2 and 1 produced Level 3 CHR. The DS configuration had 7 test points; 2 produced Level 1, 3 produced Level 2, 1 produced Level 3 CHR and 1 was uncontrollable (see Figure 10).

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. As a result, the pilots perceived the aircraft to be less responsive. Most pilots felt this lack of response helped prevent PIO and improved handling qualities. However, one pilot felt the lack of aircraft response drew him into a PIO, which led to a Level 3 rating.

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 (see Appendix D, Figure 17). 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 better than the DS filter.

Case C, 30°/sec, Rate-Limited

The no-filter configuration had 5 test points; 2 produced Level 2 and 3 produced Level 3 CHR. The FWB configuration had 5 test points; 3 produced Level 1 and 2 produced Level 3 CHR. The DS configuration had 5 test points; 1 produced Level 1, 1 produced Level 2, 1 produced Level 3 CHR and 2 were uncontrollable (see Figure 10).

The no-filter configuration produced only Level 2 and Level 3 ratings. 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 increased overall workload. The pilots had considerable to intolerable workloads while performing the tasks.

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. Even though the pilot could experience a PIO during tracking, these were bounded and could be compensated for, allowing the pilot to stay in the loop.

The DS filter was the worst of the three configurations. During 2 of the 5 test points PIO was achieved and the pilots had 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 (see Figure 11). 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 handling qualities for the task, followed by the no-filter configuration, with DS performing the worst.

Case C, 15°/sec, Rate-Limited

The no-filter configuration had 3 test points; 1 produced Level 2 CHR and 2 were uncontrollable. The FWB configuration had 3 test points; 2 produced Level 2 and 1 produced Level 3 CHR. The DS configuration had 3 test points; 2 produced Level 3 CHR and 1 was uncontrollable (see Figure 10).

The no-filter configuration led to the pilot losing control during the task 2 of 3 times. The aircraft would have departed controlled flight during these test runs due to large divergent PIO about the target during aggressive tracking (see Figure 14).

The FWB filter always kept the aircraft from becoming uncontrollable and produced Level 2 ratings 2 of 3 times. This configuration was the only one that allowed the pilot to stay in the loop the entire time. Small oscillations were generated around the target when the pilot applied abrupt control. These oscillations detracted from overall task performance, but control was always maintained.

The DS filter had approximately the same handling qualities characteristics as the no-filter configuration. Controlled flight was lost 1 of 3 times and the pilot had to back out of the loop to maintain control (leading to Level 3 ratings) the rest of the time. During every test point, the pilot had to freeze or release the controls to avoid losing control of the airplane.

The FWB filter had better handling qualities than both the no-filter and DS filter configurations. The no-filter and DS filter configurations were about the same.

Overall Simulator Results

The FWB filter yielded better handling qualities than the DS filter and no-filter configurations. The handling qualities were worse for the DS filter than with the no-filter configuration. Control was lost twice as often (4 vs. 2, see Figure 10) when using the DS filter versus no filter at all. Control during task execution was never lost while using the FWB filter. The FWB filter had better handling qualities for the majority of the rate limit cases (see Table 4).

Table 4: Handling Qualities Summary – Simulator

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

Flight Test Results

For each Phase 3 task, rate-limiting information, CHR and pilot comments were recorded. Only the tasks where rate limiting was achieved were compared. Pilot comments and CHR levels were compared for all Case C configurations and two Case D configurations. The combination of pilot ratings and comments for each configuration determined which was better. Refer to Appendix C, Figure 10, for the CHR ratings. Pertinent pilot comments are included in the text below. The Five-Point General Purpose Scale was used to describe which filter configuration resulted in the best handling qualities for each case.

Case C, 60°/sec, Rate-Limited

The no-filter configuration had 2 test points; both produced Level 1 CHR. The FWB configuration had 2 test points; 1 produced Level 1 and 1 produced Level 2 CHR. The DS configuration had 5 test points; 1 produced Level 1, 2 produced Level 2, and 2 produced Level 3 CHR (see Figure 12). Rate limiting was difficult to achieve in the no-filter and FWB filter 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.

One pilot noted a lot of compensation required with the FWB filter configuration in order to control a tendency to overshoot the target; this produced a Level 2 rating. Although given this Level 2 rating, pilot comments were similar for the FWB and no-filter configurations.

The DS filter gave the worst performance and produced several bounded PIO.

The performance of the FWB and no-filter configurations was about the same, while the DS filter performed the worst.

Case C, 45°/sec, Rate-Limited

The no-filter configuration had 6 test points; 5 produced Level 2 and 1 produced Level 3 CHR. The FWB configuration had 6 test points; 1 produced Level 1 and 5 produced

Level 2 CHR. The DS configuration had 7 test points; 2 produced Level 1, 3 produced Level 2, and 2 produced Level 3 CHR (see Figure 12).

With the no-filter configuration, only one PIO was experienced, and it was bounded. This PIO generated a Level 3 rating. There were many oscillations encountered as the pilot tried to aggressively track the target. These oscillations were present every time and generated the remaining Level 2 ratings.

The FWB filter configuration prevented PIO in all of the Phase 3 tasks. Small oscillations were encountered as the pilots tracked the target, producing 5 of 6 Level 2 ratings.

The DS filter configuration produced PIO in 2 of 7 test runs. One was divergent. Figure 17 shows the pilot compensation required to control these divergent oscillations. Although the DS filter configuration produced Level 1 ratings 2 of 7 times, it also encountered PIO (yielding Level 3 CHR) more often than any other configuration.

The FWB filter configuration was better than the no-filter configuration, which was better than the DS filter configuration.

Case C, 30°/sec, Rate-Limited

The no-filter configuration had 6 test points; 1 produced Level 1, 3 produced Level 2, and 2 produced Level 3 CHR. The FWB configuration had 7 test points; 4 produced Level 2 and 3 produced Level 3 CHR. The DS configuration had 5 test points; 2 produced Level 2, 2 produced Level 3 CHR, and 1 was uncontrollable (see Figure 12).

The no-filter and FWB filter configurations produced approximately 60 percent Level 2 CHR and 40 percent Level 3 Cooper-Harper ratings. For both configurations, the aircraft was never uncontrollable. The oscillations around the target were never divergent. Even though a pilot could experience a PIO during tracking, these were bounded and could be compensated for, allowing the pilot to stay in the loop.

The DS filter was the worst of the three configurations. During 4 of 5 test points, PIO was 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 ratings and comments showed the FWB filter and no-filter configurations were about the same, while the DS filter configuration was worse than both.

Case C, 15°/sec, Rate-Limited

The no-filter configuration had 3 test points; 2 produced Level 3 CHR and 1 was uncontrollable. The FWB configuration had 4 test points; all 4 produced Level 3 CHR. The DS configuration had 4 test points; all 4 were uncontrollable (see Figure 12).

Using 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 were encountered.

The FWB filter configuration never made task execution uncontrollable and produced Level 3 ratings every time (see Figure 13). 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 configuration 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 during task execution every time if not for the safety features of the VISTA aircraft. Figure 20 shows an example of a small pitch capture yielding a wildly oscillatory response caused by increasing phase lag.

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.

Case D, 60°/sec, Rate-Limited

The no-filter configuration had 1 test point; it produced a Level 3 CHR. The FWB configuration had 2 test points; 1 produced Level 1 and 1 produced Level 2 CHR. The DS configuration had 2 test points; 1 produced Level 2 and 1 produced Level 3 CHR (see Figure 12).

The no-filter configuration produced "[a] lot of oscillations about the target." Task execution was extremely difficult because the pilot used significant compensation to try to dampen the oscillations.

The FWB filter configuration typically produced "only 1 oscillation" about the target. Task execution required minimal to moderate pilot compensation.

The DS filter slightly reduced the number of overshoots about the target from the no-filter configuration. Because the oscillations were not easily damped out, moderate or greater compensation was always necessary.

The FWB filter performed the best, followed by DS, and the no-filter configuration was the worst.

Case D, 45°/sec, Rate-Limited

The no-filter configuration had 2 test points; 1 produced a Level 2 and 1 produced a Level 3 CHR. The FWB configuration had 2 test points; 1 produced Level 1 and 1 produced Level 3 CHR. The DS configuration had 3 test points; 1 produced Level 1, 1 produced Level 2, and 1 produced Level 3 CHR (see Figure 12).

The no-filter configuration produced several large oscillations about the target during fine tracking. These oscillations could be damped out with considerable compensation, which negatively affected overall task performance.

The FWB and DS configurations produced fewer oscillations about the target than the no-filter configuration, which lowered overall workload for the task. Task performance was about the same for the DS and FWB configurations.

The DS and FWB filter configurations were about the same and were better than the no-filter configuration.

Overall Flight Test Results

The FWB filter configuration was the best overall. It consistently reduced the magnitude and number of oscillations around the target. The FWB filter was the best of the three in every aircraft case and rate limit. For Aircraft Case C, the no-filter configuration was second best. It was better than the DS filter in every Case C rate limit. For Aircraft Case D, however, the DS filter was better than the no-filter configuration in every rate limit.

Table 5: Handling Qualities Comparison Summary - Flight

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

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CONCLUSIONS AND RECOMMENDATIONS

The Feedback-with-Bypass (FWB) filter performed better than the Derivative Switching (DS) filter in preventing pilot-induced oscillations (PIO) and improving handling qualities. The test team was able to achieve all objectives during both ground-based simulator and in-flight investigations.

While the FWB filter did not prevent PIO in all cases, it was more effective than the DS filter at preventing divergent PIO. For the aircraft configurations with poor aircraft dynamics and low actuator rate limits, a divergent PIO occurred even with the FWB filter. However, the rate of occurrence was significantly less then with either the DS filter or no filter. The DS filter performance improved as the rate limit increased, but did not prevent either bounded or divergent PIO better than the FWB filter. While the DS filter configuration reduced the number of times PIO occurred, the majority of oscillations were still divergent. The ability of the FWB filter to prevent *divergent* oscillations was the deciding factor in improving PIO susceptibility.

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

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8. Weisenseel, Annette W. The Author's Guide to Writing Air Force Flight Test Center Technical Reports. AFFTC-TIH-02-01.

APPENDIX A: SIMULINK® DIAGRAMS

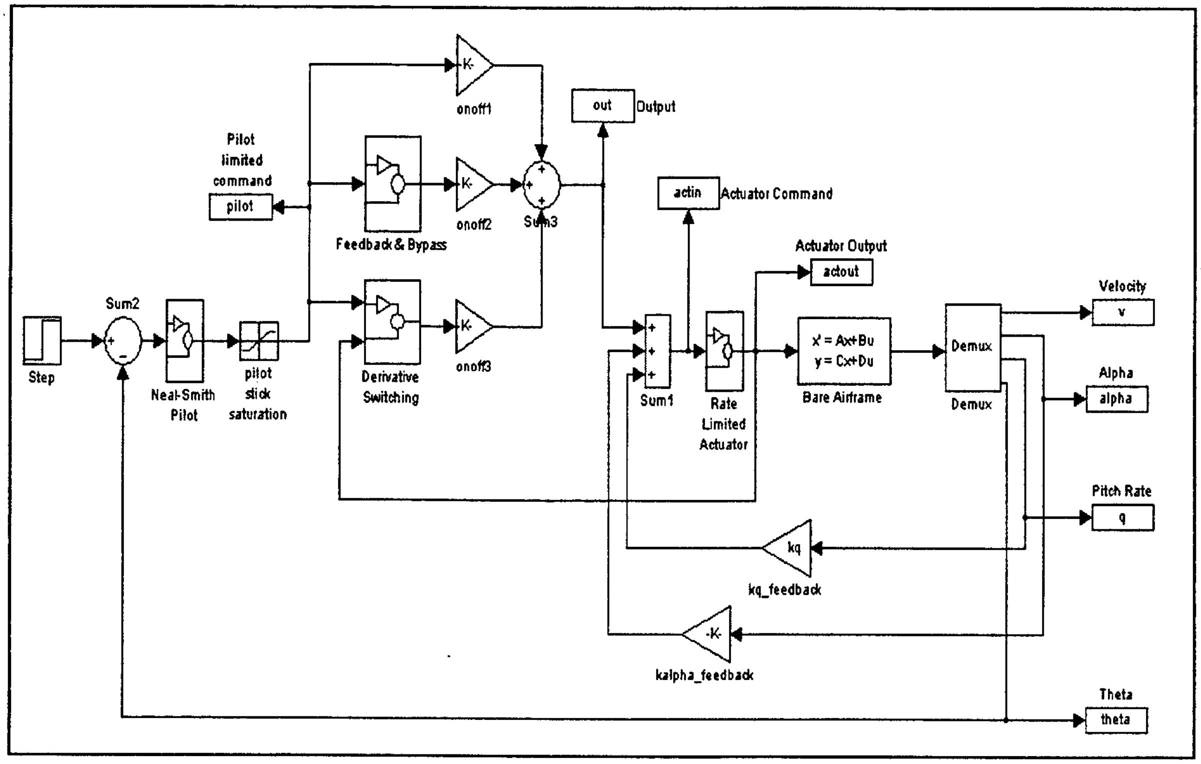

Figure 5: Aircraft Simulation Diagram

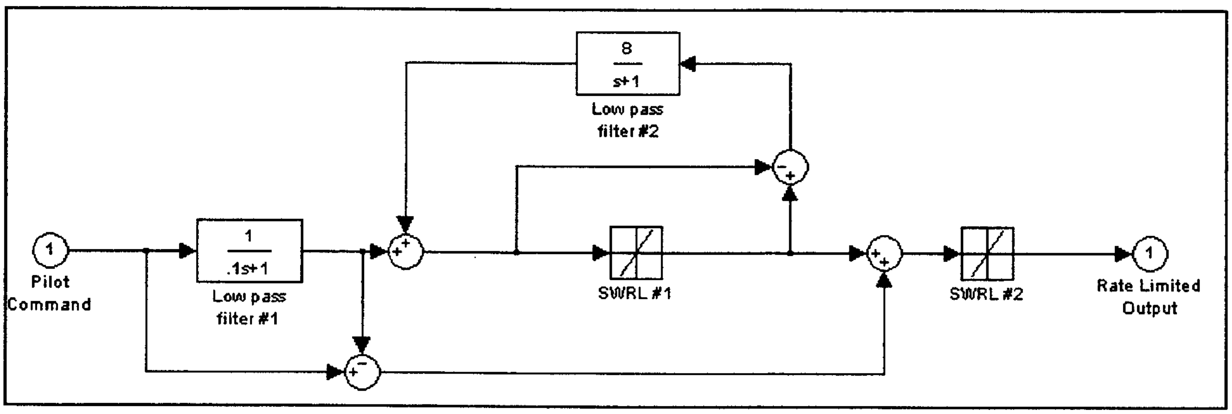

Figure 6: Saab Feedback-with-Bypass (FWB) Filter

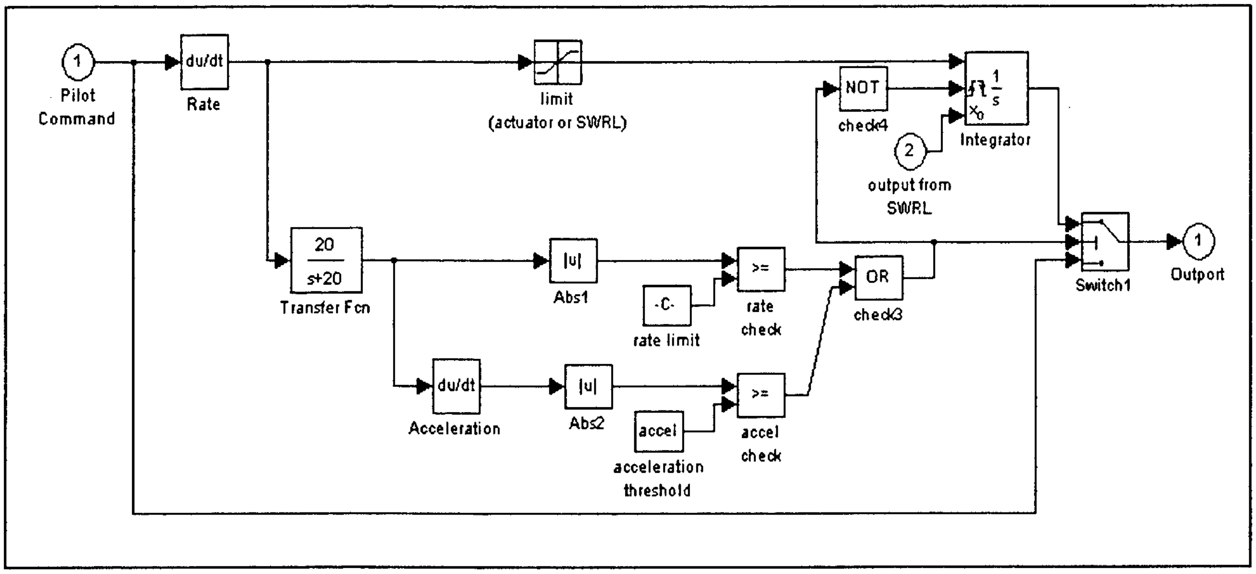

Figure 7: AFIT Derivative Switching (DS) Filter

APPENDIX B: PHASE 2 PIO RATINGS

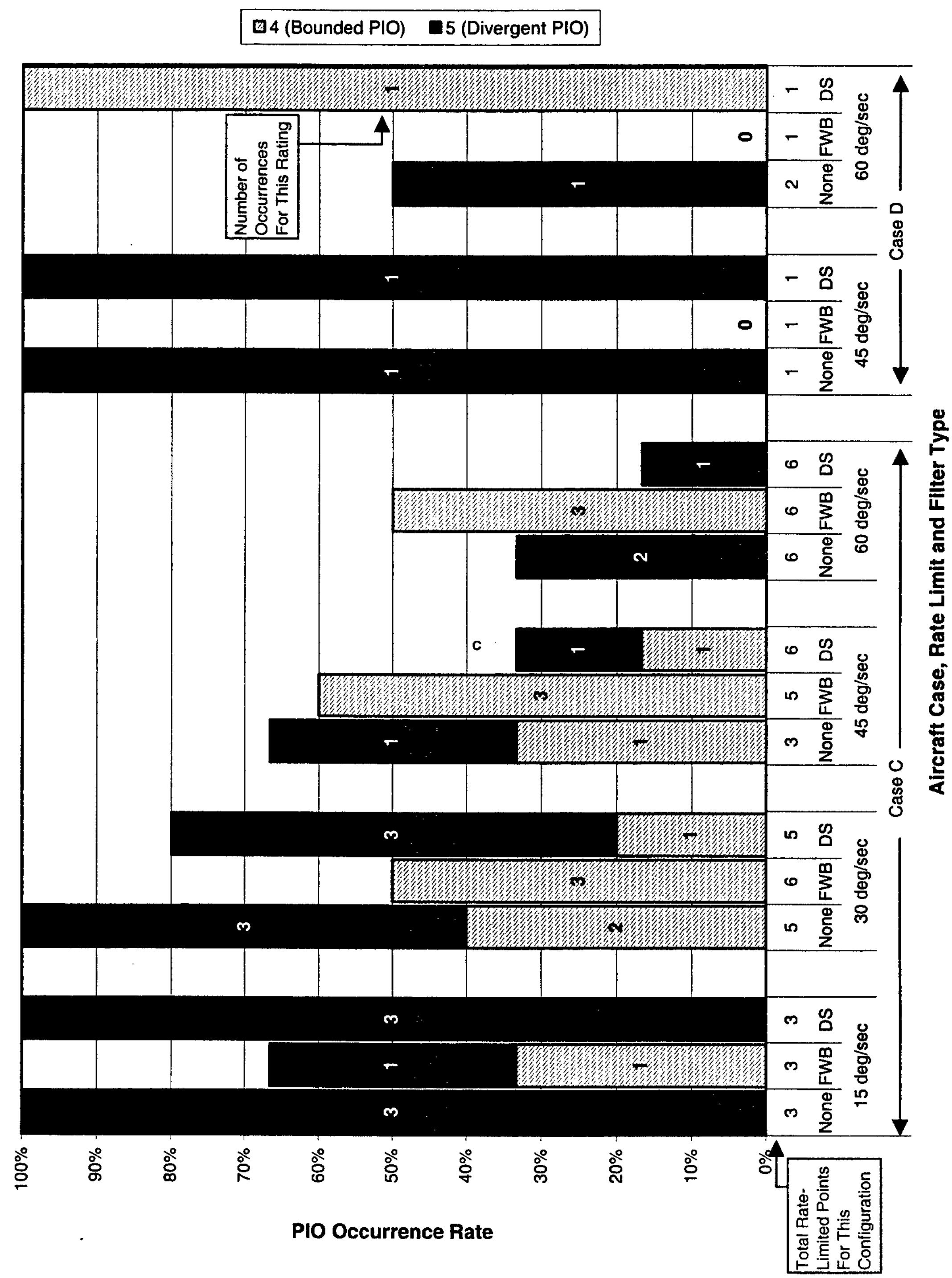

Figure 8: Simulator Rate-Limited PIO Ratings

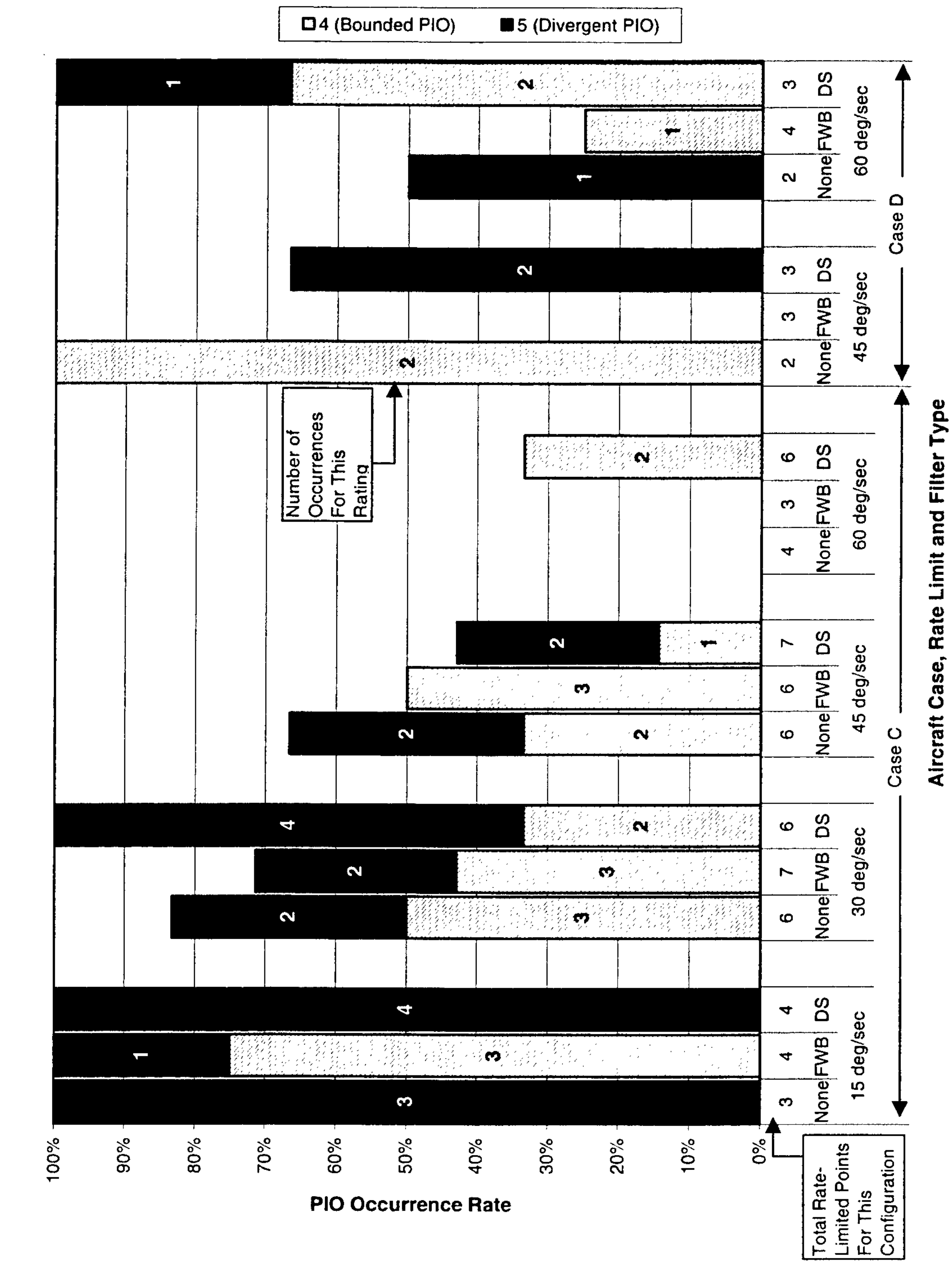

Figure 9: Flight Test Rate-Limited PIO Ratings

APPENDIX C: PHASE 3 COOPER-HARPER RATINGS

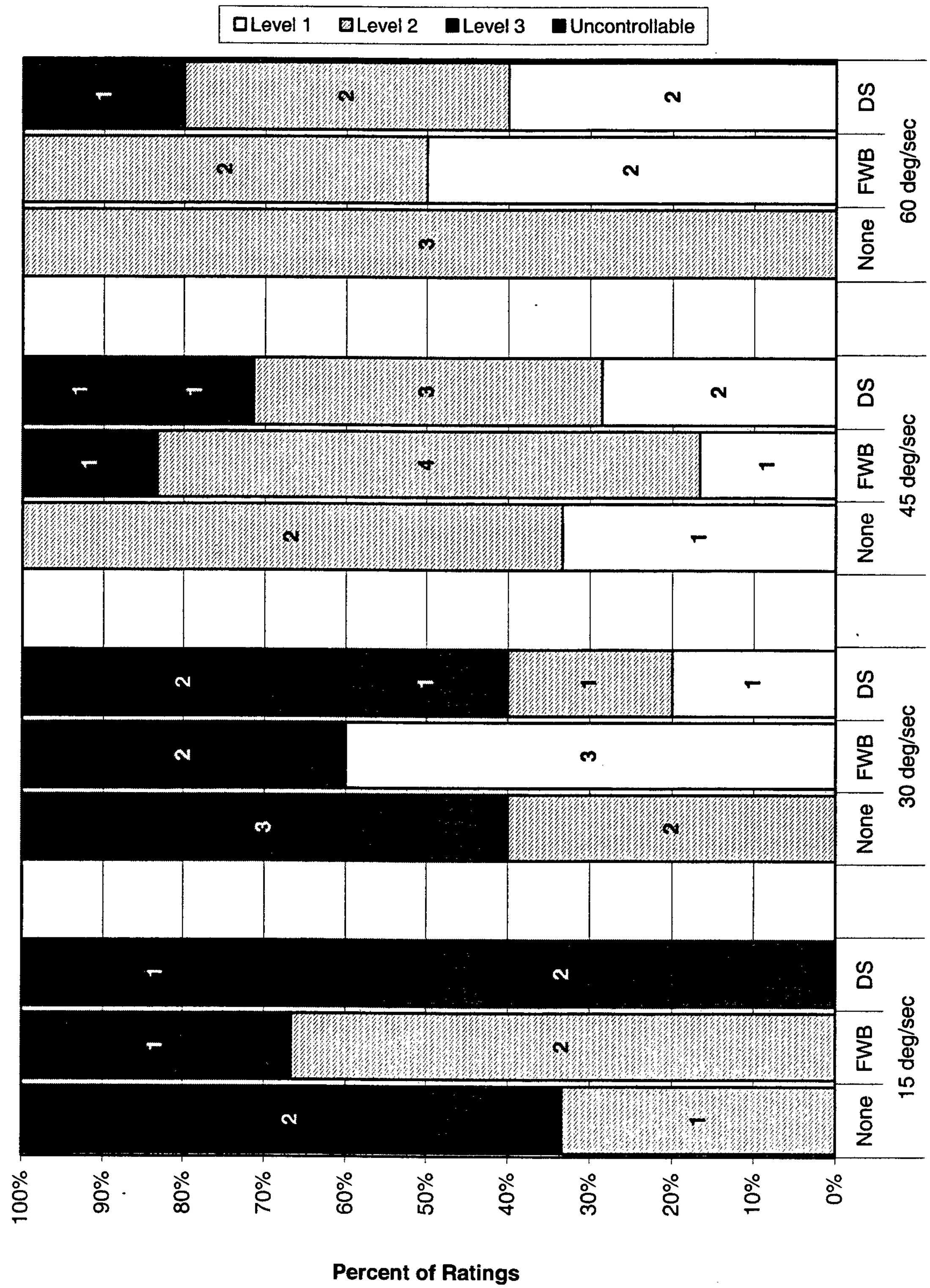

Figure 10: Simulator Rate-Limited Cooper-Harper Ratings

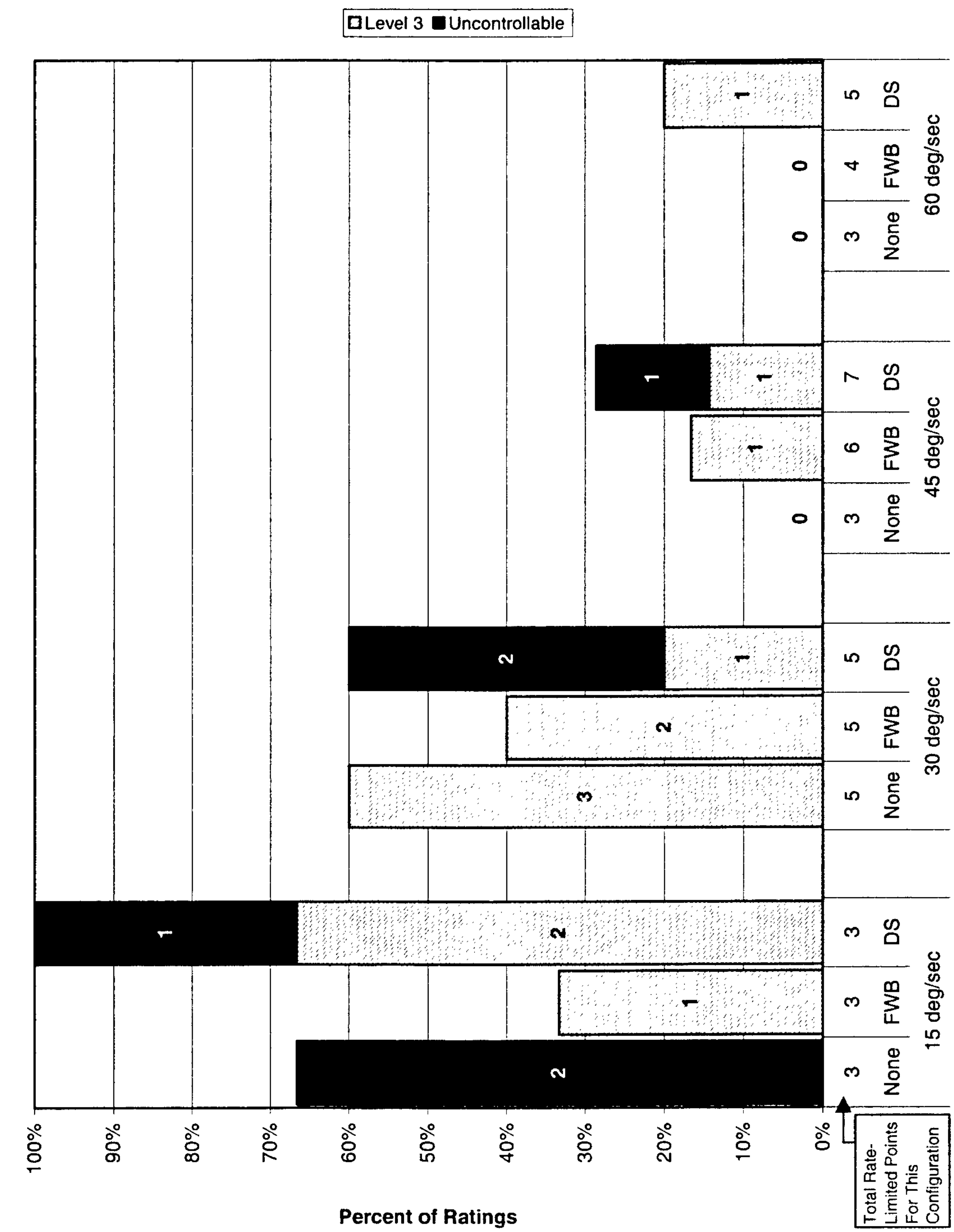

Figure 11: Simulator Rate-Limited Cooper-Harper Ratings (Level 3/Uncontrollable)

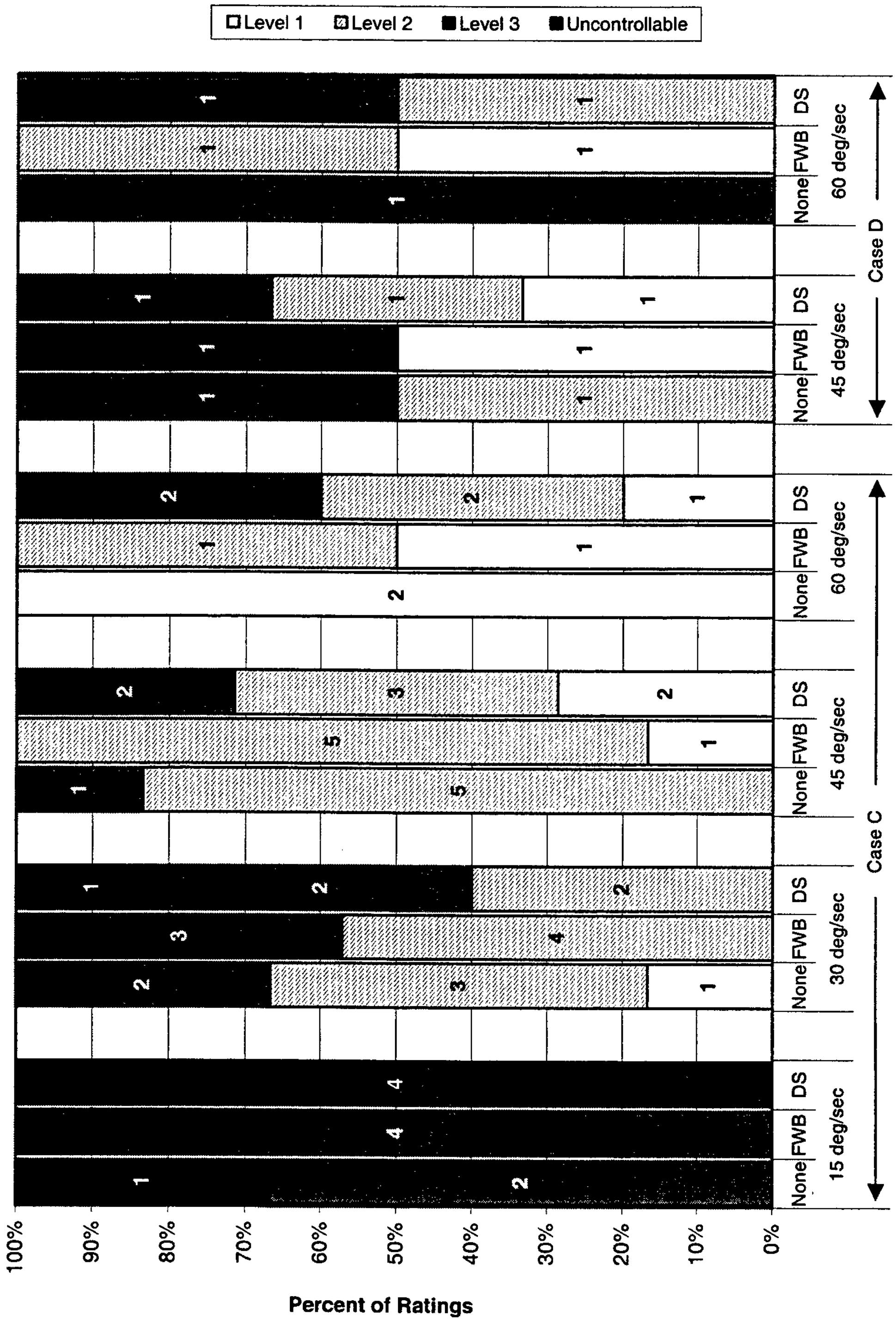

Figure 12: Flight Test Rate-Limited Cooper-Harper Ratings

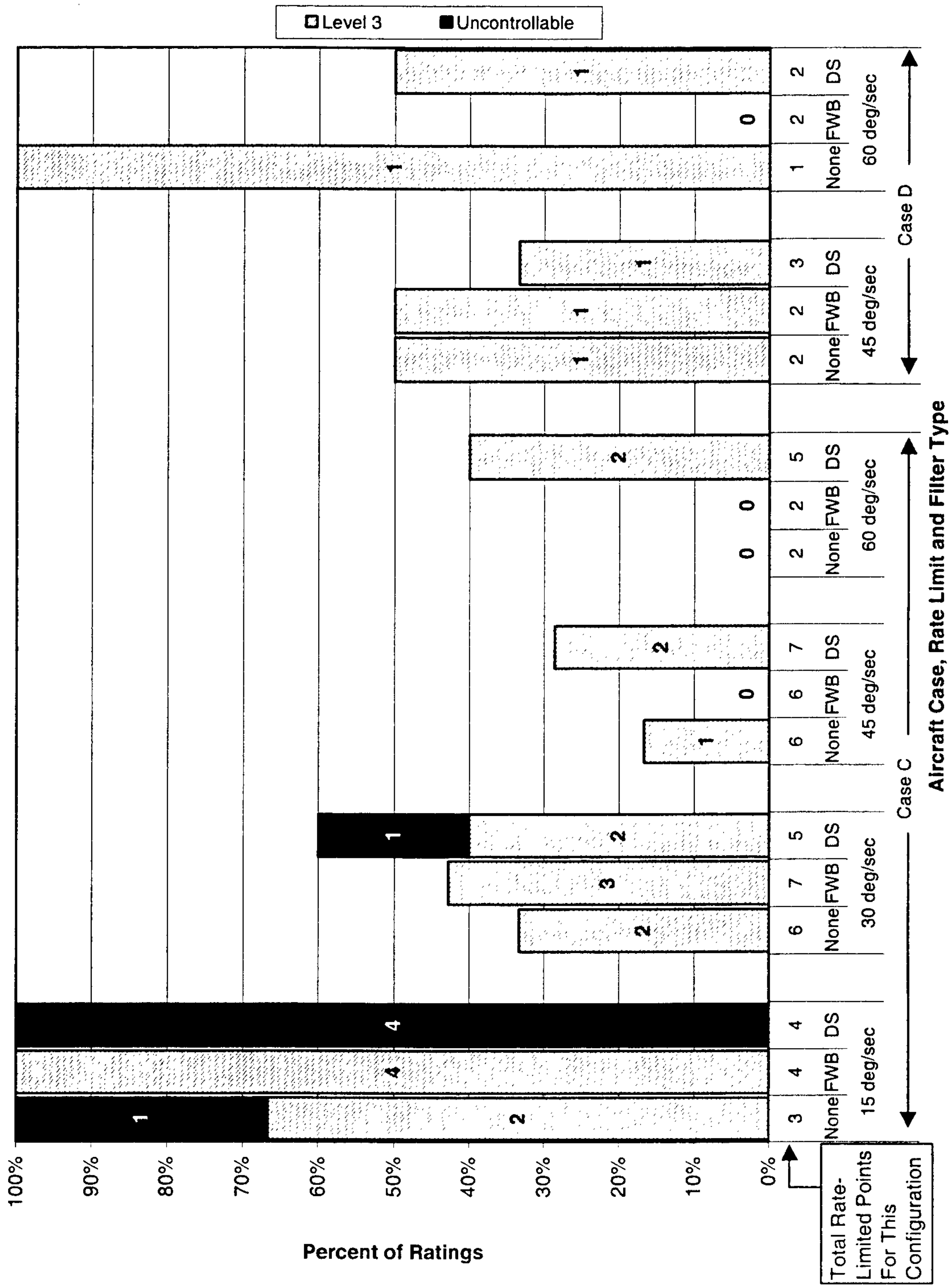

Figure 13: Flight Test Rate-Limited Cooper-Harper Ratings (Level 3/Uncontrollable)

APPENDIX D: SELECTED TEST CASE TIME HISTORIES

SIMULATOR DATA

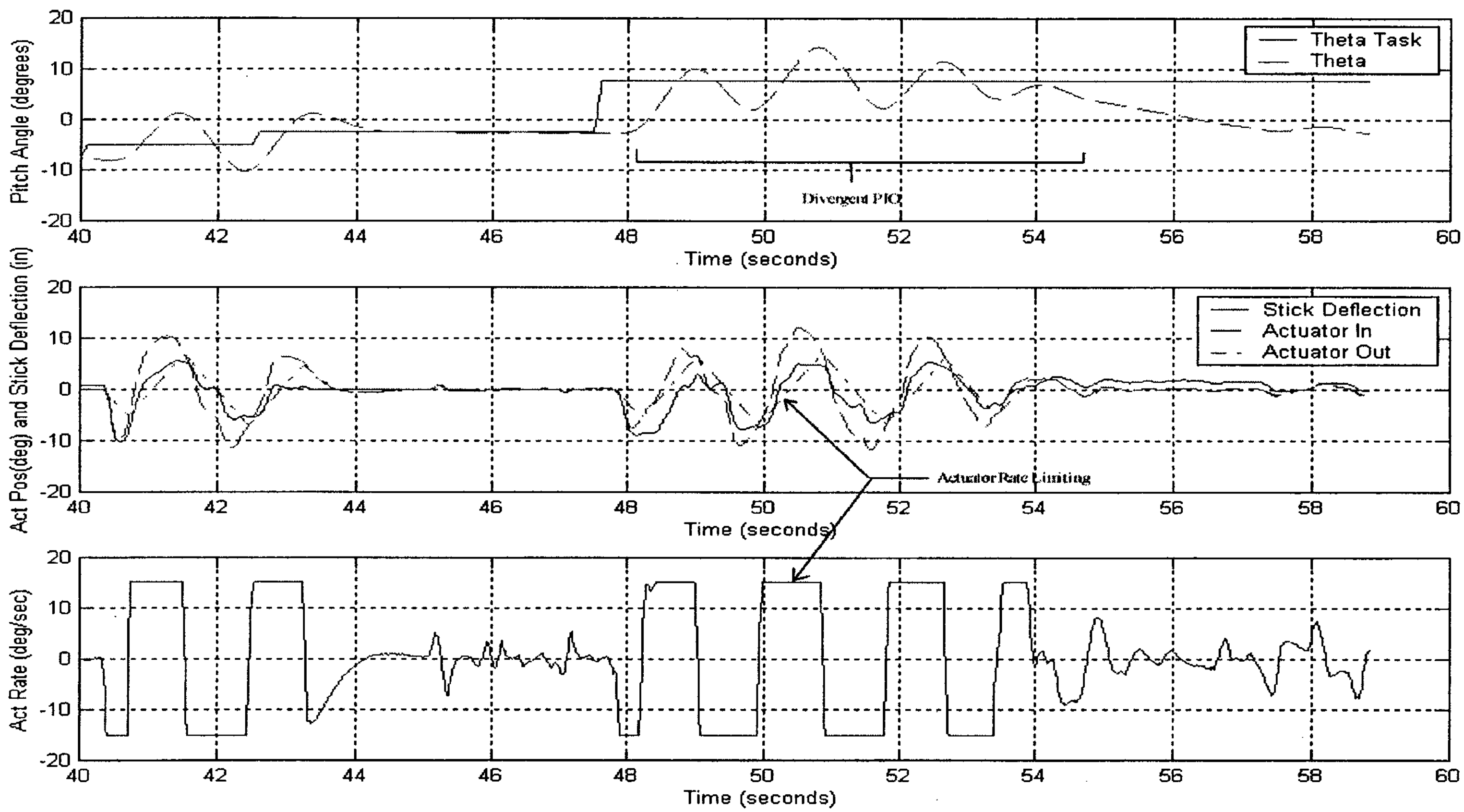

Figure 14: Sample Time History of Divergent PIO, No Filter, Case C, 15 deg/sec Rate Limit, Phase 3 Task

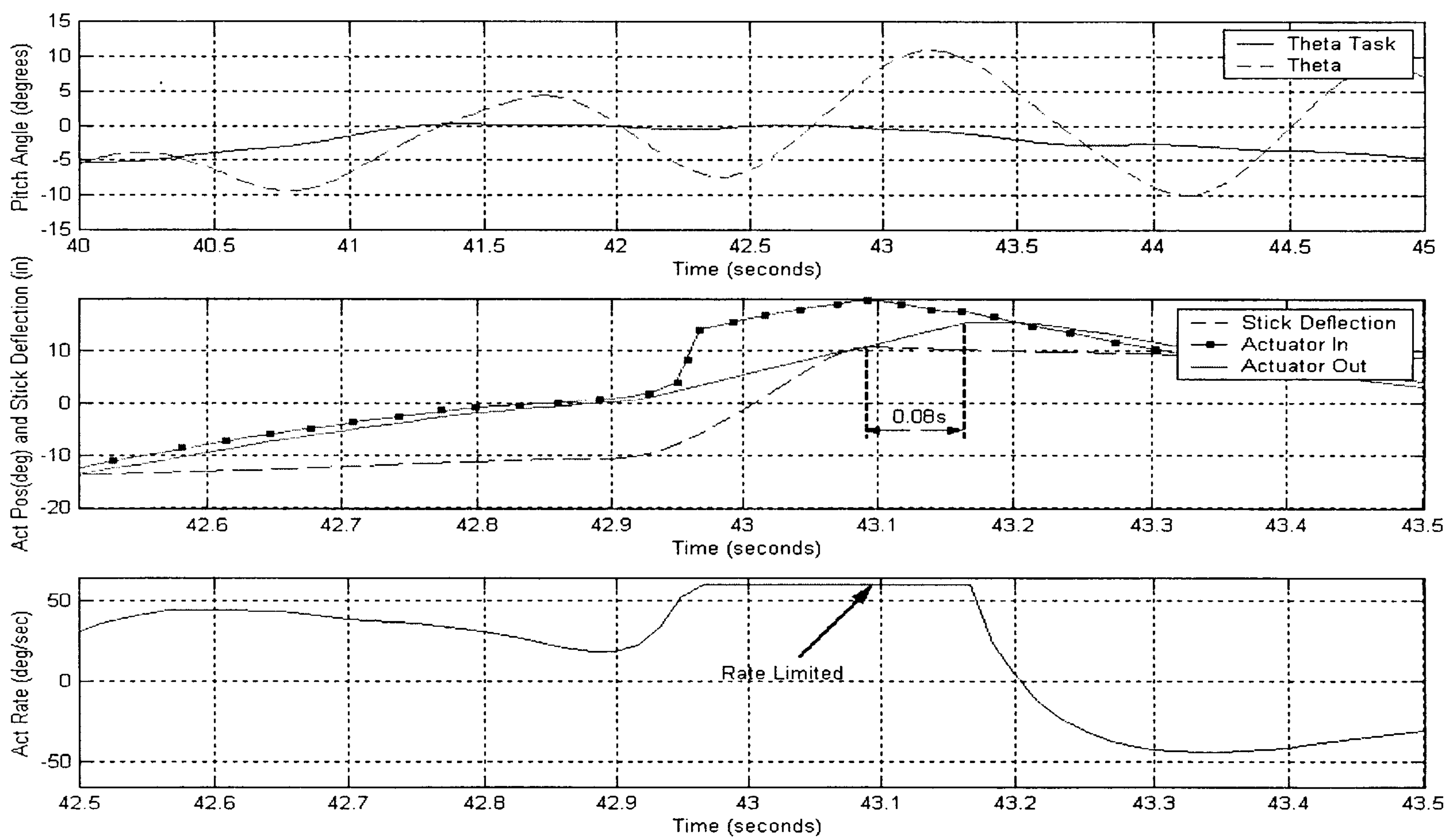

Figure 15: Time Delay For FWB Filter, Case C, 60 deg/sec Rate Limit

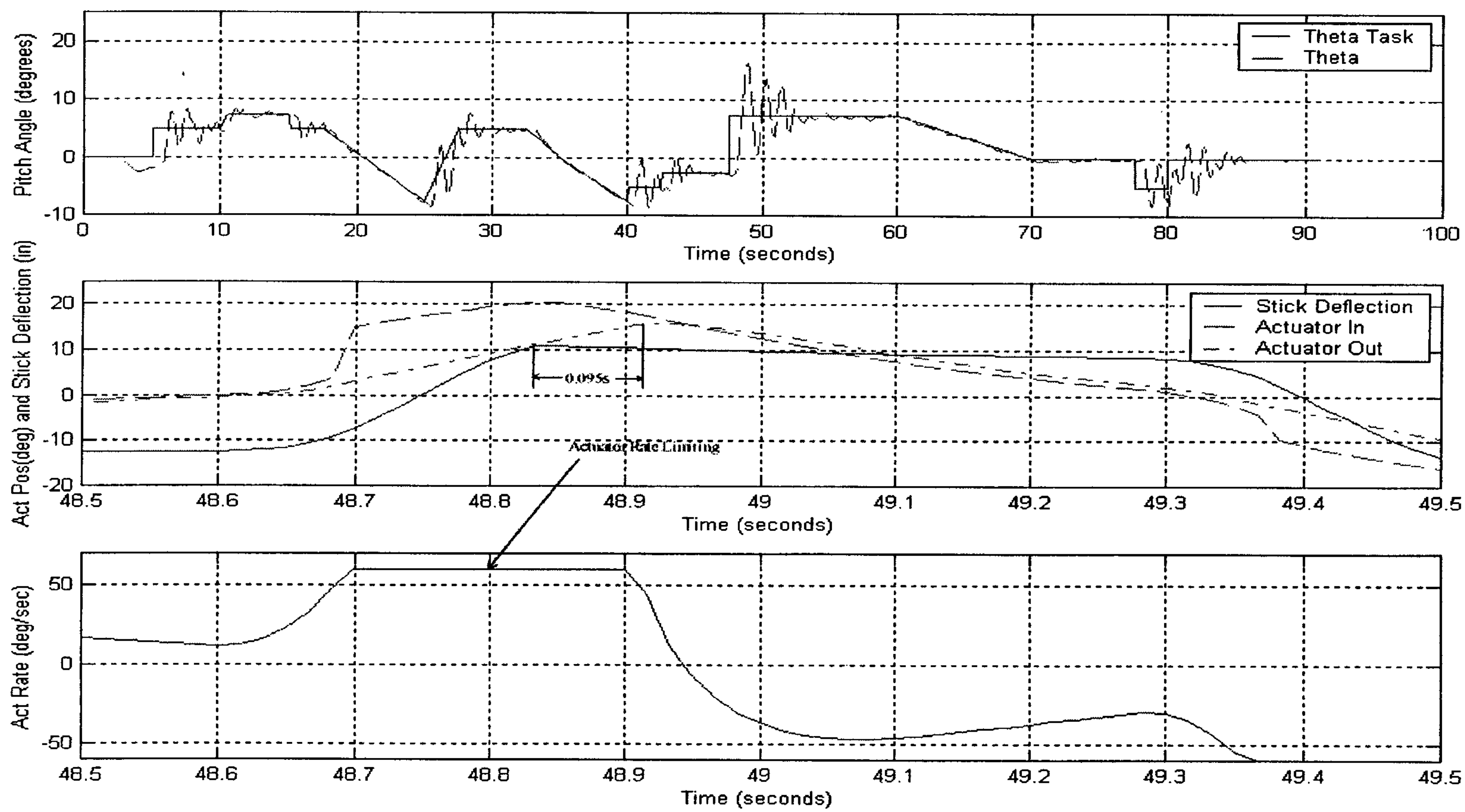

Figure 16: Time Delay For DS Filter, Case C, 60 deg/sec Rate Limit, Phase 3 Task

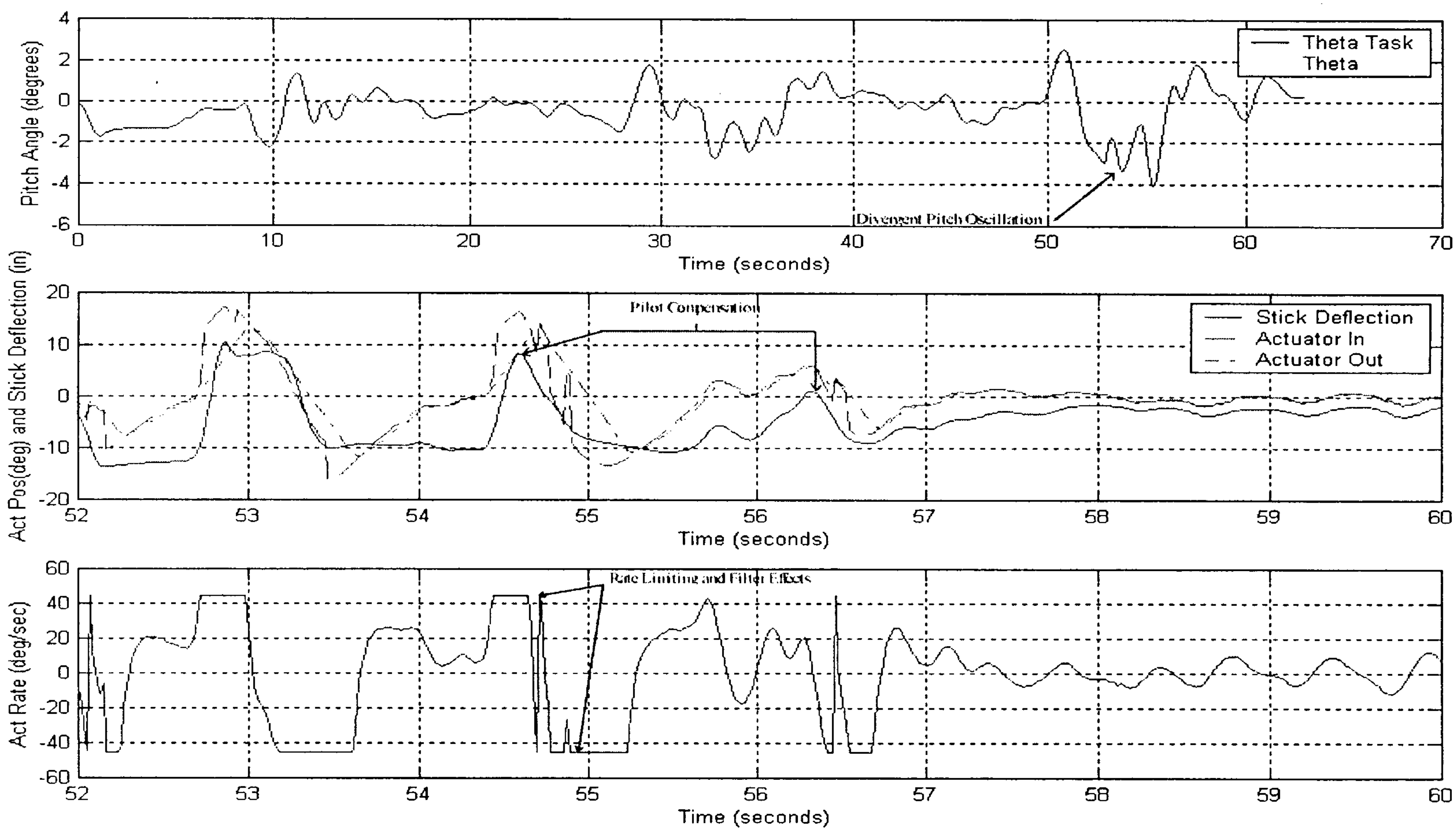

Figure 17: Divergent Pitch Oscillation, DS Filter, Case C, 45 deg/sec Rate Limit, Phase 3 Task

FLIGHT TEST DATA

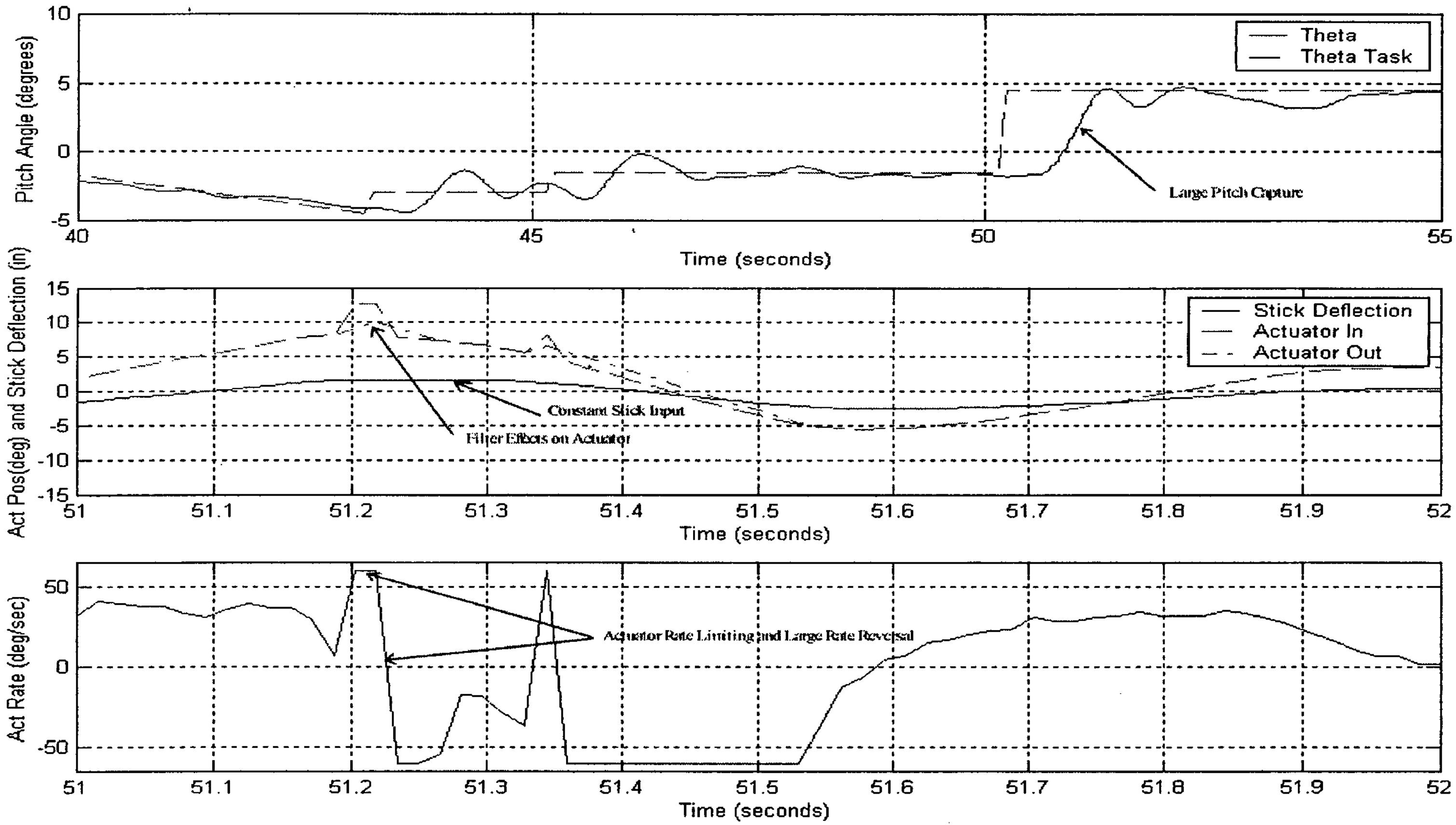

Figure 18: Large Actuator Rate Reversal during Pitch Capture, DS Filter, Case C, 60 deg/sec Rate Limit, Phase 3 Task

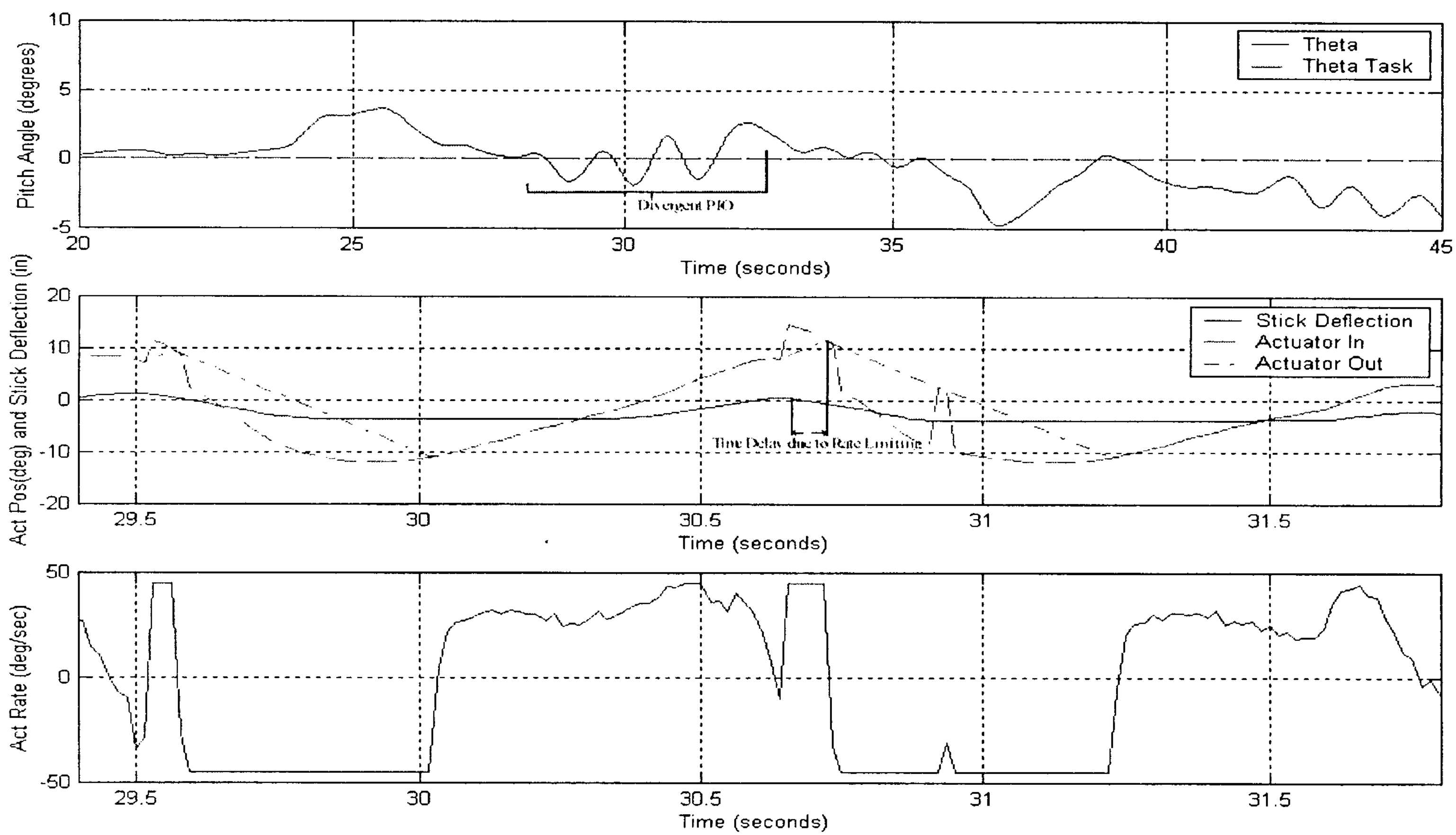

Figure 19: Divergent Pitch Oscillation, DS Filter, Case C, 45 deg/sec Rate Limit, Phase 3 Task vs. T-38

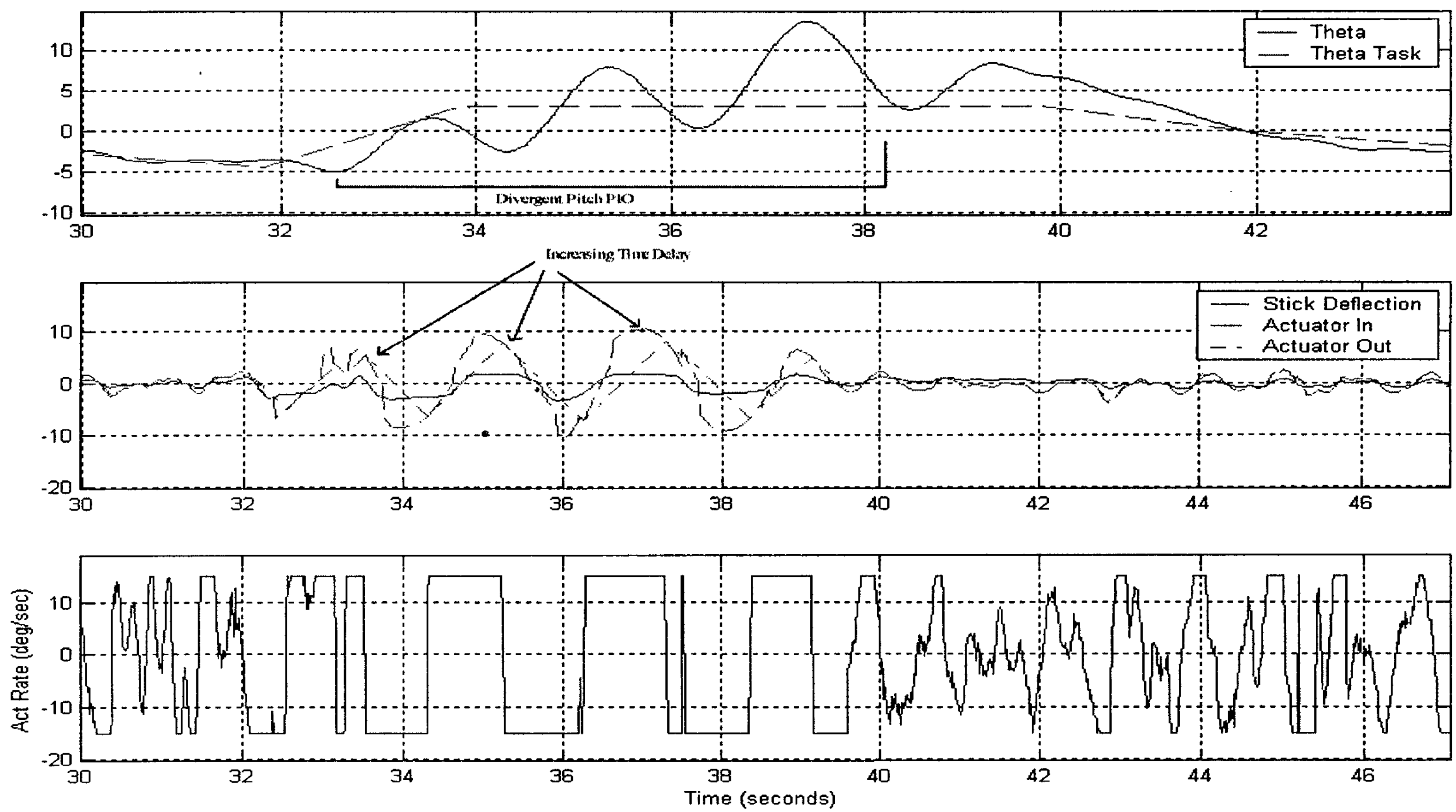

Figure 20: Increasing Time Delay, DS Filter, Case C, 15 deg/sec Rate Limit, HUD Phase 3 Task

APPENDIX E: RATING SCALES

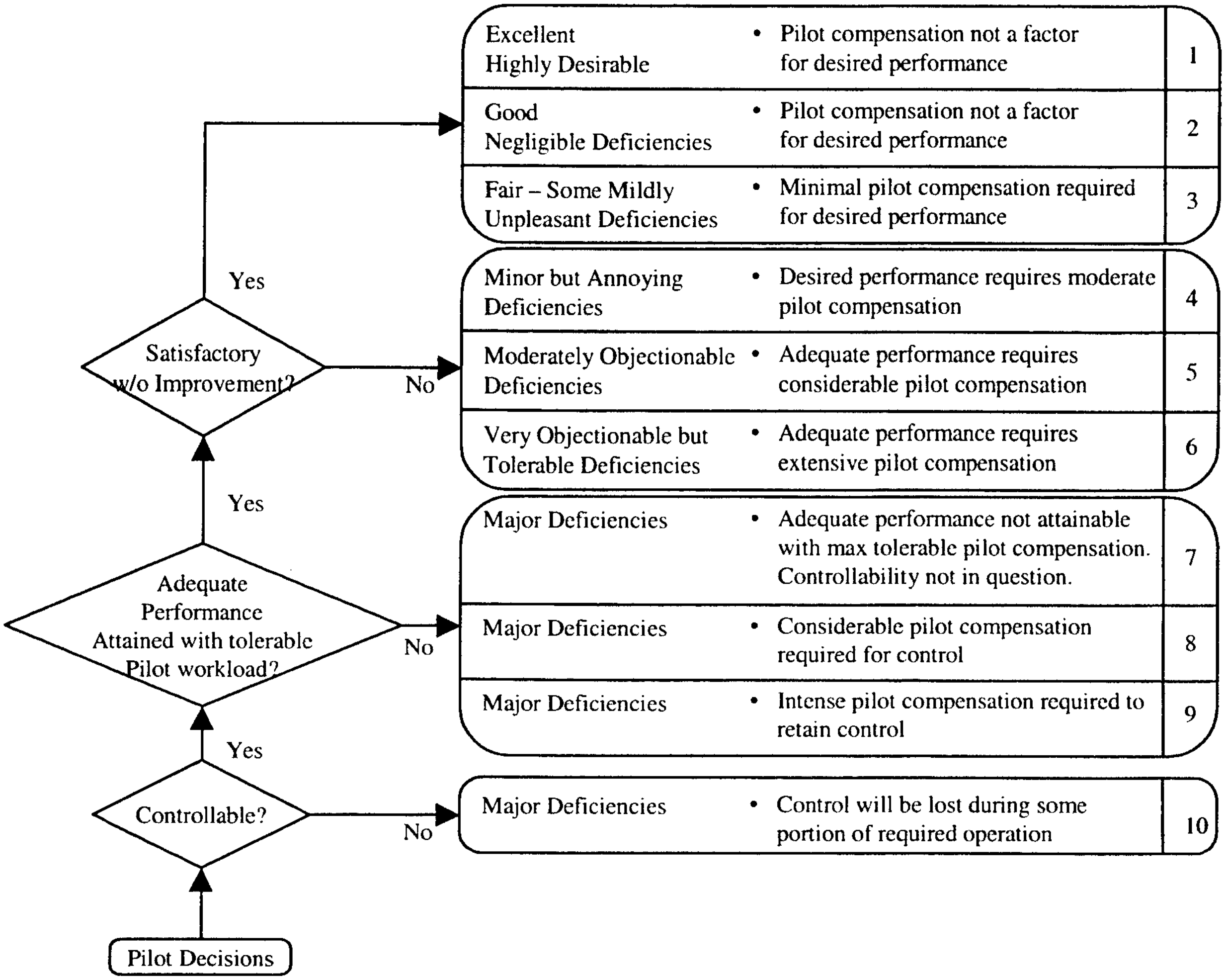

Figure 21: Cooper-Harper Rating Scale (Reference 11)

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 22: Pilot-Induced Oscillation (PIO) Rating Scales

APPENDIX F: TEST POINT CONFIGURATIONS

Table 6 below lists the planned test point configurations. The "Test Pt ID" column can be used to identify the test point in Appendix G. The "Simulator Random ID" and "Flight Test Random ID" columns provide the codes that control room personnel used to communicate given configurations to the simulator or aircraft, respectively. Finally, the "Veridian ID" column provides the two three-digit pairs used by Veridian personnel to enter the configuration into the VISTA VSS. This code can be used to correlate the data in result files obtained from Veridian to the proper test configuration.

Table 6: Test Configurations

Test Pt ID	Priority	Case	Rate	Filter	Simulator Random ID	Flight Test Random ID	Veridian ID
1	2	A	60	None	DS	MDT	66X-000
2	2	A	60	FWB	78	KRS	66X-001
3	2	A	60	DS	IK	UYR	66X-502
4	2	A	45	None	U6	EWT	64X-000
5	2	A	45	FWB	ER	RTY	64X-001
6	2	A	45	DS	MJ	E5R	64X-502
7	5	A	30	None	AS	BWY	63X-000
8	5	A	30	FWB	4H	KGW	63X-001
9	5	A	30	DS	K6	LIH	63X-502
10	5	A	15	None	TV	WFS	61X-000
11	5	A	15	FWB	D5	JMG	61X-001
12	5	A	15	DS	CD	DFY	61X-502
13	3	B	60	None	DE	NFS	76X-000
14	3	B	60	FWB	JM	WWR	76X-001
15	3	B	60	DS	3E	NJG	76X-502
16	3	B	45	None	6U	AZS	74X-000
17	3	B	45	FWB	SR	WEY	74X-001
18	3	B	45	DS	JE	TYS	74X-502
19	5	B	30	None	7D	HYW	73X-000
20	5	B	30	FWB	3R	WSU	73X-001
21	5	B	30	DS	F5	GFA	73X-502
22	5	B	15	None	D2	PCD	71X-000
23	5	B	15	FWB	GV	MHE	71X-001
24	5	B	15	DS	BN	STR	71X-502
25	1	C	60	None	SX	SFD	86X-000
26	1	C	60	FWB	7H	ADG	86X-001
27	1	C	60	DS	A2	GFT	86X-502
28	1	C	45	None	D4	KHF	84X-000
29	1	C	45	FWB	6I	QWE	84X-001
30	1	C	45	DS	A3	ASD	84X-502

Table 6: Test Configurations (Concluded)

Test Pt ID	Priority	Case	Rate	Filter	Simulator Random ID	Flight Test Random ID	Veridian ID
31	1	C	30	None	CR	GHR	83X-000
32	1	C	30	FWB	MF	SDE	83X-001
33	1	C	30	DS	ZD	KJW	83X-502
34	1	C	15	None	MH	NDS	81X-000
35	1	C	15	FWB	O9	QEG	81X-001
36	1	C	15	DS	3Q	GNS	81X-502
37	3	D	60	None	ST	ZFH	96X-000
38	3	D	60	FWB	KL	YJZ	96X-001
39	3	D	60	DS	QD	YIO	96X-502
40	3	D	45	None	MS	ARN	94X-000
41	3	D	45	FWB	JN	GFE	94X-001
42	3	D	45	DS	LO	JTS	94X-502
43	4	D	30	None	PU	FVD	93X-000
44	4	D	30	FWB	63	REA	93X-001
45	4	D	30	DS	69	JRG	93X-502
46	4	D	15	None	MX	FDS	91X-000
47	4	D	15	FWB	WX	EJU	91X-001
48	4	D	15	DS	DQ	ZDF	91X-502

LIST OF SYMBOLS

α	Angle of Attack
deg	Degree
K_α	Angle of Attack Feedback Gain
K_q	Pitch Rate Feedback Gain
θ_{task}	Pitch angle commanded by the tracking task
θ_{act}	Actual aircraft pitch angle
q	Pitch Rate
sec	Second
$\omega_{n_{sp}}$	Short Period Natural Frequency
ζ_{sp}	Short Period Damping
AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AFIT	Air Force Institute of Technology
CHR	Cooper-Harper Rating
DFLCS	Digital Flight Control System
DS	Derivative-Switching (AFIT) Filter
EP	Evaluation Pilot
FBW	Fly-By-Wire
FCS	Flight Control System
FWB	Feedback With Bypass (Saab) Filter
HQ	Handling Qualities
HQDT	Handling Qualities During Tracking
HUD	Head's-Up Display
ID	Identification
JON	Job Order Number
KIAS	Knots Indicated Airspeed
LAMARS	Large Amplitude Multimode Aerospace Research Simulator
M&S	Modeling and Simulation
PIO	Pilot-Induced Oscillation
PIOR	Pilot-Induced Oscillation Rating

RTO	Responsible Test Organization
SAS	Stability Augmentation System
S/N	Serial Number
SP	Safety Pilot
SWRL	Software Rate Limiter
TIM	Technical Information Memorandum
TPS	Test Pilot School
TR	Technical Report
USAF	United States Air Force
USAFTPS	United States Air Force Test Pilot School
VISTA	Variable Stability In-Flight Simulator Test Aircraft
VSS	VISTA Simulation System

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