Theses and Dissertations

Student Graduate Works

3-9-2007

An Analysis of Aircraft Handling Quality Data Obtained from Boundary Avoidance Tracking Flight Test Techniques

Jason D. Dotter

Follow this and additional works at: https://scholar.afit.edu/etd

Part of the Aerospace Engineering Commons

AN ANALYSIS OF AIRCRAFT HANDLING QUALITY DATA OBTAINED
FROM BOUNDARY AVOIDANCE TRACKING FLIGHT TEST TECHNIQUES

THESIS

Jason D. Dotter, Captain, USAF

AFIT/GAE/ENY/07-M24

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GAE/ENY/07-M24

AN ANALYSIS OF AIRCRAFT HANDLING QUALITY DATA OBTAINED FROM BOUNDARY AVOIDANCE TRACKING FLIGHT TEST TECHNIQUES

THESIS

Presented to the Faculty

Department of Aeronautics and Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Aeronautical Engineering

Jason D. Dotter, BS

Captain, USAF

March 2007

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AFIT/GAE/ENY/07-M24

AN ANALYSIS OF AIRCRAFT HANDLING QUALITY DATA OBTAINED FROM BOUNDARY AVOIDANCE TRACKING FLIGHT TEST TECHNIQUES

Jason D. Dotter, BS

Captain, USAF

Approved:

_____
Maj. Paul A. Blue (Thesis Advisor)

9 Mar 07
Date

_____
Maj. Brian A. Kish (Committee Member)

9 Mar 07
Date

_____
Dr. Donald L. Kunz (Committee Member)

9 Mar 2007
Date

_____
Mr. William R. Gray III (Committee Member)

9 Mar 07
Date

AFIT/GAE/ENY/07-M24

Abstract

Cooper-Harper ratings (CHRs) have been used to describe and compare aircraft handling qualities for over 40 years, but are by their very nature, subjective. The subjective and sometimes ambiguous results obtained from qualitative handling quality ratings are inconsistent with the rest of the flight test process, where quantifiable results followed by statistical analysis are the norm. This thesis presents a method for obtaining accurate and consistent flight test data that quantifies the handling qualities of a specific aircraft. The method is demonstrated using both pilot-in-the-loop simulations and flight tests with the NF-16D Variable-Stability In-Flight Simulator Test Aircraft (VISTA).

Boundary Avoidance Tracking (BAT), introduced in 2004 by Mr. William Gray III, a test pilot at the US Air Force Test Pilot School (TPS), is used here to provide a novel approach for forcing an increase in pilot workload and tracking performance in order to assess an aircraft's handling qualities. By utilizing BAT with shrinking desired performance boundaries on a point tracking task, pilots are forced to their maximum performance (i.e. minimum error) on the tracking task. This maximum achievable BAT performance can then be used as a measure of the aircraft's handling "quality".

The BAT method of assessing an aircraft's handling quality was used with both pilot-in-the-loop simulations and flight tests to obtain quantitative tracking performance data. This data was compared and correlated to CHR data. In order to collect the data, a 6-degrees-of-freedom (DOF) pilot-in-the-loop F-16 simulator was developed and implemented on a desktop computer. Twenty seven test subjects flew the BAT profile on the desktop simulator; these subjects also flew the same profile in AFRL/VA's Infinity

Cube simulator. Data from these two simulations were used to develop a flight test plan for implementation on AFRL/VA's Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) and on TPS's NF-16D VISTA. Seven test subjects then flew a modified BAT profile on the desktop simulator, the LAMARS, and 13.7 flight hours in the VISTA.   Data collected included tracking and boundary information, as well as CHRs for each of four different pitch control models. Results supporting the existence of boundary awareness were found, as well as a correlation between total bounded simulation run time and Cooper-Harper rating.

Acknowledgments

Jason D. Dotter

vi

Table of Contents

viii

List of Figures

List of Tables

List of Abbreviations and Acronyms

Symbol	**Definition**	**Units**
AFFTC	Air Force Flight Test Center	--
AFIT	Air Force Institute of Technology	--
AFRL	Air Force Research Laboratory	--
AFRL/VA	AFRL Air Vehicles Directorate	--
AFTI	Advanced Fighter Technology Integration	--
AVDS	'Aircraft Visual Display Systems' software package	--
BAT	boundary avoidance tracking	--
DoD	Department of Defense	--
EP	evaluation pilot	--
FCP	front cockpit	--
FFT	fast Fourier transform	--
FPM	flight path marker	--
HUD	heads-up display	--
KCAS	knots calibrated airspeed	knots (nm/min)
KIAS	knots indicated airspeed	knots (nm/min)
KTAS	knots true airspeed	knots (nm/min)
LAMARS	Large Amplitude Multi-Mode Aerospace Research Simulator	--
MAC	mean aerodynamic chord ($\bar{c}$)	feet
MFD	multi-function display	--
NASA	National Aeronautics and Space Administration	--
PA	pressure altitude	feet
PIO	pilot-induced oscillation	--
PSD	power spectral density	--
RCP	rear cockpit	--
SP	safety pilot	--
TMP	Test Management Project	--
TPS	U.S. Air Force Test Pilot School	--
USAF	United States Air Force	--
VISTA	Variable-Stability In-Flight Simulator Test Aircraft	--
VSS	variable stability system	--

List of Symbols

Symbol	Definition	Units
γ	flight path angle	degrees
γ_{tgt}	target flight path angle	degrees
γ_{error}	flight path track error	degrees
α	angle of attack	degrees
ϕ	bank angle	degrees
p	roll rate	deg/sec
$\dot{p}$	rate of change of roll rate	deg/sec^2
θ	pitch angle	degrees
q	pitch rate	deg/sec
$\dot{q}$	rate of change of pitch rate	deg/sec^2
β	sideslip (yaw) angle	degrees
r	yaw rate	deg/sec
$\dot{r}$	rate of change of yaw rate	deg/sec^2
$\bar{c}$	mean aerodynamic chord	feet
X_{cg}	reference center of gravity location	% of MAC
ω_{sp}	short period natural frequency	sec
ζ_{sp}	short period damping ratio	(dimensionless)

(Page Left Blank)

This page is only if required to have the first numbered page (1) start on the "front side" of a page (i.e. so if printing double sided, page one is on one side and page 2 is on its back)

AN ANALYSIS OF AIRCRAFT HANDLING QUALITY DATA OBTAINED FROM BOUNDARY AVOIDANCE TRACKING FLIGHT TEST TECHNIQUES

1. Introduction

1.1 Motivation

Accurate and consistent data that quantify the handling qualities of a specific aircraft are difficult to acquire. Cooper-Harper ratings (CHRs) (Cooper, 1966) have been used to describe and compare aircraft handling qualities for over 40 years, but are by their very nature, subjective. Additionally, the data obtained through Cooper-Harper ratings are difficult to reduce (i.e. you can't average CHRs), and by assigning a single CHR to an aircraft, some data may be lost.

Current handling qualities flight test techniques call for the test pilot to perform an operationally representative task, and then rate the aircraft using the Cooper-Harper scale (Appendix E). This rating, when pooled with other pilots' ratings, is used to categorize the aircraft's handling qualities. The two primary considerations of the pilot assigning a CHR are task performance and pilot workload. If a pilot performs as desired on the task, but is working extremely hard, then the aircraft is given a downgraded rating. Similarly, if a pilot performs poorly on the task, but is not working very hard, a downgraded rating is also given, even though the pilot might have been able to achieve better performance with a higher workload. The subjective nature and variability of how a pilot defines his or her workload may greatly influence the CHR. Once the CHRs from several different pilots have been gathered, there is no definitive guidance on interpreting

1

the data. An informal survey of flight test professionals produced several different methods for interpreting a histogram distribution of CHRs.

   The subjective and sometimes ambiguous results obtained by qualitative handling quality ratings are inconsistent with the rest of the flight test process, where quantifiable results subjected to statistical analysis is highly desired.

1.2 Research Objectives and Hypotheses

The objective of this research was to determine if a bounded tracking task could be used to produce numerical aircraft handling qualities data. To do this, four goals were developed that directed the research and experimentation:

1.2.1 Goal 1 - Determine if boundaries influence task performance.

If boundaries can affect pilot performance, then specifically designed boundaries might be used to "force" the pilot to alter pilot workload and achieve different performance levels.

1.2.2 Goal 2 - Determine if boundaries can increase task performance

If a specific sequence or type of boundary can increase task performance, then that sequence or type of boundary can be used to drive the pilot to the best performance possible in that aircraft on a specific task.

1.2.3 Goal 3 - Determine if the performance on bounded tracking tasks can be used to estimate aircraft handling qualities.

If pilots can be forced to perform to the limit of their abilities, then the maximum achievable task performance (by any pilot) can be obtained in an aircraft on a specific task. This performance limit can be used as a determination of the aircraft's best possible performance, or its handling "quality".

1.2.4 Goal 4 - Quantify the relationship between bounded tracking performance and Cooper-Harper ratings.

Finding a correlation between BAT data and CHRs will help validate the use of BAT data in handling qualities flight test, and possibly focus future test on relevant avenues of research.

1.3 Experiment Overview

An F-16 aircraft model and bounded tracking task were developed on a desktop computer and 27 test subjects flew the tracking task with variable boundaries and 3 different stabilator rate limits (60, 30 and 15 degrees per second). The 27 test subjects then flew a similar aircraft model and identical tracking task, with the same boundaries and rate limits on the Air Force Research Laboratory's (AFRL) Infinity Cube simulator. The results were compared to determine if the different control schemes present in the two simulators produced different tracking performance. Data collected focused on the

3

tracking error as a measure of task performance, as well as the length of time the simulation was flown prior to impacting a boundary.

Research was continued as part of the USAF TPS Test Management Project (TMP) BAT DART, at Edwards AFB, CA. Pitch control models representative of Cooper-Harper levels 1, 2, and 3 were developed and flown, in addition to the previously used desktop computer pitch control model, on the AFRL Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) and TPS's Variable-Stability In-Flight Simulator Test Aircraft (VISTA). Cooper-Harper performance rating definitions were developed for the previously mentioned tracking task, and an additional 7 test subjects flew the tracking task once with no boundaries to produce a baseline CHR, and once with boundaries. Data collected included all aircraft performance and longitudinal axis data, as well as Heads-Up Display (HUD) and Multi-Function Display (MFD) video.

1.4 Preview of Results

The initial simulator studies conducted at the Air Force Institute of Technology (AFIT) were focused on achieving different tracking performance on one aircraft model with different stabilator rate limits. Tighter boundaries produced smaller errors in tracking performance up to a point. When the boundaries became too small, the tracking errors usually increased and a boundary was often rapidly impacted. Despite achieving the goal of improving tracking performance with boundaries, different tracking performance was not achieved with different stabilator rate limits. Pilot performance with 15 degrees per second stabilator rate limit was almost the same as the model with 60

degrees per second stabilator rate limit. However, the two different simulators (Desktop simulation and Infinity Cube simulator) produced markedly different tracking performance. The difference in pitch control models was theorized to have caused the difference in performance. However, additional differences in the simulation environment and hardware could have caused the different tracking performance, and the effects of these (mostly) unknown variables could not be eliminated.

The three different pitch control models that were later developed, in addition to the original desktop simulation pitch control model, produced dramatically different tracking performances on the VISTA, with the same environment, hardware, and aircraft model. An apparent correlation between Boundary Avoidance Tracking (BAT) task performance and CHRs was found.

Additionally, most test subjects' initial average tracking performance did not appear to be related to boundary size. Farther into a given model run, when the boundaries decreased in distance from the tracking target to a certain size, nearly all test subjects began performing better on the tracking task at the same boundary value. This point is theorized to be the point of "Boundary Awareness" and appeared to be consistent throughout the different pitch control models.

1.5 Thesis Overview

In Chapter 2, a review of the previous work conducted by Mr. Gray on Boundary Avoidance Theory (BAT) is provided. Additional boundary avoidance work done by Capt Randy Warren for his thesis "An Investigation of the Effect of Boundary

5

Avoidance on Pilot Tracking" (Warren, 2006) and USAF TPS TMP "HAVE BAT"

(Warren et. all, 2006) is also addressed. Chapter 3 presents the design of the boundary

avoidance tracking (BAT) task and boundary profile. Chapter 4 details the research

conducted at the Air Force Institute of Technology, to include the Desktop (DT)

computer simulator and AFRL's Infinity Cube simulator, as well as the experimental

setup and results of the tracking task. Chapter 5 chronicles the research conducted at TPS

under the 'BAD DART" TMP and the results of the LAMARS and VISTA flight test.

Chapter 6 presents the conclusions and recommendations as well as a summary of the

results.

2. Background

2.1 Handling Qualities Testing

Traditional handling qualities testing uses tracking tasks to simulate an operational representative environment or task (DoD, 1990). For example, a test pilot might be instructed to track another aircraft with a HUD pipper, which is very operationally representative. Following the task, the test pilot is asked to rate the aircraft on that specific task using CHRs (Appendix F). This task is a good example of point tracking.

2.1.1 Point Tracking

Point tracking is where the pilot is given a target, or "point", and told to track it. The pilot's inputs to the aircraft control system are intended to maintain the desired condition. As the aircraft or system deviates from the desired track condition, the pilot alters his or her inputs to regain the track. Generally, as the tracking error grows, the pilot will use larger control inputs to correct the track error. Figure 1 illustrates a simple point tracking task.
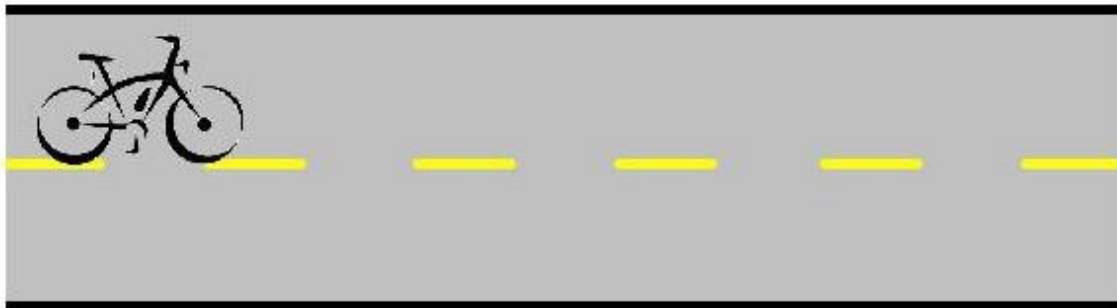
Figure 1 – Example Point Tracking Task

A bicycle rider is instructed to ride down a road and "track" the centerline of the road. Various external inputs into the system (rocks, bumps in the road, winds, etc…) may cause tracking errors that should be corrected. The farther away from the centerline that the bicycle rider finds himself, the larger the input will generally be to correct the error. Assuming that fatigue, a learning curve, and asymmetrical external inputs into the system do not exist, the rider's average absolute track error will be consistent from one section to another identical section.

2.1.2 Cooper-Harper Ratings

Prior to the tracking task, the rider would be informed that the desired performance of the bicycle is to keep the wheels within 1 foot of the centerline for the entire ride. Adequate performance would be defined as keeping the wheels within 3 feet of the centerline for the entire ride. These definitions, in addition to the rider's performance, and some measure of the workload required to obtain that performance on the task, are what is required to generate a Cooper-Harper rating. Following the tracking task, the rider would be asked to rate the bicycle on the Cooper-Harper rating scale (Appendix F), using performance and workload to determine the CHR. We can assume that the rider's experience level will have some effect on how easily he or she can track the target. A 6 year old who just learned to ride a bicycle will have large average and peak errors compared to Lance Armstrong, as an extreme example.

2.2 Boundary Avoidance Tracking (BAT)

Now let us assume that there are real physical boundaries, instead of desired performance boundaries, imposed on the bicycle rider. We will suspend the 6 foot wide "road" over the Grand Canyon, and ask the rider to perform the same task.

Figure 2 – Example Bounded Point Tracking Task

The tracking task and target have not changed, and the boundaries haven't really changed. It is still "adequate" to maintain an error of less than 3 feet from the centerline of the road. Only the consequence of "impacting" the boundary has changed. However, we can surmise that the rider's control inputs will change when a boundary is approached compared to the unbounded case shown in Figure 1. In this case, as a boundary is approached, the rider will change his or her inputs to avoid the boundary. The control

inputs at any given instant are theorized to be approximately proportional to the time remaining to impact the boundary at that instant following a slight lag due to pilot perception (Gray). The theorized relationship of the inputs to the boundary will be examined more in Section 2.3.1.

Mr. Gray, an instructor at the USAF Test Pilot School, introduced the concept of Boundary Avoidance Tracking (BAT) in a paper to the Society of Experimental Test Pilots in 2004 (Gray, 2004). Mr. Gray proposed a type of pilot-induced oscillation (PIO) that was driven by the boundaries on a pilot's point tracking task. When the boundaries got too close to the tracking target, pilots would cease tracking the target and track the boundaries instead, decreasing their point tracking performance.

2.2.1 Desired vs. Achieved Performance

The following figure is taken from the USAF TPS Flying Qualities curriculum (TPS, 2006).
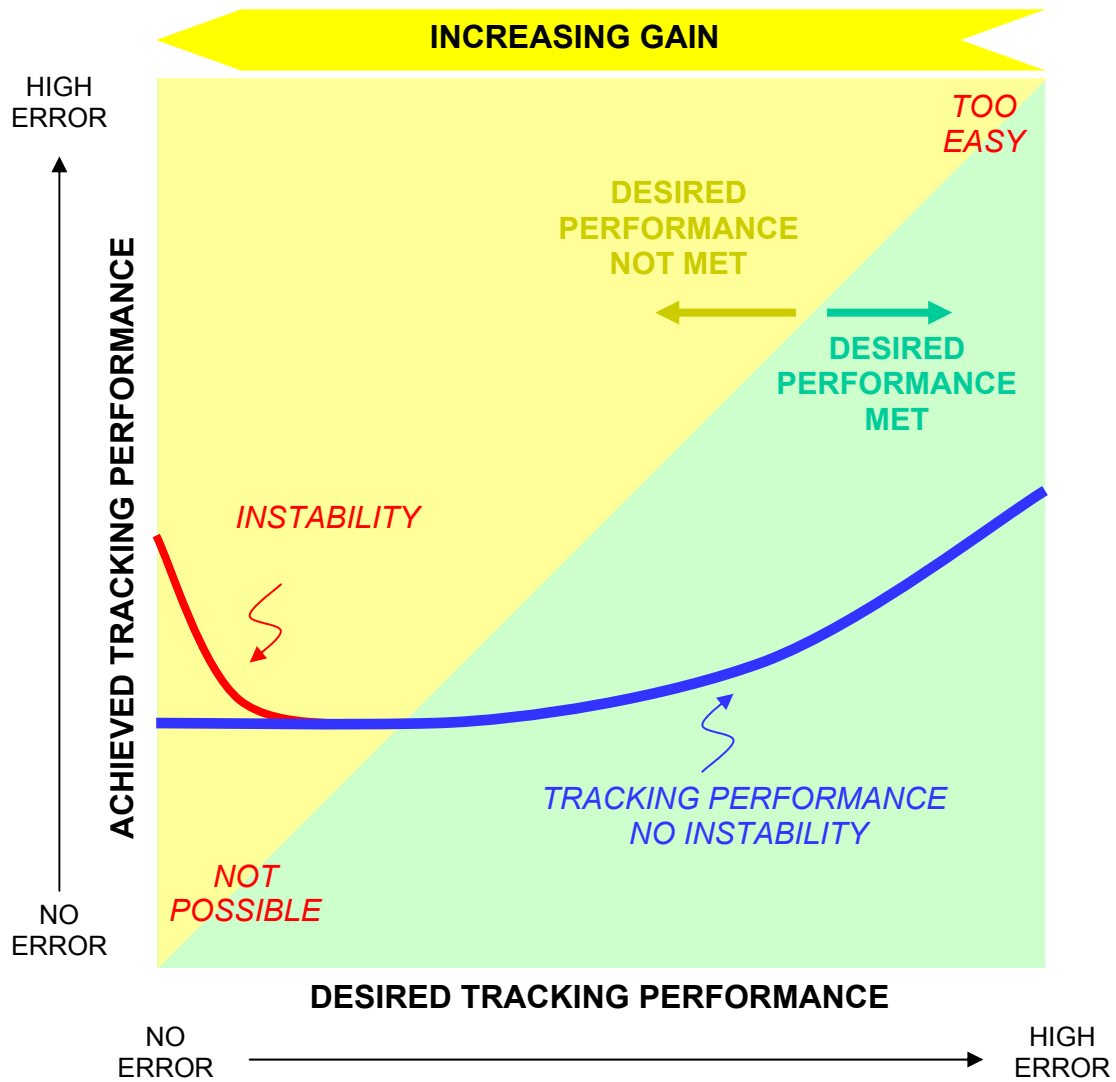
Figure 3 – Effect of Desired Performance on Achieved Tracking Performance

Figure 3 illustrates another aspect of Mr. Gray's theory: that increasing the expectations on a pilot's performance (i.e. narrowing the boundaries) will increase the performance achieved. As can be seen from the figure, there is a theoretical minimum to the achieved tracking performance, or minimum error achievable. If many different pilots flew the same task on the same aircraft, many different tracking performance curves could be plotted on the same chart. Then, the curve(s) with the lowest achieved tracking error could be used to postulate the minimum error achievable for that specific aircraft on that specific task.

An additional possible effect of adding boundaries to a tracking task can be seen in the red line portion of Figure 3. When the boundaries or expectations on the tracking task become too restrictive, the pilot will cease to track the target and begin tracking or avoiding the boundaries. The pilot's performance will suffer, tracking errors will grow, and a PIO may be encountered.

2.2.2 Testing Limitations on Simulating Real Boundaries

One of the difficulties in using boundaries in simulators or actual flight test is simulating a real-world boundary, like the ground. The consequences of an aircraft unintentionally hitting the ground are almost always catastrophic. Hence, the pilot response generated by approaching this type of boundary is nearly always very rapid and of large magnitude – usually at the maximum capability of the pilot and control inceptor(s). It is this maximum deflection input and aircraft response that is so difficult to reproduce with simulated boundaries.

2.3 Previous Testing

2.3.1 Mr. Gray's Desktop Simulator

Following theoretical and computer modeling work on his theory, Mr. Gray

developed a pilot-in-the-loop simulation using the flying qualities data of a North

American Navion (Gray, 2005:6). Using Matlab© and Simulink©, Mr. Gray presented a

bounded tracking task to the subject pilots. The tracking task consisted of matching the

altitude of a "lead" Navion that was

constantly changing (Gray, 2005:6).

The test subjects were provided

with a display that showed the

relative altitude of the pilot's

aircraft (also a Navion model) with

respect to the lead Navion (Figure

4). The task was to minimize the

altitude error between the two

aircraft by maintaining their aircraft

altitude delta line on the zero error

reference and to avoid impacting

the boundaries.
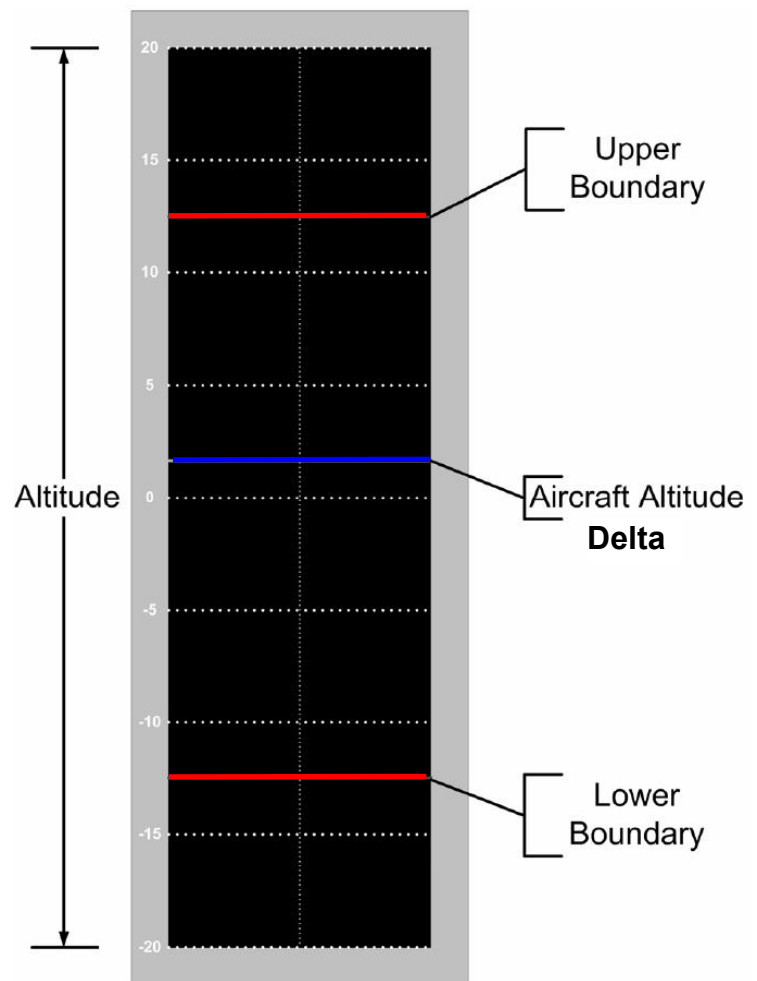
Figure 4 – Mr. Gray's Navion Simulator Display

The boundaries were moved closer to the zero-error reference by 25% once every 60 seconds, and the oscillatory flight path of the lead Navion was repeated every minute as well. Eight test subjects each flew three different scenarios: first, the standard Navion tracking task as described above; second, a 300 millisecond time delay was added to the pilot's inputs; and third, a 17 degree per second rate limit was placed on the deflection of the horizontal tail of the pilot's Navion (Gray, 2005:6). The simulation was terminated when the altitude error between the lead and subject's aircraft exceeded one of the current boundary limits.

Mr. Gray's data reduction focused on characterizing certain boundary tracking parameters which focused on the time to impact the boundary. However, he also noted a loose grouping of the successful tracking times of the different scenarios (Figure 5)
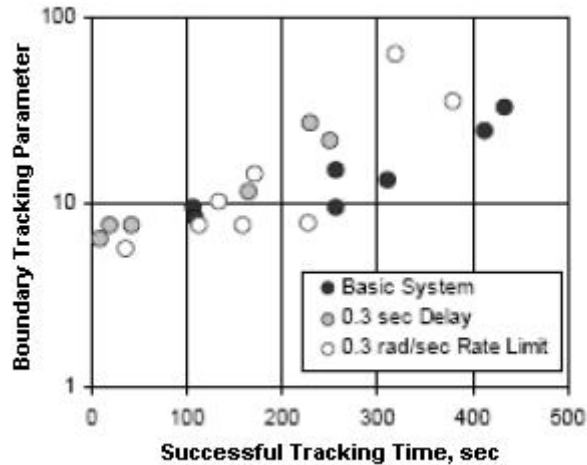
Figure 5 – Grouping of Navion Simulator Tracking Times (Gray, 2004)

The Boundary Tracking Parameter axis shown in Figure 5 is a separate parameter under investigation by Mr. Gray and holds no relevance to this thesis. Discussions with Mr. Gray about desired vs. achieved performance and the grouping of successful tracking

14

times of different flight control scenarios set the stage for the research that was conducted for this thesis.

2.3.2 Capt Randy Warren's Thesis & HAVE BAT TMP

Captain Randy Warren's TMP (Warren, et. All, 2006) and thesis (Warren, 2006) characterized BAT in a dynamic flight environment. Repeated BAT events were flown in a T-38C aircraft and analyzed. His research focused on characterizing initial parameters for BAT, and found that the time to boundary impact where pilots go to maximum feedback gain (t_{max}) was independent of pilot, maneuver, or flight conditions (Warren, 2006), but may be dependent on other unknown factors. Warren's thesis also addressed other BAT parameters, but their discussion is not relevant to the focus of this thesis, and will not be discussed further. It should be noted that the information collected and analyzed on the HAVE BAT TMP was the first in-flight data to show that Boundary Avoidance Tracking (BAT) exists.

3. Tracking Task and Boundary Profile

3.1 BAT Flight Path Angle (γ) Tracking Task

The tracking task was designed to closely mirror Mr. Gray's Navion tracking task described in Section 2.3.1. However, since the ultimate goal was to fly the tracking task in the NF-16D VISTA aircraft, flight path angle (γ) was chosen as the target, instead of an altitude differential as in Mr. Gray's simulator. The aircraft flight path angle (γ), or velocity vector, is already calculated and displayed in all modern HUD equipped aircraft.

A simulator arrangement similar to Mr. Gray's, with a target aircraft model generating target information, and a separate pilot-in-the-loop model being flown by the test subject, was chosen. The target aircraft control inputs were the gained sum of three sine waves. The frequency and amplitudes of the inputs are shown in Table 1. The sum of the three sine waves was gained by a factor of 200 prior to being input into the target aircraft pitch control, to provide appropriate target aircraft control input magnitude.

Table 1 – Sine Waves Used Target Aircraft Control Input

Input	Frequency (rad/sec)	Amplitude	Phase
Fast Sine wave	0.21	$\pi/180$	0
Medium Sine wave	0.42	$-\pi/180$	$\pi/3$
Slow Sine wave	0.84	$\pi/180$	$\pi(2/3)$

The target flight path profile that resulted from the sum-of-sines input is shown in Figure 6. There is a short repeat to the pattern approximately every 30 seconds. This

repeat was designed into the simulation to ensure that the tracking task presented the same level of difficulty in subsequent boundary step sizes.
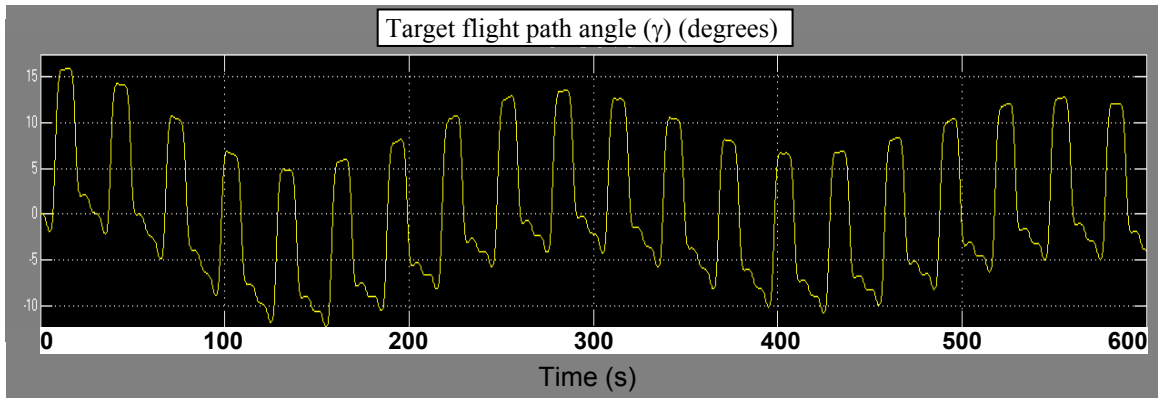
Figure 6 – Desktop Simulation Target Aircraft Flight Path Angle (γ) Profile

3.2 Boundary Profile

The target aircraft's flight path angle was the actual target for all of the tracking tasks. The deviation from this target was given boundaries, and the test subjects were instructed to treat the displayed boundaries just as they would treat the ground or another physical object that would cause catastrophic damage if they contacted them with the FPM. The boundary was initially set at a value of ±10°, and then the boundaries were stepped closer to the target by 25% every 60 seconds; the same boundary step size as Mr. Gray's Navion simulator. A time history of the boundary values for an entire simulation run is shown in Figure 7. This figure shows the relative distance (in degrees displayed in the HUD) of the boundaries from the target flight path angle.

17
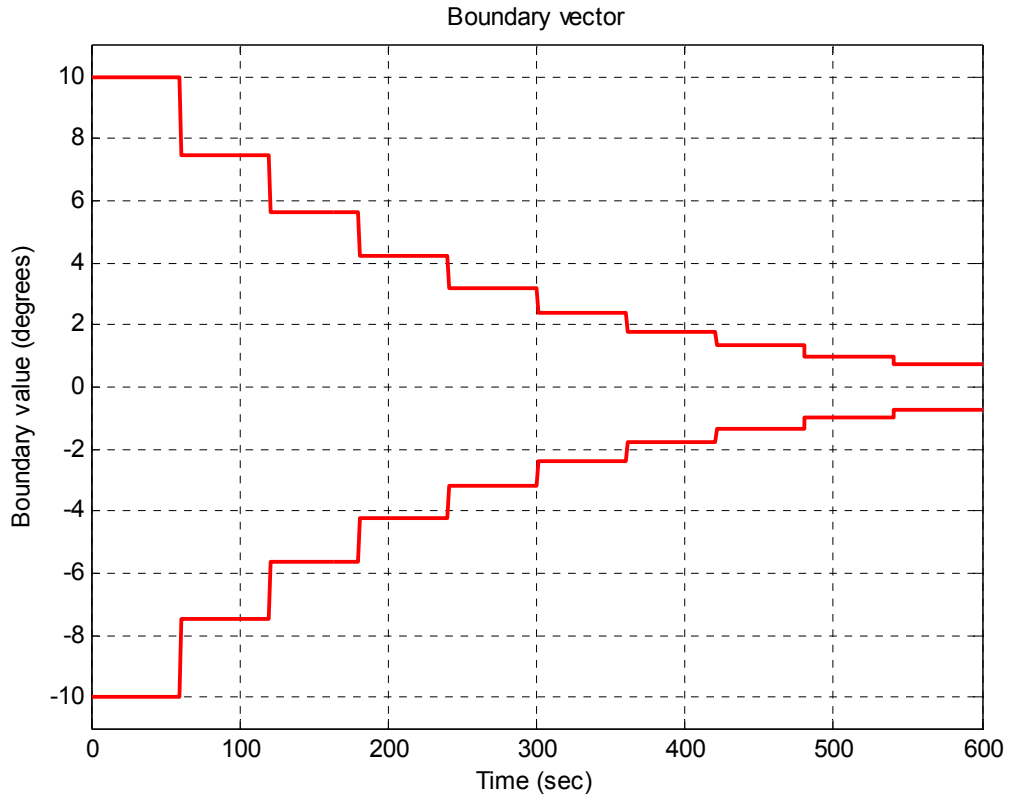
Figure 7 – Boundary Profile

If the flight path error (γ_{error}), or deviation of the ownship flight path angle (γ) from the target flight path angle (γ_{tgt}), exceeded the current boundary limit, the simulation was terminated.

4. Air Force Institute of Technology (AFIT) Research

4.1 Test Subjects

Twenty seven test subjects consisting of a mix of fighter pilots, heavy/transport pilots, and non-pilots participated in the research by flying a desktop simulator at AFIT. Relevant flight time of the test subjects is presented in Appendix D. Test subjects were instructed to track a target line and to treat displayed boundaries as if they were life or death boundaries. Some role-play was required to be a good test subject. A steak dinner was also offered to the test subject that flew the longest without impacting a boundary.

The same 27 test subjects that participated in the AFIT desktop simulator also flew the simulation in AFRL's Infinity Cube simulator. A random selection of test subjects flew the Infinity Cube prior to the desktop simulator in an effort to remove the learning curve factor from the two different simulator runs. The increased "realism" of the Infinity Cube simulator due to the wide horizontal display caused a few of the non-pilots to state that they felt a slight motion sickness following the end of their simulator runs. However, no test subject reported reduction in tracking capability due to the phenomenon.

4.2 AFIT Desktop Pilot-In-The-Loop Simulator

The desktop simulator was constructed on a Windows™ based dual Xenon processor computer with 1 GB of RAM. Separate video cards drove the simulation display and the control display. The simulation was constructed in MatLab© and Simulink© and used Aircraft Visual Display Software (AVDS, 2005) for the visual

displays and control stick interface. A Microsoft™ Flightstick Pro force feedback

joystick was used as the control inceptor, but no force profile was programmed.

4.2.1 Aircraft Aerodynamic Model

The aerodynamic model data used for the desktop simulation was obtained from a

NASA Langley wind tunnel study of a subscale F-16 (Nguyen, 1979) and provided as

part of the AFIT 'MECH 628' course on flight controls. The limits of the data used were

-10° to +45° alpha, and ±30° beta. The data were collected up to an airspeed of

approximately Mach 0.6. The leading edge flap (LEF) deflection data was merged into

the aerodynamic data matrix, and included deflection limits, but no deflection rate limits

(Nguyen, 1979). The NASA data also included a model of the F-16 afterburning

turbofan engine, in which the thrust response was modeled with a first-order lag. The lag

time constant was a function of the actual engine power level and the commanded power

(Stevens, 2003).

The data consisted of values for the body-axes dimensionless aerodynamic

coefficients of the F-16 model divided into separate data files. The aerodynamic data

files, engine model, and associated subroutines can be found in Appendix A and B of

"*Aircraft Control and Simulation*" (Stevens, 2004) and will not be reproduced in this

document. For reference, the state-space model of the open-loop (unaugmented)

longitudinal dynamics at 300 KIAS and 15,000 feet is given in Appendix A (Witte,

2004). The poles of that state space model are listed in Table 2 below to give an idea of

the type of open-loop response that can be expected at these flight conditions.

Table 2 – Desktop Simulator Model Open-Loop Longitudinal Dynamics

Model	Bare Aircraft Poles	ω_{sp}	ζ_{sp}
Desktop	$-1.5196 \pm 2.0071j$ $-0.0165 \pm 0.0787j$	2.52	0.60

Some changes were made to the simulation conditions to more accurately reflect an operationally relevant flight condition and aircraft response. The reference center of gravity (X_{cg}) location used in the desktop simulation was: $X_{cg} = 0.35\bar{c}$, where $\bar{c}$ is the mean aerodynamic chord. Initial conditions of 400 KCAS and 10000 feet Mean Sea Level (MSL) were chosen. Initial equilibrium positions were set by trimming the control surfaces for straight and level flight at the desired airspeed and altitude using the 'trimmer.m' file supplied with the F-16 aerodynamic data (Stevens, 2004).

For the BAT DART TMP, the initial conditions were changed to 350 KCAS and 20000 feet MSL to mirror the conditions chosen for the in-flight testing portion. These conditions were changed due to VISTA Variable Stability System (VSS) limitations and terrain safety margin concerns.

4.2.2 Pitch Control Model

The pitch control model for the desktop simulator was initially intended to mirror the VISTA pitch control system; however, the VISTA control system, which allows the aircraft to simulate other aircraft, is quite complex. So for the research conducted on the desktop simulator, a simpler pitch control model was chosen. The Advanced Fighter Technology Integration (AFTI) F-16 was a joint NASA and USAF program to integrate and demonstrate new aviation technologies. The aircraft demonstrated extreme

21

maneuverability including flat turns and selective fuselage pointing using forward-mounted canards, and contained a triplex digital flight control computer system with custom programming (NASA, 2002). The digital flight controls incorporated a back-up mode that could be accessed by flipping a hardware cockpit switch that would lock out the custom digital control computers and implement a simple delta pitch rate feedback control loop to enable the pilot to safely recover and land the aircraft in case of control computer failure. Figure 8 shows the AFTI back-up pitch rate feedback transfer functions.
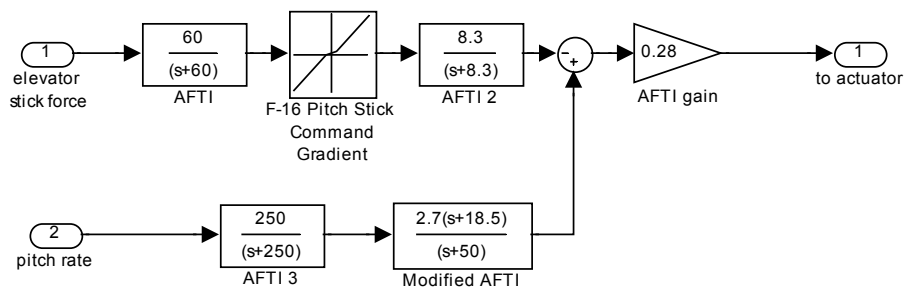
Figure 8 – AFTI F-16 Back-Up Pitch Control Feedback

The AFTI back-up pitch control laws provided a simple starting point for the desktop simulator. Feedback and total control gains were modified to produce an adequate handling aircraft. The resulting desktop simulator pitch control model is shown below in Figure 9, and reproduced in Appendix B.
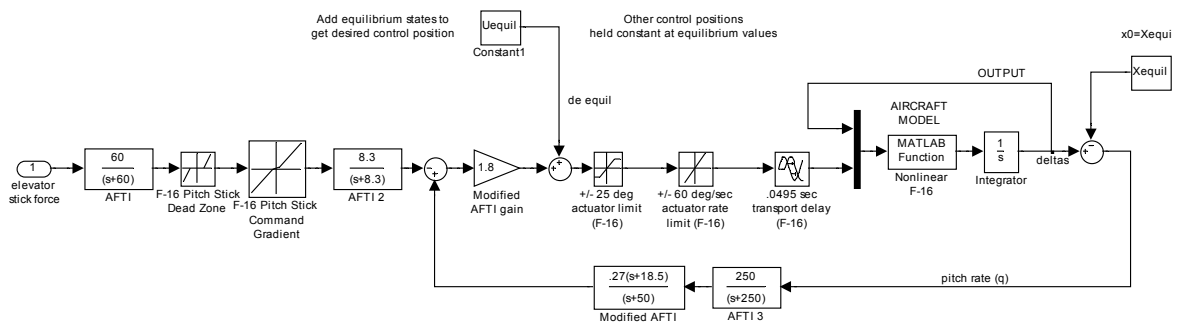
Figure 9 – Desktop Simulator Pitch Control Model

The basic F-16 pitch stick dead-zone (-1.75 to 1.75 lbs) and pitch stick command gradient (Appendix B) were inserted into the stabilator control path, as well as the basic F-16 stabilator actuator limits, stabilator actuator rate limits, and stabilator control path transport delay. These parameters were obtained from the VISTA flight control schematics (General Dynamics, 1989). The same F-16 simulation model was used for the desktop simulator studies at AFIT and TPS.

4.2.3 Simulink© Environment

The rest of the Simulink© simulation environment is shown below in Figure 10, and reproduced in Appendix B.
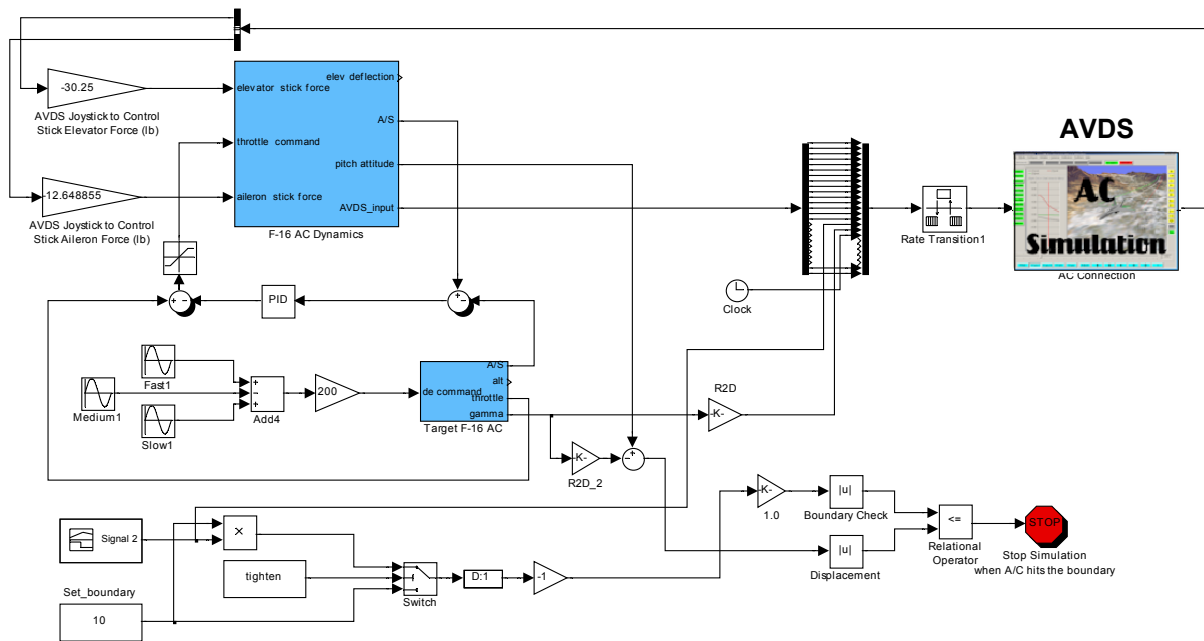
Figure 10 – Desktop Simulation Simulink© Environment

The aircraft model that the test subject flew (Figure 9) was inside the "F-16 AC Dynamics" block of Figure 10. The control inputs and visuals were input to and extracted from the Matlab© environment through the AVDS program block.

The target aircraft (F-16) dynamics and control were inside the "Target F-16 AC" block. An identical aerodynamic model, pitch control model, and thrust model as the test subject's aircraft were used for the target aircraft. Control inputs to the target aircraft were provided as a sum of three sine waves. The frequency and amplitude of the inputs were designed to keep the target aircraft's flight path response (γ_{tgt}) roughly within a ±15 degree limit. They were also designed to provide a control input response that was at most, 50% of the control system inceptor limits, actuator limits, and actuator rate limits. A proportional throttle controller was used to maintain the target aircraft's airspeed within 3% of the initial conditions; however, the altitude deviated up to 50% from the

24

initial altitude due to the flight maneuvers.   A proportional throttle controller was also

used to match the test subject's throttle command to the target aircraft's throttle

command.

The simulation visuals were constructed through AVDS and consisted of a typical

modern fighter aircraft Heads-Up Display (HUD) with airspeed, altitude, and attitude

information. The desktop simulation display is shown in Figure 11.
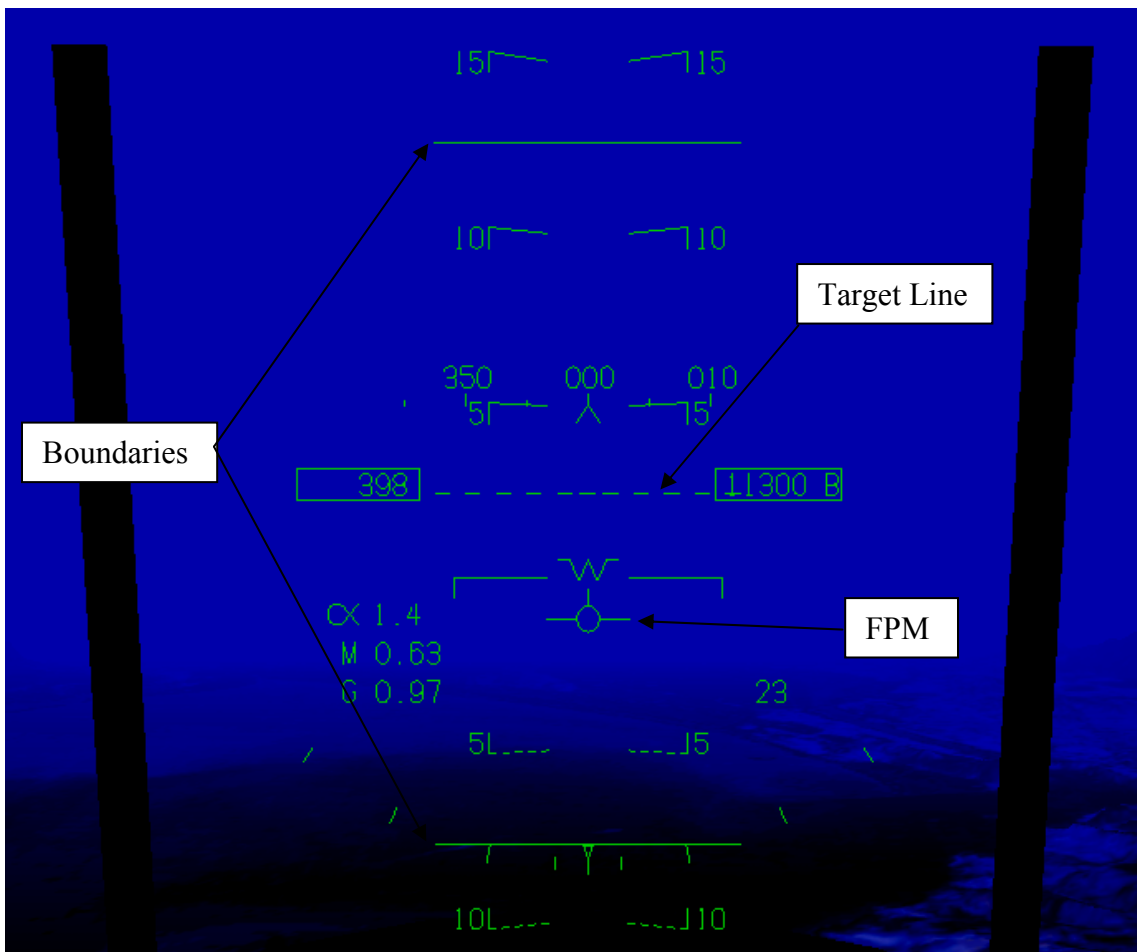
Figure 11 – Desktop Simulation Visual Display

Additionally, the target aircraft flight path angle (γ_{tgt}) was shown as a dashed

horizontal line. The current boundaries were shown as solid horizontal lines above and

below the target line. Ownship flight path angle (γ) was displayed as a flight path marker (FPM), which is typical of modern HUDs. Out-the-window terrain and visuals were inherent capabilities of the AVDS software. Sufficient terrain detail and range were chosen to provide no distractions from the tracking task and HUD information, but to provide a visual attitude reference similar to that in an actual aircraft. Recorded parameter sinks, links, and Simulink© blocks are not shown in Figure 10 for simplicity. A list of recorded parameters for the desktop simulation can be found in Appendix C.

4.2.4 Results

As stated in Section 1.4, the initial desktop simulation focused on obtaining dissimilar handling qualities through different stabilator rate limits on the pitch control model. Figure 12 illustrates one method of determining 'performance' on a bounded tracking task. The task is flown until boundary impact, and then the boundary value (in degrees) at impact is plotted vs. the average tracking error in the 5 seconds prior to boundary impact. This method shows total performance of a simulation run represented as how tight a boundary was achieved. It also can show oscillatory motion or poor tracking performance just prior to a boundary impact, as this will produce a data point that is closer to or above the 'desired line'. The 'desired line' is a line that represented achieved performance exactly matching desired performance – in this case, average flight path tracking error equaling the boundary value.
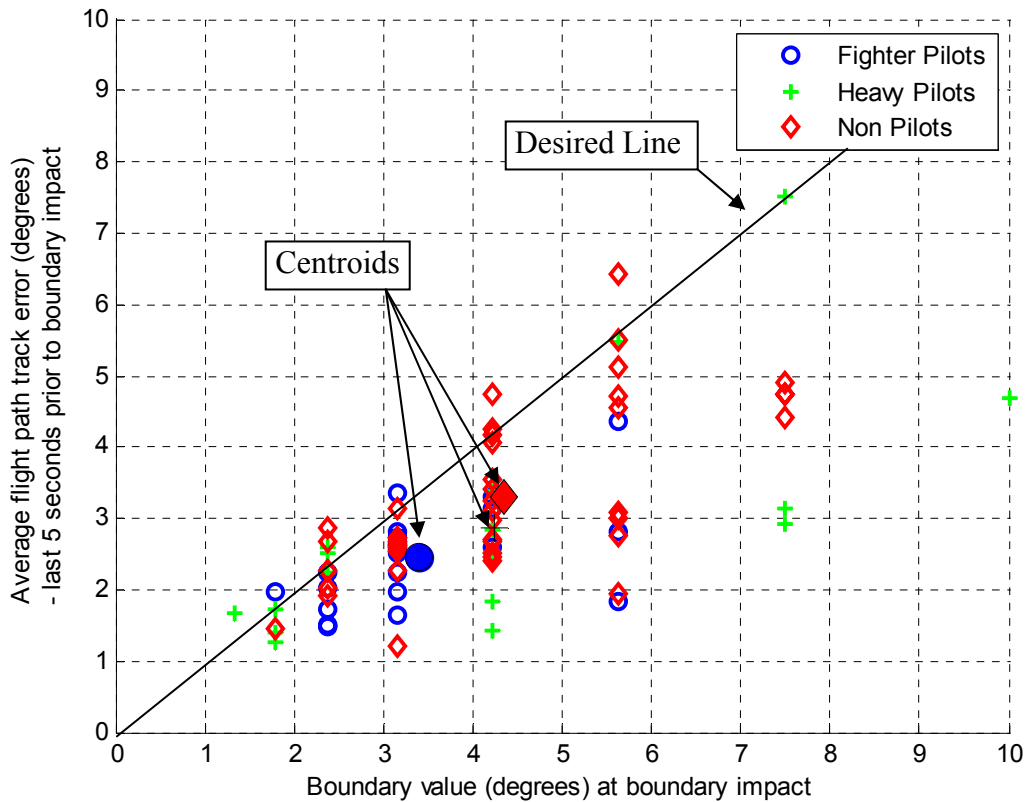
Figure 12 – Desktop Simulator Boundary Impact Analysis

As can be seen in Figure 12, varying the stabilator rate limit produced very little differentiation in performance. These results and those of the Infinity Cube simulator prompted the abandonment of stabilator rate limiting as a handling quality driver.

4.3 Infinity Cube

The Infinity Cube was an out-the-window visual system that surrounded the pilot with four displays to provide a continuous, collimated, 200° horizontal by 120° vertical field-of-view (AFRL, 2000). It provided a 45:1 contrast ratio and an effective resolution

of 6.5 arc min/line pair. Images were collimated to between -0.11 and 0.0083 diopters to present a focus distance near infinity. Aircraft models were driven on a Fedora Core PC. The control inceptor used was a fixed position force sensing sidestick similar in characteristics to the control stick installed in an early production F-16.

Figure 13 – Infinity Cube Simulator

4.3.1 Aircraft Aerodynamic and Pitch Control Model

The aerodynamic model flown in the Infinity Cube was one with basic F-16 flight characteristics developed for previous research work done by Capt Hanley (Hanley, 2003) and Capt Witte (Witte, 2004). Hanley began with the same bare airframe F-16 model used in the desktop simulation listed in Section 4.2.1. He then modified the longitudinal poles to create 4 different dynamic models. Hanley then computed the optimum angle-of-attack (α) and pitch-rate (q) feedback gains to move the closed loop poles back to the desired locations. These feedback gains were then combined with the bare aircraft open-loop dynamics to produce a new state space model. This model was implemented directly in the Infinity Cube simulator. The Hanley model "B" was chosen

due to the ease of implementation, similarity to the desktop simulator aero model, and similarity to the actual VISTA (F-16) dynamics. For reference, the state-space model of the resulting open-loop longitudinal dynamics is given in Appendix A. The longitudinal poles of that state-space model are listed below in Table 3 (Witte, 2004).

Table 3 – Infinity Cube Simulator Model Open-Loop Longitudinal Dynamics

Model	Bare Aircraft Poles	ω_{sp}	ζ_{sp}	K_q	K_α	Aircraft Poles with Stability Augmentation
Infinity Cube	-1.43 ± 1.85j -.017 ± .074j	2.34	0.61	0.156	0.123	-2.17 ± 2.22j -.017 ± .070j

The initial conditions chosen for the tracking tasks were the same as that of the desktop simulator, 400 KIAS and 10,000 feet PA. The Infinity Cube model was trimmed in a similar manner to the desktop simulation, but setup and simulation control were performed by an AFRL Engineer. No stick shaping was used and the stick force was converted directly to an elevator deflection command, and then fed to a first order elevator actuator model. This was chosen due to the ease of implementation, similarity of response to a recent F-16 flight by the author, and because the feedback loops and gains were already combined into the modified state-space A matrix.

4.3.2 Simulation Environment

The HUD information displayed to the test subjects was identical to that displayed in the desktop simulator, and shown in Figure 11. Airspeed, altitude, attitude, target line, boundary lines and velocity vector were displayed as the same color and proportional size as the desktop simulator. Out-the-window terrain and environment were similar but

generated by the Infinity Cube terrain computer and software, and were again chosen to minimize pilot distraction but also provide a visual attitude reference. The presence of a wide (200°) horizontal visual reference allowed peripheral vision to aid in attitude recognition and maintenance. A list of recorded parameters for the Infinity Cube simulation can be found in Appendix C.

4.3.3 Flight Path Angle (γ) Tracking Task

The tracking task presented to the test subjects was identical to the desktop simulator tracking task (Figure 6). A 60 Hz time history vector of the desktop simulation target aircraft's flight path angle (γ_{target}) was used as the input data for the target line in the Infinity Cube simulation. The boundary profile was also identical to the desktop simulation boundaries.

4.3.4 Results

The Infinity Cube simulation trials were conducted at the same time as the AFIT desktop simulation trail, and were still under the assumption that stabilator rate limiting would result in significantly different handling qualities. Figure 14 shows the results of the Infinity Cube simulations. Boundary value (in degrees) at impact is plotted vs. the average tracking error in the 5 seconds prior to boundary impact.

30
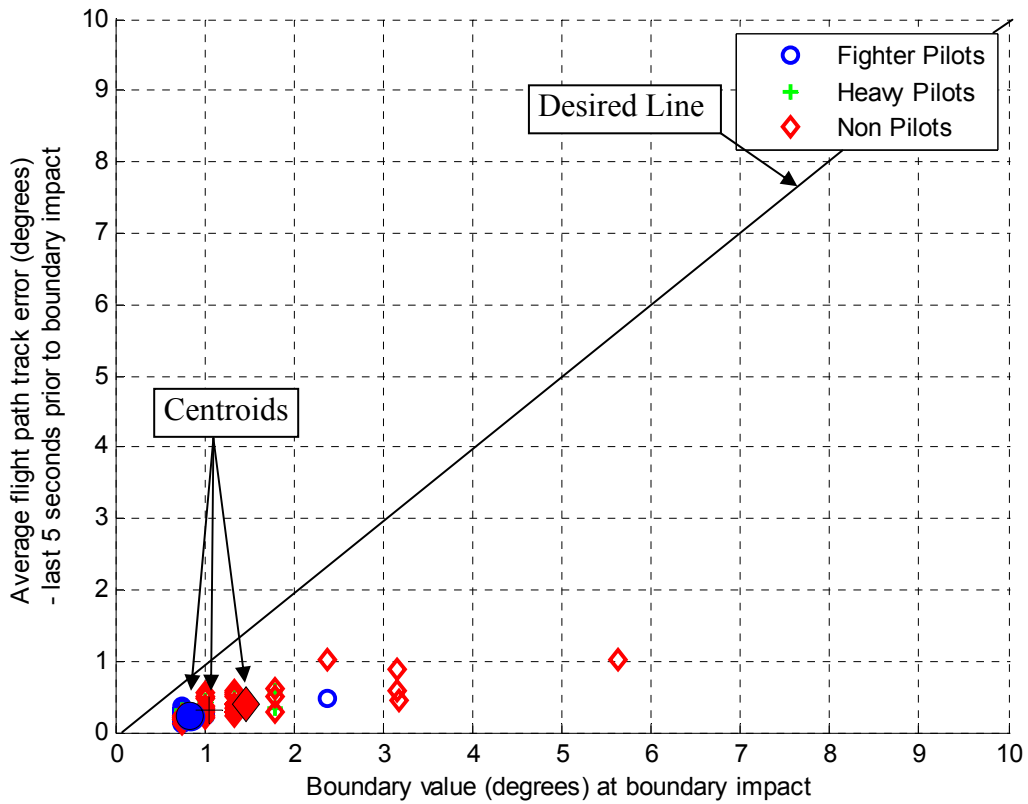
Figure 14 – Infinity Cube Simulator Boundary Impact Analysis

Figure 14 clearly illustrates the fact that the change in stabilator rate limit had very little effect on the handling qualities performance of the Infinity Cube simulation. All of the data is tightly grouped at small boundary values and low average error values. The figure below shows the desktop model simulation data plotted with the Infinity Cube simulation data.
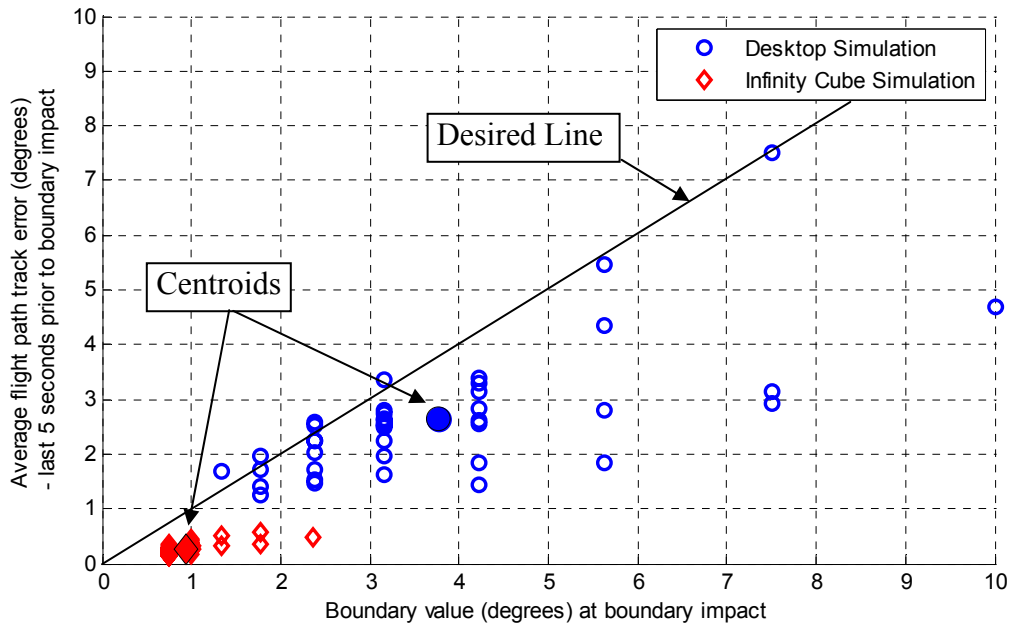
Figure 15 – Infinity Cube and Desktop Simulator Boundary Impact Analysis

The difference in task performance between the two simulators is readily apparent from Figure 15. Every Infinity Cube simulation trial achieved lower average flight path track error just prior to boundary impact, and the data for the Infinity Cube simulator is grouped much tighter than that for the desktop simulator. More importantly, the minimum achievable error (and boundary size), is much smaller for the Infinity Cube simulation. However, as stated in Section 1.4, these differences were not necessarily due to the differences in pitch control models. They could have been due to discrepancies in the simulation environment and hardware, and the effects of these (mostly) unknown variables could not be eliminated.

The conclusions drawn from Figure 15 were the nucleus for the BAT DART TMP, where 4 different pitch control models were flown on one system, with identical hardware, visual systems, control inceptors, and in-flight initial conditions.

5. USAF TPS Test Management Project (TMP) 'BAT DART'

5.1 Test Subjects

Seven test subjects, all TPS students or faculty and members of the BAT DART team, were used during the simulation runs at TPS. The relevant flight experience of the test subjects is presented in Appendix D.

5.2 Test Objective

The BAT DART Test Management Project (TMP) was conducted under the syllabus of the USAF Test Pilot School (TPS) as part of the joint Air Force Institute of Technology (AFIT) – TPS program and in support of this thesis (Dotter and others, 2006).

The objective of the BAT DART test program was to determine if the pilot plus aircraft performance on a bounded pitch tracking task could be correlated to Cooper-Harper ratings for longitudinal handling qualities, and to determine that correlation. Four different pitch-control models, including one model designed for the desktop computer simulator, were flown by the seven BAT DART team members on the Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) and on the NF-16D Variable-Stability In-Flight Simulator Test Aircraft (VISTA). The seven BAT DART team members also flew the desktop simulator, with initial conditions changed to match the VISTA and LAMARS flight profiles.

The test project consisted of two full days of simulator studies in the LAMARS at Wright Patterson AFB, Ohio, two 2-hour ground tests, and 13.7 flight hours in the

NF-16D VISTA. Flight test was accomplished from 8 to 18 September 2006. Ten test sorties were flown in NF-16D 86-00048 within the R-2508 complex at Edwards Air Force Base, California.

5.3 Flight Path Angle (γ) Tracking Task

The simulation envelope of the VISTA and terrain located in the R-2508 airspace utilized at TPS necessitated a change to the initial flight conditions for the VISTA. The desktop simulator and LAMARS initial conditions were changed to match those chosen for the VISTA to facilitate commonality between the data sets. The tracking task presented to the test subjects at TPS was not changed from that used at AFIT; however, because the initial conditions were changed, the flight path response from the same inputs was different. The γ_{tgt} profile produced and used at TPS is shown in Figure 16.
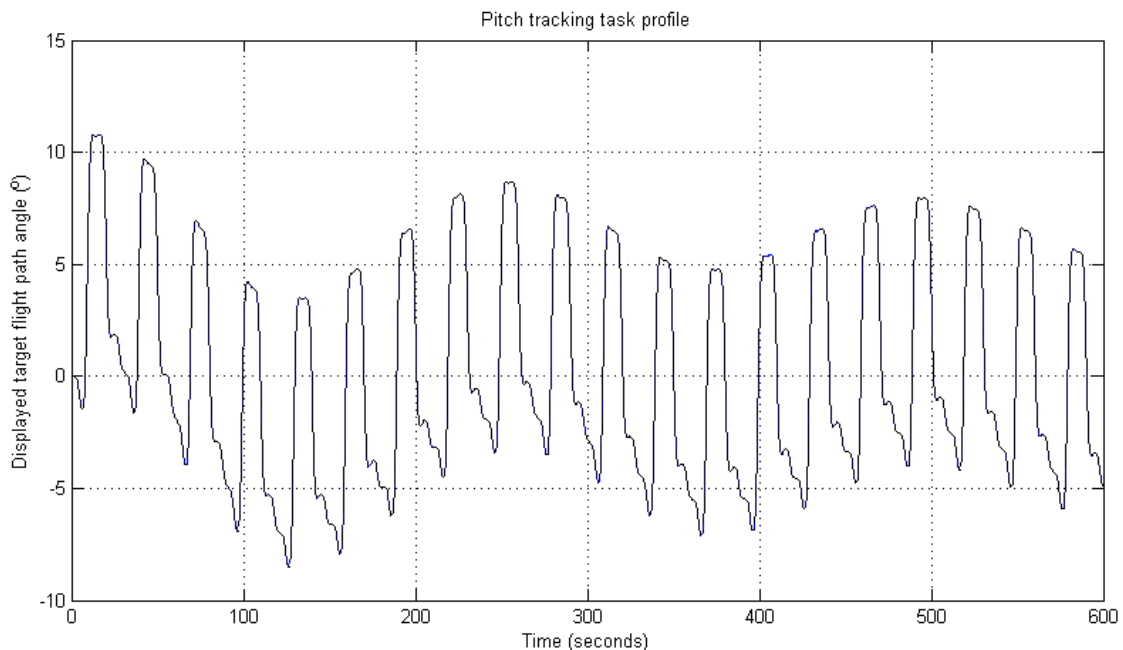
Figure 16 – USAF TPS Desktop Simulation Target Flight Path Profile

5.4 Cooper-Harper rating (CHR) task

The desktop simulator runs at TPS, as well as the LAMARS and VISTA, also included a Cooper-Harper rating task. This tracking task consisted of the same target profile as the boundary task, but with no boundaries. Also, the flight path marker was changed from the typical HUD "aircraft like" symbol to two concentric circles with radii of 15 and 25 mils respectively. The test subjects were instructed to track the target line with the new CHR flight path marker for one minute. Desired performance was defined as maintaining the target line inside the inner circle for 90% of the time. Adequate performance was defined as maintaining the target line inside the outer circle for 90% of the time. At the end of the one minute run, the test subject was asked to rate the aircraft on the Cooper-Harper scale using perceived performance and pilot workload. Figure 17 shows the changes for the CHR task to the desktop simulation HUD.
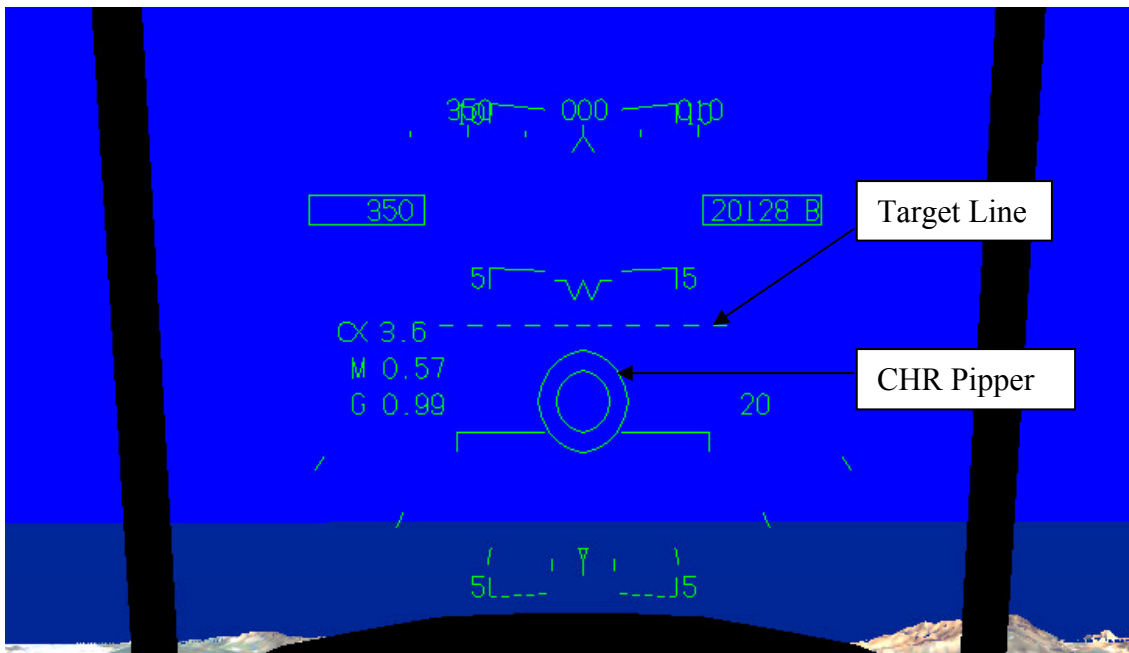
Figure 17 – TPS Desktop Simulation HUD – CHR task

5.5 TPS Desktop Simulator

     All model runs conducted at TPS used a 60 deg/sec stabilator rate limit. The TPS portion of the desktop simulator study was conducted in an attempt to ensure continuity of data with the LAMARS and the VISTA data sets. However, the differences in simulator hardware, control inceptors, and software interfaces negated any value in comparing the results in the manner anticipated. The results of the TPS portion of the desktop simulator study are shown below in Figure 18.
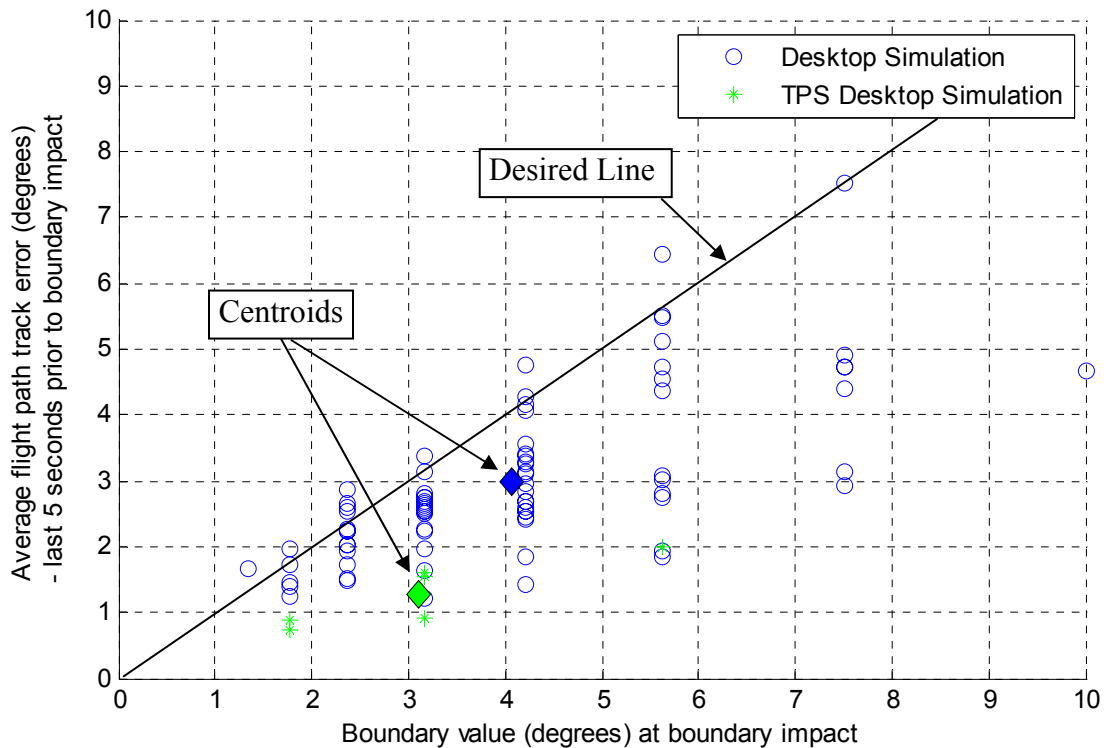
Figure 18 – Comparison of AFIT and TPS Desktop Simulation Results

5.6 LAMARS

The Large Amplitude Multi-Model Aerospace Research Simulator (LAMARS) was a 5 degree-of-freedom motion based simulator operated by the Air Force Research Laboratory. The LAMARS consisted of a simulator dome and cockpit mounted on the end of a 30 foot arm. The simulator dome and cockpit could rotate ±25° in pitch, roll and yaw at a maximum of 60° per second. The arm could articulate ±10 feet vertically or horizontally, achieving a maximum acceleration of ±3 g vertically and ±2 g horizontally.

Figure 19 – LAMAR Simulator

The interior of the LAMARS display dome allowed a ±133° horizontal by -20° to +106° vertical image composition. Current hardware installed in the display dome could project a ±60° horizontal by ±20° vertical image onto the interior surface. The control inceptor used was a fixed position force sensing sidestick similar in characteristics to the control stick installed in the Infinity Cube and early production F-16s. The LAMARS was controlled by the same computers used for the Infinity Cube described in Section 4.3,

but with additional motion control computers, hydraulics, and different visual terrain projectors and software.

The primary goal for the LAMARS portion of the study was to practice flight test techniques developed for the VISTA in-flight portion of the BAT DART TMP, as well as validate the difference in handling qualities that should be present in the 4 different pitch control models developed and selected for flight test.

5.6.1 Aircraft Aerodynamic and Pitch Control Model

The initial aerodynamic model flown in the LAMARS was the same model used in the Infinity Cube. This state-space model was re-trimmed at the new initial conditions (350 KIAS and 20,000 feet PA), wrapped with the desktop simulation pitch rate feedback and stick shaping characteristics, and became the DT (desktop) model. In addition to the previously designed desktop simulation pitch control model, Calspan Corporation was contracted to design 3 different pitch control models. The modes were required to be representative of a Cooper-Harper level 1, level 2, and level 3 aircraft in the longitudinal axis. The models constructed each consisted of 6 different longitudinal state-space A matrices that corresponded with different fuel weights anticipated in the VISTA. As the VISTA burned fuel in flight, different fuel weight versions of the same level model would be used to more accurately reproduce the same handling characteristics. Only the 6,000 lb fuel weight matrices were implemented in the LAMARS to prevent confusion and simplify testing procedures. These fuel weight state-space A matrices are shown in Appendix F along with the B, C, and D matrices common to all models. The Calspan models' open-loop short period dynamic characteristics are listed below in Table 4. The

38

basic F-16 control laws utilized previously in the Infinity Cube were used for roll and

yaw control of all models.

Table 4 – Calspan Model Open-Loop Short Period Characteristics

Model	Short Period Poles	ω_{sp}	ζ_{sp}
Level 1	-3.15 ± 3.2137j	4.5	0.7
Level 2	-0.72 ± 2.2985j	2.4	0.3
Level 3	-0.31 ± 1.5187j	1.55	0.2

Because the designed control feedbacks were inside the modified state-space

matrices, the control stick to stabilator path was implemented as a direct force to pitch

rate command.

5.6.2 Simulation Environment

The HUD information displayed to the test subjects was identical to that shown in

Figures 11 and 17; the same code that drove the Infinity Cube simulator HUD was used

to drive the HUD information in the LAMARS. Airspeed, altitude, attitude, target line,

boundary lines and velocity vector were displayed as the same color and proportional size

as the desktop simulator, and the Infinity Cube. Out-the-window terrain and environment

were similar but generated by a separate LAMARS terrain computer and software, and

were again chosen to minimize pilot distraction but also provide a visual attitude

reference. The presence of a wide (120°) horizontal visual reference again allowed

peripheral vision to aid in attitude recognition and maintenance. A list of recorded

parameters for the LAMARS can be found in Appendix C.

5.6.3 LAMARS Calibration

After some pilot-in-the-loop test flying, adjustments were made to the pitch stick gains to obtain the desired pitch response. This was done in an attempt to produce models that fell into the target CHR range of level 1, level 2, and level 3. The final pitch stick gains are shown in Table 5. No adjustment was made to the pitch stick gain for the desktop simulator pitch control model; it was implemented as shown in Figure 9.

Table 5 – Pitch Stick Gain Changes in the LAMARS

Pitch Control Model	Initial Stick Gain	Final Stick Gain
Level 1	1.0	1.00
Level 2	1.0	0.25
Level 3	1.0	0.50
Desktop Sim	1.0	1.00

The final combinations of stick gain and pitch control model were subjected to a 10-lb aft stick step and the pitch rate was recorded for comparison and verification of the VISTA configurations. The results of the step inputs are shown in Figure 20. The level 3 model was only subjected to a 2 lb aft stick step input, as this model was much more sensitive than the other 3 models. The final stick gains shown in Table 5 were used as the starting point for the VISTA calibration flight.
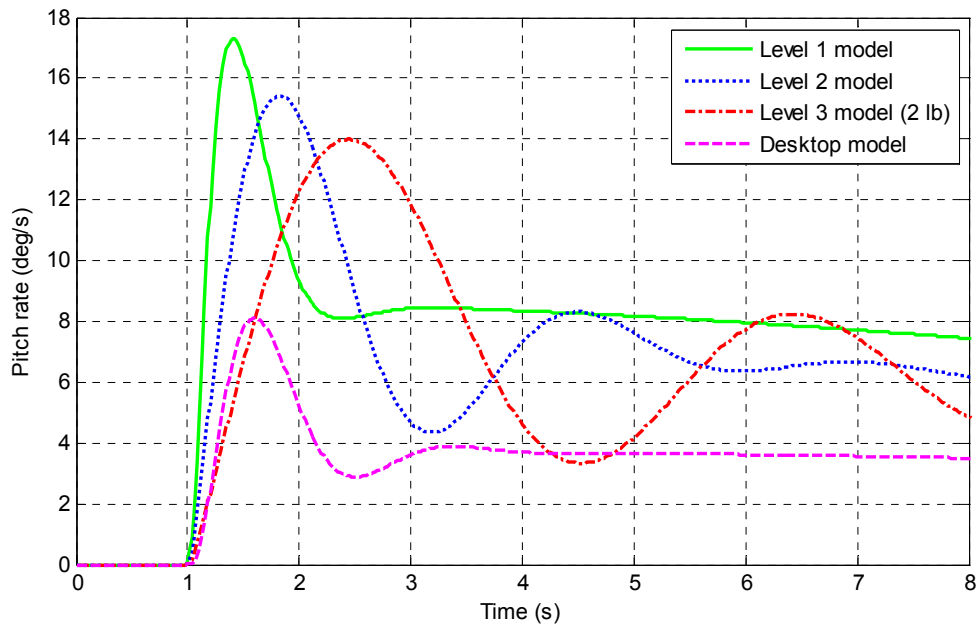
Figure 20 – LAMARS Models' pitch rate response to step input

5.6.4 Test Procedures

The same seven test subjects that participated in the desktop simulator study at TPS flew the LAMARS. They were each assigned the four pitch control models (Level 1, 2, 3, and Desktop) in a random order. The test subjects were allowed one minute of free flight with each model to allow adjustment to the new control laws. Each subject then flew the Cooper-Harper rating task described in Section 5.4, followed by the BAT task described in Section 3.1. Data were collected and pilot comments were recorded, and then the subject moved on to the next pitch control model.

5.6.5 Results

The total time that a test subject flew the LAMARS prior to a boundary impact was recorded for each pilot on each model.

Table 6 – LAMARS BAT Boundary Impact Times

	Run time (seconds)until boundary impact			
	Level 1 model	Level 2 model	Level 3 model	DeskTop model
Pilot 1	600	458	550	549
Pilot 2	580	507	517	521
Pilot 3	600	489	430	518
Pilot 4	600	546	487	486
Pilot 5	468	489	369	416
Pilot 6	458	437	428	428
Pilot 7	467	490	224	368
Average:	539	488	429	469
stdev:	70.3	34.7	109.1	66.4

It can be seen in Table 6 that the different pitch control models produced different average run times. Also the Level 1 model produced, on average, better times than the Level 2 model, which produced better average times than the Level 3 model. The Cooper-Harper ratings obtained in the LAMARS are shown below in Figure 21.
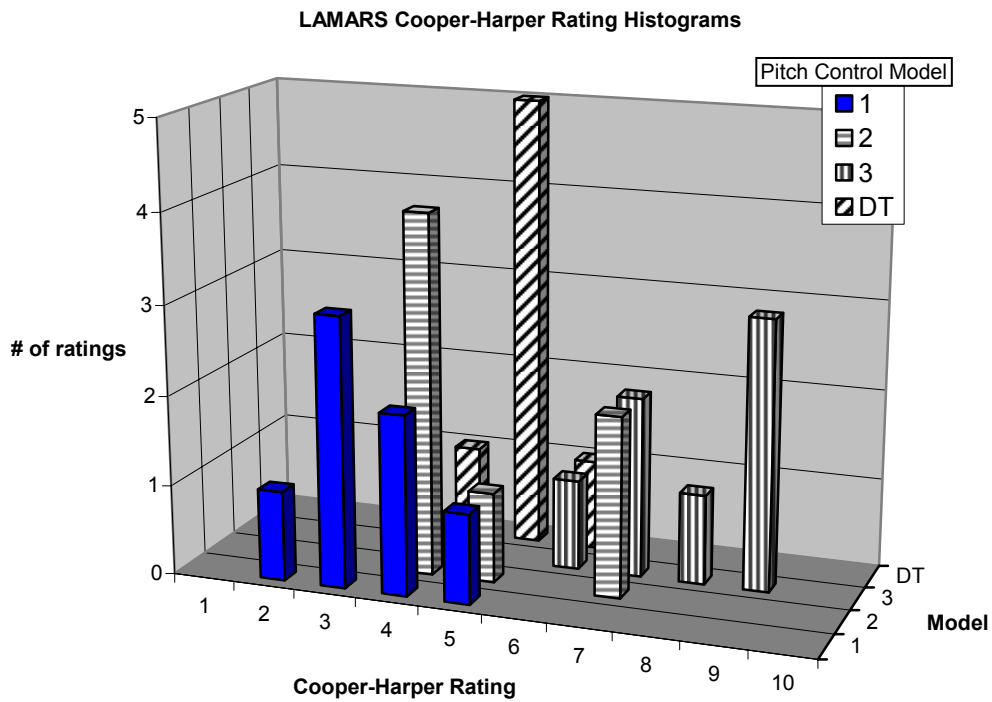
Figure 21 – LAMARS Cooper-Harper Ratings

The CHRs show decent grouping with some overlap between the Level 1, 2, and 3 models, and the DT model CHRs shows a very strong central tendency. A correlation was attempted between the BAT run times and the CHRs obtained in the LAMARS. Figure 22 below shows that a very loose correlation may be seen, but the data is extremely noisy with wide confidence intervals.
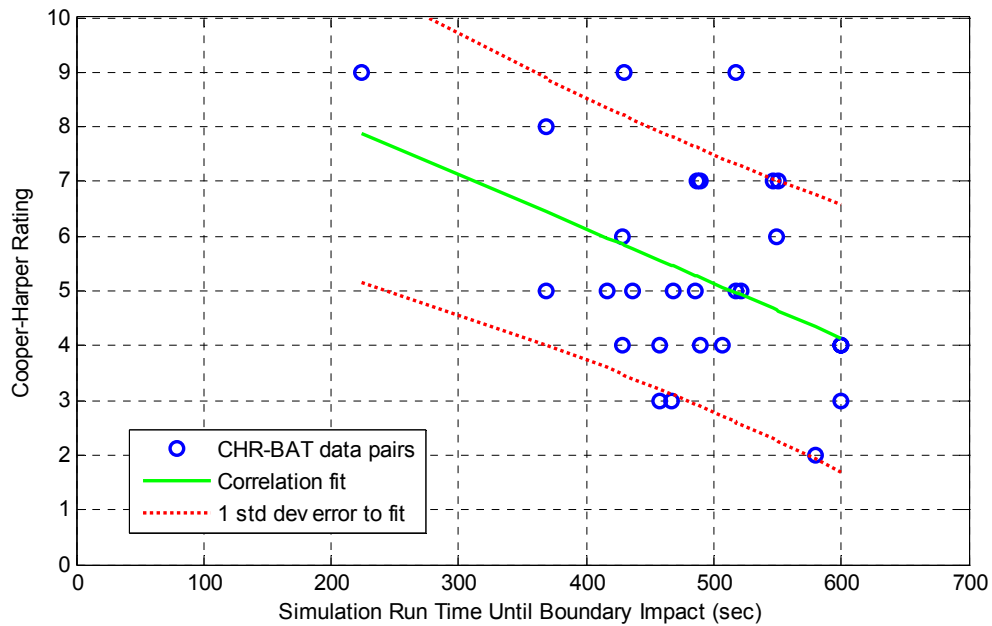
Figure 22 – LAMARS CHR-BAT Correlation

The data was further reduced in an effort to clean up the correlation by removing all of

the non-pilots from the data set. The results are shown below in Figure 23, and it can be

seen that the correlation is still very poor
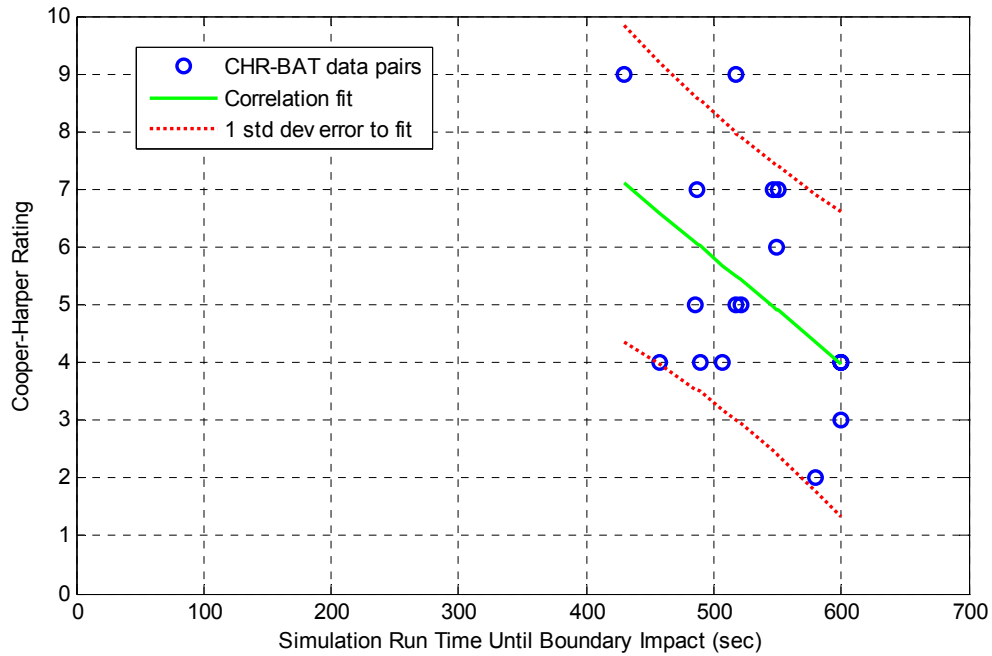
Figure 23 – LAMARS CHR-BAT Correlation – Only Experienced Pilots

Taken as a whole, the LAMARS data was discouraging, as no good correlation was found and the boundary impact times were not grouped very well into distinct data sets for each model. However, the primary LAMARS goals of test procedure checkout, flight test technique validation, and test team practice were met. The value of the LAMARS and other simulator data will be further addressed in Sections 6.1 and 6.2.

5.7 VISTA

The NF-16D VISTA was a unique aircraft based on a Block 30 F-16D in the Peace Marble II configuration. The avionics were Block 40 configuration and a custom Digital Flight Control Computer (DFLCC) was installed. The Variable Stability System (VSS), a five degree-of-freedom simulator, allowed the manipulation of flight control parameters in order to simulate specific characteristics of many different flight control systems and aircraft. The evaluation pilot (EP) sat in the front cockpit (FCP) while the safety pilot (SP) controlled the VSS from the rear cockpit (RCP).

Figure 24 – Variable-Stability In-Flight Simulator Test Aircraft (VISTA)

When the VSS was engaged, the pilot controlled the aircraft in the FCP through a sidestick using control models programmed in the VSS. Additional control modes allowed both the EP and the SP to fly the aircraft through the sidestick in either the FCP or RCP with a basic F-16 control model. The displays in the VISTA, to include the HUD, were fully configurable and re-programmable. The VISTA HUD was programmed to show the same CHR task and BAT task symbols as the desktop simulator and the LAMARS. However, due to pre-configured portions of the programmable HUD, the

altitude, airspeed, and horizon line were displayed differently than those of the other

simulators. This can be seen in Figures 11, 17, 25, and 28.
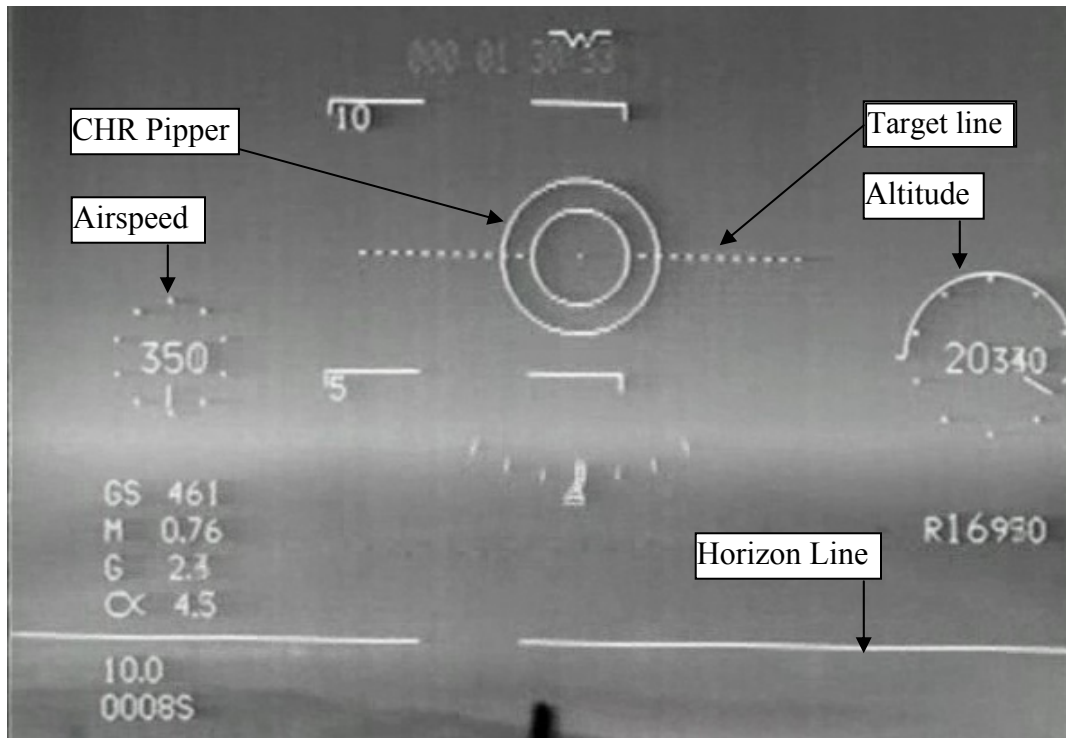
Figure 25 – VISTA CHR Task HUD View

The modified altitude and airspeed displays were determined to have no effect on

tracking performance, because these parameters were not in the test subjects cross check

while performing the tasks. The change in horizon line was determined to assist the test

subjects in discriminating between the target line, boundary lines, and the horizon line,

because the new horizon line was considerably wider than the target and boundary lines.

The VISTA was capable of recording HUD and Multi Function Display (MFD)

video as well as most of the parameters on the data bus of the VSS. A list of the relevant

data parameters recorded for the BAT DART TMP is listed in Appendix C.

47

Specific modifications to the NF-16D VSS software for the BAT DART project included:

1) Programming to simulate four different pitch control models.

2) Programming to input a target, boundary profile, and CHR pipper into the HUD, as shown in Figures 25 and 28.

3) Programming to provide for simulation control by the SP.

5.7.1 Aircraft Aerodynamic and Pitch Control Model

The 4 pitch control models and pitch stick control paths were implemented on the VISTA in the same manner as on the LAMARS. All six state space matrices for each model were available for execution, and the current fuel weight was used to select the appropriate state space model at the beginning of each model run.

5.7.2 Ground Test Procedures

Two 2-hour ground tests were conducted on 31 August and 7 September 2006 to test software integration on the VISTA. Ground electrical and hydraulic power was applied to the VISTA, and a control computer was attached which allowed test inputs and modifications to be input into the VSS. In this ground mode, the VISTA acted like a simulator, using the VSS computers and sample atmospheric data to simulate flight. Activation, control, and termination of the simulation profiles as well as data recording were tested. In-flight procedures were also tested and the flight cards developed for the actual test were used to simulate and practice for the flight test missions.

5.7.3 VISTA In-Flight Calibration

The first flight of the test program was used to calibrate, verify and validate the four pitch control model configurations, as well as practice flight test techniques and data recording. The flight test calibrations were performed at the same altitude and airspeed planned for the data flights: 350 KIAS and 20,000 feet PA. Inputs used included stick raps and step inputs manually applied by the pilot, and automated step inputs applied by the VSS. The data generated by these maneuvers were recorded by the VSS.

During the calibration flight, it was determined that the stick gains were too high in all configurations. Test profiles and step inputs results were compared to the results from the LAMARS test during post-flight analysis, and an initial approximation was made to decrease all of the stick gains by 50%. The final stick gains for the VISTA pitch control models were further reduced by another 20% on the first data flight, and were established more by test pilot feel than by analytical comparison to the LAMARS pitch response. Those corrections are shown below in Table 7.

Table 7 – VISTA Pitch Stick Gain Corrections

Pitch Model	Initial Stick Gain (from LAMARS)	Total Stick Gain Correction	Final Stick Gain
Level 1	1.00	40%	0.40
Level 2	0.25	40%	0.10
Level 3	0.50	40%	0.20
Desktop	1.00	40%	0.40

A step response comparison (Figure 26) of the final LAMARS and VISTA Level 1 stick gain-model combinations shows a large discrepancy in the measured pitch rate response. However, in the opinion of the test pilot present on the calibration flight, and the first data

collection flight, the final stick gains chosen for the VISTA produced responses that were

within 10% of the LAMARS models' responses. The discrepancies in the pitch rate

response to stick input could be due to inaccuracies in the LAMARS models, delays

inherent in the LAMARS or VISTA pitch stick to actuator control paths, or other

unknown factors.
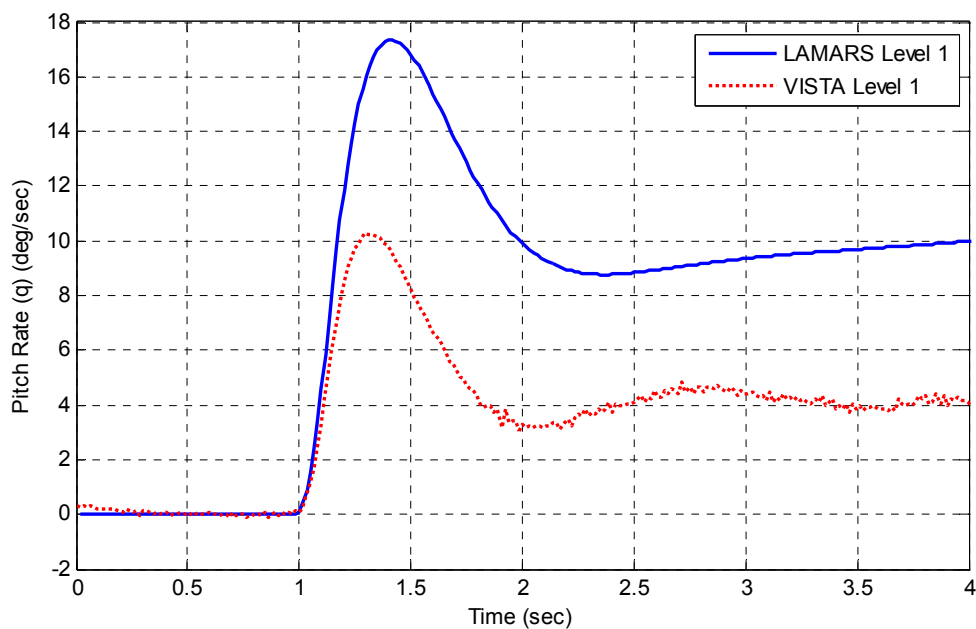
Figure 26 – Comparison of LAMARS and VISTA Level 1 Model Pitch Rate

Response to a 10 lb Aft Stick Step Input.

Historically, this is not surprising. The first flight of the YF-16 (Smith, 1979) and

fourth flight of the C-17 (Kendall, 1996) both encountered severe pilot induced

oscillations (PIOs) due to excessively high stick response sensitivity. After an extensive

series of flight tests to optimize the small-displacement sidearm controller in the F-16, the

final roll control gradient was only about one-fourth the value originally set in the simulator (DoD, 1995). Mitchell and Klyde (Mitchell, 2005) also noted in their paper on testing for PIOs that in general, simulators are notoriously bad at accurately predicting actual aircraft responses.

5.7.4 Flight Test Procedures

Following the calibration flight, data for the BAT DART investigation were collected on the remaining nine flights. Prior to each test, the aircraft was trimmed in straight and level, unaccelerated flight at the initial conditions. The new pitch control model was initialized and the SP gave the EP control of the aircraft. The EP was allowed 1 minute of free-flight to adjust to the new pitch control model. After free-flight was terminated, the SP prepared the CHR task.

Setup parameters for the Cooper Harper task were $20,000 \pm 500$ feet pressure altitude and 350 ± 10 KIAS. The Cooper-Harper pitch-tracking task was flown for one minute. The pilot attempted to keep the HUD-displayed CHR pipper (Figure 25) over the flight path angle target (γ_{target}) for as long as possible, making as aggressive inputs as necessary in an effort to achieve desired performance. Desired performance was defined as maintaining the target line inside the inner circle 90 percent of the time; adequate performance was defined as maintaining the target line inside the outer circle 90 percent of the time.

The tracking task (Figure 27) presented to the test subjects was identical to the desktop simulator tracking task used at TPS (Figure 16), as modified from the original AFIT desktop simulation tracking task. A 25 Hz time history vector of the TPS desktop

simulation target aircraft's flight path angle (γ_{target}) was used as the input data for the target line in the VISTA.
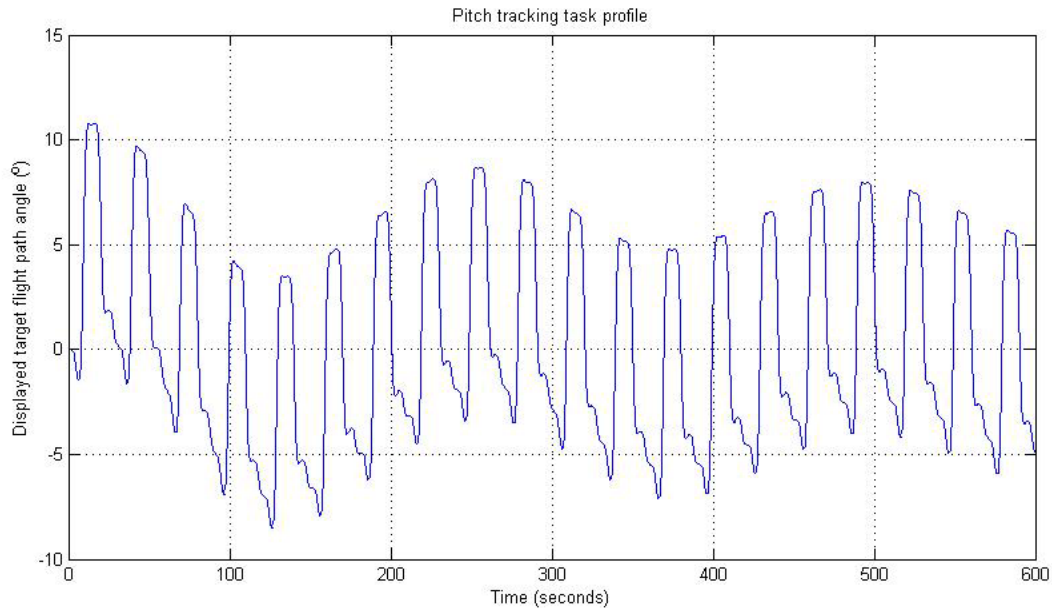
Figure 27 – VISTA Target Flight Path Angle (γ_{target}) Tracking Task Profile

The rear cockpit safety pilot (SP) controlled the throttle to maintain 350 ± 50 KIAS throughout the task. After one minute of tracking, the task was terminated. The EP assigned a Cooper-Harper rating based on perceived performance and workload. If a PIO was encountered, the pilot assigned a PIO rating (appendix E). Any comments given by the EP were also recorded.

Following the completion of the CHR tracking task, the EP then flew a boundary avoidance tracking (BAT) task using the same flight path angle target (γ_{target}) tracking profile (Figure 27) with the standard FPM (Figure 28) instead of the CHR pipper. Setup parameters for the pitch tracking task were $20,000 \pm 500$ feet pressure altitude and 350 ± 10 KIAS. The pilot attempted to keep the flight path marker (FPM) over the moving

target line while remaining inside the displayed boundaries. The SP controlled the throttle to maintain 350 ± 50 KIAS. As each BAT task progressed, the boundaries tightened in 25% increments, identical to the boundary profiles used on the desktop simulator, Infinity Cube simulator, and LAMARS. The tracking profile terminated when the center of the FPM crossed either boundary line.
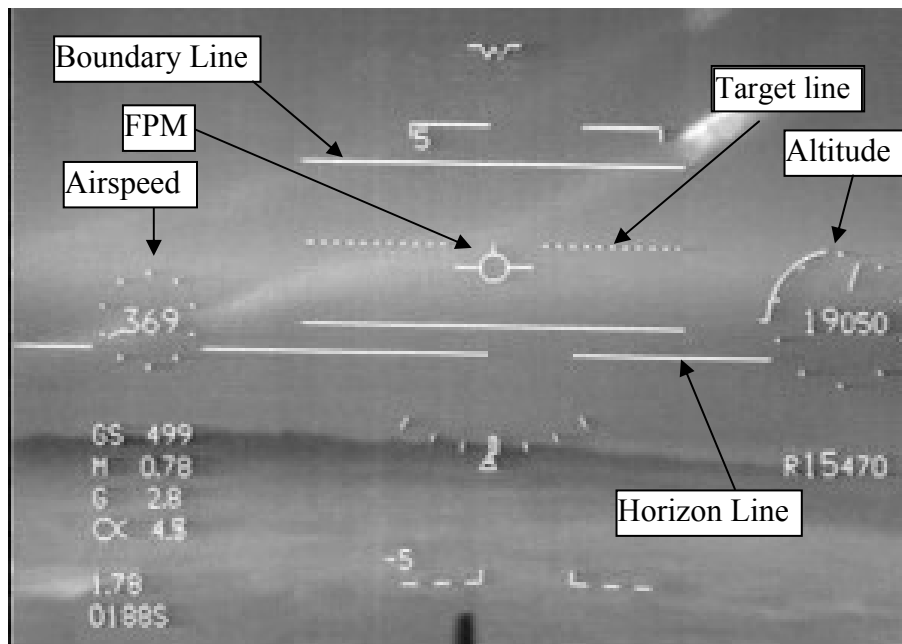
Figure 28 - VISTA BAT Task HUD View

Successful testing required diligent role-playing – the pilot was instructed to treat the boundaries as real threats, like the ground or another aircraft, and not accept an impact if at all possible. However, since test safety was of primary concern, the pilots could limit their inputs with discretion to avoid over-g, excessive buffet, wing rock, or other real-world limits such as Instrument Meteorological Conditions (IMC). The pilot commented when these real-world limits affected decision making and/or tracking. Successfully tracking the target required significant negative and positive g loading. All

test subjects were seated in the front seat (EP cockpit) of the VISTA, as the Safety Pilot (SP) retained all controls required for start/taxi/takeoff/landing/shutdown/and any contingences in the rear cockpit (RCP).

5.7.5 VISTA Results and Analysis

Two primary methods were developed to analyze the data acquired from flight test. These methods included distinguishing the levels of aircraft performance based on the length of time before boundary impact, and mean tracking error from the target compared to boundary size.

5.7.5.1 Boundary Impact Time Analysis

The first method of determining aircraft handling qualities was based on length of time progressed through the tracking exercise before contacting a boundary. The drawbacks of this method included the potential for small pilot mistakes such as momentary inattention, mannequin effect where aircraft motion induces pilot arm/hand motion on control inceptors, or external factors such as traffic or airspace boundaries to terminate a run early. When an external effect caused the test subject to terminate the exercise early, they were instructed to start the tracking task completely over or to restart the tracking task at an intermediate boundary value.

As can be seen below in Table 8, the different pitch control models produced very dissimilar results in the boundary tracking task. There was some overlap in both Level 1 compared to Level 2 results, and Level 2 compared to Level 3 results. However, there was no overlap in boundary impact times between Level 1 and Level 3.

54

Table 8 – VISTA Boundary Tracking Task Times

	Run time (seconds)until boundary impact			
	Level 1 model	Level 2 model	Level 3 model	DeskTop model
Pilot 1	517	459	*	548
Pilot 2	499	339	369	488
Pilot 3	460	457	309	499
Pilot 4	438	367	308	546
Pilot 5	427	338	101	428
Pilot 6	488	427	310	371
Pilot 7	427	220	11	457
Average:	**465**	**373**	**235**	**477**
stdev:	**36.6**	**84.9**	**143.1**	**63.8**

* - Incomplete test point due to fuel state

A one-tailed t-Test analysis (appendix F) of the times and averages of the Level 1, 2, and 3 results showed a greater than 99.99 percent chance that the results are from 3 separate models. This is significant because it shows that the BAT method can differentiate between the in-flight handling qualities present in different aircraft models. These results appear to correlate with the Cooper-Harper ratings (CHR) collected from each pilot on all pitch control models. The CHR results are shown below in Figure 29.
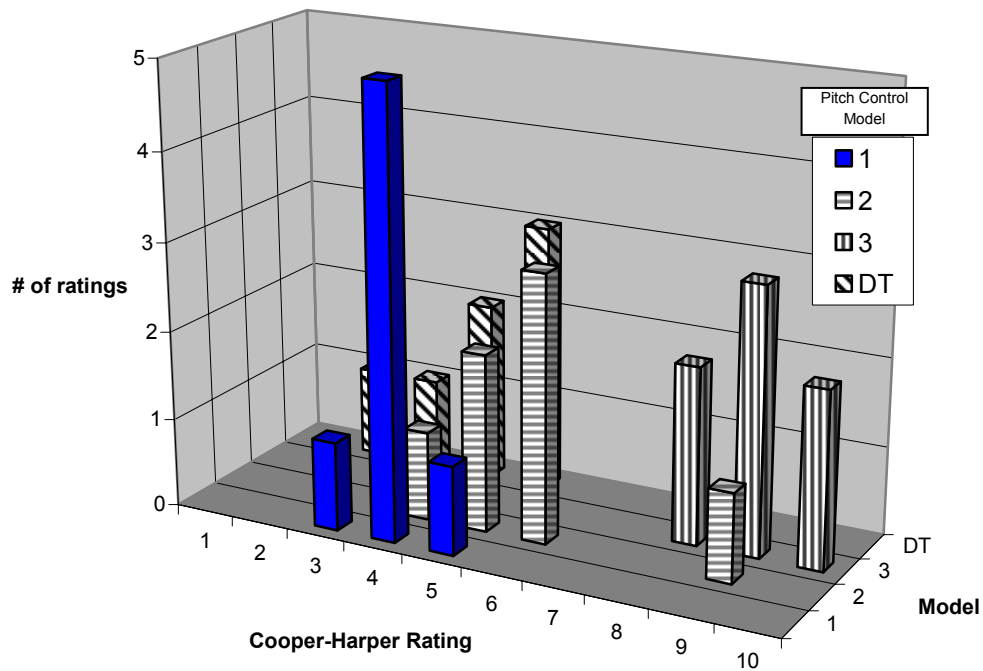
Figure 29 – VISTA Cooper-Harper Ratings

A one-tailed t-Test analysis (Appendix F) of the CHR of the Level 1, 2, and 3 results showed a 100 percent chance that the results are from three separate models.

Note that the desktop simulation model produced very different results on the LAMARS (Table 6 and Figure 21) as compared to the VISTA (Table 8 and Figure 29). One possible reason for this change, compared to the Level 1, 2, and 3 models, is that the desktop model had an active pitch rate feedback control loop. Or one of the implementations could have been different than the other one. Because of this discrepancy, the desktop model data was not compared directly to the other models, but its data was used in the total correlations below.
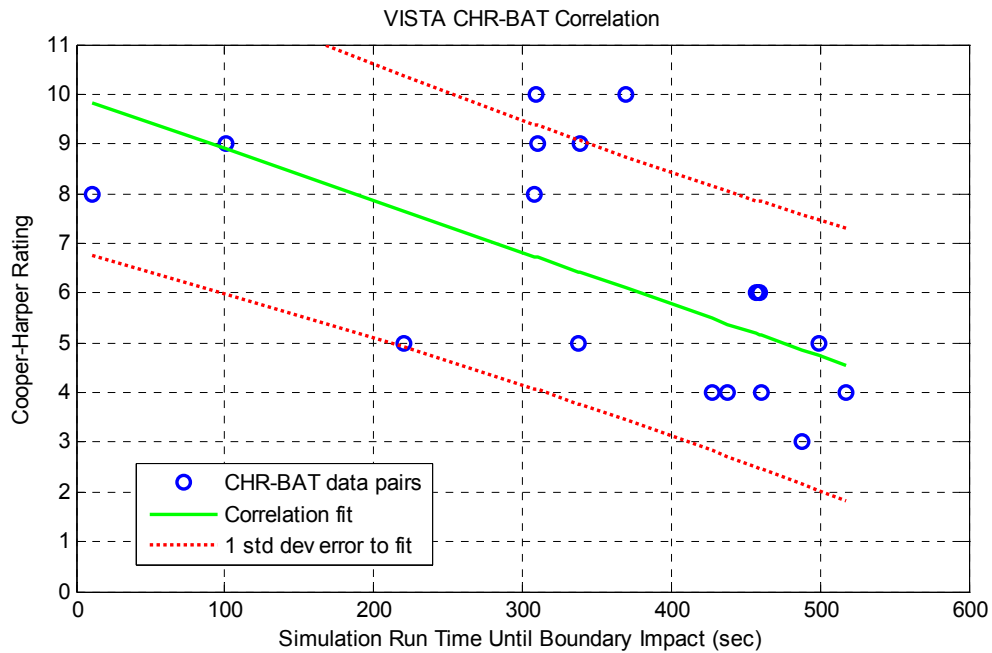
Figure 30 – VISTA CHR-BAT Correlation

Pilot assigned Cooper-Harper ratings were plotted against the subsequent BAT task simulation run time until boundary impact. As can be seen in Figure 30, the data is fairly scattered. If the test subjects' data is pared down to only the test subjects with pilot ratings, the results are more coherent. Figure 31 shows the same data with only pilot subjects included. One data point was also removed due to a combination of factors that were deemed to have caused an early boundary impact by the test subject: clouds in the working area, improperly adjusted stick arm-rest, and mannequin effect.

VISTA CHR-BAT Correlation
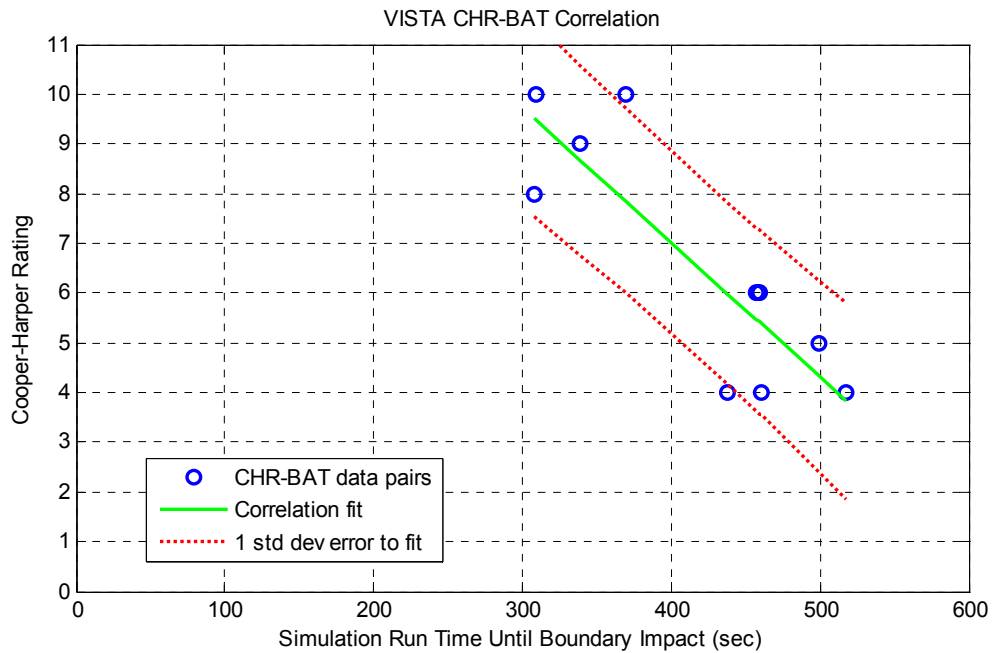
Figure 31 – VISTA CHR-BAT Correlation – Pilot Only Test Subjects

Conclusions were then made to predict Cooper-Harper ratings. For example, from Figure 31, it can be concluded that should a pilot fly the model tracking task for 450 seconds, he or she will also probably rate the aircraft between 4 and 7 on the Cooper-Harper scale for that same task.

One additional way to look at the similarities between the BAT data and the CHR data is to put the BAT data into a 1 Dimensional chart, similar to a histogram of Cooper-Harper ratings.
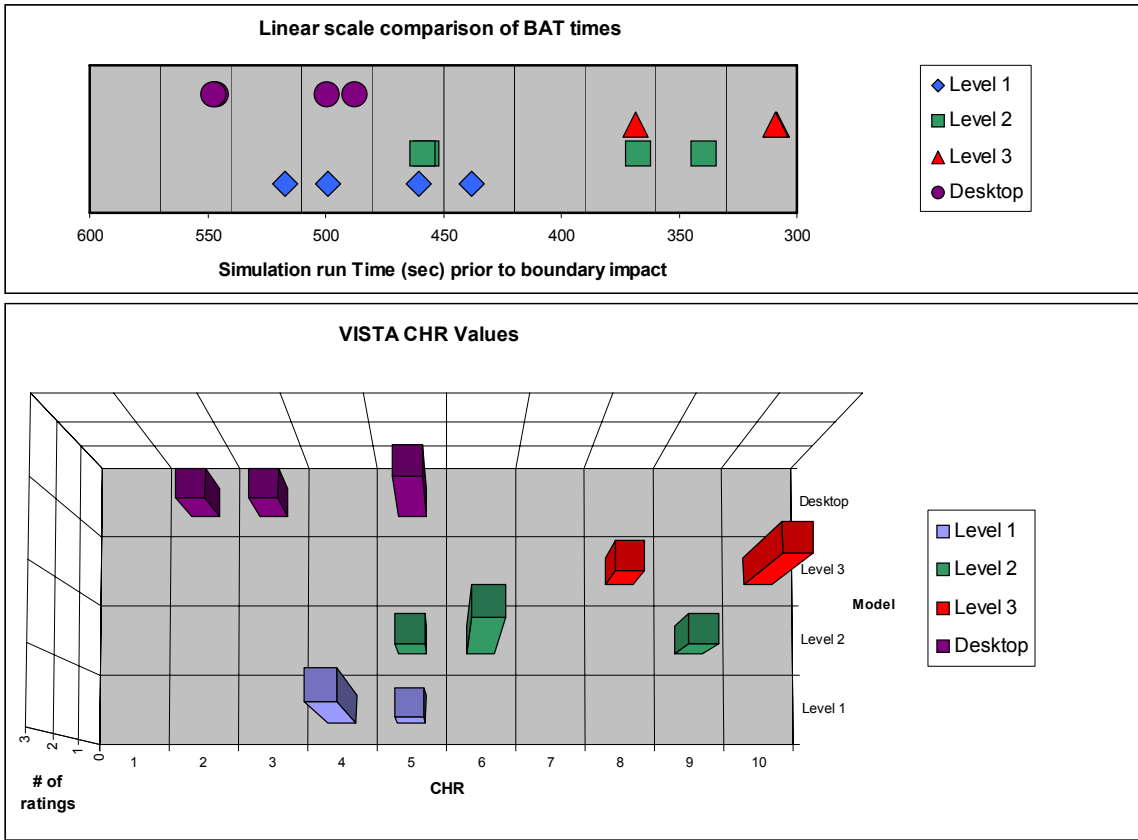
Figure 32 – VISTA CHR-BAT Comparison – Pilot Only Test Subjects

Figure 32 contains the same data points as Figure 31, and reveals a marked similarity between the location and distribution of the BAT data and the CHR data. This positive correlation and similarities between BAT boundary impact times and CHR ratings shows that boundary avoidance tracking tasks can be used to compare different aircraft pitch control systems and achieve an accurate measure of actual aircraft handling qualities.

5.7.5.2 Mean Tracking Error Analysis

The second method of determining aircraft handling qualities was based on mean tracking error. This method was more effective in determining boundary avoidance, and also held some utility in determining aircraft handling qualities. A typical boundary tracking task can be seen below in Figure 33. The figure shows a plot of tracking error and the instantaneous displayed boundaries over the length of the task run. Also shown are the pilot's longitudinal stick inputs on the same time scale. The run was terminated when the tracking error equaled the current boundary value, or from the EP's HUD view, when the flight path marker crossed the displayed boundary.
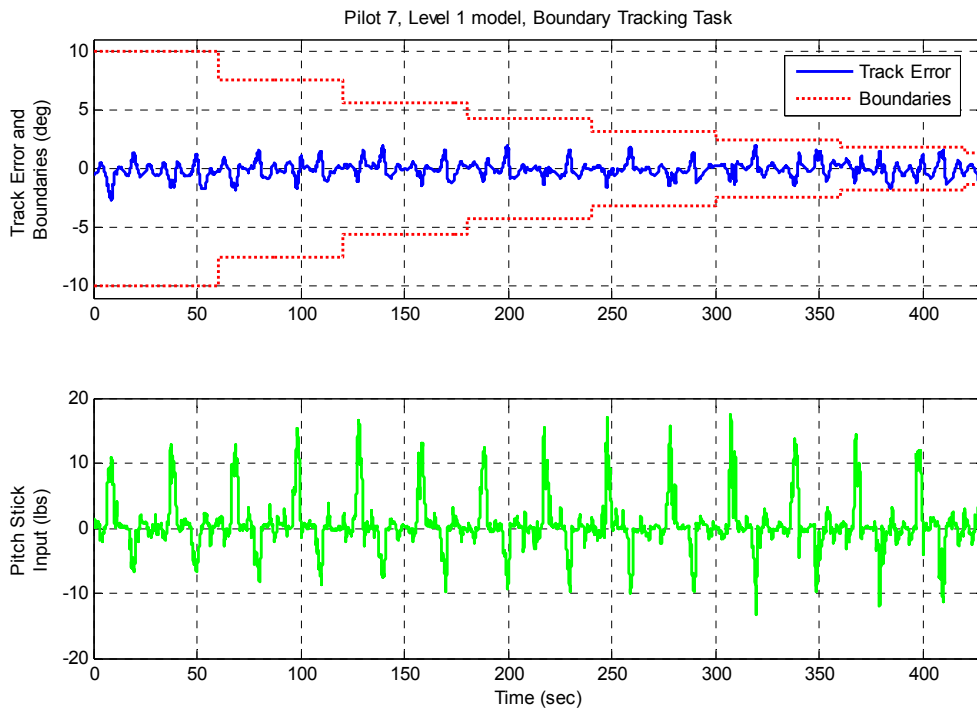
Figure 33 – Tracking Error, Boundaries and Stick Inputs of Typical Boundary Tracking Task

A closer look at the tracking error throughout the run shows little variability in the peak errors as the boundaries impose on the task. However, a plot of the average tracking error for the 60 seconds each discreet boundary value was displayed illustrates that the boundaries have a definite impact on pilot performance. As shown in Figure 34, as the boundaries got closer to the tracking task target, the pilot's average error decreased to a minimum value. After this point, the pilot was no longer able to increase performance and further shrinking of the boundaries disrupted the target track, causing an increase in average tracking error. The result is that for this pilot flying this task on this 'aircraft', the minimum average tracking error, or best performance has been found. Also, a boundary value that will produce the best performance has been identified, and can be used in subsequent tests to drive the pilot to maximum performance.
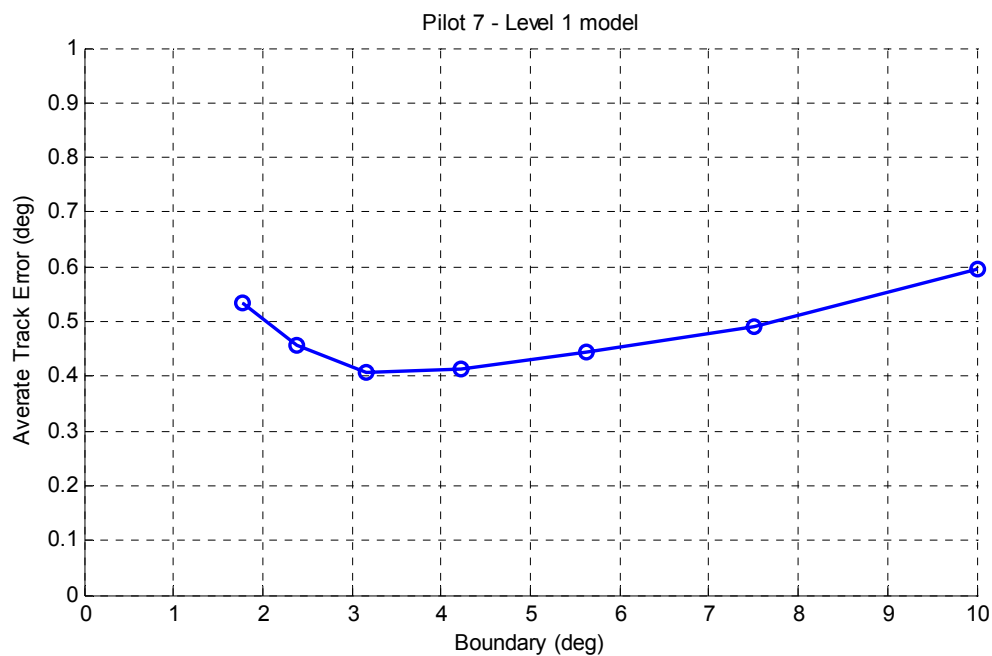
Figure 34 – Average Track Error per Boundary Step Size

To take this analysis method one step farther, the minimum average tracking error for all test subjects in each boundary step size on each model was compiled, and the minimum values for each model and boundary step size were plotted in Figure 35. It is readily apparent that test subjects flying the Level 1 model could achieve performance (defined as smaller average error) that was equal to or better than the performance on the Level 2 model. The same can be said for test subjects flying the Level 2 model versus the Level 3 model.
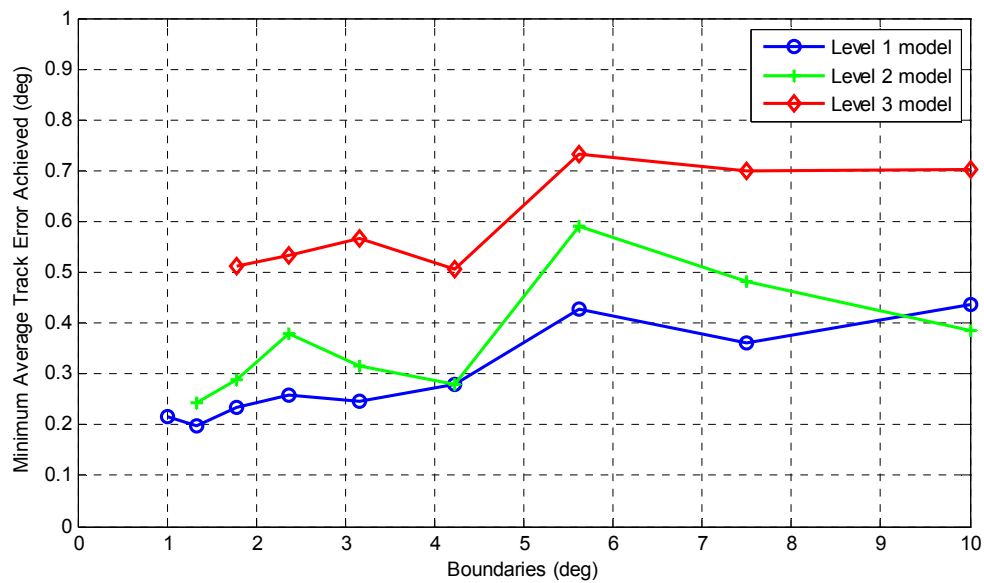
Figure 35 – Minimum Average Track Error - All Pilots, All Test Runs

Another thing to note from Figure 35 is the fact that the decrease in boundary size does not consistently affect pilot performance until the boundaries are inside of 5.6 degrees. This is theorized to be the point of boundary awareness: the maximum boundary size that will consistently cause an increase in task performance. The best

average performance does not decrease, and in many cases it increases while the boundaries are 5.6 degrees or larger. The early increase in minimum average error with time may be due to pilot familiarity with the aircraft model and workload management prior to boundary awareness. That the boundary awareness performance improvement seems to be consistent across all three models is significant. This implies that the setup of the tracking task and boundary relationships are factors that contribute to when boundary awareness occurs. Or, even more significantly, that all pilots may have the same limit for boundary awareness.
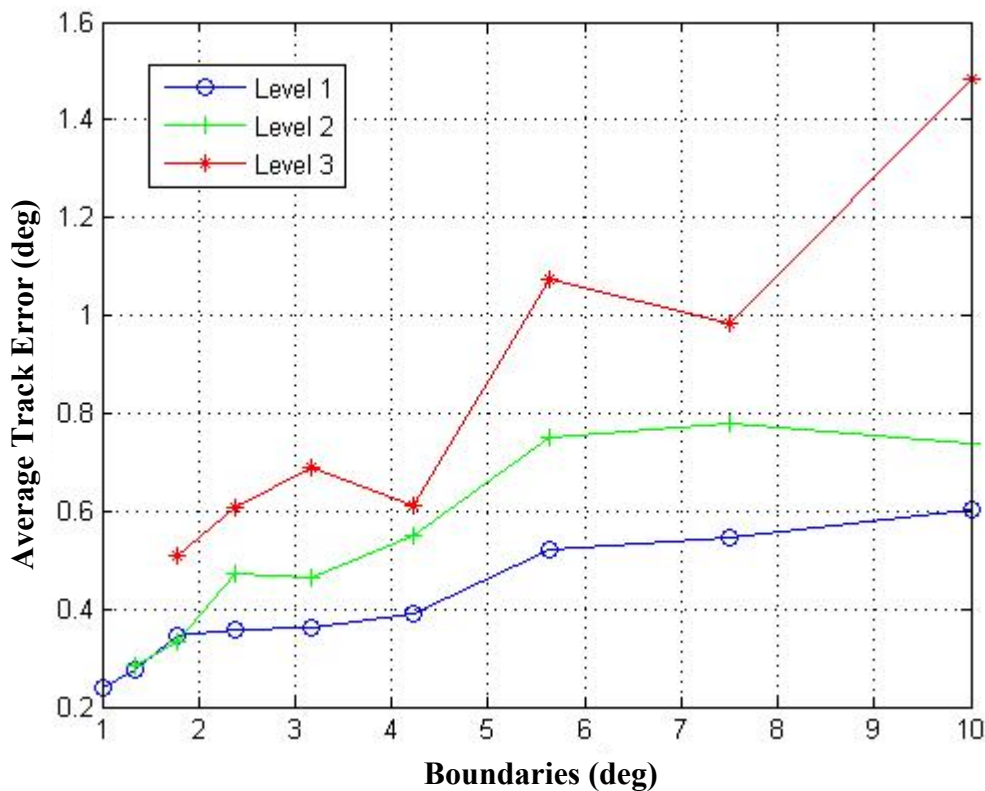
Figure 36 – Mean of Individual Pilot's Average Tracking Errors

Figure 36 shows the mean of the average track errors for each boundary value from all test subjects and all test runs. The same boundary awareness break point at 5.6 degrees boundary value can also be observed in this figure. It is interesting to note that

the mean of the average tracking errors for the Level 1 and Level 2 models are within 3 percent for boundary values of 1.33 and 1.78 degrees. However, none of the test pilots was able avoid boundary impact on the Level 2 model long enough to achieve the 1 degree boundary value, while three of the test pilots passed 540 seconds on the Level 1 model test run and flew in the 1 degree boundary value. Further analysis and/or testing of these two pitch control models at small boundary values is warranted to determine why the average tracking performance is similar only at these small boundary values, even though absolute minimum tracking error was different

One additional comparison can be shown between average tracking error and boundary size. Figure 37 shows the mean flight path error in the 5 seconds prior to boundary impact plotted against the boundary size at boundary impact.
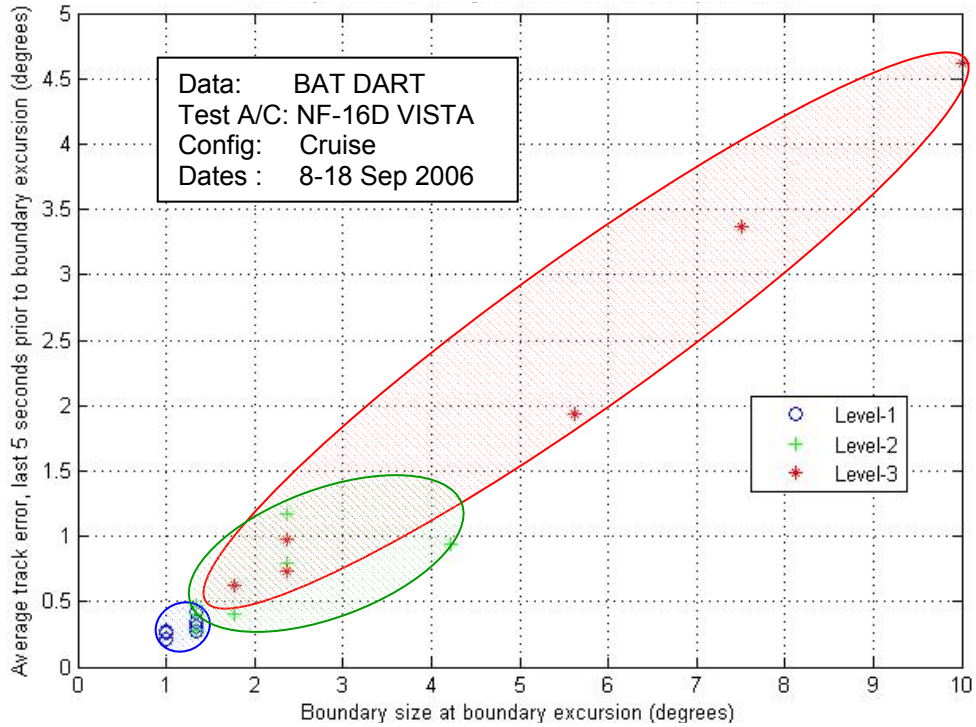
Figure 37 – Mean Track Error vs. Boundary Size at Impact

The grouping of the boundary impact times of the different models is very revealing as it shows that just about any pilot, regardless of experience level, could achieve very good performance on the Level 1 pitch control model. However, the wide spread of the Level 3 impact times shows that pilot skill level and experience play a large role in determining the best performance achievable on a pitch control model with poor handling qualities. In this case, the magnitude of the standard deviation of the impact times for each model seems to correlate with the Cooper-Harper Ratings, as seen in Table 8 and Figure 29.

6. Conclusions and Recommendations

6.1 Conclusions of Research

Handling qualities research and testing is arguably the most important aspect of manned

flight test. Verifying that the response of the pilot-aircraft system matches the

expectations and requirements is the ultimate goal of any flight test program.

Historically, the flight test community has relied on two forms of data to evaluate

handling qualities: pilot comments and Cooper-Harper ratings. This thesis proposes a

new set of techniques and data to evaluate aircraft handling qualities.

The goal of this research was to determine if a bounded tracking task could be

used to produce numerical aircraft handling qualities data. To accomplish this goal a

nonlinear 6 DOF F-16 aircraft model and bounded flight path angle (γ) tracking task were

developed on a desktop computer. Test subjects flew the model and tracking task with

variable flight path angle boundaries and 3 different stabilator rate limits. The test

subjects then flew the tracking task with the same boundaries and rate limits on the

AFRL's Infinity Cube simulator. Stabilator rate limiting was discarded as a method to

produce different handling qualities, and further investigation focused on the dissimilar

results obtained in the different simulators. The results were compared to determine if

the different control schemes present in the two simulators produced different tracking

performance. Data analysis focused on the average tracking error per boundary size as a

measure of task performance, as well as the length of time the simulation was flown prior

to impacting a boundary.

Research was continued as part of the USAF TPS TMP 'BAT DART', at

Edwards AFB, CA. Pitch control models representative of Cooper-Harper levels 1, 2,

and 3 were developed by the Calspan Corporation for integration into the LAMARS and the VISTA. Cooper-Harper performance rating definitions were developed for the tracking task, and an additional 7 test subjects flew the tracking task on the desktop simulator, the LAMARS, and the VISTA. Each test subject flew the tracking profile twice: once with no boundaries to produce a baseline CHR, and once with boundaries to collect BAT data.

Differences in simulation hardware, software, and control inceptors called into question the validity of the desktop simulation and LAMARS data in comparison with actual flight test data. Overlaps and shifts in the range of model results in the LAMARS data were inconsistent with the data produced during flight test in the VISTA. However, the primary goal of the LAMARS visit was to prepare for the flight test portion of the research, and this was accomplished to the satisfaction of the test team.

Analysis of the VISTA flight test data produced a correlation between total simulation run time prior to impacting a boundary, and Cooper-Harper rating for each model. However, it should be noted that this correlation is only valid for the tracking task and boundaries used in this research. Data supporting the existence of boundary awareness was obtained by examining the average flight path track error for all test subjects. Prior to boundary awareness, a decrease in boundary size did not consistently produce an increase in performance; whereas immediately after boundary awareness occurred, nearly all pilots on all models improved their performance.

The boundary avoidance tracking (BAT) flight test techniques developed during this thesis and the 'BAT DART' TMP have been shown to provide consistent and relevant handling qualities data, with the added benefit of being subject to statistical

analysis. Pilot comments will always remain the primary method of evaluating and correcting aircraft handling quality deficiencies, but BAT data could conceivably augment or even replace the Cooper-Harper rating as a reference data set for comparing and evaluating aircraft handling qualities. Further research and flight test is warranted to possibly generalize the proposed flight test techniques so that they can be applied on a variety of aircraft platforms.

6.2 Lessons Learned

The initial tracking task was designed with the goal of eventually implementing the test on the VISTA. However, little knowledge of the limitations and system requirements of the VISTA was available at the time. A thorough understanding of the intended platform of implementation is recommended to properly design a flight test task.

Creation of the three pitch control models was requested of the Calspan Corporation for two reasons: 1) Again, unfamiliarity with the VISTA software interface and limitations. 2) Lack of time available to the test team due to the regular syllabus requirements in the middle of TPS. However, the time gained by having someone outside the test team build and implement the pitch control models was lost to requirements creep caused by miscommunication. This was further exasperated by one contractor being responsible for passing required models and software to another contractor, and the miscommunications that developed therein. Having a single individual or team that has ownership and responsibility for creation, distribution, and implementation of new models or ideas is recommended to avoid miscommunication of vital project concepts.

An initial goal for the LAMARS testing was to have aerodynamic models, pitch control model implementation, recorded parameters, and testing procedures identical to those planned for the VISTA. However, practical implementation considerations as well as the complete difference in hardware and software systems between the two different testing platforms made this goal unobtainable. However, the primary goal of test procedure and test team practice was met, and the testing continued as planned. Focusing on the minimum data necessary to support the research, in this case different models flown on one system – the VISTA, allowed the research to continue to a valid conclusion.

Historically, simulation of fly-by-wire or highly augmented aircraft has produced results which don't necessarily match initial flight test responses. A cautious and well thought out approach to stick sensitivity in initial flight testing of new aircraft designs or models will assist in mitigating the effect of any unexpected aircraft responses.

6.3 Recommendations for Action and Future Research

The general properties of the tracking task used throughout the research were taken from Mr. Gray's initial pilot in-the-loop simulation. However, the visual representation of the simulation information and boundaries chosen for this research allowed more precise aircraft control and tracking precision. Thus, the tracking task was not optimally designed for the simulations used. The result was that during a large percentage of the tracking task execution, the pilot was out of the loop with the aircraft, and the short period response dominated the aircraft dynamics. A frequency analysis of the pitch stick inputs was attempted on the VISTA data, but the results were inconclusive. Four frequencies dominated the data, obtained from fast Fourier transforms (FFTs) and

69

power spectral densities (PSDs) of the pilot pitch stick inputs. These four frequencies corresponded to the approximate short period of the pitch model, and the three input frequencies to the tracking task. At smaller boundary values, some frequencies slightly higher than the aircraft short period began to manifest, but the data was too noisy to make any conclusions. If the data recording frequency were increased, and the pilot in-the-loop time maximized, it might be possible to observe a change in the pilot's input bandwidth in the frequency domain as the boundaries decrease in size.

In any future BAT research that will attempt to analyze pilot inputs in the frequency domain, it is recommended that the tracking task be designed to keep the pilot in the aircraft control loop for as large a percentage of time as possible.

Due to the fact that the frequency content of a pilot's stick inputs could occur up to approximately 20 Hz, the minimum sample rate to observe this data should be approximately 50 Hz. However, the data from the VISTA was recorded at 66.66 Hz and the FFTs and PSDs were still extremely noisy. An increase in sample rate might allow a better analysis of the data in the frequency domain.

Bibliography

Aircraft Visual Display Software (AVDS). Version 1.3.6.4. Computer Software. Rasmussen Simulation Technologies LTD,

Cooper, George E., & Harper, Robert P., Jr., NASA TN D-5153 "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities", Cornell Aeronautical Laboratory, 1966

Department of Defense. MIL-STD-1797A, "Flying Qualities of Piloted Aircraft," Jan 1990.

Department of Defense. MIL-STD-1797A, "Flying Qualities of Piloted Aircraft," Jan 1990; Notice of Change, 28 June 1995

Dotter, Jason. "An Investigation into Pilot Performance and PIOs as influenced by Boundaries", Air Force Institute of Technology, 2005 Master's Thesis Mini-defense

Dotter, Jason, and others. "Limited Investigation and Characterization of Boundary Avoidance Tracking Deterministic Analytical Rating Task (BAT DART). Technical Report, Air Force Flight Test Center, Edwards AFB,CA,2006

General Dynamics. "711ZC001" – VISTA F-16 Flight Control Schematics, 1989

Gray, William. "Boundary-Escape Tracking: A New Conception of Hazardous PIO." Society of Experimental Test Pilots, 2004.

Gray, William. "Boundary-Avoidance Tracking: A New Pilot Tracking Model." American Institute of Aeronautics and Astronautics, 2005.

Hanley, James G. "A Comparison of Non-Linear Algorithms to Prevent Pilot-Induced Oscillations Caused by Actuator Rate Limiting." Air Force Institute of Technology, 2003

Ishmael, Stephen D. et al. "Design Implications From AFTI/F-16 Flight Test" NASA, 1984

Kendall, E. R., "The Design and Development of Flying Qualities for the C-17 Military Transport Airplane," in *Advances in Aircraft Flight Control*, Tischler, M. B., ed., Taylor & Francis, PA, 1996

Matlab© / Simulink©. Version 2006a. Computer software. The Mathworks, Inc., Natick MA, 2006.

Mitchell, D. & Klyde, D. "Testing for Pilot-Induced Oscillations" *AIAA-2005-5811* AIAA Atmospheric Flight Mechanics Conference and Exhibit, San Francisco, CA 2005

Nguyen, L. T., et al. "Simulator Study of Stall/Post-Stall Characteristics of a Fighter Airplane with Relaxed Longitudinal Static Stability." *NASA Technical Paper 1538*. Washington, D.C.: NASA, December 1979.

NASA, http://www1.dfrc.nasa.gov/Gallery/Photo/F-16AFTI/HTML/EC91-630-8.html

School, U.S. Air Force Test Pilot. *Flying Qualities Phase Syllabus, Part IV* – "Handling Qualities – Hour 1" . Edwards AFB, CA, 2002.

Smith, J. W., "Analysis of a Lateral Pilot-Induced Oscillation Experienced on the First Flight of the YF-16 Aircraft," NASA TM-72867, 1979.

Stevens, Brian L., Lewis, Frank L. "Aircraft Control and Simulation." John Wiley & Sons, Inc., Hoboken, NJ, 2003.

Warren, Randy. "An Investigation of the Effects of Boundary Avoidance on Pilot Tracking." Air Force Institute of Technology, 2006.

Warren, Randy, and others, "A Limited Investigation of Boundary Avoidance Tracking (HAVE BAT)" Technical Report, Air Force Flight Test Center, Edwards AFB, CA, 2006

Witte, Joel B. "An Investigation Relating Longitudinal Pilot-Induced Oscillation Tendency Rating to Describing Function Predictions for Rate-Limited Actuators." Air Force Institute of Technology, 2004.

Vita

Captain Jason Dotter was born in Oklahoma City, Oklahoma and graduated high school from Clinton, Oklahoma in 1992. He attended Oklahoma University (OU) where he graduated in 1997 with a Bachelor of Science Degree in Aerospace Engineering and a minor in Physics.

After graduation, Jason entered the U.S. Air Force Officer Training School, where he was commissioned a Second Lieutenant in December 1997. Jason entered Specialized Undergraduate Pilot Training (SUPT) in March of 1998 at Columbus AFB, Mississippi, and received his pilot rating one year later as part of class 99-06. He attended Introduction to Fighter Fundamentals class 99K in preparation for his transition to the F-15E Strike Eagle.

Jason began his F-15E training as part of class 99DBE at Seymour Johnson AFB, North Carolina and graduated in March of 2000. He was assigned to the 335FS "Chiefs" at Seymour Johnson for three years, and then transitioned to the 333FS "Lancers" as an F-15E RTU instructor pilot.

Captain Dotter was selected for the joint AFIT/TPS program in February 2004 and began classes at AFIT in September of that year. Jason graduated from the U.S. Air Force Test Pilot School in December 2006 as part of class 06A. After the completion of his AFIT degree, he will be assigned to the 416th FLTS at Edwards AFB, California where he will test F-16s. Captain Dotter has over 1500 hours of flight experience; 1000+ in the F-15E, and has flown over 30 different aircraft.

Appendix A – Aerodynamic State Space Models

Unaugmented F-16 Longitudinal State Space Equations (Witte, 2004):

$$a = \begin{vmatrix} -0.033104 & 0.14957 & -0.3207 & -0.56111 \\ -0.015511 & -1.2826 & 1 & -0.002462 \\ 0.008081 & -4.0875 & -1.7556 & 0.001283 \\ 0 & 0 & 1 & 0 \end{vmatrix} \qquad b = \begin{vmatrix} -0.5193 \\ -0.05243 \\ -11.085 \\ 0 \end{vmatrix}$$

$$c = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \qquad d = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$$

Hanley Case "B" State Space Equations used in Infinity Cube (Witte, 2004):

$$A = \begin{vmatrix} -0.033093 & 0.17889 & -0.3122 & -0.56093 \\ -0.01551 & -1.2796 & 1.0009 & -0.002444 \\ 0.008312 & -3.4615 & -1.5741 & 0.005109 \\ 0 & 0 & 1 & 0 \end{vmatrix} \qquad b = \begin{vmatrix} -0.5193 \\ -0.05243 \\ -11.085 \\ 0 \end{vmatrix}$$

$$c = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \qquad d = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$$

Calspan constructed Cooper-Harper Level 1, 2, and 3 models:

Level 1 A matrix:

$$a = \begin{vmatrix} -0.024639 & -1.0043 & 0.040619 & -0.56157 \\ -0.015213 & -1.3797 & 0.95555 & 0 \\ -0.16363 & -14.015 & -4.9044 & 0 \\ 0 & 0 & 1 & 0 \end{vmatrix}$$

Level 2 A matrix:

$$a = \begin{vmatrix} -0.025649 & -1.09 & -0.0079639 & -0.56157 \\ -0.014239 & -1.297 & 1.0024 & 0 \\ -0.064287 & -5.5746 & -0.12427 & 0 \\ 0 & 0 & 1 & 0 \end{vmatrix}$$

Level 3 A matrix:

$$a = \begin{vmatrix} -0.025929 & -1.1138 & 0.01609 & -0.56157 \\ -0.013969 & -1.2740 & 1.0102 & 0 \\ -0.036679 & -3.2329 & 0.67529 & 0 \\ 0 & 0 & 1 & 0 \end{vmatrix}$$

B, C, and D matrices common to all Calspan models (Level 1, 2, and 3):

$$b = \begin{vmatrix} 0.1397 \\ -0.13469 \\ -13.745 \\ 0 \end{vmatrix} \qquad c = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \qquad d = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$$

Appendix B – Pitch Control Models

Add equilibrium states to
get desired control position

Uequil
Constant1

Other control positions
held constant at equilibrium values

x0=Xequil

Xequil

de equil

OUTPUT

AIRCRAFT
MODEL

1
elevator
stick force

$\dfrac{60}{(s+60)}$

AFTI

F-16 Pitch Stick
Dead Zone

F-16 Pitch Stick
Command
Gradient

$\dfrac{8.3}{(s+8.3)}$

AFTI 2

1.8

Modified
AFTI gain

+/- 25 deg
actuator limit
(F-16)

+/- 60 deg/sec
actuator rate
limit (F-16)

.0495 sec
transport delay
(F-16)

MATLAB
Function

Nonlinear
F-16

$\dfrac{1}{s}$

Integrator

deltas

$\dfrac{.27(s+18.5)}{(s+50)}$

Modified AFTI

$\dfrac{250}{(s+250)}$

AFTI 3

pitch rate (q)

Desktop Simulator Pitch Control Model

B1

40

(10.85, 30.25)

30

20

10

0

Output force

(0.44, 4.25)

(-0.44, -4.25)

-10

-20

-30

(-10.85, -30.25)

-40

-10.85   -0.44   0.44   10.85

Input force

Desktop Simulator -
Pitch Stick Command Gradient

B2

Appendix C – Simulation Environments
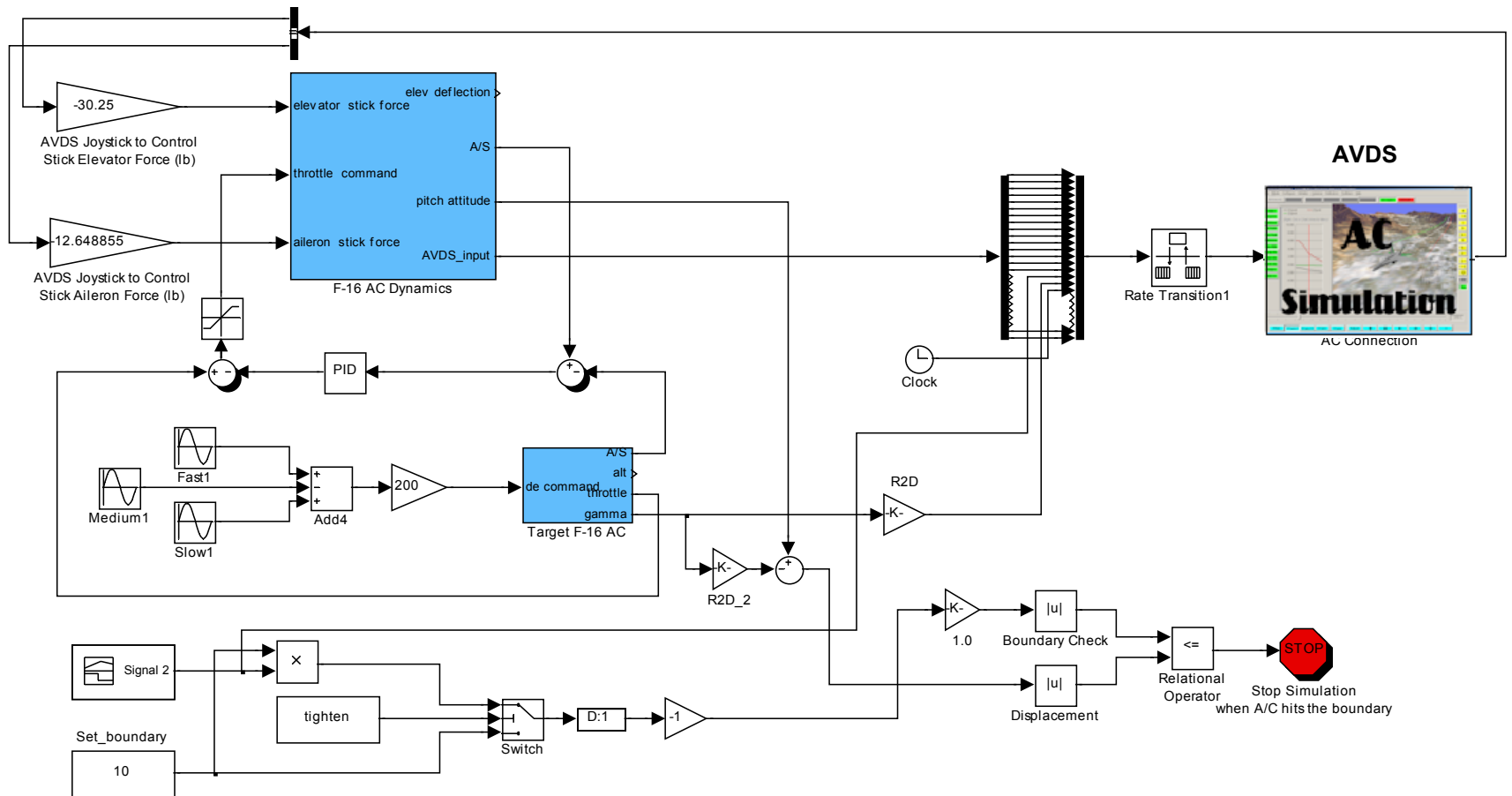
Desktop Simulator Simulink Environment

C1

Appendix D – Recorded Parameter Lists

Desktop Simulation:

airspeed	(KCAS)
pitch attitude (θ)	(degrees)
flight path angle (γ)	(degrees)
rate of change of flight path angle ($\dot{\gamma}$)	(degrees/sec)
stick force	(lbs)
elevator displacement	(degrees)
load factor	(g)
target altitude	(feet)
target airspeed	(KCAS)
target flight path angle (γ_{tgt})	(gamma)
boundary value	(degrees)
flight path track error (γ_{error})	(degrees)
rate of change of flight path track error ($\dot{\gamma}_{error}$)	(degrees/sec)

Infinity Cube Simulation:

flight path angle (γ)	(degrees)
rate of change of flight path angle ($\dot{\gamma}$)	(degrees/sec)
stick force	(lbs)
elevator command (TEU)	(degrees)
elevator displacement (TEU)	(degrees)
elevator rate	(degrees/sec)
load factor	(g)
target flight path angle (γ_{tgt})	(gamma)
boundary value	(degrees)
flight path track error (γ_{error})	(degrees)
rate of change of flight path track error ($\dot{\gamma}_{error}$)	(degrees/sec)

LAMARS:

time	(sec)
pitch stick force	(lbs)
aileron stick force	(lbs)
elevator command (TEU)	(degrees)
elevator position (TEU)	(degrees)
elevator rate	(degrees/sec)
flight path angle (γ)	(degrees)
rate of change of flight path angle ($\dot{\gamma}$)	(degrees/sec)
target flight path angle track error (γ_{error})	(degrees)
rate of change of flight path track error ($\dot{\gamma}_{error}$)	(degrees/sec)
target flight path angle (γ_{tgt})	(degrees)
boundary	(degrees)
acceleration in z-axis	(g)
pitch (θ)	(degrees)
pitch rate (q)	(deg/sec)
true airspeed	(KTAS)
indicated airspeed	(KIAS)
barometric pressure altitude	(feet)

VISTA:

elapsed time	(sec)
boundary	(degrees)
flight path angle (γ)	(degrees)
target flight path angle (γ_{tgt})	(degrees)
flight path angle track error (γ_{error})	(degrees)
target HUD display elevation	(degrees)
calibrated air speed	(KCAS)
pressure alt	(feet)
true airspeed	(KTAS)
true heading	(degrees)
configuration number	(#)
flight path marker elevation (in HUD)	(degrees)
forward pitch stick command	(lbs)
forward roll stick command	(lbs)
forward rudder pedal command	(lbs)
mach number	(M)
acceleration in y-axis	(g)
acceleration in z-axis	(g)
rate of change of velocity in x-axis	(ft/sec^2)
angle of attack (α)	(degrees)
bank angle (ϕ)	(degrees)
roll rate (p)	(deg/sec)
rate of change of roll rate ($\dot{p}$)	(deg/sec^2)

pitch (θ)	(degrees)
pitch rate (q)	(deg/sec)
rate of change of pitch rate ($\dot{q}$)	(deg/sec^2)
sideslip (β)	(degrees)
yaw rate (r)	(deg/sec)
rate of change of yaw rate ($\dot{r}$)	(deg/sec^2)
record number	(#)
left flaperon position	(degrees)
left horizontal tail position	(degrees)
left leading edge flap position	(degrees)
right flaperon position	(degrees)
right horizontal tail position	(degrees)
right leading edge flap position	(degrees)
rudder position	(degrees)

Appendix E – Test Subject Data

AFIT Desktop simulation and Infinity Cube Test Subjects:

Fighter Pilots		Heavy Pilots		Non-Pilots	
Test Subject	Flight Hours	Test Subject	Flight Hours	Test Subject	Flight Hours
Pilot 1	2100	Pilot 10	2700	Pilot 16	300
Pilot 2	1150	Pilot 11	1800	Pilot 17	0
Pilot 3	2300	Pilot 12	3800	Pilot 18	0
Pilot 4	2000	Pilot 13	2000	Pilot 19	0
Pilot 5	1600	Pilot 14	1500	Pilot 20	200
Pilot 6	1100	Pilot 15	2100	Pilot 21	0
Pilot 7	2500			Pilot 22	8
Pilot 8	1000			Pilot 23	0
Pilot 9	1900			Pilot 24	20
				Pilot 25	0
				Pilot 26	0
				Pilot 27	0

TPS Desktop simulation, LAMARS, and VISTA Test Subjects:

Test Pilots		Non-Pilots	
Test Subject	Flight Hours	Test Subject	Flight Hours
Test Pilot 1	1300	Test Pilot 5	100
Test Pilot 2	3000	Test Pilot 6	200
Test Pilot 3	2000	Test Pilot 7	0
Test Pilot 4	4000		

Cooper-Harper Scale

Excellent Highly Desirable	• Pilot compensation not a factor for desired performance	1
Good Negligible Deficiencies	• Pilot compensation not a factor for desired performance	2
Fair – Some Mildly Unpleasant Deficiencies	• Minimal pilot compensation required for desired performance	3
Minor but Annoying Deficiencies	• Desired performance requires moderate pilot compensation	4
Moderately Objectionable Deficiencies	• Adequate performance requires considerable pilot compensation	5
Very Objectionable but Tolerable Deficiencies	• Adequate performance requires extensive pilot compensation	6
Major Deficiencies	• Adequate performance not attainable with max tolerable pilot compensation. Controllability not in question.	7
Major Deficiencies	• Considerable pilot compensation required for control	8
Major Deficiencies	• Intense pilot compensation required to retain control	9
Major Deficiencies	• Control will be lost during some portion of required operation	10

Yes

Satisfactory w/o Improvement? — No

Yes

Adequate Performance Attained with tolerable Pilot workload? — No

Yes

Controllable? — No

Pilot Decisions

PIO Rating Scale

Description	Rating
No tendency for pilot to induce undesirable motions	1
Undesirable motions tend 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
Ocillations 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 releasing or freezing stick	5
Disturbance or normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick	6

Do Undesirable Motions Tend to Occur?
- no
- yes → **Is Task Performance Compromised?**
  - no
  - yes
- no → **Causes Oscillations?**
  - yes → **Divergent?**
    - no
    - yes
  - no → **Pilot Initiates Abrupt Maneuvers or Tight Control**
    - no → **Causes Divergent Oscillation?**
      - yes
      - no → **Pilot Attempts to Enter Control Loop**

Appendix G – Statistical Analysis of VISTA Data

	Level1	Level2
Pilot 1	427	338
Pilot 2	438	367
Pilot 3	488	427
Pilot 4	460	457
Pilot 5	517	459
Pilot 6	427	220
Pilot 7	499	339

	Level1	Level3
Pilot 1	427	101
Pilot 2	438	308
Pilot 3	488	310
Pilot 4	460	129
Pilot 5	517	
Pilot 6	427	11
Pilot 7	499	369

	Level2	Level3
Pilot 1	338	101
Pilot 2	367	308
Pilot 3	427	310
Pilot 4	457	129
Pilot 5	459	
Pilot 6	220	11
Pilot 7	339	369

t-Test: Two-Sample Assuming Equal Variances

		Level1	Level2
	Mean	465.171	372.516
	Variance	1342.06	7210.27
	Observations	7	7
	Pooled Variance	4276.16	
	Hypothesized Mean Difference	0	
	df	12	
	t Stat	2.65079	
99.99	P(T<=t) one-tail	0.01057	
	t Critical one-tail	1.78229	
	P(T<=t) two-tail	0.02115	
	t Critical two-tail	2.17881	

t-Test: Two-Sample Assuming Equal Variances

		Level1	Level3
	Mean	465.171	204.782
	Variance	1342.06	20536.3
	Observations	7	6
	Pooled Variance	10066.7	
	Hypothesized Mean Difference	0	
	df	11	
	t Stat	4.6648	
100.00	P(T<=t) one-tail	0.00034	
	t Critical one-tail	1.79588	
	P(T<=t) two-tail	0.00069	
	t Critical two-tail	2.20099	

t-Test: Two-Sample Assuming Equal Variances

		Level2	Level3
	Mean	372.516	204.782
	Variance	7210.27	20536.3
	Observations	7	6
	Pooled Variance	13267.6	
	Hypothesized Mean Difference	0	
	df	11	
	t Stat	2.61746	
99.99	P(T<=t) one-tail	0.01197	
	t Critical one-tail	1.79588	
	P(T<=t) two-tail	0.02394	
	t Critical two-tail	2.20099	

Boundary Impact Time Statistical Analysis

	Level1	Level2
Pilot 1	4	5
Pilot 2	4	6
Pilot 3	3	4
Pilot 4	4	6
Pilot 5	4	6
Pilot 6	4	5
Pilot 7	5	9

	Level1	Level3
Pilot 1	4	9
Pilot 2	4	8
Pilot 3	3	9
Pilot 4	4	10
Pilot 5	4	9
Pilot 6	4	8
Pilot 7	5	10

	Level2	Level3
Pilot 1	5	9
Pilot 2	6	8
Pilot 3	4	9
Pilot 4	6	10
Pilot 5	6	9
Pilot 6	5	8
Pilot 7	9	10

t-Test: Two-Sample Assuming Equal Variances

	Level1	Level2
Mean	4	5.85714
Variance	0.33333	2.47619
Observations	7	7
Pooled Variance	1.40476	
Hypothesized Mean Difference	0	
df	12	
t Stat	-2.9314	
P(T<=t) one-tail	0.00629	
t Critical one-tail	1.78229	
P(T<=t) two-tail	0.01257	
t Critical two-tail	2.17881	

100.0

t-Test: Two-Sample Assuming Equal Variances

	Level1	Level3
Mean	4	9
Variance	0.33333	0.66667
Observations	7	7
Pooled Variance	0.5	
Hypothesized Mean Difference	0	
df	12	
t Stat	-13.229	
P(T<=t) one-tail	8.1E-09	
t Critical one-tail	1.78229	
P(T<=t) two-tail	1.6E-08	
t Critical two-tail	2.17881	

100.0

t-Test: Two-Sample Assuming Equal Variances

	Level2	Level3
Mean	5.85714	9
Variance	2.47619	0.66667
Observations	7	7
Pooled Variance	1.57143	
Hypothesized Mean Difference	0	
df	12	
t Stat	-4.6904	
P(T<=t) one-tail	0.00026	
t Critical one-tail	1.78229	
P(T<=t) two-tail	0.00052	
t Critical two-tail	2.17881	

100.0

Cooper-Harper Rating Statistical Analysis

G2

REPORT DOCUMENTATION PAGE		Form Approved OMB No. 074-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of the collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to an penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) 15-03-2007	2. REPORT TYPE Master's Thesis	3. DATES COVERED (From – To) July 2005 – March 2007

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
AN ANALYSIS OF AIRCRAFT HANDLING QUALITY DATA OBTAINED FROM BOUNDARY AVOIDANCE TRACKING FLIGHT TEST TECHNIQUES	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Dotter, Jason D., Captain, USAF	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865	8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/GAE/ENY/07-M24

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) USAF Test Pilot School ATTN: Mr. William Gray III 220 S. Wolfe Ave. Edwards AFB, CA 93523	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

Cooper-Harper ratings (CHRs) have been used to describe and compare aircraft handling qualities for over 40 years, but are by their very nature, subjective. The subjective and sometimes ambiguous results obtained from qualitative handling quality ratings are inconsistent with the rest of the flight test process, where quantifiable results followed by statistical analysis are the norm. This thesis presents a method for obtaining accurate and consistent flight test data that quantifies the handling qualities of a specific aircraft. The method is demonstrated using both pilot-in-the-loop simulations and flight tests with the NF-16D Variable-Stability In-Flight Simulator Test Aircraft (VISTA).

Boundary Avoidance Tracking (BAT), introduced in 2004 by Mr. William Gray III, a test pilot at the US Air Force Test Pilot School (TPS), is used here to provide a novel approach for forcing an increase in pilot workload and tracking performance in order to assess an aircrafts handling qualities. By utilizing BAT with shrinking desired performance boundaries on a point tracking task, pilots are forced to their maximum performance (i.e. minimum error) on the tracking task. This maximum achievable BAT performance can then be used as a measure of the aircraft's handling "quality".

The BAT method of assessing an aircraft's handling quality was used with both pilot-in-the-loop simulations and flight tests to obtain quantitative tracking performance data. This data was compared and correlated to CHR data. In order to collect the data, a 6-degrees-of-freedom (DOF) pilot-in-the-loop F-16 simulator was developed and implemented on a desktop computer. Twenty seven test subjects flew the BAT profile on the desktop simulator; these subjects also flew the same profile in AFRL/VA's Infinity Cube simulator. Data from these two simulations were used to develop a flight test plan for implementation on AFRL/VA's Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) and on TPS's NF-16D VISTA. Seven test subjects then flew a modified BAT profile on the desktop simulator, the LAMARS, and 13.7 flight hours in the VISTA. Data collected included tracking and boundary information, as well as CHRs for each of four different pitch control models. Results supporting the existence of boundary awareness were found, as well as a correlation between total bounded simulation run time and Cooper-Harper rating.

15. SUBJECT TERMS
Boundary avoidance tracking, BAT, flight test, Test Pilot School, TPS, Air Force Institute of Technology, AFIT, BAT DART, Cooper-Harper ratings, CHR, NF-16D, VISTA, LAMARS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Paul A. Blue, Maj, USAF
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	103	19b. TELEPHONE NUMBER (Include area code) (937) 255-6565, ext 4714 (paul.blue@afit.edu)
U	U	U			

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18