12-2006

Retrofit Reconfigurable Flight Control System and the F/A-18C

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Recommended Citation

Doyle, Matthew E., "Retrofit Reconfigurable Flight Control System and the F/A-18C. " Master's Thesis, University of Tennessee, 2006.
https://trace.tennessee.edu/utk_gradthes/1543

To the Graduate Council:

I am submitting herewith a thesis written by Matthew E. Doyle entitled "Retrofit Reconfigurable Flight Control System and the F/A-18C." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Robert B. Richards, Major Professor

We have read this thesis and recommend its acceptance:

S. Corda, A. Pujol, Jr.

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Acceptance for the Council:

Linda Painter
Interim Dean of Graduate Studies

(Original signatures are on file with official student records.)

RETROFIT RECONFIGURABLE FLIGHT CONTROL SYSTEM AND THE F/A-18C

A Thesis
Presented for the
Master of Science
Degree
University of Tennessee, Knoxville

Matthew E. Doyle
December 2006

DEDICATION

This thesis is dedicated to my wife, Kara, for her never-ending support and encouragement through all of our endeavors.

ACKNOWLEDGEMENTS

I wish to thank all of those who helped me write this thesis in order to complete my Master of Science degree in Aviation Systems. In particular I would like to thank Dr. Bob Richards for all of his time and effort. I would also like to thank Debbie Syders and Betsy Harbin for all their help while participating in the Aviation Systems Program.

In addition, I would like to thank the rest of the Retrofit Reconfigurable Control Law test team. Dr. Tony Page, Dean Meloney and Jeff Monaco were instrumental in the success of this program. Jacque Romano's knowledge of the F/A-18 flight control system and the fleet support flight control computers is second to none. In addition, Jake Piercy's contribution as test conductor for the simulation and flight testing allowed for smooth and efficient execution.

ABSTRACT

The United States Navy has completed the initial flight test of a Reconfigurable Control Law System (RCLAWS) on the F/A-18C. The purpose of reconfigurable control is to allow for the safe operation of an aircraft that has experienced a sudden change in aircraft dynamics resulting from aircraft damage or flight control effector damage. The RCLAWS utilized during this flight test are novel in that they are designed to augment the production flight control system instead of replacing it. In order to reduce verification and certification requirements, this retrofit reconfigurable methodology supplements pilot commands to compensate for undesirable aircraft dynamics instead of manipulating control surfaces directly. Through comparison of the aircraft's actual response to model data of the aircraft's desired response, the RCLAWS determines what commands need to be applied to produce the desired aircraft response.

Flight test data have been collected to determine the viability of the in-line retrofit reconfigurable control method. Although flight data indicate a modest improvement within the limited flight test envelope, simulation analysis has indicated that the retrofit RCLAWS provide substantial improvements for more aggressive failures. Simulation shows RCLAWS has proven to reduce the aircrew workload in a recent catastrophic failure present in the F/A-18 community and provide predictable aircraft dynamics for a safe recovery.

PREFACE

The following thesis is a highly revised version of a paper by the name of "Research Flight Test of a Retrofit Reconfigurable Flight Control System" presented at the 37th Annual Society of Flight Test Engineers symposium in 2006 by Dean Meloney, Dr. Anthony Page and Matthew Doyle:

Meloney, D., Page, A., and Doyle, M., "Research Flight Test of a Retrofit Reconfigurable Flight Control System," SFTE, 37th Annual International Symposium, Reno, NV, September 2006.

My primary contributions to this paper include (1) simulation and in-flight data collection, (2) post-flight analysis of pilot handling quality ratings, (3) aircraft technical and historical expertise, (4) flight test maneuver selection and refinement, (5) collecting various contributions into a single document, and (6) assisting in writing and editing of the simulation and flight test results portions.

Information contained in this thesis is unclassified and was obtained through the author's participation in a Department of Defense F/A-18 flight test project and its associated reports and manuals. Any conclusions, recommendations and opinions presented within this document are the opinion of the author and should not be interpreted as that of the Department of Defense, the United States Navy, VX-23 or the University of Tennessee Space Institute.

Public Release, 265SPR-133.06. DoD Directive 5230.24 – DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

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LIST OF ACRONYMS

AAW	Active Aeroelastic Wing
ACTIVE	Advanced Control Technology for Integrated Vehicles
ADC	Air Data Computer
ADS	Autopilot Disconnect Switch (paddle switch)
AOA	Angle of Attack
ASM	Actuator Signal Management
BAI	Barron Associates, Incorporate
BIT	Built In Test
BLIN	BIT Logic Inspection (Fault Code)
CAS	Control Augmentation System
CASTLE	Controls Analysis and Simulation Test Loop Environment
CCDL	Cross Check Data Link
CR	Cruise Configuration
DAF	Dial-A-Function
DDAS	Digital Data Acquisition System
DDI	Digital Display Indicator
DEL	Direct Electrical Link
DFBW	Digital Fly By Wire
DMOT	Detailed Method of Test
DPRAM	Dual-Port Random Access Memory
FCC	Flight Control Computer
FCS	Flight Control System
FSFCC	Fleet Support Flight Control Computer
FQ	Flying Qualities
g	Gravitational Acceleration
HARV	High Angle of Attack Research Vehicle
HIDEC	Highly Integrated Digital Electronic Control
HILS	Hardware in the Loop Simulation
Hp	Pressure Altitude
HQR	Handling Quality Ratings
HUD	Heads Up Display
HYD	Hydraulic
IBIT	Initiated Built In Test
IFCS	Intelligent Flight Control System
INS	Inertial Navigation System
INS ATT	Inertial Navigation System Attitude
IRIG	Inter-Range Instrumentation Group
ISM	Input Signal Management
ITS	Integrated Test Set
KCAS	Knots Calibrated Airspeed
LAU	Launcher (missile)
LED	Leading Edge Down

LEF	Leading Edge Flap
LEU	Leading Edge Up
LMCS	Lockheed Martin Control Systems
MC	Mission Computer
MECH	Mechanical Link
MFS	Manned Flight Simulator
MHz	Megahertz
ModSDF	Modular Six Degree of Freedom
MUX	Multiplex
NASA	National Aeronautics and Space Administration
NATOPS	Naval Aviation Training and Operating Procedures Standardization
NAVAIR	Naval Air Systems Command
NROTC	Naval Reserve Officer Training Corps
NRT	Non-Real Time
NWS	Nose Wheel Steering
Nz	Load Factor
OFP	Operation Flight Program
PA	Powered Approach Configuration
PBIT	Periodic Built In Test
PCM	Pulse Code Modulation
PIO	Pilot Induced Oscillation
PSF	Pounds per Square Foot (dynamic pressure)
PSFCC	Production Support Flight Control Computers
RAM	Random Access Memory
RCLAWS	Reconfigurable Control Laws
RLS	Reservoir Level Sensing
RSRI	Rolling Surface to Rudder Interconnect
RTPS	Real-time Telemetry Processing System
SBIR	Small Business Innovative Research
SDC	Self-Designing Controller
SEC	Source Error Correction
SRFCS	Self Repairing Flight Control System
SSE	Simulated Single Engine
TED	Trailing Edge Down
TEF	Trailing Edge Flap
TEU	Trailing Edge Up
TISM	Test Instrumentation Support Module
UA	Up/Auto (Flaps and Gear up)
USS	United States Ship
v10.1	Version 10.1 (Flight Control OFP)
v10.5.1	Version 10.5.1 (Flight Control OFP)
v10.7	Version 10.7 (Flight Control OFP)
VISTA	Variable-Stability In-Flight Simulator Test Aircraft
VFA	Strike Fighter Squadron

Chapter 1: Introduction

BACKGROUND

During the early days of flight, aircrew controlled aircraft motion via cables and/or rods that connected the flight control surfaces to the pilot controls. With the advent of the jet era, the control surfaces required more force to displace due to higher dynamic loads and larger control surfaces. These changes necessitated the advent of the hydraulic-mechanical flight control system. These systems utilized the mechanical advantage of hydraulics to drive the actuators of the control surfaces. The actuators, however, were still physically connected to the pilot controls, usually via push/pull rods or cables.

When the electronics era ensued, engineers were determined to develop a method to replace the heavy, unreliable cables and rods with an electronic flight control system. The first Digital Fly By Wire (DFBW) aircraft was flown on May 25, 1972. The test bed for this ground breaking technology was a National Aeronautic and Space Administration (NASA) F-8 Crusader that had been extensively modified with an electronic flight control system controlled via a digital computer (NASA TN-7843, 1974). Now, instead of cables and rods, the flight control actuators were only connected to the pilot control inputs via wires and a flight control computer.

Most modern military high performance aircraft from the F-16 Falcon and the F/A-18 Hornet to the F/A-22 Raptor and even many commercial aircraft have utilized this fly by wire technology. Fly by wire technology has allowed additional innovation in the field of flight controls. In earlier, conventionally controlled aircraft, when a flight control surface failed due to actuator failure or aircraft damage, the aircrew had to either quickly learn to fly the new, unknown flight control system or attempt to egress the aircraft prior to crashing. With fly by wire technology and an understanding of control system modeling and response, the aircrew now has other options.

Reconfigurable flight control is one such option upon which aircrew can now rely upon. Reconfigurable flight control techniques endeavor to eliminate undesired motion (e.g., axis coupling) that can result from aircraft damage or flight control failure. Failures have occurred that have left aircraft in a flyable state. However, pilots could not always control and safely land the aircraft as a result of insufficient time to learn the vastly different dynamics of the new system. The benefits of flight control reconfiguration to aid the pilot in these situations have been well established (Page, et al, 2006 and Tomayko, 2003). Due to the considerable verification and validation efforts required to certify flight control software, however, the techniques have been slow to transition to production platforms. To help address the certification issue, some researchers have started examining retrofit reconfigurable control methods that are designed to upgrade, rather than replace, the existing control laws of current production aircraft.

The retrofit control architecture recently tested at Naval Air Station (NAS) Patuxent River is one such system. Through a Small Business Innovative Research (SBIR) contract, Barron Associates, Incorporated (BAI) developed the control algorithms and supported the United States Navy during all phases of testing throughout this program. This architecture is unique because it affects reconfiguration by modifying the pilot control stick and rudder commands instead of control surfaces directly. By comparing sensor data of the aircraft’s actual response to model data of the aircraft’s nominal response, the Reconfigurable Flight Control Laws (RCLAWS) determine what additions need to be made to the pilot's commands to produce the desired aircraft response.

RECONFIGURABLE FLIGHT CONTROL AND THE F/A-18C

A large part of the design philosophy behind most combat aircraft, including the F/A-18C, is survivability. Unfortunately, reconfigurable flight control was in its infancy during the development and testing of the F/A-18. Even without reconfigurable control as defined today, the developers were able to provide aircrew several means to control the aircraft during flight control or sub-system failures.

The F/A-18C flight control system (FCS) is a fly by wire system that contains multiple back-up modes to the primary control augmentation system (CAS) such as direct electrical link (DEL) and mechanical link (MECH). DEL is a back-up mode that contains both a digital and analog operating mode for aileron and rudder control. DEL allows aircraft control in all three axes in the event of a CAS failure. If the DEL mode fails, the FCS secondary back-up mode is MECH, which provides a direct mechanical linkage to the horizontal stabilators for pitch and roll control. When operating in any of these degraded modes, the aircraft is much more susceptible to pilot induced oscillations (PIO), sideslip excursions and large pitch transients. The author's experience with these modes has been limited to the simulator. Even though flying qualities are severely degraded in some cases, the control of the aircraft was not in question and a safe, simulated landing was made each time as long as the aircraft was flown in the recommended envelope.

The F/A-18C also has failure modes for the leading edge flaps (LEFs) and trailing edge flaps (TEFs). However, unlike DEL or MECH modes which provide roll, pitch and yaw control during CAS failures, when a failure exists that affects automatic flap scheduling, they are commanded to a known flyable configuration. For example, with a single LEF failure with the flap in the AUTO position (up), the LEF and TEF symmetric commands will freeze, however the differential LEF commands will continue and allow the operational LEF to schedule as appropriate. In flaps HALF or FULL, the failed LEF will freeze, while the remaining LEF and TEFs will schedule normally. In the event of a catastrophic failure in the hydraulic drive unit shaft, the LEFs are designed to fail to approximately 5 degrees leading edge up (LEU) by use of a specifically designed transmission and brake. Testing has shown that all of these LEF failure cases are controllable and a safe landing can be made. However, events in the past several years have shown that in some cases the transmission fails to stop the LEF at 5 degrees LEU and the results have been catastrophic. More discussion will be devoted to this topic during the real world application section, chapter 8. TEF failure modes are much simpler and result in both the TEFs being commanded to zero degrees. Although this results in higher than normal approach speeds and degraded approach characteristics in pitch and roll, this configuration is considered controllable.

In addition to the FCS having multiple back-up modes, the hydraulic (HYD) system that drives the control surfaces in their normal operating mode is also highly redundant. The F/A-18C has two separate HYD systems that drive the flight control surfaces. Every flight control surface with the exception of the speed brake is backed up on both HYD systems. In addition, each HYD system, denoted HYD 1 and HYD 2, is split into two circuits denoted A and B, i.e., HYD 1A, HYD 1B, HYD 2A and HYD 2B. The F/A-18C HYD system incorporates further redundancy in the form of a reservoir level sensing (RLS) system. The RLS system attempts to prevent excessive loss in hydraulic fluid and thus actuator functionality by attempting to isolate the leak in a single circuit. For example, if there is a leak in the right LEF actuator that is normally driven by the HYD 2A system, the RLS system will secure the A circuit at approximately 60% reservoir capacity, but will allow HYD 2B to continue to function. If this did not secure the loss of fluid (which it should in the example of the right LEF), when the reservoir reaches 32%, the A circuit will open and the B circuit will close in an attempt to isolate the leak. At 4%, both circuits come back on line and all fluid will be lost in that system. With the combination of the two separate HYD systems, the individual circuits in each system and the RLS system, the F/A-18 is flyable with the vast majority of hydraulic system emergences as shown in Figure 1. The author's experience during hydraulic malfunctions, both in flight and in simulation, resulted in degraded handling qualities due to the sometimes non-symmetric flight control surface deflections and the resulting coupling in the other axes.

When the author was initially approached with this project, his first response was that the F/A-18 already had multiple back-up modes and redundancy built into the basic flight controls and airframe systems, therefore it appeared to be unnecessary to test reconfigurable flight control on an F/A-18. The author certainly did not expect to discover vastly improved handling qualities. Fortunately, after further study and completion of multiple simulator and flight tests, the author realized that his initial opinion that reconfigurable flight control was inapplicable to the F/A-18C and other highly redundant fly by wire aircraft was absolutely incorrect. This paper will discuss the methods to safely and efficiently test a new in-line retrofit module. In addition, it will discuss the results and the added benefits of reconfigurable flight control on extremely redundant aircraft such as the F/A-18C, including a real world application.

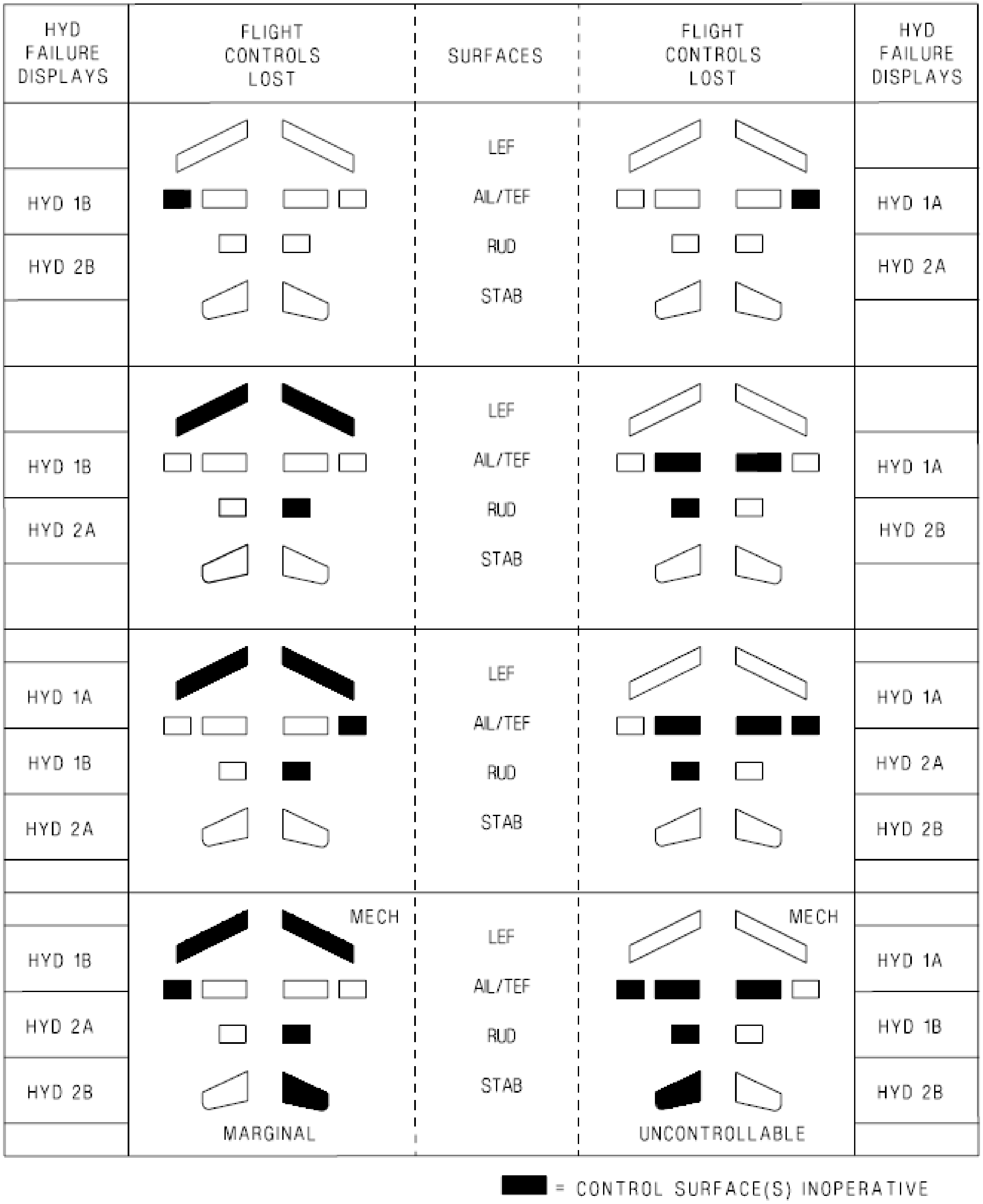

Figure 1: F/A-18C Hydraulic Malfunction Reference Chart

Chapter 2: Background of Retrofit Reconfigurable Flight Control Systems

OVERVIEW OF RECONFIGURABLE FLIGHT CONTROL SYSTEMS

In December 1989, NASA Ames Research Center performed the first demonstration of real time reconfiguration on a high performance fighter aircraft (Stewart and Shuck, 1990 and Tomayko, 2003). These flights were flown on the NASA F-15 Highly Integrated Digital Electronic Control (HIDEC) Flight Research aircraft. This demonstration utilized the inherent fault detection capabilities built into modern fly by wire aircraft and took advantage of the excess control power and surface displacements provided by the aircraft's large flight envelope to modify flight control surface displacement to preserve aircraft stability in the event of a failure. This demonstration was known as the Self-Repairing Flight Control System (SRFCS). This method, however, required knowledge of flight control system health to respond correctly to any malfunctions.

Reconfiguration via adaptive control presents an alternative to failure detection that does not require knowledge of the characteristics of the failures. In 1996, an F-16 flying a Self-Designing Controller (SDC) demonstrated an adaptive approach using a time-varying model of the aircraft dynamics in coordination with a model used to show the desired response to drive the control surfaces to achieve the desired aircraft state (Ward, et al, 1998). The most recent example of reconfigurable flight took place from 1996 to 1999 when NASA's F-15 Advanced Control Technology for Integrated Vehicles (ACTIVE) aircraft flew a follow on to the SFRCS project. This project was referred to as the Intelligent Flight Control System (IFCS) (Monaco et al, 2004 and Tomayko, 2003). This system was similar to the SDC demonstration in that prior knowledge of flight control failures was not required for reconfiguration. In addition, the F-15 ACTIVE aircraft incorporated a propulsion-controlled aircraft (PCA) system that allowed the aircraft to land without utilizing the flight control system (Burcham et al, 1999). Each reconfigurable flight control system introduced in these examples replaced the pre-existing flight control system, however, and typically required significant aircraft modifications.

Even with numerous demonstrations and advancing technologies, these systems have not been integrated into newer aircraft. Several reasons exist for the slow acceptance of reconfigurable flight controls, including the expense associated with integration into a known flight control system and the costs and time associated with the verification and validation of this new technology. Furthermore, aircraft designers have been unwilling to depart from the proven systems already installed in the aircraft (Page, et al, 2006). Several companies have attempted to mitigate the risks associated with reconfigurable flight control by introducing an add-on, retrofit module that modifies instead of replacing existing flight controls. This modification delivers the benefits of reconfigurable flight without the expense, time and risks associated with replacing entire flight control systems. There are currently two methods to implement a retrofit reconfigurable control system, parallel and in-line, which are described below.

PARALLEL RETROFIT RECONFIGURABLE FLIGHT CONTROL SYSTEMS

One method to implement a retrofit control law is possible through the modification of the output of the existing (production) control law, as shown in Figure 2. Because the retrofit control module can perform its calculations at the same time as the production control laws, this method is referred to as "parallel" implementation. In the standard implementation of the parallel system, instead of the retrofit control laws performing their calculations independent of, and simultaneous with, the existing control laws, the retrofit control module utilizes the output of the production control laws, as depicted by the dashed line in Figure 2. The control module then augments the output of the production controller to actuate the control surfaces (Monaco et al, 2004). The greatest advantage of the parallel architecture is that there are typically more aerodynamic surfaces (flight control effectors) that can be manipulated to achieve the desired aircraft response than aircrew controls (flight control inceptors). For example, including only aerodynamic control surfaces (without engine effects and excluding the speed brake), the F/A-18C has ten surfaces that can either individually or in combination affect the flight path of the aircraft and only a simple control stick and rudder pedals for aircrew inputs. Therefore, the parallel architecture has a greater capability to handle a wider variety of aircraft failures than similar architectures that do not directly control the aerodynamic control surfaces. For this reason, much of the reconfigurable flight control testing has concentrated on the parallel method. The Self-Designing Controller, flown in 1996 on the Variable-Stability In-Flight Simulator Test Aircraft (VISTA) F-16 operated by Calspan exemplifies a successful parallel retrofit control system (Ward, et al, 1998). During this experiment, the aircraft landed successfully with a simulated elevon failure.

In spite of these benefits, this method also has created complications in the verification and validation of these systems. The parallel architecture allows the retrofit control laws to overwrite the production control laws if necessary to maintain the desired state. Therefore, one must verify and validate both the production control laws and the retrofit control laws instead of only the production control laws

IN-LINE RETROFIT RECONFIGURABLE FLIGHT CONTROL SYSTEMS

Another method of implementation a retrofit control law is also possible through the modification of the pilot input prior to the existing control laws, as shown in Figure 3. This implementation of retrofit control laws requires that the retrofit control module perform its calculations prior to the existing control laws, hence this method is referred to as an "in-line" or "series" approach. From aircraft sensor data, the retrofit control module modifies the control inputs prior to the production control laws to achieve the desired aircraft system response. Thus, one major advantage of the in-line architecture is that the production control laws are still in control of the control surfaces. As a result, any safety features such as command limiting, structural filtering and safety logic are still in effect (Monaco et al, 2004).

The in-line method allows for slightly easier verification and validation as a retrofit system because production control laws still retain end control of the aircraft. Unfortunately, however, this implementation creates several deficiencies. As stated above for the parallel method, there are typically more control surfaces (effectors) than control inputs (inceptors). Therefore, the in-line method is less powerful because it has less capability to handle a range of aircraft failures than the parallel method. In essence,

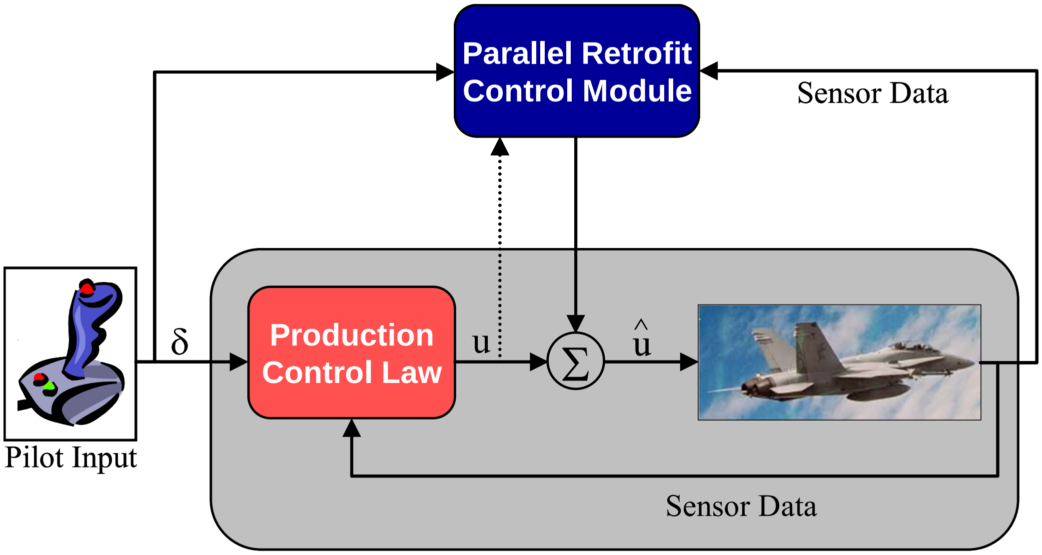

Figure 2: Parallel Retrofit Control Design

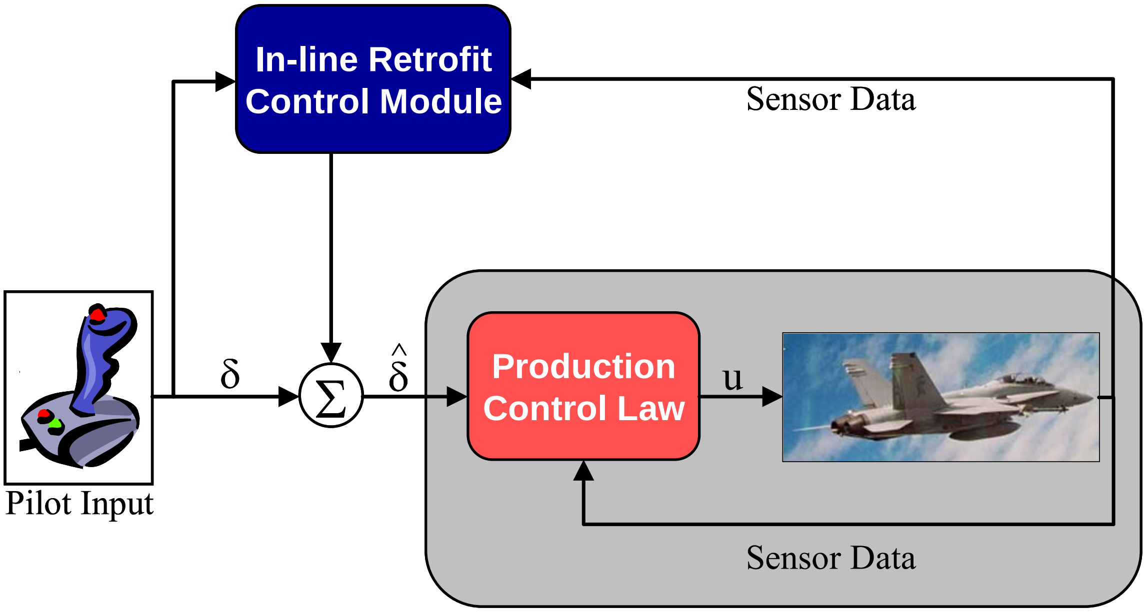

Figure 3: In-Line Retrofit Control Design

Source: Meloney, D. and Doyle, M., “Test Plan for F/A-18 Retrofit Reconfigurable Control System Flight Test,” SA-05-04-3266C, April 2005.

if the pilot cannot command the desired flight control surface response, then the in-line retrofit reconfigurable method can not accomplish it. The in-line method was utilized for the test flight program described in this paper.

Chapter 3: Description of Test Airplane and Test Equipment

F/A-18C DESCRIPTION

The F/A-18C airplane is a single-seat, high performance, twin engine, supersonic fighter and attack airplane manufactured by McDonnell Douglas Corporation (now Boeing, St. Louis), as shown in Figure 4. The airplane is characterized by moderately swept, variable camber mid-mounted wings, twin vertical stabilizers mounted forward of the horizontal stabilators (canted outboard 20 degrees), and wing leading edge extensions mounted on each side of the fuselage from the wing roots to just forward of the windscreen. The airplane is configured with full span leading edge flaps, inboard trailing edge flaps, and outboard ailerons on each wing. The flight control system consists of two digital flight control computers with two 701E processors that utilize a full authority control augmentation system to operate the hydraulically driven control surfaces. Pilot interface for the flight control system is through a conventional, center mounted control stick, rudder pedals and dual engine throttles on the left console. Spring cartridges in all axes are designed to provide the pilot control stick and rudder feel. The F/A-18C airplane is powered by two General Electric F404-GE-400 or -402 augmented turbofan engines.

FLEET SUPPORT FLIGHT CONTROL COMPUTERS

AIRCRAFT SYSTEM DESIGN

The Fleet Support Flight Control Computer (FSFCC) system, originally designated the Production Support Flight Control Computer (PSFCC), consists of a set of modified F/A-18A/B/C/D Flight Control Computers (FCCs) (Carter and Stephenson, 1999 and NAWCAD RTR, 1999). The modified computers contain an additional 1750A processor in each channel of each FCC. This arrangement allows engineers to flight test experimental flight control laws on the 1750A processor. A key safety feature of this arrangement is that the 701E processor is available at all times to resume control of the aircraft with a known, certified set of control laws. The FSFCC provides the United States Navy with the capability to flight test experimental flight control laws in a very cost efficient manner by reducing the upfront validation and verification requirements normally associated with flight critical software. In addition, they allow for increased flexibility to make rapid software changes without extensive regression testing. These modified FCCs replace standard FCCs and interface with the rest of the FCS components in the same manner as the standard system, as shown in Figure 5.

The FSFCCs are designed to automatically return control to the standard 701E processor based on aircraft envelope checks and flight control system health status. In addition to the automatic disengage capability, the pilot can also manually revert to the standard 701E processor via the Autopilot Disconnect Switch (ADS), more commonly known as the paddle switch, at any time. Features of the FSFCC system include:

a. Baseline Version 10.1 (v10.1) flight control laws always available to resume control of the aircraft.
b. Compatible with any fleet F/A-18A/B/C/D with Mission Computer (MC) dial-a-function (DAF) software.

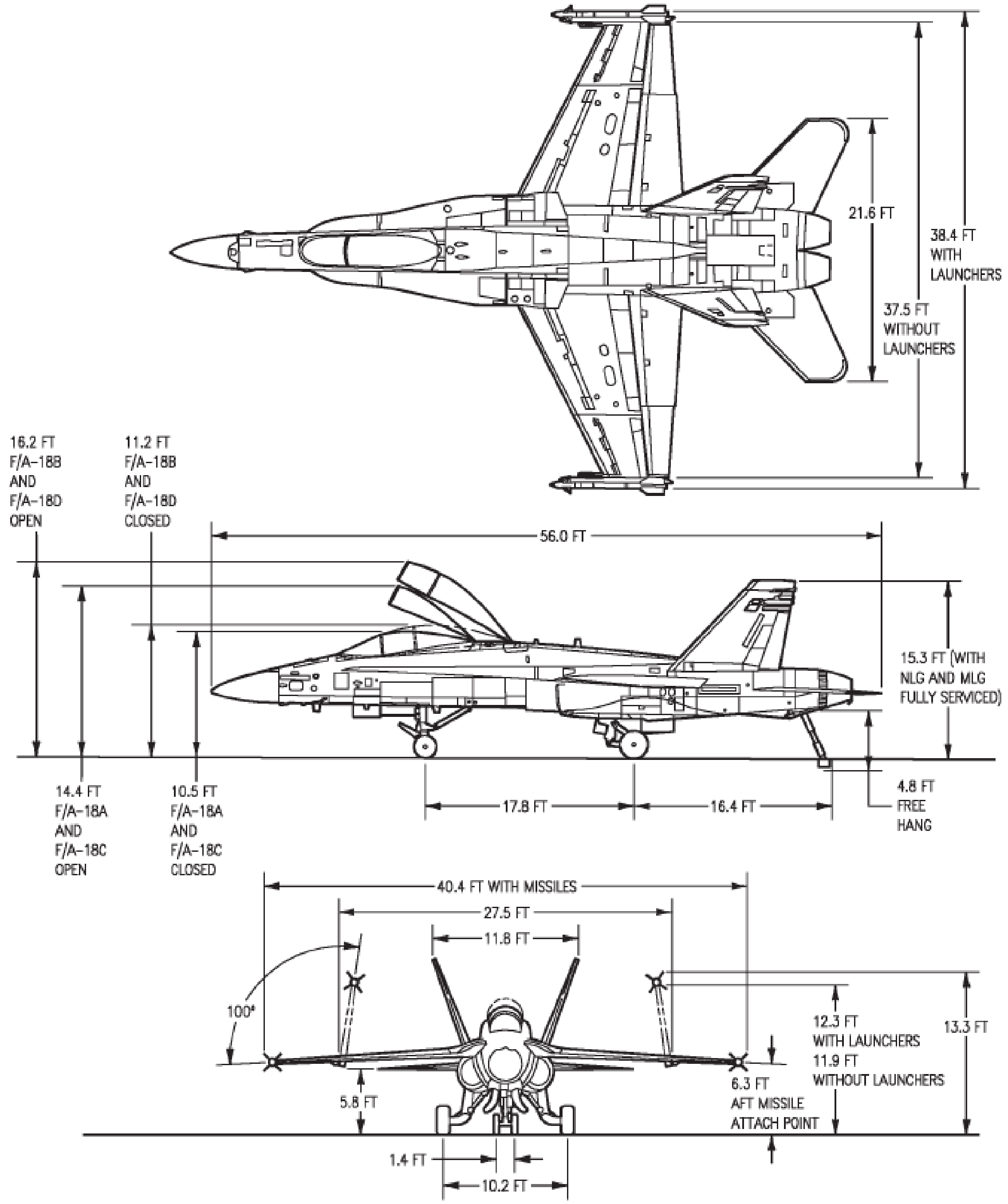

FIGURE 4: Three View of the F/A-18A/B/C/D Hornet

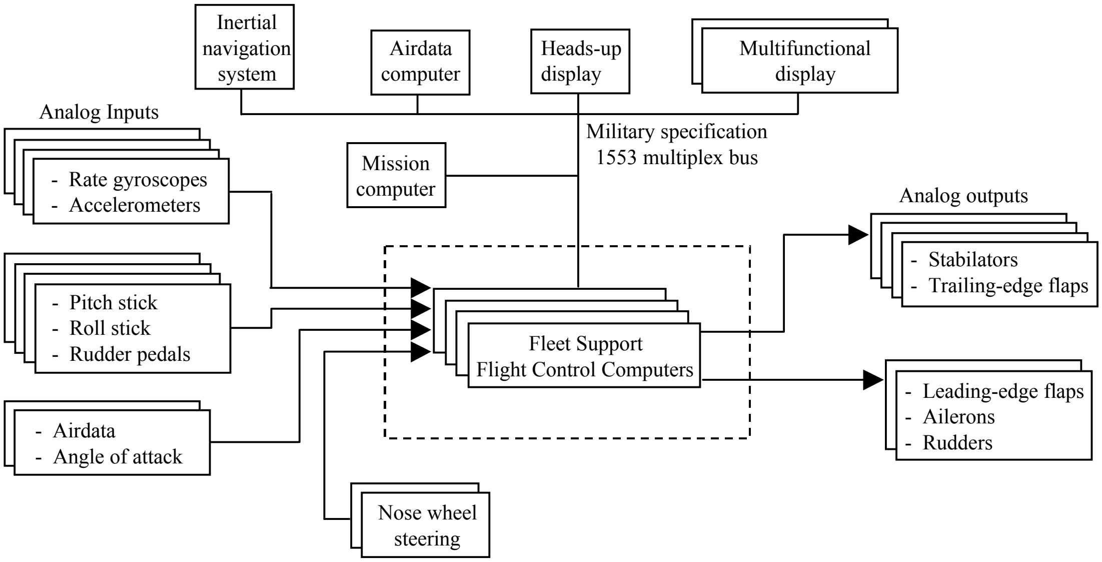

Figure 5: F/A-18C FCS Components

Source: Carter, J., and Stephenson, M., "Initial Flight Testing of the Production Support Flight Control Computer at NASA Dryden Flight Research Center, "NASA/TM-1999-206581, August 1999.

c. No special hardware or additional sensors, interfaces or buses required
d. Uses existing DAF for module activation and parameter modification.
e. Allows easily programmable test-specific disengage criteria as well as manual disengage capability through the existing paddle switch.
f. Supports rapid prototyping through Ada software development.

HARDWARE SYSTEM ARCHITECTURE

The FSFCC hardware architecture is the same as that used for NASA's F/A-18 High Angle-of-Attack Research Vehicle (HARV) program (Carter and Stephenson, 1999). Lockheed Martin Control Systems (LMCS) modified a standard F/A-18 701E FCC chipset to accommodate a 40 MHz PACE (Performance Semiconductor Corporation, Sunnyvale, CA) 1750A processor, an analog #6 board and an additional analog I/O #2 board. The analog #6 and analog I/O #2 boards are not currently used but are available for future growth. The 701E is always responsible for and retains complete and direct control of all actuators through the Actuator Signal Management (ASM) module. The 701E is always operating in parallel with the 1750A so it may resume control of the aircraft at any time. The system is identical to a standard F/A-18 FCC executing v10.1 control laws when 1750A processor is not engaged. When the 1750A is engaged, the 701E Operational Flight Program (OFP) uses a transient free switch to replace the 701E actuator commands with the 1750A commands.

SOFTWARE SYSTEM ARCHITECTURE

The 701E changes required for FSFCC affected the Executive, Input Signal Management (ISM), ASM, Data Management, Built-In-Test (BIT), and the inner loop control laws. A diagram of some of these components along with the interface to the 1750A is shown in Figure 6.

Changes were made to the 701E Executive to control 1750A arming and engaging, as well as modification to the cross-channel data link (CCDL) transfer tests. ISM was modified to execute CCDL transfer of FSFCC specific parameters. ASM was modified to allow 1750A commands to be used instead of the standard 701E commands. Fade logic was also added to ASM for mode transitions between 701E and 1750A commands providing transient suppression. Data Management was changed to provide additional FSFCC specific 1553 data. Periodic BIT (PBIT) was modified to test the Dual-Port Random Access Memory (DPRAM) and the 701E/1750A interface.

Communication between the 701E and 1750A is accomplished through the DPRAM interface. Selected sensor input data, cockpit discrete states, 701E commands, surface positions, and FCC internal variables are placed in DPRAM by the 701E for use by the 1750A. The 1750A writes its actuator commands, status and 1553 data into DPRAM for use by the 701E and transmittal on the 1553 data bus.

HARDWARE ARM/ENGAGE/DISENGAGE INTERFACES

Operation of FSFCC requires the use of several aircraft components. From the cockpit, the pilot utilizes the Digital Display Indicator (DDI) to load FSFCC table and row codes into the MC. The pilot can specify FSFCC table and row numbers by entering a four to

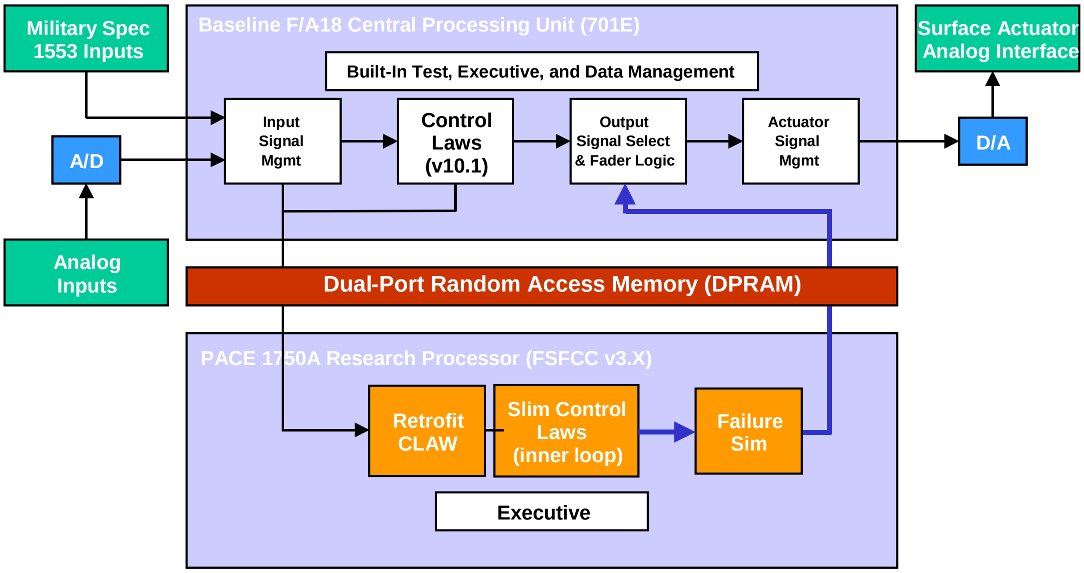

Figure 6: FSFCC 701E/1750A Software Architecture

Source: Meloney, D. and Doyle, M., “Test Plan for F/A-18 Retrofit Reconfigurable Control System Flight Test,” SA-05-04-3266C, April 2005.

six letter code using the DAF B, C, and D buttons on the Flight Test Flight Control System (FTFCS) display, shown in Figure 7. Each FSFCC table and row number combination designates either parameter modification or module activation. The 1750A processor can then be armed by pressing the DAF A button. The Nose Wheel Steering (NWS) button is used to engage the 1750A processor, and the pilot can confirm engagement on the DDI. The paddle switch is used by the pilot to manually disengage the FSFCC. If the system automatically disengages, the Master Caution light is illuminated, an FCS caution is displayed on the DDI, and an audible tone is heard in the pilot's headset. The MC and the FSFCC process the pilot's DDI inputs and feeds them to the 1750A processor via the 1553 bus and the DPRAM.

COMMAND FADING

Command fading is accomplished using transient free switch logic from the standard F/A-18A/B/C/D control laws. A linear transition between the 701E to the 1750A command occurs over a preset fade rate. A representation of the command fading that occurs following disengage is presented in Figure 8. The same command fading occurs for the engagement sequence (701E to 1750A) as disengage (1750A to 701E). Default fade rates for all 1750A surface commands was 1.1 seconds in FSFCC Version 3.1.6 OFP and subsequent utilized for this testing.

During engagement of the FSFCC, 701E trim values are transferred to the 1750A and used to prevent large transients during engagement. The 701E sets trim values to zero after the transfer. However, upon disengaging the 1750A, the trim values are not transferred back to the 701E, so a trim transient resulted on several occasions. This transient was on the order of +/- 1g.

VERSION 3.1.6 FSFCC MODULES

FSFCC software version 3.1.6 contains three modules: the RCLAWS, the Slim Control Laws, and the Failure Simulation modules.

RCLAWS MODULE

The RCLAWS module makes comparisons between the aircraft sensor outputs and the predicted response to the pilot’s inputs. When active, the RCLAWS modifies the pilot’s inputs to better produce the intended aircraft response. For example, a pure longitudinal stick pull would normally result in a pure pitch response. In the event of stabilator damage or failure, however, there will be additional lateral coupling. The RCLAWS will add lateral command as necessary to produce a pure pitch response, within the capability of the degraded system. When inactive, the RCLAWS module passes the pilot’s commands directly to the Slim Control Laws.

The RCLAWS module is comprised of three separate components that work in combination to provide the reconfiguration (Ward and Monaco, 2005). The first component is a state space reference model that defines the desired aircraft motion in response to pilot control inputs. High fidelity simulation data was utilized to generate low-order equivalent system transfer functions that yielded pitch and roll rate response to a control input. The hardware implementation of the reference model in the FSFCCs allows for an 80Hz update, which is the same update rate as the standard FCCs commands.

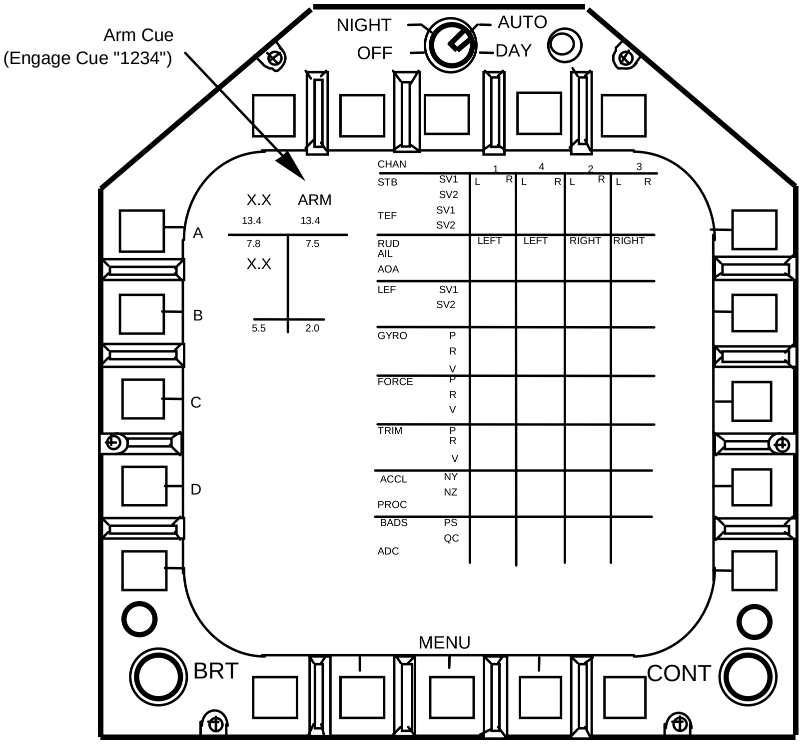

Figure 7: FTFCS Display

Source: NAWCAD PAX-99-192-RTR, F/A-18 Fleet Support Flight Control Computer Basic Replication Mode Evaluation, 18 October 1999.

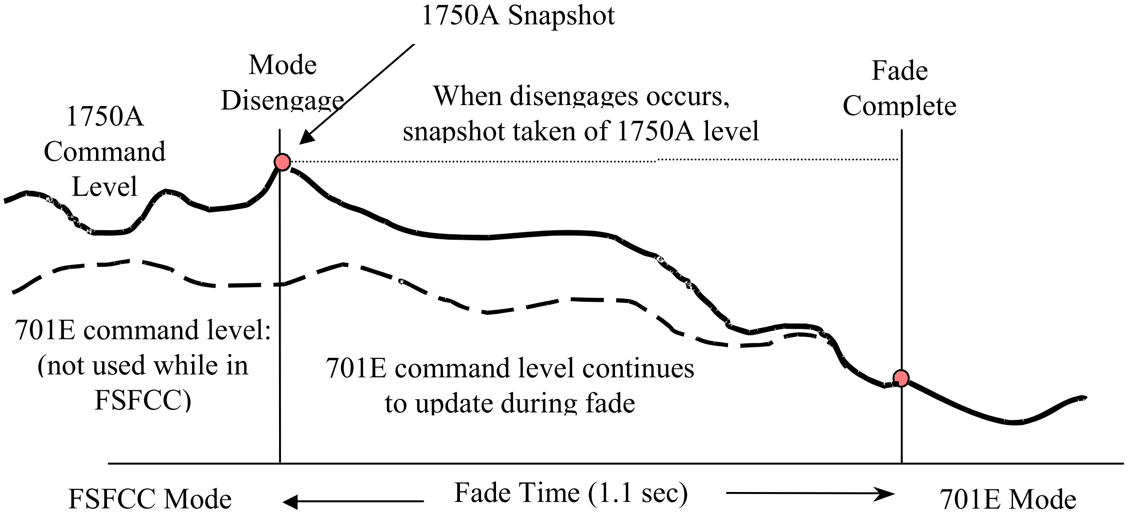

Figure 8: Command Fade Between 701E and 1750A

Source: NAWCAD PAX-99-192-RTR, F/A-18 Fleet Support Flight Control Computer Basic Replication Mode Evaluation, 18 October 1999.

The second component is a state space representation of the aircraft's actual flight dynamics. Onboard aircraft variables such as angular rate information, angle of attack (AOA), and stick positions are utilized in this algorithm. Due to limitations of the FSFCCs the aircraft dynamics model is updated at a rate of 5Hz. The low update rate when compared to the reference model and the FCC commands will be discussed in chapter 5, simulation results.

The final component of the RCLAWS module is the receding horizon optimal controller used to determine the appropriate gain scheduling for reconfiguration. This controller is the utilized to determine the appropriate increments to the control stick inputs for the reference model to match the aircraft dynamics model for a given control stick input. The gain scheduling is implemented at 10Hz in the flight test hardware.

In addition to affecting pilot stick outputs, the RCLAWS has the capability to regulate uncommanded yaw motion by adding increments about a zero pedal command. Because of the computational limitations of the research flight hardware, namely processor capabilities of the 1750A research processor, the pedal reconfiguration is not included in this derivation of the reconfigurable control laws, but is instead implemented as a fixed-gain regulator about a zero reference. This is capable in an aircraft such as the F/A-18C due to the fact that rudder pedal inputs during flight are typically associated with extremely dynamic maneuvering vice navigational maneuvering. The stick only RCLAWS configuration and the stick/pedal configuration were tested extensively during simulation testing; those simulation results are discussed in chapter 5. The decision to incorporate a stick only RCLAWS configuration and the rudder pedal modification is discussed during flight test results, chapter 7, and the conclusions and recommendations, chapter 9.

SLIM CONTROL LAWS

The Slim Control Laws are a functional duplicate of the inner loop of the production v10.1 control laws. The 1750A processor's resources, however, are extremely limited, and it cannot host both the entire v10.1 OFP and the RCLAWS. To get around this limitation, engineers at Barron Associates, Inc. and Boeing, St. Louis, have rewritten the inner loop control laws as the "slim control laws" (Meloney and Doyle, 2005). Because the 701E is continuously calculating many of the FCC internal variables in parallel with the 1750A, the requirement for the 1750A to calculate the same parameters has been eliminated. Instead of independently calculating all of the internal variables, the 1750A receives many of them over the DPRAM from the 701E, effectively sharing the workload. In addition, the outer loop control laws are not replicated in the slim control laws, and therefore functions such as speed brake compensation and autopilot are not supported. The Slim Control Law module is always active when the 1750A processor is engaged.

FAILURE SIM MODULE

The Failure Sim module takes outputs from the Slim Control Laws module and passes them back to the 701E processor's output signal selection logic. When active, the Failure Sim module fails a selected control surface by overriding the Slim Control Laws' command with a command to a fixed position at a rate not greater than 8 degrees/second. The "failure" is introduced at least 2 seconds after the FSFCC is engaged. The control surface and the position to which the surface is commanded are determined by which FSFCC table and row numbers have been chosen by the pilot through the DAF interface. When inactive, the Failure Sim module passes the Slim Control Laws output directly to the 701E processor's output signal selection logic.

FSFCC OPERATIONAL PROCEDURES

TABLE/ROW NUMBER SELECTION, ENGAGEMENT AND DISENGAGEMENT

FSFCC row and table numbers are specified to modify parameters, set modules as active or inactive, and set disengage limits for the FSFCC. FSFCC table/row number combinations are specified by selecting a series of DAF table/row numbers. The MC sends the values stored in the selected DAF table/row to the FSFCC, and the FSFCC converts these values to an FSFCC table/row number combination. To operate the DAF, the FTFCS display must be enabled on the DDI (Figure 7). With the FTFCS display enabled, push tiles 2 through 5 are labeled D through A, respectively. The pilot specifies an FSFCC table/row combination by pressing a sequence of buttons B through D. Table B-1 specifies valid sequences and describes the function of each.

When the pilot depresses these three buttons (B, C, and D) in a sequence, the values of the corresponding table/row numbers will be sent to the FSFCC, and the FSFCC will store the sequence until a value of 1 (button A) is received. Upon receiving a 1, the FSFCC will convert the previous values (four to six of them) to the corresponding FSFCC table/row combination. If the table/row combination is found to be valid for arming, the ARM cue will be displayed on the FTFCS display. The ARM cue will not be displayed if the FSFCC table/row modifies an internal parameter. In the event of a parameter modification, the pilot will receive no feedback after pressing button A, but the engineers in the ground station will be able to verify that the correct parameter has been changed to the correct value. In addition, the pilot has no indication of the correct sequence is being entered. The pilot shall confirm with the ground station that the code corresponding to the correct table and row numbers has been entered prior to arming the 1750A processor.

When the pilot selects a valid, armable code and presses the "A" button, the 1750A processor will arm, and the selected code will only be visible on the FSFCC display at RTPS. Engagement of the FSFCC can be initiated by depressing the NWS button. When engaged, a "1 2 3 4" symbol will be displayed on the FTFCS display in place of the ARM cue, shown in Figure 7

The FSFCC may be disengaged at any time by depressing the paddle switch. The system may also automatically disengage when either an automatic disengage limit is reached or an engagement requirement is no longer satisfied. This results in an FCS caution displayed on the DDI, a Master Caution indication, and an audible tone in the pilot's headset.

701E ARM/ENGAGE/DISENGAGE LOGIC

A top level block diagram of the arm, engage, and disengage logic for FSFCC is presented in Figure 9. The first step in this process is to make an arm request. The pilot initiates this by depressing the DAF "A" button to initiate a valid, armable sequence. The 1750A monitors this MC interface and then sends an arm request to the 701E. Once the

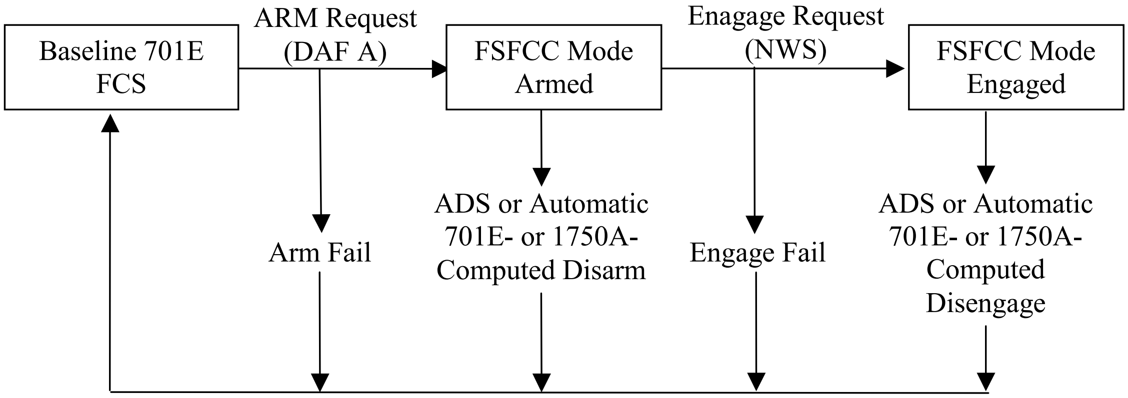

Figure 9: Top Level Arm/Engage/Disengage Block Diagram

Source: Meloney, D. and Doyle, M., "Test Plan for F/A-18 Retrofit Reconfigurable Control System Flight Test," SA-05-04-3266C, April 2005.

1750A is successfully armed, a pilot engage request can be made using the NWS button. Again, the 1750A monitors the NWS button and sends an engage request to the 701E. A pilot disarm or disengage request can be made at any time via the paddle switch, which is monitored by the 701E. Automatic disarm or disengage can be triggered by 701E monitoring of arm or engage criteria. In addition, the 1750A may set a disarm or disengage discrete, which results in reversion to the 701E processor.

In order to engage the FSFCC, selected Envelope Criteria and System Status Criteria must be met. Envelope Criteria for FSFCC engagement is defined for the parameters shown in Table B-1. System Status Criteria is defined in Table B-2. FSFCC engage limits for each Envelope Criteria parameter can be selected with the appropriate sequence in Table B-3.

Any or all Envelope Engage Criteria parameters may be disabled either prior to or in flight. Once disabled, those parameters will not cause the 1750A to disengage until the Envelope Engage Criteria is explicitly re-enabled by the pilot. In addition, each Envelope Engage Criterion has predefined, selectable upper and lower limits. The intent of the automatic disengage is to serve as an additional safety measure. The automatic disengage limits are intended to keep the aircraft from entering potentially unsafe parts of the flight envelope; they are not intended to prevent the aircraft from unintentionally entering otherwise safe parts of the envelope.

FSFCC/RCLAWS OPERATING MODES

As previously described, there are three separate modules within the FSFCC. The RCLAWS module and the Failure Simulation (sim) module can each be active independently; the Slim Control Laws module is always active. The active/inactive options of the three modules create four unique modes that can be engaged within the FSFCC. Each mode is selected by following the DAF procedure described above. The DAF entries are converted within the FSFCC to a table and row number pair and then passed into the 1750A processor through DPRAM. A summary of the four unique modes and the table and row numbers used in the FSFCC is presented in Table 1. Each mode will be evaluated as described in simulation test planning, chapter 4. A detailed summary of all valid table and row numbers along with a description of each mode selection is given in Table B-3

Table 1: FSFCC Table and Row Numbers

FSFCC Mode	Module Status	Table Number	Row Number
Basic Replication Mode	RCLAWS inactive Failure Sim inactive	0	0
Retrofit Control Mode	RCLAWS active Failure Sim inactive	21	0
Basic Replication with Failures	RCLAWS inactive Failure Sim active	22	0 - 25
Retrofit Control with Failures	RCLAWS active Failure Sim active	23	0 - 25

Chapter 4: Simulation Test Planning

OVERVIEW

Simulation testing was broken down into two categories, software testing and hardware in the loop simulation (HILS). The Non-Real-Time (software) testing utilized the Modular Six Degree of Freedom (ModSDF) analysis program located at Boeing Aircraft in St. Louis, Missouri, and the Controls Analysis and Simulation Test Loop Environment (CASTLE) program located at NAS Patuxent River, Maryland. The software piloted simulations were conducted at the Boeing Simulation Facility in St. Louis, Missouri. The hardware in the loop testing was accomplished at the Manned Flight Simulator (MFS) complex at NAS Patuxent River, Maryland.

TEST ENVELOPE

Figure 10 presents the test envelope and test point conditions that were flown. In addition to the test points shown, a test point at 10,000 feet and 1.20 Mach number was evaluated during the NRT and piloted software simulations. Further discussion of the Class B envelope is included in chapter 6, Flight Test Planning.

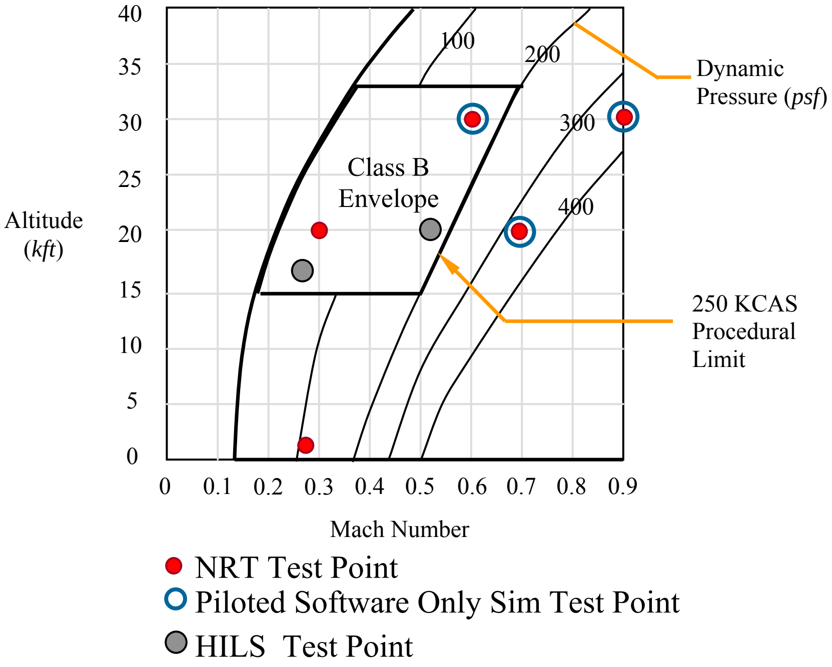

Figure 10: NRT Simulation, Piloted Simulation and HILS Test Envelope

Source: Monaco, J., Ward, D., and Bateman, A., “A Retrofit Architecture for Model-Based Adaptive Flight Control,” AIAA 2004-6281, AIAA 1st Intelligent Systems Technical Conference, Chicago, IL, September 2004.

TEST CONFIGURATION

Test points were performed in the following configurations: 1) Cruise (CR), defined as landing gear and flaps up; 2) Powered Approach (PA), defined as landing gear down and flaps full; 3) PA1/2, defined as gear down and flaps half; and 4) Simulated Single Engine (SSE), defined as gear down, flaps half and one throttle at flight idle. During the testing, the test team recommended that the speed brakes remain retracted whenever the 1750A processor was engaged because the slimmed control laws did not include speed brake compensation.

NRT SIMULATION METHOD OF TEST

NRT test maneuvers consisted of straight and level flight, throttle steps, doublets (all axes), loaded rolls, cross control inputs and general flying qualities. Failure simulations included single and multiple control surface failures. For CASTLE simulations, all ten control surfaces on the F/A-18C were considered in various test scenarios as shown in Figure 11. Figure A-4 sets forth the particular CASTLE test matrix used during the testing. The simulation results will be discussed in chapter 5.

PILOTED SIMULATION AND HILS METHOD OF TEST

The test points consisted of pitch doublets, pitch attitude captures, bank-to-bank rolls, heading captures, and tracking tasks at each test condition. Pitch doublets, pitch attitude captures, bank-to-bank rolls and heading captures were combined into an Integrated Test Set (ITS). In addition, the pilots performed an in-flight refueling task during the manned software simulation. Heading captures were performed at the test team's discretion, because early simulator results indicated that little value was added by performing these maneuvers. Simulated wave offs were performed in lieu of the tracking task at 16,000 feet to assess PA handling qualities. The complete test matrices and DMOT are presented in Table B-4 and appendix 4, respectively. Each test point was performed in each of the following FSFCC modes:

1. FSFCC engaged without RCLAWS and without simulated failure. This mode provided baseline Handling Quality Ratings (HQRs) for the replicated portion of the F/A-18C control laws running on the 1750A research processor.

2. FSFCC engaged with RCLAWS and without simulated failure. The results of this test were compared to those from the preceding mode to ensure the validity of the aircraft model in the RCLAWS module, and to ensure non-interfering (zero) inputs without a failure.

3. FSFCC engaged without RCLAWS and with simulated failure. This mode provided information on how the aircraft handles after a failure, but without the advantages of flight control reconfiguration. After the failure engaged, the pilot attempted to trim the rates to zero before maneuvering. The pilot repeated this point for each of the several different failures engaged.

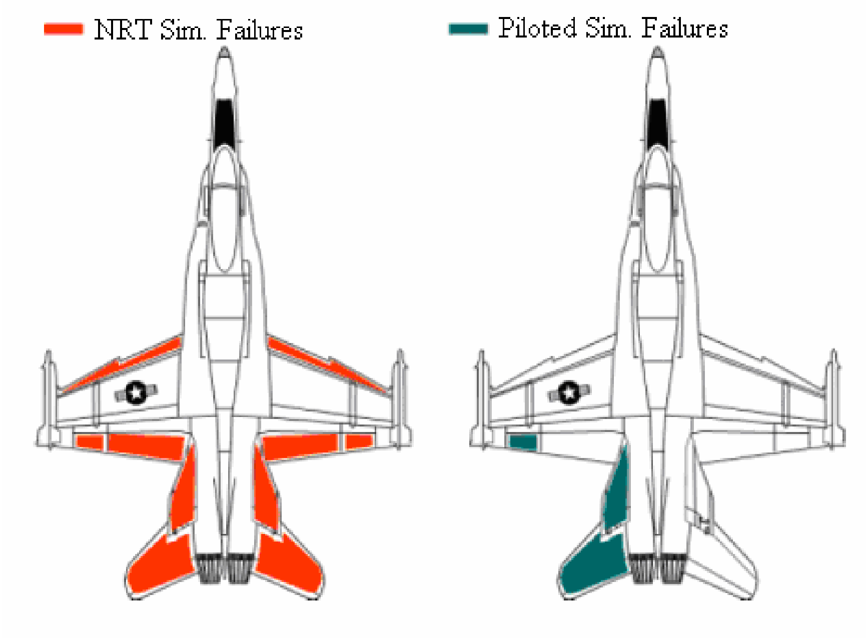

Figure 11: NRT Simulation and Piloted Simulation Control Surface Failures

Source:Monaco, J., “Retrofit Reconfigurable Control System for the F/A-18:Design and Flight Testing of Adaptive Flight Control Systems for Existing Aircraft,” Draft Report, March 2006.

4. FSFCC engaged with RCLAWS and with simulated failure. This test showed the benefits of the reconfiguration technique. The pilot also repeated this mode for multiple different failure scenarios.

The left stabilator, left aileron and left rudder , as shown in Figure 11, were failed for various maneuvers during the piloted software simulation. For HILS and flight test points that include simulated failures, the test team commanded one of two surfaces (right stabilator or right aileron, as shown in Figure 12) to a fixed position. The rational behind choosing failures on different sides of the aircraft during testing was to demonstrate RCLAWS flexibility. For simulated stabilator failures, the FSFCCs commanded the surface to a fixed position within a range of ±6 degrees about the 1g trim position. For simulated aileron failures, the FSFCCs fixed the surface within a range from 25 degrees trailing edge up (TEU) to 42 degrees trailing edge down (TED), not to exceed ±30 degrees from the 1g trimmed position prior to FSFCC engagement. For a simulated rudder failure, the FSFCCs commanded the surface to a fixed position of ±4 degrees (UA), or ±30 degrees (PA) about the 1g trim position.

The pilots flew test points in the order of increasing risk. PA configuration events were tested before those in SSE. Pilots also completed ITSs before other test points for a given configuration. Test points followed the build up in FSFCC modes, following the order presented in the preceding paragraph. When the Failure Sim Module was active, simulated failures were built up in severity: aileron failures were simulated first, followed by stabilator failures for the CR configuration. During the PA test points, stabilator

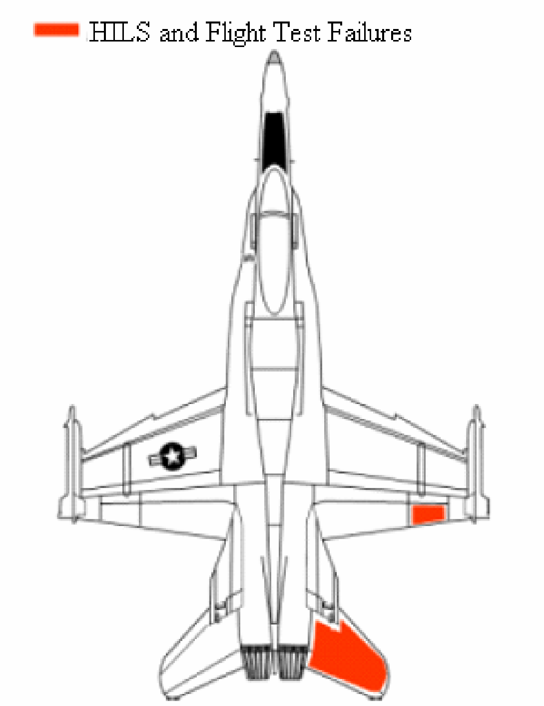

Figure 12: HILS and Flight Test Control Surface Failures

Source:Monaco, J., “Retrofit Reconfigurable Control System for the F/A-18:Design and Flight Testing of Adaptive Flight Control Systems for Existing Aircraft,” Draft Report, March 2006.

failures were tested prior to aileron failures. The reason for the two different approaches was that with an aileron failure in the PA configuration, the ailerons are normally in a drooped position. The drooped position, coupled with a zero degree aileron failure would allow for very little roll contribution in the positive direction for the functional aileron. Therefore, in PA, the aileron failure scenarios were more severe than the stabilator failures.

Chapter 5: Simulation Test Results

SOFTWARE TESTING RESULTS

The software testing proved invaluable in the development and implementation of the final version of the retrofit system utilized for the HILS and flight testing. Numerous changes to the original design of the RCLAWS algorithms were made to allow integration into the 1750A research processor. For example, the desired update rate for all retrofit control computations is 80 Hz. However, the processor capacity restricts the update rates for aircraft model to 5 Hz and the control system gains to 10 Hz. Fortunately, software testing in the CASTLE simulator and the piloted simulations at the Boeing Simulation Facility allowed for full 80 Hz capability. In addition, the software simulations allowed for use of an integrated stick and pedal retrofit algorithm instead of just a stick only architecture that was implemented for the HILS and flight test portions. Lastly, the software simulations allowed for use of sideslip as a variable in the dynamics model of the aircraft. Unfortunately, the F/A-18C cannot easily compute sideslip on the aircraft for implementation into the retrofit algorithm. Instead, the algorithm used yaw rates provided by the onboard rate gyros. Simulation showed that for the flight test envelope, the exclusion of sideslip from the algorithm was not significant. In addition, without flight test clearance requirements, the simulation test envelope was not restricted to the modified Class B envelope. Testing was conducted at a wide range of dynamic pressures and altitudes to document the strengths and weaknesses of the in-line retrofit method.

With these limitations removed, the test team was able to observe a more realistic implementation of the in-line method. The bulk of the testing consisted of approximately 1,800 test cases. Test cases typically consisted of 13 single and multi-axis maneuvers with 23 failure modes at six different conditions. Figure A-3 shows the scoring criteria utilized in the CASTLE simulations. Figure A-4 and Figure A-5 show the CASTLE simulation results for two of the six flight conditions tested. The six flight conditions are shown in Figure 10. As shown in the figures, the CASTLE results are extremely positive. The results showed that, as expected, the potential of reconfiguration provided an improvement in flying qualities increased as airspeed increased. This can be partly attributed to the increased control power associated with higher dynamic pressures. In addition, with higher dynamic pressure points, the control surfaces are more faired when a failure is inserted, effectively allowing the operational control surface increased deflection in both directions to counter the undesired coupling.

With the software piloted simulation, the pilots were asked to perform the maneuvers described in chapter 4 and the DMOT, appendix D, and then assign HQRs for with and without retrofit enabled. The HQR scale is described in Figure A-1. Two pilots were used for these tests. Boeing’s chief test pilot at the time (Pilot A) and a Navy, fleet experienced F/A-18 test pilot (Pilot B) were the aircrew that performed the piloted simulation evaluation. Overall, Pilot A and Pilot B rated the nominal F/A-18 as an HQR 1 or 2 aircraft and an HQR 2 or 3 aircraft, respectively, dependent on task and flight environment. With failure modes engaged and retrofit not engaged, both aircrew rated the flying qualities between HQR 5 and 7. However, once the retrofit system was engaged, Pilot A assessed the handling qualities as an HQR 2, and Pilot B assessed an HQR of 2 to 3.

Figure A-2 shows the combined HQRs for both piloted simulation flights. Figure 13 and Figure 14 show the HQRs for all of Pilot B's maneuvers. During the in-flight refueling task, Pilot B commented "The elimination of the constant left stick input and the roll coupling were a sure improvement. It was hard to see a degradation in tanking resulting from any yaw coupling that may have been present." (Rouland, 2002)

RUDDER PEDAL MODIFICATION IMPLEMENTATION

Another item that was concentrated on during the CASTLE simulations was the effect of a stick and rudder reconfiguration system instead of a stick only reconfiguration system. The 1750A research processor only contains 32 kilobytes of usable random access memory (RAM) for use by the RCLAWS module, the Slim Control Laws, and the Failure Simulation, see Figure 15. Multiple test scenarios were conducted to investigate the implication of conducting the test with and without inclusion of the rudder into the reconfirmation algorithm. Test results showed that although the inclusion of the rudder pedal made vast improvements during some test cases, it was less important in others. The cases where rudder pedal inputs were helpful were predominately outside the Class B envelope (high dynamic pressure). For test points within the Class B envelope, only small directional deviations were observed. Therefore, for flight test, which is required to be executed within the Class B envelope, the rudder pedal could be excluded from the retrofit reconfiguration implementation without adversely affecting the data quality significantly.

In an attempt to control the small uncommanded yaw motion, an optional "rudder pedal modification" was designed. The rudder pedal modification was implemented as a simple fixed gain proportional integral control law with a zero model reference. This is possible because during the majority of the F/A-18C flight envelope, rudder pedals are not used for maneuvering. While the pilot is not technically prevented from making pedal inputs with the retrofit rudder pedal modification command option enabled, the system will attempt to cancel any yaw motion caused by the pilot's input. The consequence is that the yaw response will appear sluggish or unresponsive to pedal inputs. The capability to insert pedal commands can be enabled or disabled by selecting the appropriate FSFCC table and row numbers (Table B-3).

HARDWARE IN THE LOOP RESULTS

The HILS test results were used to optimize the FSFCC implementation of the RCLAWS. In particular, HILS testing was used to: define the envelope limits for automatic reversion from the research to the production (701E) control laws, finalize the flight test instrumentation message data and display layout for ground monitoring, and tune the cost functions and gain schedules for the reconfigurable controller. Flight conditions and HQR tolerances (Table B-5) were defined by the pilots and engineers based on HILS experience. In addition, liberal use of the simulator helped to streamline the flight test program by identifying candidate maneuvers early in the program that were not interesting from the point of view of reconfiguration. Original candidate flight test maneuvers included heading captures and simulated single engine wave offs, but these maneuvers were eventually dropped because the handling qualities did not change significantly regardless of the failure scenario or whether the retrofit reconfigurable controller was active. Lastly, the HILS simulator sessions increased test efficiency by

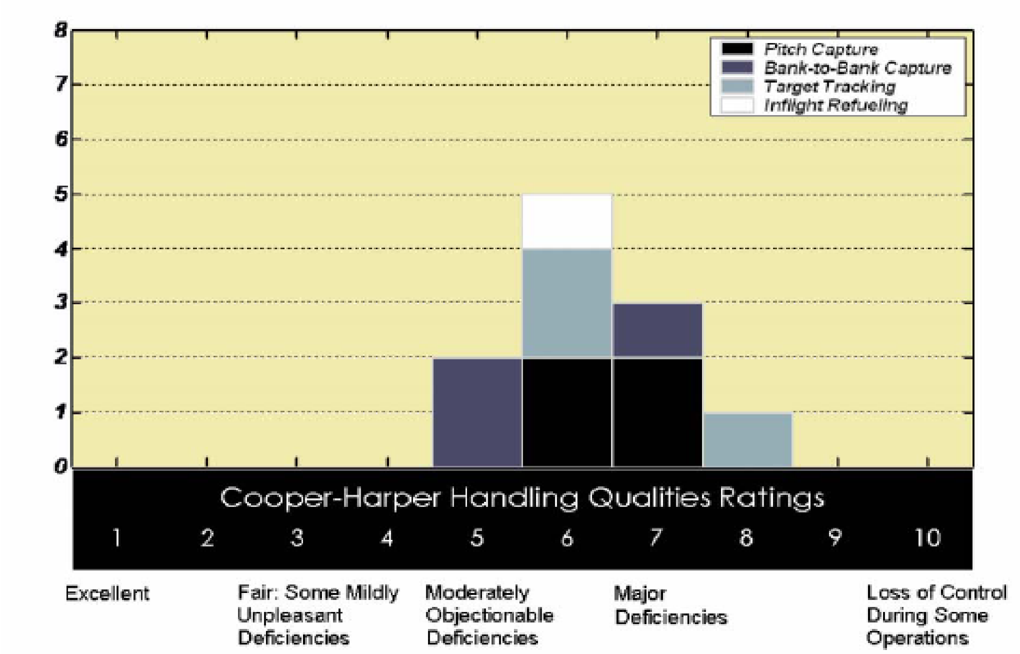

Figure 13: Software Simulation Results, Production CAS, Pilot B, All Maneuvers

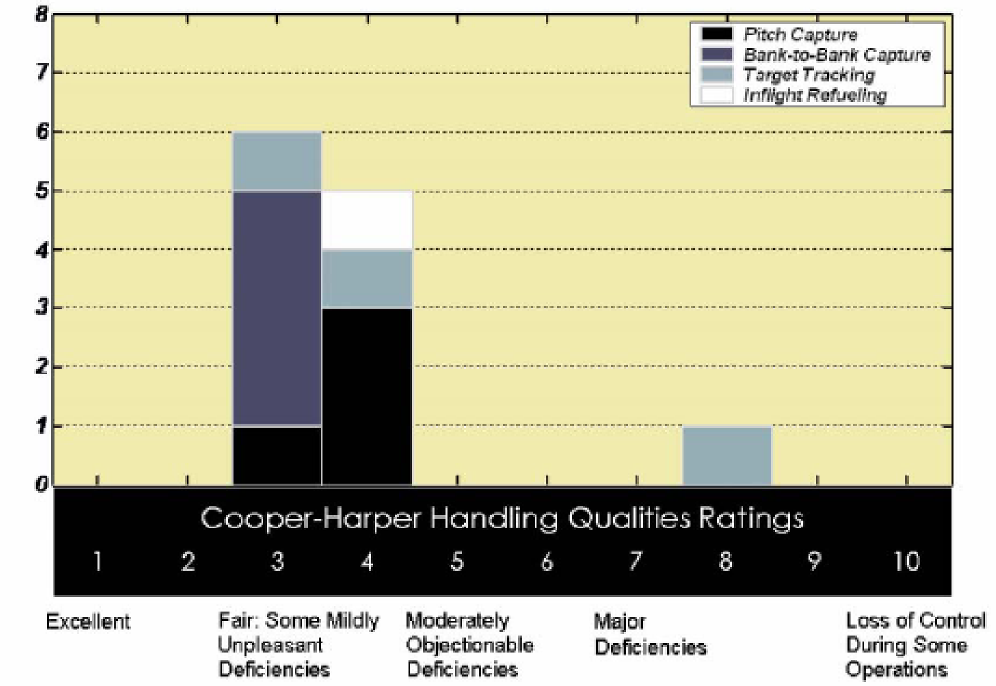

Figure 14: Software Simulation Results, Retrofit Control, Pilot B, All Maneuvers

Source: Monaco, J., “Retrofit Reconfigurable Control System for the F/A-18:Design and Flight Testing of Adaptive Flight Control Systems for Existing Aircraft,” Draft Report, March 2006.

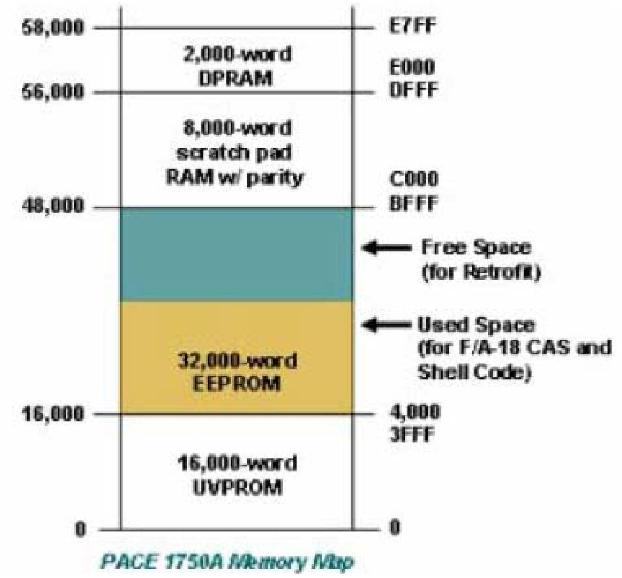

Figure 15: 1750A Research Processor Memory Available for RCLAWS

Source: Meloney, D. and Doyle, M., "Test Plan for F/A-18 Retrofit Reconfigurable Control System Flight Test," SA-05-04-3266C, April 2005.

allowing the aircrew and ground crew to practice the maneuver set up, the maneuver execution, and develop a logical flow for test points. The author believes the extensive use of the HILS was extremely important in a research project with limited funding and should be incorporated into future test projects.

During the MFS sessions, three aircrew from Air Test and Evaluation Squadron (VX) 23 (one Navy (the author), and two Marine fleet F/A-18 pilots), performed the evaluation. During the evaluation, it was noted that a standard aggressive pitch capture tended to produce undesirable handling qualities. Post-flight analysis determined that the stick input rate was so aggressive that the slow update rate of the aircraft dynamics model (5 Hz) was inadequate for the standard maneuver. It was determined that future HILS and flight test would incorporate a less aggressive pitch capture. This was noted as compensation, however, it was also noted that a reduced maneuver would have likely not been required in a fully capable, production retrofit system without insufficient dynamic model update rates. Qualitative results from the HILS sessions were remarkably similar to previous piloted simulations. The results from all three aircrew average one to two HQRs better for the RCLAWS engaged test points. A compilation of the test maneuvers and HQRs assigned by pilot C is shown in Figure 16 and Figure 17 for production CAS and RCLAWS, respectively.

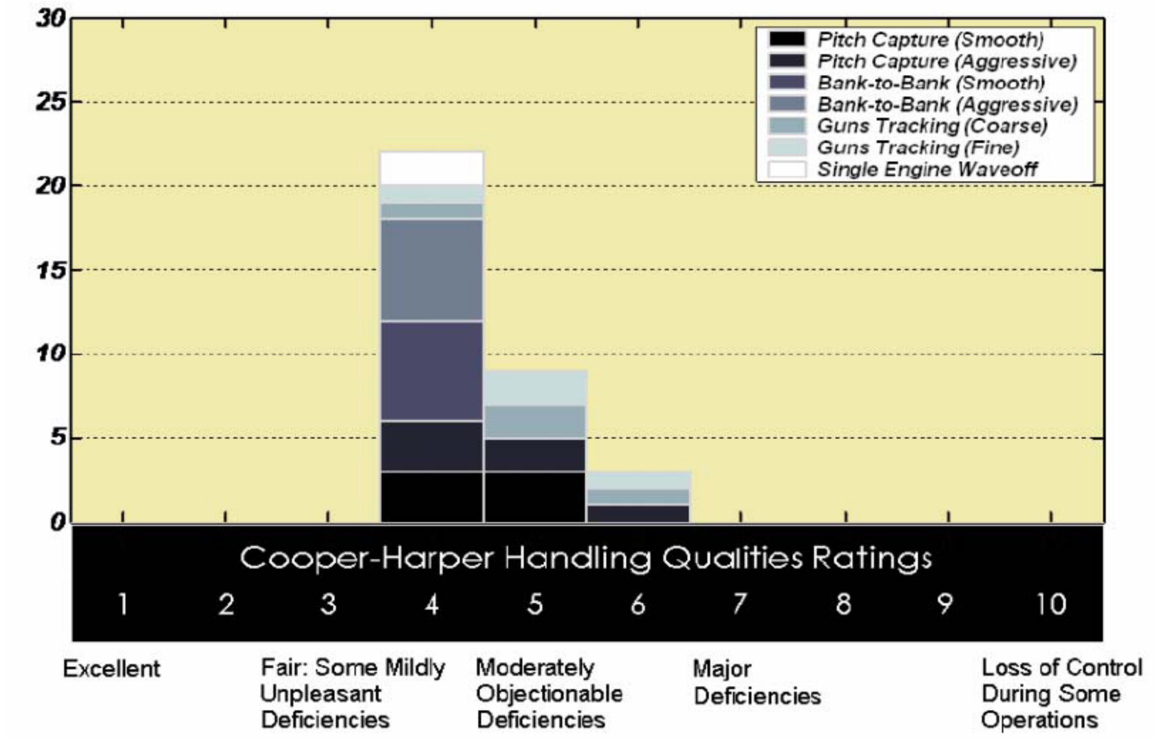

Figure 16: HILS Test Results for Production CAS, Pilot C, All Maneuvers

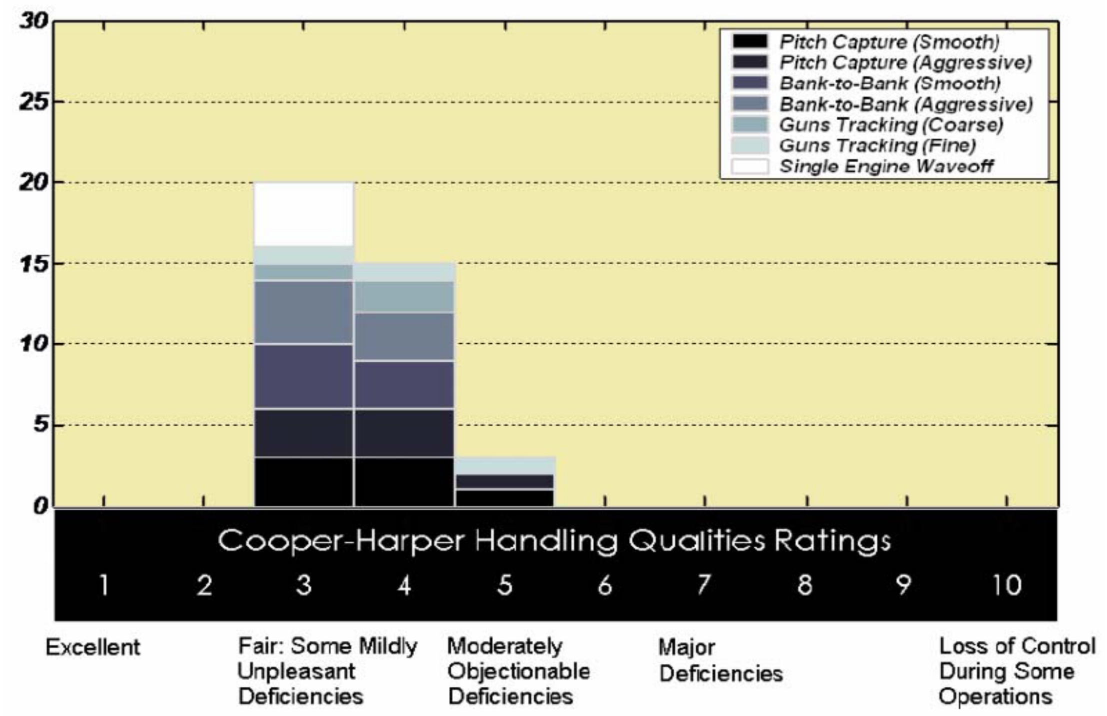

Figure 17: HILS Test Results for Retrofit Control, Pilot C, All Maneuvers

Source: Monaco, J., "Retrofit Reconfigurable Control System for the F/A-18:Design and Flight Testing of Adaptive Flight Control Systems for Existing Aircraft," Draft Report, March 2006.

Chapter 6: Flight Test Planning

OVERVIEW

The primary objective of this testing was to gather flight test data, both quantitative and qualitative, to validate simulation results and support the further development of the RCLAWS. The secondary objective of this testing was to evaluate the effectiveness of the RCLAWS to control the aircraft with a degraded FCS. Initially, the operating budget allowed for three flights to perform the in flight evaluation of the RCLAWS. A fortunate reduction in flight hours costs for the chase aircraft allowed for a fourth flight.

TEST ENVELOPE

The FSFCC was engaged within the modified NASA-designated Class B envelope shown in Figure 18 (12,000 feet to 33,000 feet, less than 250 KCAS). If the limits of the modified Class B envelope were exceeded, the FSFCC 1750A processor would automatically disengage, as described in chapter 3. By limiting flight to this envelope, the risk of structural damage to the aircraft was significantly reduced in the event that an error in the FSFCC software commanded a control surface to full deflection. In deriving the test envelope, NASA used normal load factor transients as a metric to define the boundaries in a simulator (Carter and Stephenson, 1999). With the automatic disengage Nz threshold set at 4g, multiple control surfaces were failed hard-over at a number of different flight conditions, and the 1750A was expected to disengage the system prior to the aircraft exceeding the 6g normal acceleration operational limit of the test aircraft. For any flight condition that exceeded the load-factor transient limit, the point was considered outside of the Class B envelope. In addition, a specialized Ada software load for laboratory testing was developed and executed. This special Ada software load simulated worst-case scenarios, commanding multiple control surfaces to their limits instantaneously. These scenarios were tested throughout the NASA Class B envelope and provided additional confirmation that the FSFCCs could be safely flown within the NASA Class B envelope.

The low dynamic pressures maintained the relatively low aircraft energy state necessary to ensure minimum structural risk to the aircraft if a major computer malfunction were to occur. There was no lower limit to dynamic pressure. The lower altitude limit of the original NASA Class B envelope was 15,000 feet and was chosen to allow sufficient altitude for recovery from potential out-of-control flight. For this test, the lower altitude limit was decreased to 12,000 feet to allow reasonable aircraft response in the Power Approach (PA) configuration while still providing sufficient altitude for recovery from any unexpected out-of-control flight. The resulting envelope is referred to as the modified Class B envelope.

Due to limited capacity of the 1750A research processor, the flight dynamics model to which the RCLAWS compare the actual aircraft response was tuned to two predefined flight conditions, designated by the gray diamonds in Figure 18. The two points defined in this software allowed Cruise (CR) Flying Qualities (FQ) to be tested at 20,000 feet / 235 KCAS, and PA FQ to be tested at 16,000 feet / 8.1 degrees AOA.

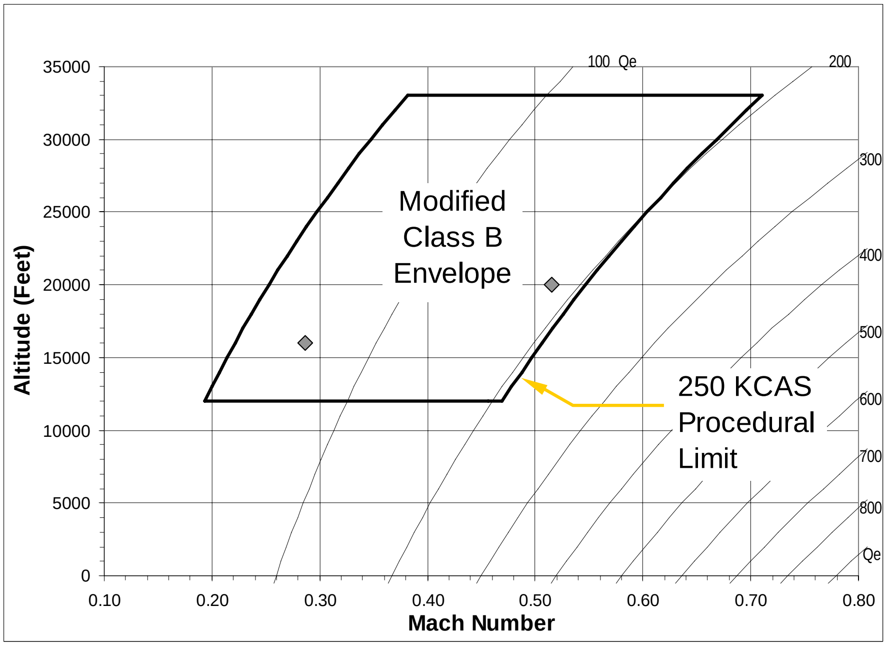

Figure 18: Flight Test Envelope

Source: Meloney, D. and Doyle, M., “Test Plan for F/A-18 Retrofit Reconfigurable Control System Flight Test,” SA-05-04-3266C, April 2005.

FLIGHT CLEARANCE ISSUES

Testing at NAS Patuxent River is generally performed to support fleet requirements and Naval Air Systems Command (NAVAIR) acquisition programs. The culture and processes in place are tailored to this type of work. As a result, extra planning and extensive coordination was required for this flight test research program. In addition, the budget restrictions of a research program created a need for thorough planning to maximize the efficiency of data gathering.

A major cost driver of flight testing flight control systems can be the verification and validation of flight critical software. This was one of the primary advantages of using the FSFCC: the research software can only be engaged in a limited part of the envelope, and this can greatly reduce the software testing burden. While the retrofit system was subjected to extensive hardware-in-the-loop testing, module level testing of the research software was not performed. The primary safety of flight risk mitigation was to conduct the flight tests at altitude in a low dynamic pressure part of the envelope.

With this envelope restriction as the primary risk-mitigation, it was possible to coordinate agreement on a flight clearance, written in such a way that the research software could be substantially modified between flights without requiring a new flight clearance. In its place, an FSFCC software modification process was developed that required a greatly reduced approval chain for changes made within certain bounds. This allowed reduced down time and the associated costs. This was a significant departure from the normal NAVAIR procedure that would normally require a new clearance for each new software configuration. It is the author’s experience that this departure was unprecedented and vital to the success of this program. The extensive coordination and planning allowed for a project with a very modest budget to conduct efficient flight test.

The NAVAIR flight clearance process, in this case, was very cooperative with the test team in allowing them to utilize their expertise to provide a safe test environment. The author believes this cooperation between the test team and the flight clearance team should be adopted for future projects to allow for more cost and time efficient test programs.

Another significant flight clearance issue was the fact that V10.1 is no longer the current F/A-18A/B/C/D FCC software version. Version 10.5.1 (v10.5.1) contains substantial improvements, particularly in the areas of redundancy management and high angle-of-attack performance. While flying with v10.l was still acceptable, it does present an increased risk over flight with v10.5.1. In order to mitigate the risk, the pertinent differences between v10.5.1 and v10.1 were briefed before every flight with special attention to changes in emergency procedures. For example, AOA probes failures during take-off in v10.1 are not sufficiently incorporated into the failure logic, and presented one of the greatest risks in reverting to v10.1 software. To mitigate this risk, AOA probes were double checked prior to flight and monitored for failure during take-off. In addition, pilots were required to perform at least one takeoff in the simulator with a failed AOA probe prior to being scheduled for a test flight. A full list of differences between v10.1 and v10.5.1 is included in appendix C.

TEST CONFIGURATION AND LOADOUT

Flight test was conducted in the loadout defined as: clean configuration with a single centerline. Therefore, no pylons were loaded on under wing stations (stations 2, 3, 7, and 8), missile well covers were installed on the fuselage stations (stations 4 and 6) and empty LAU-7s were loaded on the wingtips (stations 1 and 9). The only store loaded was a 330 gallon external fuel tank on the centerline station (station 6).

Test points were performed in the following configurations: Cruise (CR) defined as landing gear and flaps up and Powered Approach (PA) defined as landing gear down and flaps full. Because the slimmed control laws did not include speed brake compensation, it was recommended that speed brakes remain retracted whenever the 1750A processor was engaged.

METHOD OF TEST

The method of test was identical to the method utilized at the HILS sessions with the learning points incorporated. Two test maneuvers were removed from the flight cards: heading capture and SSE. Buildup in FSFCC modes was again followed (e.g., baseline prior to RCLAWS, no failure prior to failure).

INSTRUMENTATION AND REAL TIME MONITORING

Data were collected using the onboard instrumentation system, which was a Digital Data Acquisition System (DDAS). The DDAS is a time division multiplex data acquisition system featuring programmable format definition and modular remote multiplexing units. Analog and digital signals were encoded and inserted into an unencrypted Pulse Code Modulation (PCM) data stream for onboard recording and telemetry down link. The PCM data stream included embedded Inter-Range Instrumentation Group (IRIG-B) time code for data synchronization with aircraft and cockpit voice recording system (CVRS) data.

The PCM data stream and analog pilot's voice were transmitted to the ground station via the aircraft telemetry system. The telemetry transmitter provided 10 watts of output power and had a frequency range between 1435.5 and 1535.5 MHz. The transmitter frequency was selectable from the cockpit.

REAL TIME DATA REQUIREMENTS

Selected parameters were monitored real time to ensure test mission safety, as well as to verify satisfactory test point completion. The Real-Time Telemetry Processing Station (RTPS) ground station was used for in-flight telemetry monitoring. The basic RTPS project engineer station is comprised of ten strip chart recorders (8 channels/chart), two digital displays (16 parameters/display), seven color monitors, one user-interactive station with graphics displays, and various hardcopy units.

The initial required telemetry setup included pilot's voice, IRIG-B range time, and safety of test parameters (e.g., Nz, AOA, sideslip, etc). Strip chart data were used to select areas for post-flight data reduction. On board recorded parameters were used for quantitative data analysis post flight.

Chapter 7: Flight Test Results

OVERVIEW

Four test flights were made in two aircraft with two pilots at NAS Patuxent River in 2005 and 2006. Both aircraft were F/A-18C models, had similar instrumentation systems, and were equivalent for the purposes of this test. The same maneuvers were flown during the flight testing as were flown in the HILS sessions except for heading capture and the SSE evaluation. Pitch doublets, pitch attitude captures, bank angle captures, and target tracking were performed in CR, and pitch doublets, pitch attitude captures, and bank angle captures were performed in PA. The same FSFCC modes and failure combinations that were performed in the simulator were also tested in flight. The first three flights were flown by Pilot D (the author), a United States Navy fleet experienced F/A-18 test pilot, and the last flight was flown by Pilot E, a United States Marine Corps fleet experienced F/A-18 test pilot. The test matrix was completed during the first three flights, and the fourth flight was used to revisit the most revealing test points with a second pilot for a different perspective. Both pilots had flown similar test points in the simulator prior to their flights, and both pilots started their first flight with a comparison of FSFCC modes 1 and 2 (RCLAWS both inactive and active without failures, respectively).

All four flights proceeded as expected, with the exception of three cases of unanticipated aircraft response. Of these three cases, the first and third occurred during test maneuvers, and the second occurred during the second flight when the aircraft was configured in PA with RCLAWS engaged.

UNANTICIPATED AIRCRAFT RESPONSE

During the first flight, uncommanded yaw oscillations were noted during the vertical portion of a guns tracking maneuver with the right aileron failed at 0 degrees from trim. The pilot discontinued the tracking task momentarily, but after the oscillation ceased, was comfortable enough to reacquire the target and continue tracking. In-flight analysis suspected and post-flight data analysis confirmed that the aircraft temporarily dropped below the airspeed tolerance, and this had caused higher-than-anticipated flight control gains. As described in chapter 6, the RCLAWS module was optimized about only two points in the modified Class B envelope. The solution for the remaining flights was to remain within the tolerances, and to have the test conductor make reminder airspeed calls to the aircrew as necessary during the guns tracking maneuver.

In the PA configuration during the second flight, the test team noted a high frequency, small amplitude oscillation in the retrofit increment to the lateral stick command. The magnitude of the oscillation was small enough that the pilot perceived no lateral motion. That flight was executed with FSFCC version 3.1.7 software, which allowed the pilot to select from nominal, 75%, or 125% reconfigurable control gains for all axes in flight. Nominal gains were used for the entirety of the first and second flights. After the second flight, however, the FSFCC software was modified to version 3.2.7, which used the nominal pitch gains, but enabled the pilot to select diminished reconfigurable control gains for the roll axis (60% of nominal).

During the fourth flight, a small amplitude, low frequency roll oscillation was noted during smooth pitch attitude captures for the 0 degree aileron failure with the retrofit system engaged at the PA flight condition. The point was re-tested after having the pilot select a reduced roll gain (60% of nominal). The oscillation was lessened, but not eliminated. Post-flight data analysis revealed that these roll oscillations were likely due to the simplified gain schedules employed.

OVERALL HANDLING QUALITIES RESULTS

Table 2 and Table 3 give flight test HQRs for pilots D in CR and PA configurations, respectively. Table 4 gives the flight test HQRs for Pilot E. In these tables, commas separate ratings from different executions of the same test point, and ratings enclosed in brackets were flown with the optional rudder pedal modification off. Table B-5 describes the maneuvers and tolerances used to define desired and adequate performance for HQRs, and Figure A-1 is the standard Cooper-Harper Handling Qualities Rating scale used for HQRs given in this program. Figure 19 and Figure 20 are graphical depictions of the combined pilot D and pilot E HQRs for production CAS and RCLAWS, respectively.

As mentioned earlier, there were two maneuvers that involved unanticipated aircraft motion. These maneuvers resulted in worse HQRs with the RCLAWS engaged than with the RCLAWS disengaged. Additionally, there are three other cases for which the HQR is worse with the RCLAWS engaged. The first case occurred during the vertical portion of the fine target tracking maneuver with the 6 degree stabilator failure at the CR flight condition, the pilot noted some undesired yaw response. The second case occurred during the 0 degree right aileron failure in the PA configuration, the pilot noted a hesitation as the aircraft rolled through wings level during the aggressive bank-to-bank roll. Post-flight data analysis indicated that both problems were due to the lack of integrated yaw control in the retrofit design. In particular the hesitation through wings level for the PA point was linked to an interaction of the RCLAWS with the optional rudder pedal modification. Though the same problem was not noted on the next test point, a 0 degree failure of the right stabilator, the test team decided not to use the rudder pedal modification for the remainder of the test program. A production reconfigurable control system would be designed for full reconfiguration in all three axes, and would therefore not suffer this same interaction problem.

The final case with a worse HQR for the RCLAWS engaged was the aggressive pitch capture for the 30 degree aileron failure in CR for Pilot E. Even though a worse HQR (HQR 4 versus HQR 3) was given for the RCLAWS-engaged case, pilot comments during the test maneuvers indicated that the handling qualities were better with the retrofit system. Immediately after finishing the integrated test set, the pilot was asked for his overall impression. He stated that the aircraft was much more controllable with the retrofit system. He went on to state he “would consider the overall handling qualities of the aircraft with the 30 degree aileron failure and the RCLAWS active to be HQR 3 to 4 whereas the handling qualities for the same failure without the RCLAWS would be HQR 5 to 6.” (Kelly, 2006)

Table 2: CR Flight Test HQRs for Pilot D

		Flight 1		Flight 1		Flight 1		Flight 1	
CR Flight Condition		No Failures		Aileron = 0 deg		Aileron = +15 deg		Stab = 0 deg	
		Baseline	Retrofit	Baseline	Retrofit	Baseline	Retrofit	Baseline	Retrofit
Pitch Capture	Smooth	2	2	2	2	5	4	4	3
	Aggressive	2	2	2	2	5	4	4	3
Bank to Bank	Smooth	2	2	2	2	3	3	3	3
	Aggressive	2	2	3	3	3	3	4	3
Target Tracking Level Turns	Coarse	2	2	2	2	3	3	3	3
	Fine	2	2	3	2	3	3	3	3
Target Tracking Maneuvering	Coarse	2	2	3	5	5	4	4	3
	Fine	2	2	3	DND	5	4	4	3

		Flight 2		Flight 2		Flight 3	
CR Flight Condition		No Failures		Aileron = 0 deg		Aileron = +15 deg	
		Baseline	Retrofit	Baseline	Retrofit	Baseline	Retrofit
Pitch Capture	Smooth	5	3	3	3	3	[3]
	Aggressive	6	3	3	3	5	[3]
Bank to Bank	Smooth	4	3	3	3	3	[3]
	Aggressive	4	3	3	3	3	[3]
Target Tracking Level Turns	Coarse	5	4, [3]	3	3	3	[3]
	Fine	5	4, [3]	3	3	3	[3]
Target Tracking Maneuvering	Coarse	5	5, [4]	3	3	3	[3]
	Fine	5	5, [4]	3	3	3	[4]

Table 3: PA Flight Test HQR’s for Pilot D

		Flight 2 & 3		Flight 2		Flight 3		Flight 3	
PA Flight Condition		No Failures		Aileron = 0 deg		Aileron = -15 deg		Aileron -30 deg	
		Baseline	Retrofit	Baseline	Retrofit	Baseline	Retrofit	Baseline	Retrofit
Pitch Capture	Smooth	2, 3	2	3	2	3	[3]	3	[3]
	Aggressive	2, 3	2	3	3	3	[3]	3	[3]
Bank to Bank	Smooth	2, 3	2	4	4	3	[3]	3	[3]
	Aggressive	2, 3	2	4	5	3	[3]	3	[3]

		Flight 2		Flight 3		Flight 3	
CR Flight Condition		Stab = 0 deg		Stab = -3 deg		Stab = -6 deg	
		Baseline	Retrofit	Baseline	Retrofit	Baseline	Retrofit
Pitch Capture	Smooth	3	3	3	[3]	4	[3]
	Aggressive	3	3	5	[3]	4	[3]
Bank to Bank	Smooth	3	3	4	[3]	3	[3]
	Aggressive	3	3	4	[3]	3	[3]

Table 4: Flight Test HQRs for Pilot E

CR Flight Condition		Flight 4 No Failures		Flight 4 Aileron = +30 deg	
		Baseline	Retrofit	Baseline	Retrofit
Pitch Capture	Smooth	2	-	2	[2]
	Aggressive	3	-	3	[4]
Bank to Bank	Smooth	2	-	4	[3]
	Aggressive	3	-	4	[3]
Target Tracking Level Turns	Coarse	2	-	4	[4]
	Fine	2	-	4	[4]
Target Tracking Maneuvering	Coarse	2	-	5	[4]
	Fine	2	-	5	[4]

PA Flight Condition		Flight 4 No Failures		Flight 4 Aileron = 0 deg		Flight 4 Stab = -6 deg	
		Baseline	Retrofit	Baseline	Retrofit	Baseline	Retrofit
Pitch Capture	Smooth	2	-	3	[4]	2	[3]
	Aggressive	2	-	4	[4]	3	[3]
Bank to Bank	Smooth	2	-	4	-	4	[3]
	Aggressive	2	-	5	-	5	[3]

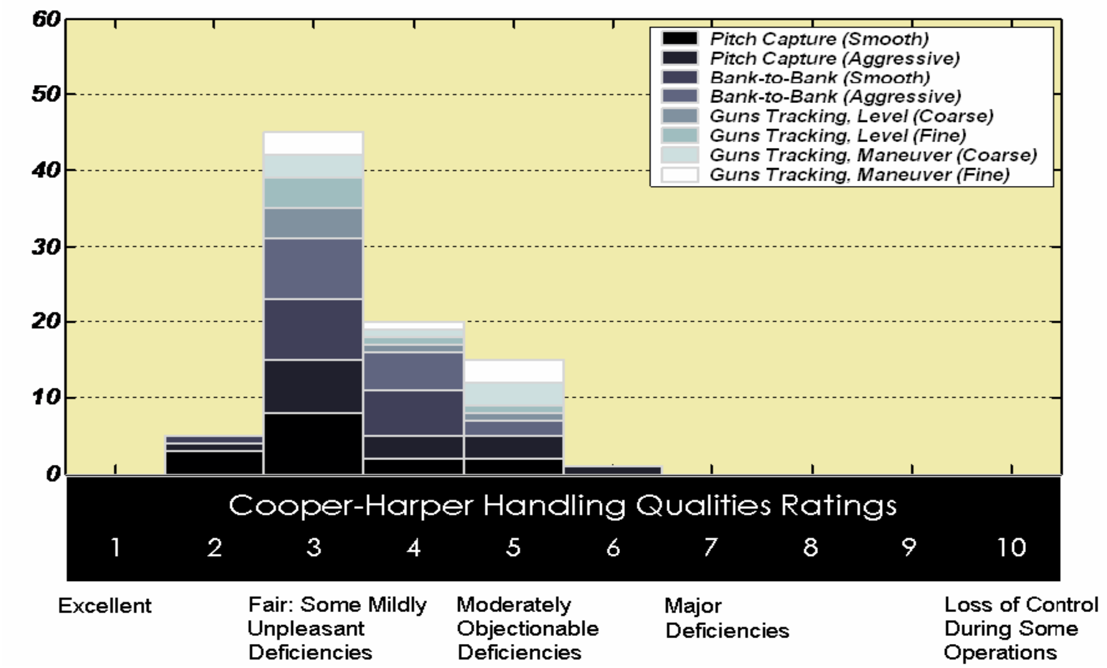

Figure 19: Flight Test Results for Baseline Control, Pilots D & E, All Maneuvers

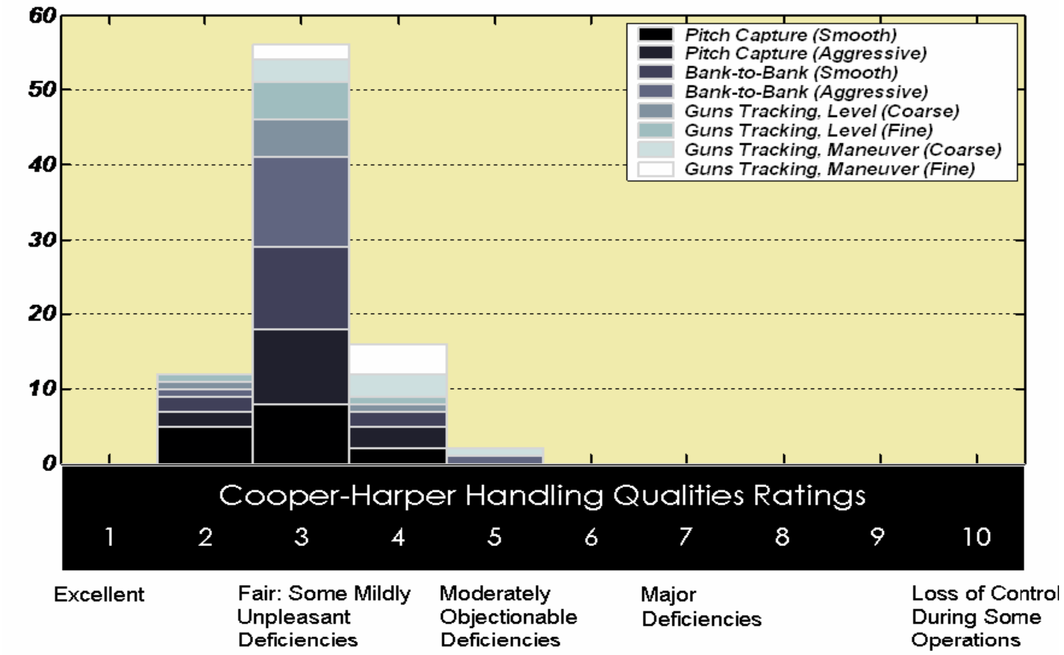

Figure 20: Flight Test Results for Retrofit Control, Pilots D & E, All Maneuvers

Source: Monaco, J., "Retrofit Reconfigurable Control System for the F/A-18:Design and Flight Testing of Adaptive Flight Control Systems for Existing Aircraft," Draft Report, March 2006.

Twelve individual comparisons of the RCLAWS to the baseline (non-retrofit) system were made for the no failure case. In each of these comparisons, the pilot noted no difference in the aircraft response. This is verified by the identical HQRs and gives evidence that the retrofit system does not affect the baseline response if the vehicle is behaving nominally (i.e., not interfering).

The performance with the RCLAWS engaged is better than the baseline system for 35 out of the 85 individual comparisons with a simulated surface failure. The baseline system is rated better than the RCLAWS in only 5 cases with a simulated failure. All but one of these cases is attributed to compromises in the retrofit design due to limitations in the flight hardware. For the final case, pilot comments indicated that, despite receiving a worse rating, the RCLAWS-engaged performance was preferred.

Of the 45 failure cases for which the RCLAWS and baseline system were given equal ratings, only four of them were worse than HQR 3 (all HQR 4). This is partly due to the fact that only small magnitude failures were tested as part of the build up approach and partly due to the robustness of the F/A-18C platform and the baseline control laws. Therefore, there was little room for the RCLAWS to improve upon the performance of the baseline system for many of the failure scenarios tested within the limited scope of the flight test plan and test envelope.

Even with the F/A-18's robust design, the HQRs averaged 0.5 points better with the RCLAWS engaged during a failure than they did without. The mean HQR for RCLAWS-engaged failure points is approximately 3 with a standard deviation of 0.6, and the mean HQR for all RCLAWS-disengaged failure points is approximately 3.5 with a standard deviation of 0.9. While the mean values may appear to be very close, an examination of the data reveals a definite improvement in performance with the retrofit system. This improvement is evidenced by the fact that, with simulated failures active, there are twice as many HQR 2 test points for the retrofit system as for the baseline system (12 test points versus 6 test points) and significantly fewer HQR 5 ratings for the retrofit system versus the non-retrofit system (2 test points versus 15 test points).

QUANTITATIVE RESULTS

Not only did the HQRs show an improvement with the RCLAWS active, the quantitative data showed a significant reduction in the coupling as a result of control stick input. Figure 21 shows the flight test data from a +15 degree right aileron failure in the CR configuration without RCLAWS active. Figure 22 shows the data from the same failure configuration with RCLAWS active.

The data presented show a pitch doublet performed multiple times in succession. In Figure 21 without RCLAWS, there is significant roll coupling to a roughly pure pitch doublet (denoted with arrows). Conversely with RCLAWS active, in Figure 22, the roll coupling is significant reduced. In this example, the coupling was approximately 3 times less with RCLAWS active than production CAS alone. This reduction was also evident in the relative HQRs assigned by the pilot. The CAS alone event received an HQR of 5, while the RCLAWS event received an HQR of 4, again a 1 point improvement with the reconfigurable flight controls.

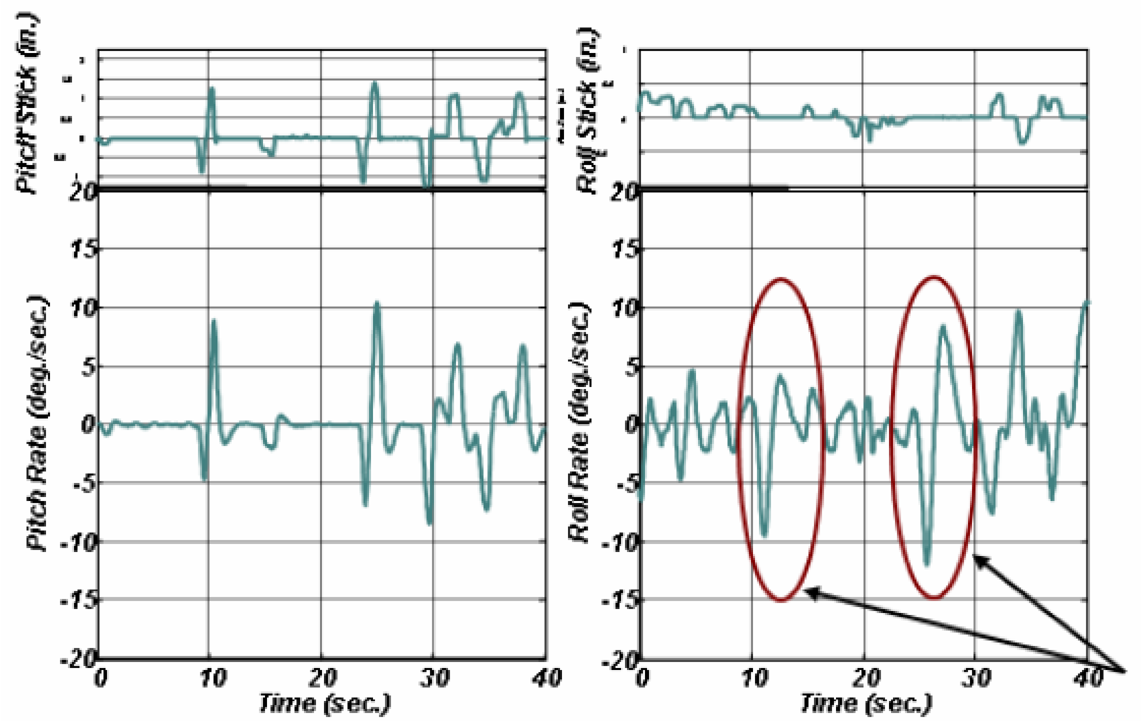

Figure 21: Production CAS, +15 degree aileron failure, Pitch Doublets

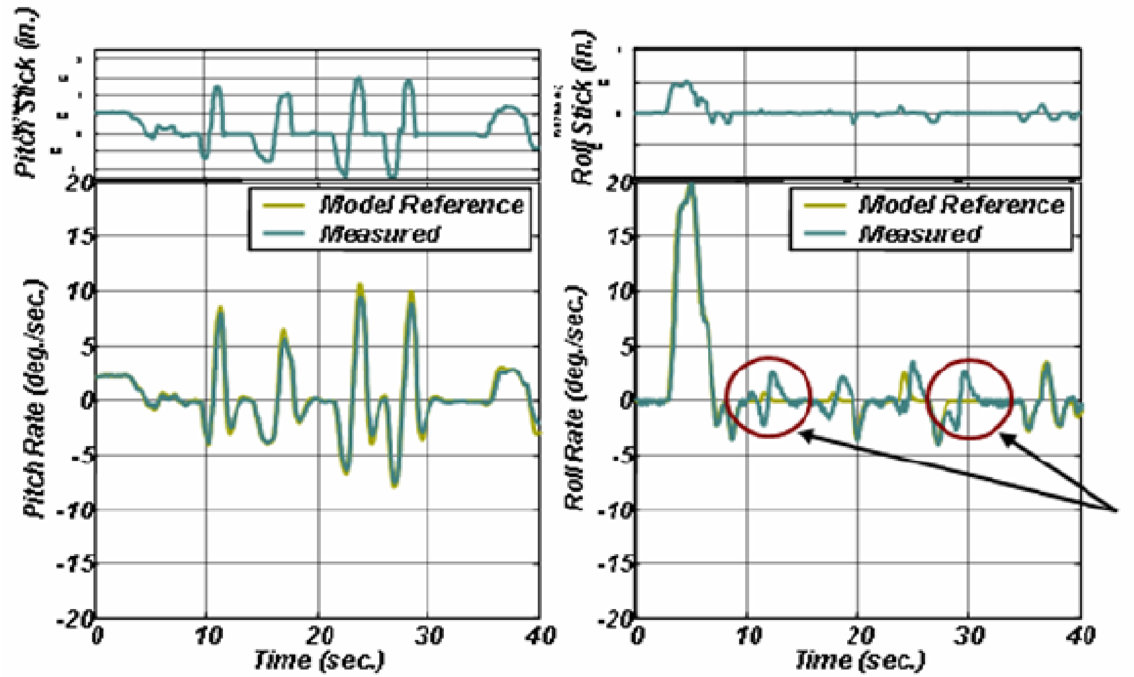

Figure 22: RCLAWS, +15 degree aileron failure, Pitch Doublets

Source: Monaco, J., “Retrofit Reconfigurable Control System for the F/A-18:Design and Flight Testing of Adaptive Flight Control Systems for Existing Aircraft,” Draft Report, March 2006.

ADDITIONAL RCLAWS CONTRIBUTION TO THE F/A-18C

Pilot feedback indicates that for a platform as robust as the F/A-18C, the greatest advantage of the RCLAWS is realized at the onset of the failure. While a modest improvement in handling qualities was seen during post-failure maneuvering, the author believes the greatest benefit is the system's ability to immediately recognize a departure of aircraft motion from that commanded, and to apply control inputs to compensate. Without RCLAWS engaged, the pilot was sometimes surprised by the magnitude of the motion resulting from an inserted failure, even though the failure was expected. The pilot often spent a significant amount of time reacquiring straight and level flight and trimming the aircraft to zero rates (if zero rates were within the trim capability of the failed system). With RCLAWS engaged, however, failure insertion was often transparent to the pilot, and any change in aircraft dynamics was only noticed upon maneuvering. The almost indistinguishable insertion of the failures will be very beneficial in the real world application, chapter 8.

This was also noticed in the simulator during the single engine exercises. Although the rudder pedal contributions were due to the rudder pedal modification vice reconfigurable control, there was no appreciable directional or lateral component to corrections for power additions with RCLAWS active vice a significant requirement without RCLAWS. This would be even more dramatic of a difference in a non-centerline mounted multiengine aircraft such as the C-17 with a fully capable retrofit algorithm.

Chapter 8: F/A-18C Real World Fleet Applications

OVERVIEW

In the past two years, there have been three United States Navy Class A mishaps involving out of control flight associated with flight control effector failures in the F/A-18. The United States Navy defines a Class A mishap as any mishap that causes more than $1 million damage or causes the loss of life. In two of the three incidents the F/A-18 was destroyed at a cost of over $30 million to the government. In the remaining mishap, the F/A-18 was destroyed and a United States Navy pilot also lost his life. All three of these incidents have been partially caused by the mechanical failure of the inboard leading edge flap. In the first two incidents, the pilot lost control at the onset of the failure and it was never fully regained. In the most recent incident, the pilot did not loose control until the aircraft slowed for transition to a landing configuration. Based upon the circumstances of the third incident and the simulations conducted since the incident, this author contends that the aircraft involved in the mishaps remained flyable, not withstanding the major flight control effector failure. Nevertheless, the mishaps were virtually unavoidable because the pilot could not always learn to control the new aircraft in the short time available prior to loss of control.

LEF FAILURE BACKGROUND

As denoted in the aircraft description in chapter 3, the LEFs are full span in the F/A-18C. The LEFs are separated, however, into two parts at the wing fold joint. These parts are commonly referred to as the inboard LEF and the outboard LEF. Although the inboard and outboard sections of the LEF appear as though they are not physically tied to one another, they are mechanized to operate as a pair and schedule in unison.

Over the 28 year history of the F/A-18 flying in the United States Navy inventory, there have been 14 documented cases of LEF failures. Four of these cases have involved inboard LEF failures (all of which led to a mishap) and the remaining 10 cases have involved outboard LEF failures (all of which landed successfully). Outboard LEF failures are considerably more benign than the inboard LEF failures due in part to their respective sizes and location relative to the remainder of the wing surface. The inboard LEF is approximately twice as large as the outboard LEF. Engineers suspect that the outboard LEF failure has been caused by an asymmetry control unit failure that allows the outboard LEF to reach its structural limit of 55 degrees LEU. Flight characteristics of the failure show that a moderate roll off into the direction of the failure can be easily countered with lateral stick and trim. In several cases, the outboard LEF has even departed the aircraft due to air loads, resulting in no significant adverse handling qualities.

The first inboard LEF failure occurred during developmental testing of the F/A-18 at NAS Patuxent River, Maryland in 1982. Fortunately, the pilot survived and was therefore able to describe not only the failure, but also the aircraft's reduced flying qualities. Engineers determined that the failure was caused by a failed hydraulic drive unit (HDU) spline. As a result of this failure, engineers changed the LEF drive mechanization (HDU spline) to incorporate a brake mechanism that froze the LEF at approximately 4 degrees LEU. This device, referred to as the torque limiter, successfully prevented additional inboard LEF failures for 22 years in United States Navy F/A-18C aircraft. In 2002, however, an F/A-18C flying under normal operating conditions experienced an inboard LEF failure that resulted in the loss of the aircraft. Similarly, twice in early 2006, two F/A-18 aircraft and one pilot were lost due to a failed inboard LEF. An engineering investigation is currently underway to determine the root cause of these mishaps. Regardless of the exact cause of the failure, the air loads will drive the failed control surface to approximately 55 degrees LEU which results in adverse handling qualities and the possibility of out of control fight.

INBOARD LEF FAILURE AND OUT OF CONTROL FLIGHT

In the 2004 and first 2006 mishaps, the aircraft initially departed controlled flight with an abrupt roll in the direction of the failure. The pilot momentarily regained control, but then lost it again with a highly coupled departure and never regained controlled flight. The most recent mishap, however, the aircrew recovered the plane to an upright attitude and flew almost 100 miles prior to departing controlled flight. The most recent mishap demonstrated that, although the aircraft was in a failure state, the highly redundant flight control system allowed the aircraft to transit a considerable distance. In the end, however, the aircraft and pilot succumbed to new dynamics and departed controlled flight.

An investigation began to determine why the aircraft was controllable in some conditions and was uncontrollable in others. A group of aircrew from VX-23 at NAS Patuxent River, Maryland and several flying qualities and flight controls engineers sought to recreate the scenario in the MFS facility in order to develop a technique that allowed aircrew to either fly and land the plane, or that at least allowed them additional time to reach a location more conducive to rescue. Replicating the failed surface in the MFS was not as easy a task as first thought. The aerodynamic models used to simulate the flying qualities of the aircraft were not thought to exist for such a dramatic failure. Developing those models would have been time intensive and very difficult. Fortunately, NASA possessed the required aerodynamic models and allowed the United States Navy to use them in the analysis. NASA developed these aerodynamic failure models for use with their Active Aeroelastic Wing (AAW) program flown on the F/A-18. With these flying qualities models in place in the high fidelity simulators at MFS, the engineers and aircrew were able to recreate the scenarios and determine a possible reason for the immediate loss of control in two cases, yet the ability to continue flight for a period of time in the third case.

During the MFS sessions, the team observed that the aircraft was flying at greater than 300 KCAS when the LEF failed in all three cases. Upon failure, the aircraft began a rapid roll into the direction of the failed surface. The roll rate was controllable with lateral control inputs. In all three of the recent cases, the aircraft was able to return to upright, mostly straight and level flight. In two of the three cases, however, the aircraft began to slow down. At approximately 275 to 300 KCAS, the aircraft departed controlled flight and the pilot was unable to regain control. The simulation at MFS showed these exact traits. Upon further investigation and diagnosis of the flight control position relative to the control stick position, the team observed that the aircrew needed a cross controlled input to maintain a wings level attitude and a constant heading when the aircraft slowed below 300 KCAS. The team concluded that lateral stick was required opposite the failed wing flap to oppose roll off, and that a rudder input in the direction of the failure was required to prevent a constant skidded turn opposite the failure.

Most F/A-18 pilots would agree that the Hornet has a superior ability to maneuver in all portions of the envelope. This maneuverability is due in large part to the extremely complex flight control system that determines the correct flight control position for a commanded stick and rudder input. The flight controls surfaces are very autonomous in the F/A-18. For example, both the LEF and TEF schedule automatically with changing airspeed and AOA. In addition, a rolling surface to rudder interconnect (RSRI) provides for turn coordination automatically. In the case of a failed LEF, however, the otherwise extremely helpful flight control system contributed to the departures. As mentioned above, the aircrew had to command a cross controlled input to maintain straight and level flight. If the RSRI is functioning, the FCCs interpret any lateral stick input as a commanded turn. The commanded lateral stick automatically commanded rudder deflection into the direction of turn for coordination. This commanded lateral stick adversely affected the flying qualities in two ways. First, without actually being in a turn, that needs rudder for coordination, the commanded rudder is suspected to increase sideslip away from the failure, contributing to the flat turn that builds as airspeed decreases. Second, the RSRI commanded rudder reduced the amount of rudder deflection available to the aircrew to prevent sideslip buildup.

The auto scheduling flaps compound the problem of the RSRI. As one can imagine, if a large obstruction is placed on the leading edge of a wing, it no longer efficiently creates lift. The obstruction, however, would create a large amount of parasitic drag. This rapid reduction of lift and increase in parasitic drag on the failed side has been identified as the possible cause for the rapid roll into the direction of the failure. As the airspeed decreases on a standard wing, the coefficient of lift is typically decreasing along with the induced drag. However, in the case of the F/A-18C wing, the flaps are scheduling to maintain the lift with slowing airspeed. This results in an increasing coefficient of lift and corresponding induced drag on the non-failure side. Conversely, on the failed side, as airspeed decreases, even though there is a large, non-aerodynamic surface impeding airflow, the parasitic drag decreases. As airspeed continues to drop and the functional LEF is scheduled as commanded (as described in chapter 2, the TEFs are frozen with a LEF failure in CR), the induced drag eventually overcomes both the parasitic drag on the failed wing and the rudder authority of the pilot which has been reduced due to the RSRI. The author has concluded that this combination results in a classic adverse yaw departure and aircraft control was lost. In two of the three cases, after control is lost, the outstanding flight control system and departure recovery logic resident in the F/A-18 allowed the aircrew to briefly regain control of the aircraft in a nose low attitude. Once the pilot attempted recovery, however, AOA increased and the flaps again began to auto-schedule, which lead to a re-departure similar to the first.

The solution devised through extensive simulation was to disable all of the “helpful” modes of the F/A-18. The team realized that there was sufficient control power to offset the parasitic drag induced by the failed LEF, as long as the aircraft stayed above approximately 300 KCAS. The new procedure dictated that the pilot maintain 300 KCAS or more (not to exceed 350 KCAS) until the aircraft was switched to a back-up mode, which removed flap scheduling and reduced the gains associated with the RSRI.

This back-up mode is referred to as “gain override.” This mode tells the FCCs to configure the aircraft for set, known conditions regardless the aircraft’s actual conditions. For example, if gain override is selected with the flaps up, the jet configures the aircraft for flight at 35,000 feet, 0.7 Mach number and 2 degrees AOA. In simulation, gain override mode allowed the pilot to reconfigure the aircraft to permit a safe landing. The author and numerous other F/A-18 test pilots attempted flights without performing the gain override procedures without success. In each attempt with gain override, however, although the workload was considerable both at onset and throughout the remainder of the flight, a safe controllable landing was made. As a result of the simulation testing, the gain override procedures were incorporated in the emergency procedures for a LEF failure and distributed to the F/A-18 community to prevent future loss of life.

INBOARD LEF FAILURE AND RECONFIGURABLE FLIGHT CONTROL SIMULATION PLANNING

The RCLAWS program had already begun testing when the two most recent F/A-18 LEF mishaps occurred. Many questions were raised regarding how the capabilities of the RCLAWS architecture would handle the LEF failures. Unfortunately, such a determination was outside the scope of the RCALWS test plan. In light of this limitation, the author set out to determine the effectiveness of the RCLAWS in-line method of reconfiguration and whether or not it would prevent the loss of aircraft and aircrew after the completion of the RCLAWS test program. Once the MFS sessions determined the cause of the departures, several engineers concluded that the RCLAWS in-line method would not be able to maintain aircraft control. Many thought, the utilization of the gain override modes of the FCCs would prevent RCLAWS from maintaining control. Nevertheless, the author still endeavored to demonstrate the system’s response in the simulated environment.

The MFS facility would have been the ideal environment to demonstrate the capabilities of the RCLAWS against this failure with HILS. Unfortunately, two circumstances prevented use of the MFS facility for the HILS. First, was the requirement for the failure mode had to be resident in the failure module of the RCLAWS architecture as written in the FSFCCs. Adding this failure to logic already resident in the software would have required extensive software modifications and was outside the scope of this thesis. Second and more importantly, as previously discussed, the RCLAWS, as implemented on the FSFCCs, are optimized around two airspeeds only (235 KCAS in CR and 8.1 AOA in PA) due to the limited computation space in the 1750A processor. Adequate determination of the feasibility of the RCLAWS to maintain control over the envelope from failure insertion at a tactical airspeed to a simulated landing was outside the capability of the FSFCCs. In addition, as implemented in the FSFCCs, the 701E will not allow the 1750A to arm if gain override has been selected. These factors therefore prevented use of the MFS facility to determine RCLAWS effectiveness against a LEF failure.

Software simulation, however, could provide a means to test RCLAWS response to the catastrophic LEF failure. During the early CASTLE simulations, the test team investigated a LEF failure for a hard over failure in both directions (LEU and LED). However, the LEU failure was limited to 4 degrees LEU, since engineering analysis believed that 4 degrees LEU was the failure mode of that control surface. During these tests, the RCLAWS provided improved or unchanged handling qualities throughout the envelope as shown in Figure A-4 and Figure A-5. Once again, the problem of programming the CASTLE simulator to simulate the desired failure was not without difficulty. The NASA derived aerodynamic models were coded in a different version of CASTLE. Once the software engineers had completed the transformation, the failure was loaded into the CASTLE simulator.

Despite the obvious disadvantage of not being able to perform the simulation at the MFS facility due to FSFCC restrictions, there were several advantages to performing this test in the CASTLE simulator. First, the CASTLE simulations enabled the test team to observe the effect of RCLAWS in a larger operational environment, instead of seeing the effect at only one or two predefined points. In addition, the CASTLE simulator is not resource limited like the 1750A processor on the FSFCCs, and it can incorporate rudder commands into the reconfiguration algorithm. This incorporation allows for a more powerful reconfiguration system. As discussed in chapter 4, there is also the added advantage of incorporating beta feedback into the dynamics module to provide a better reconfiguration response from RCLAWS. Lastly, the CASTLE simulation allows use of reconfigurable flight control with or without gain override selected.

Although there were numerous advantages to the CASTLE simulation, the limited budget for this testing required that tradeoff in the implementation of the RCLAWS algorithm. As set forth in chapter 4, the engineers optimized the CASTLE simulator around seven flight conditions during the simulation test planning. The two flight conditions most similar to the failure flight profile to a landing were the 20,000 feet, 0.7 Mach and the 20,000 feet, 0.3 Mach number. Although it would have been ideal to utilize a larger envelope, budget constraints required performance of the evaluation between these predefined points. Fortunately, the simulator logic utilizes a linear algorithm that allowed a smooth transition to the closest predefined test condition. Therefore, while performing the deceleration from approximately 325 KCAS to a landing speed of approximately 190 KCAS, the RCLAWS used a combination of the two known conditions to interpolate the correct dynamic response. Although this interpolation limited the accuracy of the results, the author contends that these particular test cases and the associated results were comparable to the outcome with a perfect dynamic model of the entire envelope. Finally, unlike the previous flight and HILS results, that this simulation utilized FCS OFP Version 10.5.1 (v10.5.1) instead of v10.1 utilized in the FSFCCs.

INBOARD LEF FAILURE AND RECONFIGURABLE FLIGHT CONTROL SIMULATION SESSION

During the simulation events, the author endeavored to prove that reconfigurable flight control would provide a better aircraft response than the gain override technique to allow for a transit and landing. The simulation tested four different scenarios. The first case simulated the baseline v10.5.1 aircraft without the benefit of RCLAWS to confirm that CASTLE simulation response was similar to both the MFS data and the mishap data. The second case incorporated an all axis reconfigurable algorithm. This algorithm utilized not only the rudders, but also integrated beta feedback into the RCLAWS computations for higher fidelity. The third case utilized the RCLAWS control laws, but in this case the RSRI, thought to contribute to the departures, was disabled. This case attempted to isolate the cause of the departure between the auto scheduling flaps and the RSRI. The final configuration involved RCLAWS with gain override selected. The author tested this scenario to determine if RCLAWS required the use of gain override to perform the required task of transit and a simulated landing. The author also repeated the final case utilizing trim to increase control authority.

The author tested all four scenarios with a fleet representative loadout and gross weight. The loadout flown included three drop tanks, two 1,000 pound bombs and four air to air missiles. The fuel state for these tests was approximately 10,000 pounds. It should be noted, that during MFS sessions in order to get to a speed in which a safe landing could be made, all external stores had to be jettisoned and fuel load adjusted to approximately 3,000 pounds. In order to more accurately demonstrate an average pilot's response to the failure and as dictated in the NATOPS manual, the pilot delayed stores jettison until reaching approximately 245 KCAS and transitioning to a landing configuration. The author utilized the same stores jettison criteria for the CASTLE simulations. In all cases, the right LEF was failed to full deflection LEU (approximately 55 degrees) between 325 and 335 KCAS.

During the baseline case, the aircraft responded similarly to both the mishap events and the MFS sessions with a sharp roll off in the direction of the failure. The author countered the roll with left lateral stick and regained level flight with approximately 2 inches of lateral stick (3 inches is maximum lateral stick deflection). As the aircraft began to slow, the lateral stick increased to full. Slowing below approximately 280 KCAS, the author slowly applied right rudder to stop an approximately 2 degree/second yaw rate. With previous failure experience and prior knowledge of the failure flight characteristics, the author was able to achieve approximately 260 KCAS prior to reaching an unrecoverable departure. At the point of departure, the pilot had applied full lateral stick and full rudder. These results were comparable to the previous MFS sessions and flight mishap data, however, the author was able to get to a slightly slower airspeed after applying multiple practices with LEF failures.

For the second case with the benefits of RCLAWS, the author expected a much lower controllable airspeed prior to departure. At the onset of the failure, the aircraft rolled right approximately 5 degrees and then returned to level flight with no aircrew action. The only failure indications to the pilot were the FCS caution and status page indicating a failed LEF, an aural tone in the headset and the Master Caution. At approximately 300 KCAS, an ITS was performed with extremely positive results (HQR 4). The only notable deviation from a nominal aircraft during the ITS was a slight yaw coupling with a pure pitch input. Slowing the aircraft proved to be a much easier task without having to fight the roll off with almost full lateral stick. RCLAWS commands to the FCCs were comparable to the first case. As the aircraft slowed, a slight left yaw rate developed that was easily countered with slight opposite pedal (approximately 20 pounds). From 250 KCAS to 235 KCAS, the retrofit input to the FCCs was commanding within 1/2 inch of full lateral stick. After slowing to approximately 235 KCAS (below normal jettison airspeed), however, the aircraft departed flight and was unrecoverable. Although the aircraft departed, it was able to attain a slower speed with a considerably reduced workload. Post departure, the RCLAWS continued to supplement the pilot commands even though the author had released the controls in accordance with published procedures and desired to allow the FCCs to utilize the outstanding departure recovery logic to recover the aircraft. This simulation case demonstrated the benefits of in-line reconfiguration in the case of an inboard LEF failure, but also demonstrated a case where the RCLAWS was not non-interfering with the desired aircraft response.

The third case proved to be the most informative for purposes of comparison to the MFS sessions. This third simulation also utilized RCLAWS, however the RSRI was disabled to isolate the LEF scheduling. Again the failure was inserted at approximately 325 KCAS and a slight roll off occurred that corrected itself to level flight with no pilot input. As the aircraft began to slow, a slight (2 degree/second) right yaw rate developed. At approximately 300 KCAS the aircraft departed to the right or into the failure. As the pitch attitude increased nose low and airspeed increased above approximately 320 KCAS, however, the pilot regained aircraft control. A second attempt to slow the aircraft again resulted in a departure. Analysis of the RCLAWS input indicated that the RCLAWS were commanding full lateral stick at the departure with no corresponding rudder input. It is interesting to note, however, that the departure was so abrupt and unexpected that the aircrew could not counter it with full the application of rudder. This case demonstrated that no single factor was the cause of the departures. From the MFS sessions, the consensus was that the departures were partially caused by the RSRI reducing the rudder authority available to oppose sideslip. This simulation showed, however, that without RSRI, the pilots could not slow the aircraft below approximately 300 KCAS. Therefore, it is the author's conclusion that although the RSRI may be a contributing factor to the eventual departure of the aircraft below approximately 250 KCAS, without RSRI, the aircraft is uncontrollable below 300 KCAS. In addition to the frozen flap scheduling commands provided by the gain override mode, the largest contribution to the increased controllability with gain override selected is the reduced, but not eliminated, gains of the RSRI system.

The final case simulated the RCLAWS engaged with gain override selected. As described earlier, this mode freezes the flap scheduling and reduces the RSRI control gains. Again, at the onset of the failure, the aircraft rolled slightly but then corrected without pilot interaction. During the deceleration from 325 KCAS, the pilot performed ITSs approximately every 10 KCAS. Again, a slight directional coupling was detected with pitch inputs. In addition, the author also noted the roll rate to the left was slightly less than the roll rate to the right during the bank to bank rolls. Analysis showed that during the left rolls, the pilot inputs together with the RCLAWS contributions commanded the stick full deflection to the left. This full stick deflection caused the lower roll rates when in a left roll. Nevertheless, the reduced roll rates were adequate to transit and land. Slowing the aircraft to 250 KCAS required no action from the pilot except throttle modulation. Below 250 KCAS, a slight left yaw rate developed that was easily countered with a small application of rudder pedal (approximately 20 pounds). In the end, the pilot slowed the aircraft to approximately 13 degrees AOA (215 KCAS) in the landing configuration, without having to jettison the external stores. Although 215 KCAS is still above an approved landing speed, this performance demonstrated the capabilities of the RCLAWS module in combination with gain override.

After noting the reduced roll rate during the fourth simulation run and recalling that the failure condition could be countered with trim during MFS sessions, the author sought to investigate the effects of trimming out the failure. As described in chapter 3, the RCLAWS modify the pilot inputs to achieve the desired response. The FCCs, however, have the added capability to effectively deflect flight controls through the use of the lateral trim. After inserting the failure, the pilot trimmed left lateral stick so that the RCLAWS module was producing zero command. The pilot repeated the same ITSs at 300 KCAS. This time, the roll rate was approximately equal in both directions. Again, the pilot was able to slow the aircraft to 215 KCAS with stores loaded with no adverse qualities.

INBOARD LEF FAILURES WITH RCLAWS RESULTS

The goal of the simulation testing was to provide the pilot with a better aircraft response to the failure than the current gain override method. The second simulation demonstrated that the RCLAWS alone effectively allowed the aircrew to slow the aircraft to approximately 235 KCAS, airspeed well within the jettison envelope of these stores that conforms with standard controllability check practices. In addition, RCLAWS allowed the aircrew to slow the aircraft by an additional 10 KCAS in comparison to the non-retrofit approach. A stores jettison at approximately 250 KCAS and a subsequent simulated landing established that this configuration was indeed a successful implementation of the RCLAWS to prevent the loss of aircraft and life.

Although the simulation was successful, from approximately 250 KCAS down to 235 KCAS, the RCLAWS module was commanding within approximately 1/2 inch of full lateral deflection. This deflection left the aircrew not only with little maneuverability, but also on the verge of an uncontrollable departure. Once the pilot jettisoned the stores and adjusted the gross weight, the RCLAWS flew an approach similar to a trimmed out non-retrofit approach.

Although the second simulation demonstrated the effectiveness of RCLAWS to allow the pilot to achieve a typical jettison envelope without the use of gain override, the author learned two additional lessons from this simulation. The first lesson reinforced earlier testing results. The author contends that the greatest benefit of RCLAWS occurs at the onset of the failure. Instead of the aircraft violently departing with a snap roll in the direction of the failure, the aircraft rolled slightly into the failed wing yet returned to level flight within 10 seconds with no aircrew input. This aircraft response to failures could significantly benefit the aircrew for several reasons. When an aircraft emergency appears, especially when compounded by an unanticipated aircraft response, the pilot's typical first reaction is to retard the throttles and assess the situation. Unfortunately, in the case of the "smart" flight controls on the F/A-18, slowing the aircraft led to a larger problem due to the auto scheduling flaps and RSRI. With RCLAWS, the aircraft does not depart with the onset of the LEF failure which allows the aircrew to calmly assess the situation and determine the proper course of action.

Closely related to the almost transparent failure insertion, is the reduction in trim requirements with the RCLAWS. This again allows the aircrew to concentrate on diagnosing the situation and developing a plan. In addition, for some aircrew that typically pilot fly by wire aircraft, trimming the aircraft is almost foreign. It was noted that during the MFS sessions, almost one-half of the pilots did not trim out the almost full lateral stick deflection until reminded of that option. For example, during a typical F/A-18 sortie, the author only trims the aircraft if there is a large asymmetric loadout, or for landing. Aircraft with such complex flight control systems rarely require pilot trim to attain the desired flight condition. The RCLAWS rapid identification and response to failure onsets is the most enhancing feature of this reconfigurable flight control system.

The second significant lesson learned occurred during the third and fourth simulations. The rapid departure that occurred at 300 KCAS during the third simulation was very unexpected for two reasons. First, the author had flown this failure approximately fifteen times in the simulated environment. During those simulations, the aircraft was controllable to below 300 KCAS, or if a departure was evident, sideslip would slowly build unlike the rapid, nose slice departure experienced with RSRI off. Second and more importantly with the other departures, the pilot had been holding flight control inputs in that would tell the pilot when a full control deflection was being reached. In the case of RCLAWS, because the pilot has the stick centered for straight and level flight and the RCLAWS module is commanding a lateral stick deflection to oppose the roll off the pilot has no sense of an impending limitation to the control authority.

This realization led to the second significant finding from the simulations. Human factors are integral to this system's successful incorporation into a production aircraft. In a failure situation, the aircrew will need to know the outputs of the RCLAWS to the FCCs. Whether it is simply a stick and rudder plot that is displayed on the DDI when a failure is present, or a numerical output that shows commanded lateral or longitudinal stick deflection, a display is necessary to communicate to the pilot that available control authority is approaching a limit. The final simulation case also demonstrated the importance of human factors. As stated above, the use of trim allowed for increased control authority and improved handling qualities. The direction or magnitude of trim required, however, is not always intuitive, especially for multiple failures. A display for the aircrew, therefore will enable the pilot to reduce the RCLAWS commanded stick deflection with trim and increase the effective control authority.

Lastly, the second simulation case showed that although the RCLAWS are designed to be non-interfering, an out of control flight scenario is currently outside the capabilities of the algorithm. F/A-18 out of control flight procedures dictate that controls are neutralized and no rudder inputs are commanded. However, post departure, the RCLAWS algorithm interpreted the centered control stick and no rudder inputs as straight and level flight when the aircraft was actually out of control. The RCLAWS then commanded rudder inputs to oppose the buildup in sideslip and lateral and longitudinal inputs to counter the pitch and roll oscillations associated with an F/A-18 that is out of control. These commands prevented the production control laws from achieving a rapid recovery. Further research is needed to prevent RCLAWS from interfering with aircraft control in regimes where aircraft dynamics are not sufficiently modeled.

RECOMMENDED RCLAWS IMPLEMENTATION FOR LEF FAILURES

Overall, the simulation showed that indeed, the RCLAWS provided a slight increase in the aircraft handling qualities and allowed the pilot to attain a slower airspeed prior to departing controlled flight. This will allow an inexperienced or more likely, a task overloaded pilot, to concentrate on flying the aircraft with known control inputs instead of commanding almost full lateral stick just to maintain wings level. The reduced workload will allow the aircrew a better likelihood of being able to fly and possibly recover the aircraft. Figure 23 and Figure 24 show the relative workload on the pilot as

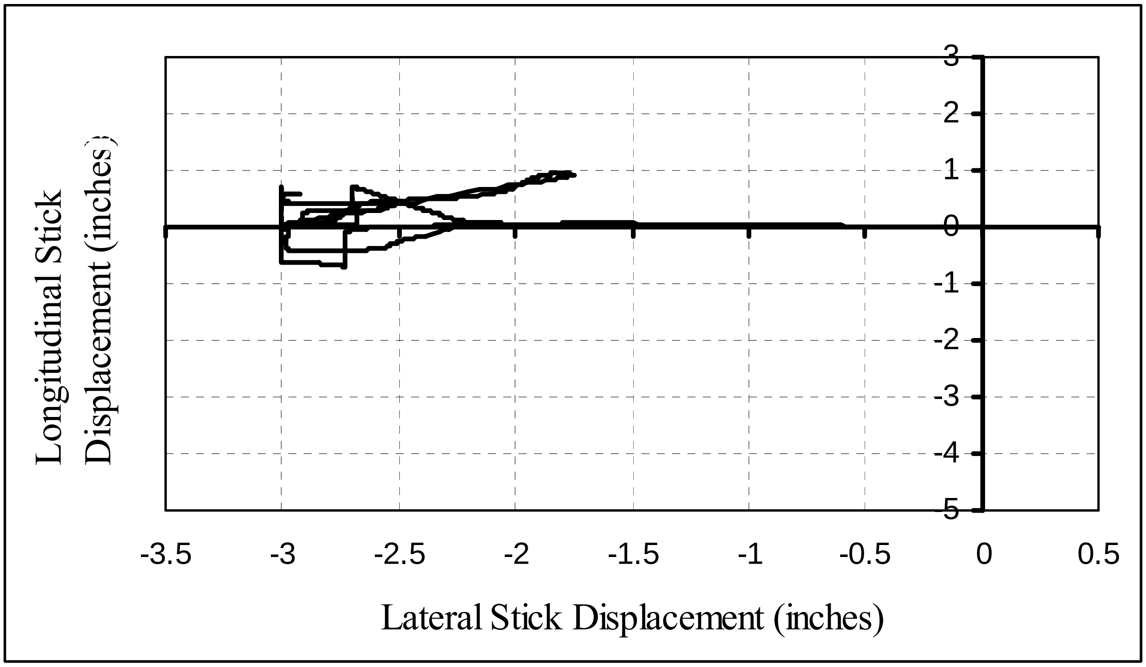

Figure 23: CASTLE Simulation, Pilot Stick Position with Production Control Laws and LEF Failure

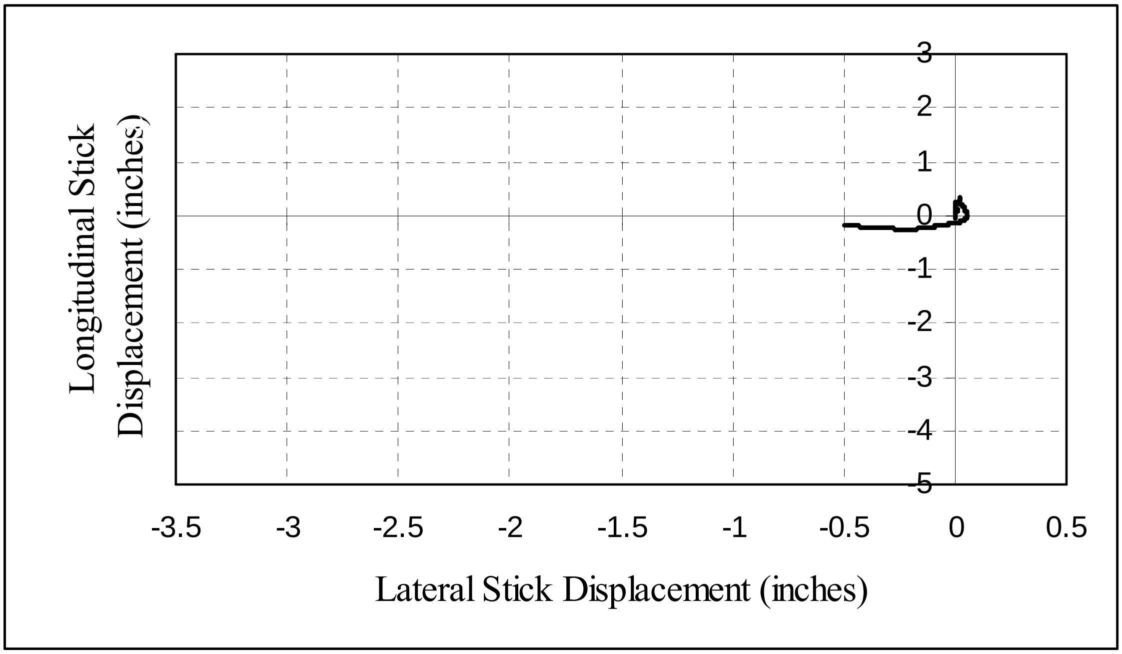

Figure 24: CASTLE Simulation, Pilot Stick Position with RCLAWS and LEF Failure

indicated by the control stick position with production control laws and RCLAWS, respectively. In the figures, only the left lateral stick displacement is shown for clarity. From the figures, it can be concluded that the pilot in command of the RCLAWS aircraft had the benefits of reduced physical workload in the terms of both failure onset and follow on control stick inputs required to maintain level flight. RCLAWS, even in the less powerful in-line configuration, provides a definite improvement over production control laws and should be incorporated into the F/A-18C to prevent future loss of aircraft.

The final simulation with RCLAWS and gain override showed the most promise in terms of the slowest airspeed achieved without the jettison of ordnance and with the least perceived pilot workload. Ideally, an RCLAWS algorithm integrated into the F/A-18C could incorporate the use of gain override when necessary for aircraft control. Unfortunately, the gain override mechanization in the F/A-18C does not allow for selection of gain override throughout the entire flight envelope. For example, if gain override is selected above approximately 350 KCAS, the aircraft begins a divergent pitch oscillation that can result in the loss of the aircraft. There are still several possibilities to incorporate the advantages of gain override without endangering the aircraft and crew. The first is the incorporation a dynamic pressure or airspeed above which the RCLAWS is prohibited from utilizing gain override in its reconfiguration. When the airspeed is below the threshold, the RCLAWS would automatically convert to gain override and display this to the pilot for inclusion in a decision regarding landing. A second method is to simply allow the RCLAWS to transition to gain override only after the pilot selects gain override. The author prefers this implementation because it allows the pilot to remain in the decision matrix on whether or not to select a different gain set. In addition, it allows for a human to make the decision if it is safe to select the backup mode. If an air data failure was present that masked the true airspeed of the aircraft, and gain override was selected outside the known safe envelope, the aircraft would most likely be lost.

Chapter 9: Conclusions and Recommendations

CONCLUSIONS

Unfortunately the RCLAWS do not return a damaged flight control system to its original handling qualities. For example, even with RCLAWS engaged, the handling qualities still averaged a full point lower on the HQR scale for the system with failures. These limitations are partially due to performing the reconfiguration through increments to the pilot commands, instead of the flight control surfaces directly. In addition, testing at low dynamic pressure effectively limits the control power available to the in-line retrofit system. Simulator testing outside of the modified Class B envelope indicates that the greatest advantage of the RCLAWS system over the baseline system is realized at higher Mach numbers with failures of larger magnitude. Nevertheless, RCLAWS demonstrate both quantitative and qualitative improvements over the production system in the limited test envelope.

RCLAWS' greatest contribution to the aircrew was two-fold. First, the reconfiguration algorithm allowed aircrew to pilot the plane in a manner to which they were accustomed. The RCLAWS' contributions from the comparison of the actual aircraft response and the desired aircraft response permitted familiar control inputs to result in familiar aircraft motion. This alleviated the difficult task of learning an aircraft's new dynamics after a flight control effector failure or aircraft damage. Second, the RCLAWS' expeditious response to unanticipated aircraft motion resulting from damage or failure significantly reduced both the workload and the accompanying emotional response of the aircrew. Failures were almost transparent to the aircrew at insertion.

The RCLAWS project also highlighted the importance of two planning factors that should be incorporated into future F/A-18C projects. First, the test team's interaction with the flight clearance process from the beginning of the project substantially contributed to the results achieved. The test team realized from the start of this project that effective communication with, and education of, the flight clearance department and relentless cooperation between the two organizations was vital to the success of this program. The author believes that this unprecedented involvement and coordination by both sides should be adapted for future projects.

Second, the effective use of simulation prior to the flight test portion of the project also led to the success of this program. The piloted software simulation allowed the team to develop control law changes in a cost effective environment, and to determine which flight control effector failures provided the best demonstration of RCLAWS strengths. In addition, proactive use of HILS allowed testing of the actual flight hardware in a high fidelity simulation of the aircraft's expected response. The HILS testing not only allowed the aircrew to become familiar with the expected response, refine test maneuvers execution and practice emergency procedures, but also allowed the ground test team to build an efficient routine that would allow for increased success while airborne. Although simulation and HILS have been used occasionally used during other test programs, this program demonstrated that research projects with a limited budget can gain additional experience and knowledge through more widespread use of simulation and HILS that allows for more efficient programs.

Lastly, the author's investigation into an RCLAWS application to a real world fleet F/A-18C failure revealed that even an aircraft as robust as the F/A-18C can benefit from reconfigurable flight control technology. Although the test team developed a technique that allowed the aircraft to recover without the aid of RCLAWS, simulation showed that with RCLAWS, the probability of a successful recovery rose dramatically due to the reduced workload and rapid response of the control laws to a failure. As such, the author contends that incorporation of reconfigurable control law technology into the F/A-18C will save additional lives and aircraft in the future of this platform.

RECOMMENDATIONS

ALL AXIS RECONFIGURABLE CONTROL

Although there was considerable improvement in the handling qualities of the F/A-18C with RCLAWS active instead of inactive, as shown by the flight test results, the simulation results demonstrated that the three input reconfiguration algorithm (lateral and longitudinal stick and rudder) configuration was more capable than the stick only reconfiguration. Even though the simulation established that the reduced benefits of the stick only configuration were acceptable within the Class B envelope, the deficiencies were still noticeable. The rudder pedal modification compromise, although sometimes beneficial, had to be secured for half of the testing due to undesirable effects on handling qualities. As shown in the both NRT simulation results and the real life application, the importance of the rudder pedal in the algorithm is significant when outside the Class B envelope. Therefore, future testing should include the benefits of all axis reconfiguration.

INCREASE TEST ENVELOPE

The modified Class B envelope significantly helped to reduce the flight clearance issues and increase the overall safety margin afforded to this program. Simulation and flight test results, however, demonstrated that increasing dynamic pressure resulted in increased control power and thus reconfiguration opportunities. The flight tests with RCLAWS during this program showed that the software is stable and highly unlikely to command a flight control surface that would cause an aircraft overstress. Future testing, even with FSFCCs, should be conducted in an expanded envelope to show the true capability of RCLAWS to recognize and react to a flight control failure.

AIRCRAFT INCORPORATION

Although the in-line method of reconfiguration is still in its infancy, there are many benefits that could be realized by its incorporation into any fly by wire aircraft. The in-line method, however, still requires verification and validation prior to production incorporation. If this method proves to be easier to certify, installation into aircraft could yield positive results. Even though the parallel method is more powerful, the in-line method could be a stepping stone that saves aircraft and lives in the near future. The flight tests with minor failures, and subsequent simulation testing with an actual fleet representative failure that caused multiple mishaps, demonstrated this method's potential on the highly redundant F/A-18. Future application in both the military and the commercial sector of aviation could benefit greatly from application of the in-line approach used during this testing.

THRUST CONTRIBUTIONS

Several programs in recent years have capitalized on the lessons learned in the Sioux City crash of United Airlines flight 232, and utilized thrust in the reconfiguration algorithm. In 1995, an MD-11 landed safely despite sole control from differential and symmetric thrust from the engines (Tomayako, 2003). Propulsive effects are another powerful tool that can be used for reconfiguration. With the increasing use of full authority digital engine control (FADEC) in both civilian and military aviation, electrical control of the engine could lead to an even more powerful reconfiguration algorithm. The propulsive effects are slightly less on a fighter aircraft such as the F/A-18 because of the location of the engines relative to the center of gravity. Nevertheless, the engine effects are still beneficial and should be incorporated into future retrofit reconfigurable algorithms on fighter aircraft as demonstrated in the successful landing of the F-15 ACTIVE aircraft under only propulsive affects. Propulsive contributions are more substantial on a wide body aircraft such as the C-17 or most commercial passenger aircraft. Unfortunately, this method would also likely result in greater certification requirements.

FUTURE OF FSFCC TESTING

The FSFCCs provided a relatively easy, cost effective method to test flight control software. The flight critical nature of the remainder of the envelope required the use of these innovative devices. Unfortunately, these FCCs were designed and built over seven years ago. Vast improvements in technology have been made since then that should allow for increased capabilities in the memory capacity and thus functionality of the FSFCCs. With a more capable system, the test team could have easily tested a larger portion of the envelope, even within the modified Class B envelope. In addition, with a higher computing capacity, the FSFCCs should be able to incorporate all of the latest safety improvements that have been incorporated into FCS OFP v10.7. Such incorporation would allow for increased safety while testing with the FSFCCs. Lastly, an increase in processing capacity of the FSFCCs would allow for a stick and rudder algorithm that has proven to be more powerful over a wider range of conditions than the stick only algorithm. Even without improvements, however, test teams should utilize the FSFCCs for future research projects, especially those with fiscal constraints or tight deadlines.

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22. Kelly, M., “Pilot Daily Flight Report for RCLAWS Flight 4,” via email, 16 February 2006.

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Appendices

Appendix A: FIGURES

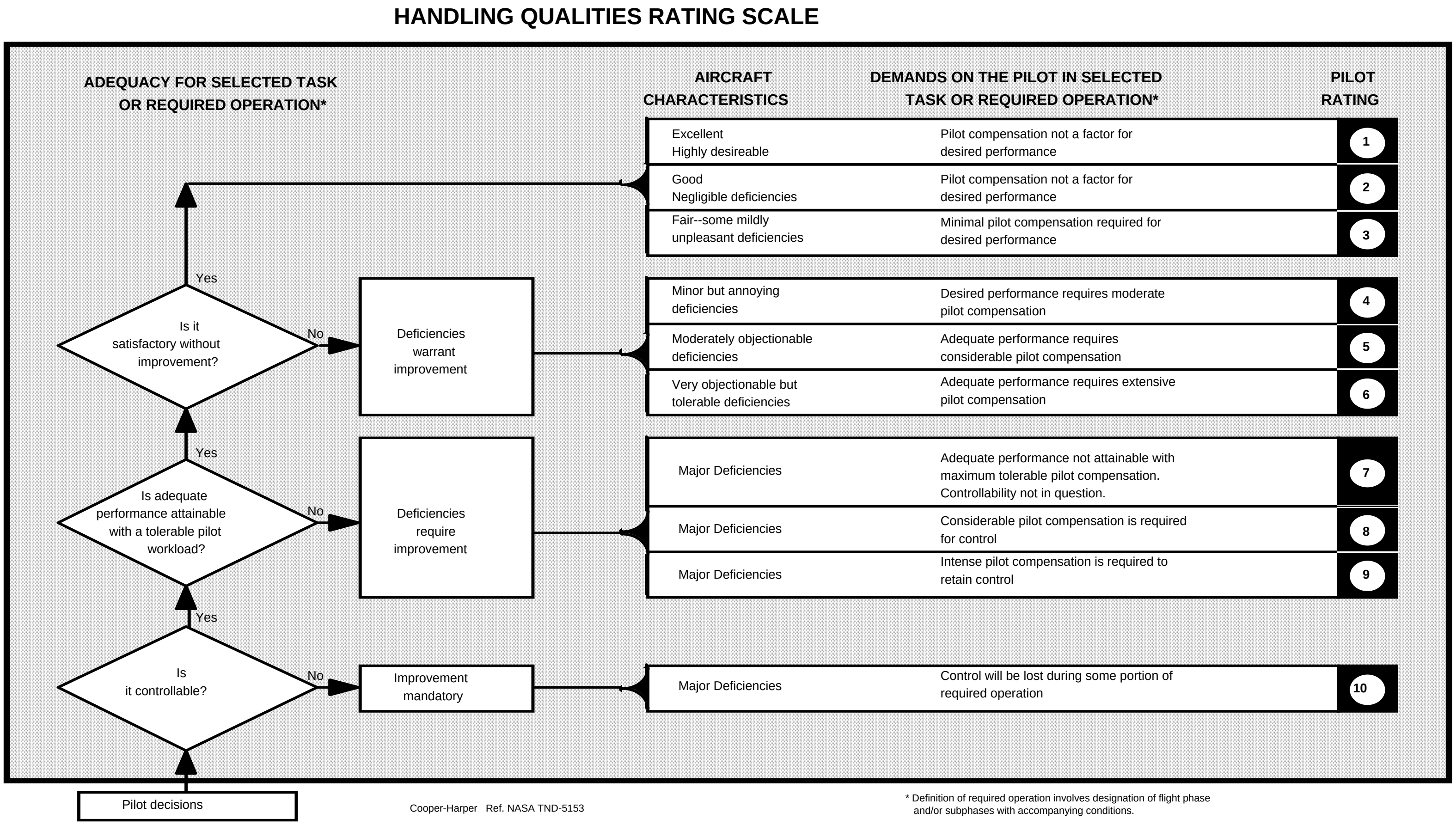


Figure A-1 Cooper Harper Handling Qualities Rating Scale

Source: Cooper, G. E.; and Harper, R. P., Jr.: “The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities,” NASA TN D-5153, April 1969.

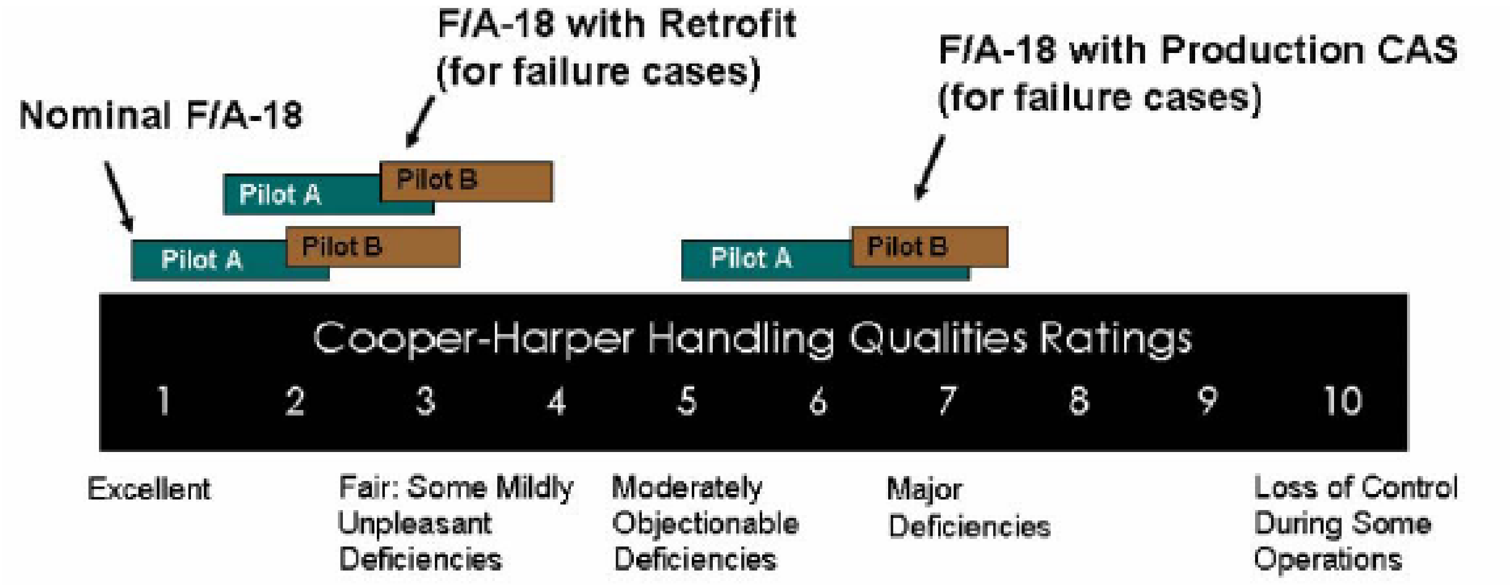
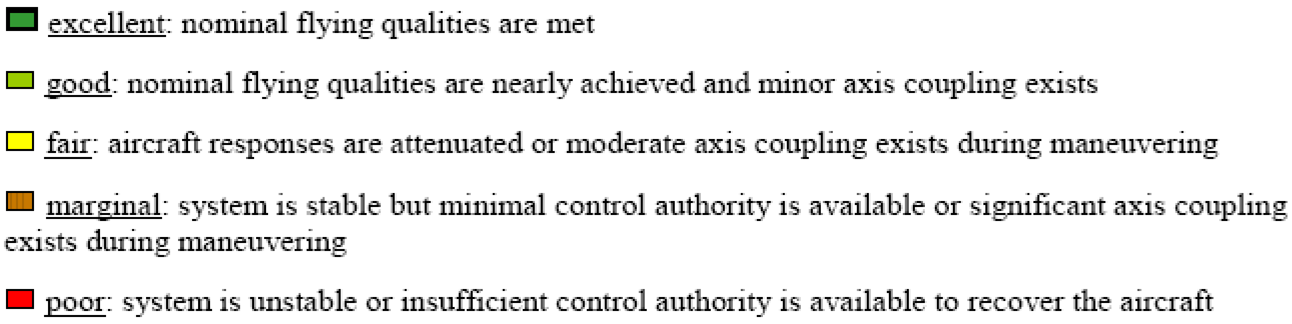


Figure A-2: Combined Piloted Simulation HQRs

Source: Monaco, J., Ward, D., and Bateman, A., "A Retrofit Architecture for Model-Based Adaptive Flight Control," AIAA 2004-6281, AIAA 1st Intelligent Systems Technical Conference, Chicago, IL, September 2004.



🟩 excellent: nominal flying qualities are met

🟩 good: nominal flying qualities are nearly achieved and minor axis coupling exists

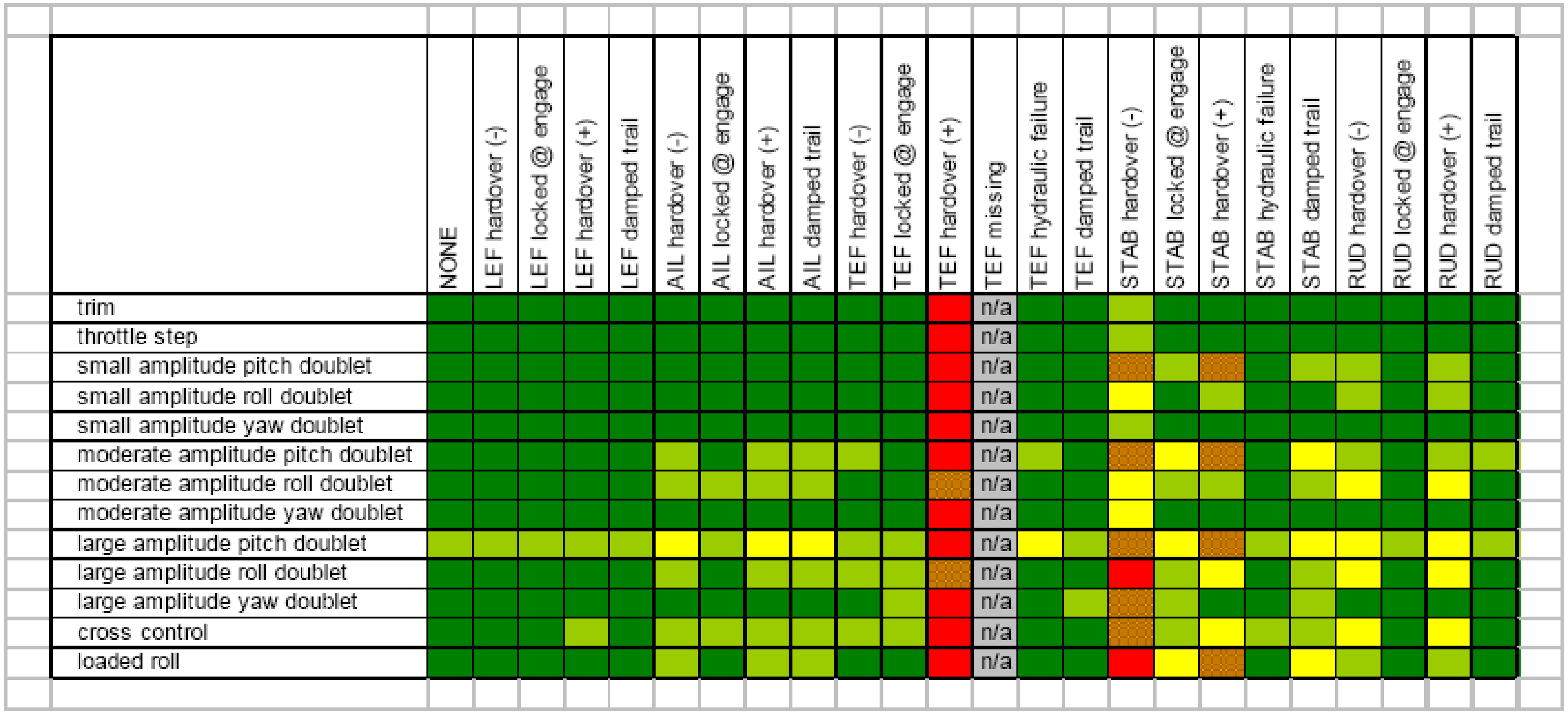
🟨 fair: aircraft responses are attenuated or moderate axis coupling exists during maneuvering

🟫 marginal: system is stable but minimal control authority is available or significant axis coupling exists during maneuvering

🟥 poor: system is unstable or insufficient control authority is available to recover the aircraft

Figure A-3: CASTLE Simulation Scoring Criteria

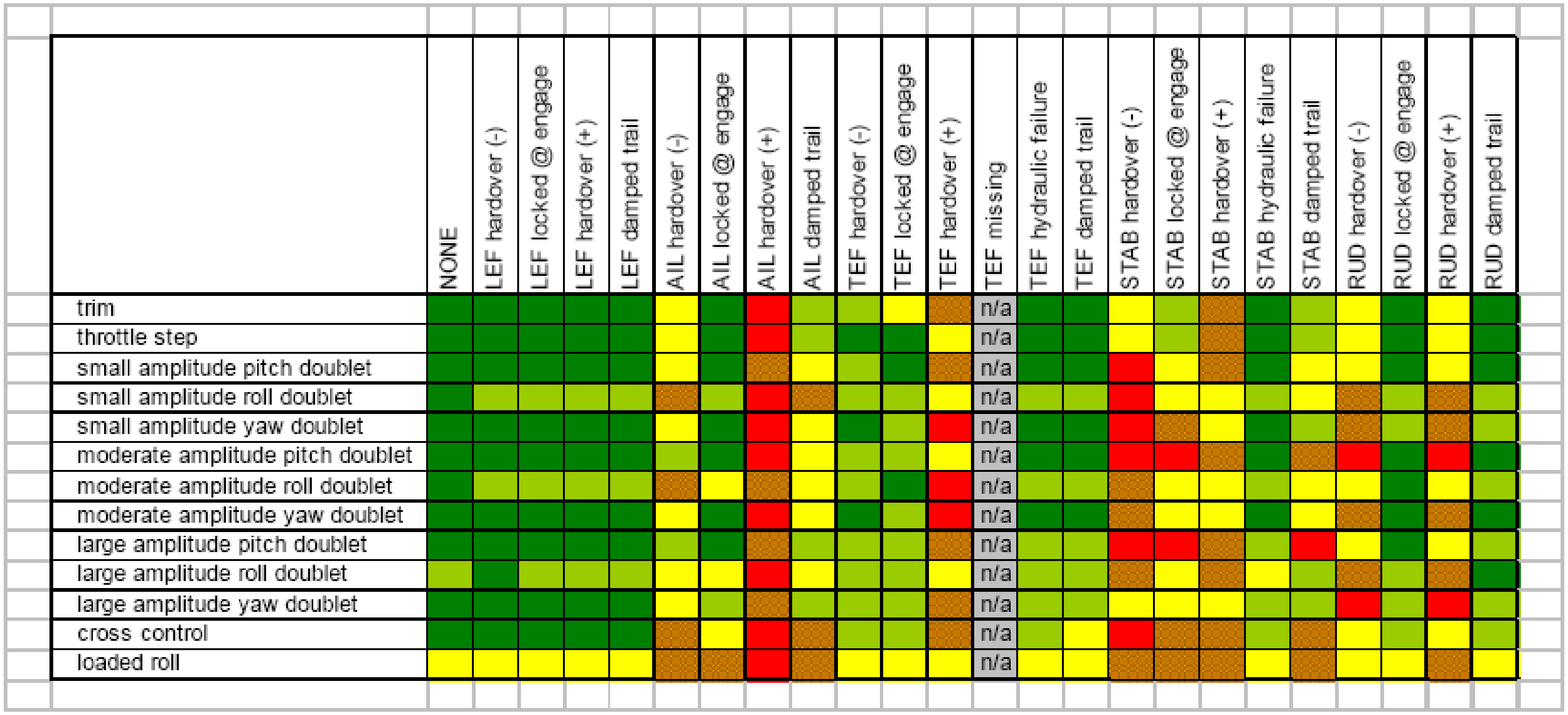
Source: Ward, D., and Monaco, J., "System Identification for Retrofit Reconfigurable Control of an F/A-18," Journal of Aircraft, Vol. 42, No. 1, 2005, pp. 63-72.



	NONE	LEF hardover (-)	LEF locked @ engage	LEF hardover (+)	LEF damped trail	AIL hardover (-)	AIL locked @ engage	AIL hardover (+)	AIL damped trail	TEF hardover (-)	TEF locked @ engage	TEF hardover (+)	TEF missing	TEF hydraulic failure	TEF damped trail	STAB hardover (-)	STAB locked @ engage	STAB hardover (+)	STAB hydraulic failure	STAB damped trail	RUD hardover (-)	RUD locked @ engage	RUD hardover (+)	RUD damped trail
trim	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	n/a	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
throttle step	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	n/a	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
small amplitude pitch doublet	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	n/a	🟩	🟩	🟧	▨	🟧	🟩	▨	▨	🟩	▨	🟩
small amplitude roll doublet	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	n/a	🟩	🟩	🟨	🟩	▨	🟩	🟩	▨	🟩	▨	🟩
small amplitude yaw doublet	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	n/a	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
moderate amplitude pitch doublet	🟩	🟩	🟩	🟩	🟩	▨	🟩	▨	▨	▨	🟩	🟥	n/a	▨	🟩	🟧	🟨	🟧	🟩	🟨	▨	🟩	▨	▨
moderate amplitude roll doublet	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	🟩	🟩	🟧	n/a	🟩	🟩	🟨	▨	▨	🟩	▨	🟨	🟩	🟨	🟩
moderate amplitude yaw doublet	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	n/a	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
large amplitude pitch doublet	▨	▨	▨	▨	▨	🟨	▨	🟨	🟨	▨	▨	🟥	n/a	🟨	▨	🟧	🟨	🟧	▨	🟨	🟨	▨	🟨	▨
large amplitude roll doublet	🟩	🟩	🟩	🟩	🟩	▨	🟩	▨	▨	▨	▨	🟧	n/a	🟩	🟩	🟥	▨	🟨	🟩	▨	🟨	🟩	🟨	🟩
large amplitude yaw doublet	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟥	n/a	🟩	▨	🟧	▨	🟩	🟩	▨	🟩	🟩	🟩	🟩
cross control	🟩	🟩	🟩	▨	🟩	▨	▨	▨	▨	▨	▨	🟥	n/a	🟩	🟩	🟧	▨	🟨	▨	▨	🟨	🟩	🟨	🟩
loaded roll	🟩	🟩	🟩	🟩	🟩	▨	🟩	▨	▨	🟩	🟩	🟥	n/a	🟩	🟩	🟥	🟨	🟧	🟩	🟨	▨	🟩	▨	🟩

Figure A-4: F/A-18 CASTLE Simulation results for NRT Transonic Test Point (30,000 feet and 0.9 Mach)

Source: Monaco, J., “Retrofit Reconfigurable Control System for the F/A-18:Design and Flight Testing of Adaptive Flight Control Systems for Existing Aircraft,” Draft Report, March 2006.



	NONE	LEF hardover (-)	LEF locked @ engage	LEF hardover (+)	LEF damped trail	AIL hardover (-)	AIL locked @ engage	AIL hardover (+)	AIL damped trail	TEF hardover (-)	TEF locked @ engage	TEF hardover (+)	TEF missing	TEF hydraulic failure	TEF damped trail	STAB hardover (-)	STAB locked @ engage	STAB hardover (+)	STAB hydraulic failure	STAB damped trail	RUD hardover (-)	RUD locked @ engage	RUD hardover (+)	RUD damped trail
trim	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟢	🟢	🟨	🟫	n/a	🟩	🟩	🟨	🟢	🟫	🟩	🟢	🟨	🟩	🟨	🟩
throttle step	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟢	🟩	🟩	🟨	n/a	🟩	🟩	🟨	🟢	🟫	🟩	🟢	🟨	🟩	🟨	🟩
small amplitude pitch doublet	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟫	🟨	🟢	🟩	🟫	n/a	🟩	🟩	🟥	🟨	🟫	🟩	🟨	🟨	🟩	🟨	🟩
small amplitude roll doublet	🟩	🟢	🟢	🟢	🟢	🟫	🟢	🟥	🟫	🟢	🟢	🟨	n/a	🟢	🟢	🟥	🟨	🟨	🟢	🟨	🟫	🟢	🟫	🟢
small amplitude yaw doublet	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟨	🟩	🟢	🟥	n/a	🟩	🟩	🟥	🟫	🟨	🟩	🟢	🟫	🟢	🟫	🟢
moderate amplitude pitch doublet	🟩	🟩	🟩	🟩	🟩	🟢	🟩	🟥	🟨	🟢	🟢	🟨	n/a	🟩	🟩	🟥	🟥	🟫	🟩	🟫	🟥	🟩	🟥	🟩
moderate amplitude roll doublet	🟩	🟢	🟢	🟢	🟢	🟫	🟨	🟫	🟨	🟢	🟩	🟥	n/a	🟢	🟢	🟫	🟨	🟨	🟢	🟨	🟨	🟩	🟨	🟢
moderate amplitude yaw doublet	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟨	🟩	🟢	🟥	n/a	🟩	🟩	🟫	🟨	🟨	🟩	🟨	🟫	🟩	🟫	🟩
large amplitude pitch doublet	🟩	🟩	🟩	🟩	🟩	🟢	🟩	🟫	🟢	🟢	🟢	🟫	n/a	🟢	🟢	🟥	🟥	🟫	🟢	🟥	🟨	🟩	🟨	🟢
large amplitude roll doublet	🟢	🟩	🟢	🟢	🟢	🟨	🟨	🟥	🟨	🟢	🟢	🟨	n/a	🟢	🟢	🟫	🟨	🟫	🟨	🟢	🟫	🟢	🟫	🟩
large amplitude yaw doublet	🟩	🟩	🟩	🟩	🟩	🟨	🟢	🟫	🟢	🟢	🟢	🟫	n/a	🟢	🟢	🟨	🟨	🟨	🟢	🟢	🟥	🟢	🟥	🟢
cross control	🟩	🟩	🟩	🟩	🟩	🟫	🟨	🟥	🟫	🟢	🟢	🟫	n/a	🟢	🟨	🟥	🟫	🟫	🟢	🟫	🟨	🟢	🟨	🟢
loaded roll	🟨	🟨	🟨	🟨	🟨	🟫	🟫	🟥	🟫	🟨	🟨	🟨	n/a	🟨	🟨	🟫	🟫	🟫	🟨	🟫	🟨	🟨	🟫	🟨

Figure A-5: F/A-18 CASTLE Simulation results for NRT Class B Test Point (20,000 feet and 0.3 Mach)

Source: Monaco, J., “Retrofit Reconfigurable Control System for the F/A-18:Design and Flight Testing of Adaptive Flight Control Systems for Existing Aircraft,” Draft Report, March 2006.

Appendix B: TABLES

Table B-1: Envelope Engage Limits

Parameter		Upper Engage Limit	Lower Engage Limit
Pitch Rate (degrees/sec)	PA Entry 1	5.0	-5.0
	PA Entry 2	**10.0**	**-10.0**
	PA Entry 3	15.0	-15.0
	UA Entry 1	15.0	-15.0
	UA Entry 2	**30.0**	**-30.0**
	UA Entry 3	50.0	-50.0
Roll Rate (degrees/sec)	PA Entry 1	20.0	-20.0
	PA Entry 2	**40.0**	**-40.0**
	PA Entry 3	60.0	-60.0
	UA Entry 1	100.0	-100.0
	UA Entry 2	**150.0**	**-150.0**
	UA Entry 3	200.0	-200.0
Yaw Rate (degrees/sec)	PA Entry 1	5.0	-5.0
	PA Entry 2	**10.0**	**-10.0**
	PA Entry 3	15.0	-15.0
	UA Entry 1	5.0	-5.0
	UA Entry 2	15.0	-15.0
	UA Entry 3	**25.0**	**-25.0**
Normal Acceleration (g-s)	PA Entry 1	1.5	0.5
	PA Entry 2	1.8	0.2
	PA Entry 3	**2.0**	**0.0**
	UA Entry 1	3.0	0.0
	UA Entry 2	**4.0**	**-1.0**
	UA Entry 3	5.0	-2.0
Lateral Acceleration (g-s)	PA Entry 1	0.25	-0.25
	PA Entry 2	**0.5**	**-0.5**
	PA Entry 3	0.75	-0.75
	UA Entry 1	**0.5**	**-0.5**
	UA Entry 2	0.75	-0.75
	UA Entry 3	1.0	-1.0

Table B-1: continued

Parameter		Upper Engage Limit	Lower Engage Limit
Angle-of-Attack (degrees)	PA Entry 1	10.0	5.0
	PA Entry 2	**15.0**	**0.0**
	PA Entry 3	20.0	-5.0
	UA Entry 1	**30.0**	0.0
	UA Entry 2	35.0	**-5.0**
	UA Entry 3	40.0	-10.0
Impact Pressure (psf)	PA Entry 1	85	28
	PA Entry 2	**140**	**50**
	PA Entry 3	213	67
	UA Entry 1	204	35
	UA Entry 2	**213**	**40**
	UA Entry 3	219	60
Static Pressure (psf)	PA Entry 1	1360	785
	PA Entry 2	**1455**	**975**
	PA Entry 3	1540	1195
	UA Entry 1	975	540
	UA Entry 2	**1195**	**630**
	UA Entry 3	1760	730
Bank Angle (degrees)	PA Entry 1	45	-45
	PA Entry 2	**60**	**-60**
	PA Entry 3	90	-90
	UA Entry 1	45	-45
	UA Entry 2	60	-60
	UA Entry 3	**90**	**-90**
Altitude (feet)	PA Entry 1	25000	10000
	PA Entry 2	**30000**	**12000**
	PA Entry 3	35000	15000
	UA Entry 1	25000	10000
	UA Entry 2	**30000**	**12000**
	UA Entry 3	35000	15000

Notes: (1) **Boldfaced parameters** are engaged by default and will remain engaged throughout the test program.

(2) **Boldfaced limits** are defaults.

(3) Grayed-out entries are outside of other limits (NATOPS, Flight Clearance, modified Class B), and will not be used.

Table B-2: System Status Arming and Engaging Criteria

Criterion*	701E-monitored Arm Criterion	701E-monitored Engage Criterion	1750A-monitored Engage Criterion
AOA/Air Data Fail	X	X	
1750A No Go Indication	X	X	
Actuator Failure	X	X	
Dual Discrete Fail	X	X	
Quad Discrete Fail	X	X	
Quad Sensor Fail	X	X	
1750A Processor Failures	X	X	
Dual Port Ram Invalid	X	X	
MUX Bus Invalid	X	X	
DEL/MECH Mode Engaged	X	X	
Master Caution set by FCC	X	X	
Channel OFF	X	X	
RFCS Data Not Ready		X	
RFCS Command not Valid		X	
Manual SPIN Selected			X
SPIN Mode			X
Heading Hold Requested or Engaged			X

* All parameters must be false to arm or engage.

Table B-3: FSFCC Version 3.1.6 Mode Selections

Sequence	Table Number	Row Number	Description
A	0	0	Slimmed F/A-18 Replication Mode
CBBB	1	0	Pitch Rate Check Enabled
CBBC	1	1	Pitch Rate Check Disabled
CBBD	1	2	Reset Pitch Rate Parameters to Nominal Values
CBCB	1	3	Pitch Rate Upper Engage Limit Table UA Entry 1
CBCC	1	4	Pitch Rate Upper Engage Limit Table UA Entry 2
CBCD	1	5	Pitch Rate Upper Engage Limit Table UA Entry 3
CBDB	1	6	Pitch Rate Upper Engage Limit Table PA Entry 1
CBDC	1	7	Pitch Rate Upper Engage Limit Table PA Entry 2
CBDD	1	8	Pitch Rate Upper Engage Limit Table PA Entry 3
CCBB	1	9	Pitch Rate Lower Engage Limit Table UA Entry 1
CCBC	1	10	Pitch Rate Lower Engage Limit Table UA Entry 2
CCBD	1	11	Pitch Rate Lower Engage Limit Table UA Entry 3
CCCB	1	12	Pitch Rate Lower Engage Limit Table PA Entry 1
CCCC	1	13	Pitch Rate Lower Engage Limit Table PA Entry 2
CCCD	1	14	Pitch Rate Lower Engage Limit Table PA Entry 3
DBBB	2	0	Roll Rate Check Enabled
DBBC	2	1	Roll Rate Check Disabled
DBBD	2	2	Reset Roll Rate Parameters to Nominal Values
DBCB	2	3	Roll Rate Upper Engage Limit Table UA Entry 1
DBCC	2	4	Roll Rate Upper Engage Limit Table UA Entry 2
DBCD	2	5	Roll Rate Upper Engage Limit Table UA Entry 3
DBDB	2	6	Roll Rate Upper Engage Limit Table PA Entry 1
DBDC	2	7	Roll Rate Upper Engage Limit Table PA Entry 2
DBDD	2	8	Roll Rate Upper Engage Limit Table PA Entry 3
DCBB	2	9	Roll Rate Lower Engage Limit Table UA Entry 1
DCBC	2	10	Roll Rate Lower Engage Limit Table UA Entry 2
DCBD	2	11	Roll Rate Lower Engage Limit Table UA Entry 3
DCCB	2	12	Roll Rate Lower Engage Limit Table PA Entry 1
DCCC	2	13	Roll Rate Lower Engage Limit Table PA Entry 2
DCCD	2	14	Roll Rate Lower Engage Limit Table PA Entry 3
CBBBB	3	0	Yaw Rate Check Enabled
CBBBC	3	1	Yaw Rate Check Disabled
CBBBD	3	2	Reset Yaw Rate Parameters to Nominal Values
CBBCB	3	3	Yaw Rate Upper Engage Limit Table UA Entry 1
CBBCC	3	4	Yaw Rate Upper Engage Limit Table UA Entry 2
CBBCD	3	5	Yaw Rate Upper Engage Limit Table UA Entry 3
CBBDB	3	6	Yaw Rate Upper Engage Limit Table PA Entry 1
CBBDC	3	7	Yaw Rate Upper Engage Limit Table PA Entry 2
CBBDD	3	8	Yaw Rate Upper Engage Limit Table PA Entry 3
CBCBB	3	9	Yaw Rate Lower Engage Limit Table UA Entry 1
CBCBC	3	10	Yaw Rate Lower Engage Limit Table UA Entry 2

Table B-3. Continued.

Sequence	Table Number	Row Number	Description
BCBD	3	11	Yaw Rate Lower Engage Limit Table UA Entry 3
CBCCB	3	12	Yaw Rate Lower Engage Limit Table PA Entry 1
CBCCC	3	13	Yaw Rate Lower Engage Limit Table PA Entry 2
CBCCD	3	14	Yaw Rate Lower Engage Limit Table PA Entry 3
CCBBB	4	0	Nz Check Enabled
CCBBC	4	1	Nz Check Disabled
CCBBD	4	2	Reset Nz Parameters to Nominal Values
CCBCB	4	3	Nz Upper Engage Limit Table UA Entry 1
CCBCC	4	4	Nz Upper Engage Limit Table UA Entry 2
CCBCD	4	5	Nz Upper Engage Limit Table UA Entry 3
CCBDB	4	6	Nz Upper Engage Limit Table PA Entry 1
CCBDC	4	7	Nz Upper Engage Limit Table PA Entry 2
CCBDD	4	8	Nz Upper Engage Limit Table PA Entry 3
CCCBB	4	9	Nz Lower Engage Limit Table UA Entry 1
CCCBC	4	10	Nz Lower Engage Limit Table UA Entry 2
CCCBD	4	11	Nz Lower Engage Limit Table UA Entry 3
CCCCB	4	12	Nz Lower Engage Limit Table PA Entry 1
CCCCC	4	13	Nz Lower Engage Limit Table PA Entry 2
CCCCD	4	14	Nz Lower Engage Limit Table PA Entry 3
CDBBB	5	0	Lateral Acceleration Check Enabled
CDBBC	5	1	Lateral Acceleration Check Disabled
CDBBD	5	2	Reset Lateral Acceleration Parameters to Nominal Values
CDBCB	5	3	Lateral Acceleration Upper Engage Limit Table UA Entry 1
CDBCC	5	4	Lateral Acceleration Upper Engage Limit Table UA Entry 2
CDBCD	5	5	Lateral Acceleration Upper Engage Limit Table UA Entry 3
CDBDB	5	6	Lateral Acceleration Upper Engage Limit Table PA Entry 1
CDBDC	5	7	Lateral Acceleration Upper Engage Limit Table PA Entry 2
CDBDD	5	8	Lateral Acceleration Upper Engage Limit Table PA Entry 3
CDCBB	5	9	Lateral Acceleration Lower Engage Limit Table UA Entry 1
CDCBC	5	10	Lateral Acceleration Lower Engage Limit Table UA Entry 2
CDCBD	5	11	Lateral Acceleration Lower Engage Limit Table UA Entry 3
CDCCB	5	12	Lateral Acceleration Lower Engage Limit Table PA Entry 1
CDCCC	5	13	Lateral Acceleration Lower Engage Limit Table PA Entry 2

Table B-3. Continued.

Sequence	Table Number	Row Number	Description
CDCCD	5	14	Lateral Acceleration Lower Engage Limit Table PA Entry 3
DBBBB	6	0	Angle-of-Attack Check Enabled
DBBBC	6	1	Angle-of-Attack Check Disabled
DBBBD	6	2	Reset Angle-of-Attack Parameters to Nominal Values
DBBCB	6	3	Angle-of-Attack Upper Engage Limit Table UA Entry 1
DBBCC	6	4	Angle-of-Attack Upper Engage Limit Table UA Entry 2
DBBCD	6	5	Angle-of-Attack Upper Engage Limit Table UA Entry 3
DBBDB	6	6	Angle-of-Attack Upper Engage Limit Table PA Entry 1
DBBDC	6	7	Angle-of-Attack Upper Engage Limit Table PA Entry 2
DBBDD	6	8	Angle-of-Attack Upper Engage Limit Table PA Entry 3
DBCBB	6	9	Angle-of-Attack Lower Engage Limit Table UA Entry 1
DBCBC	6	10	Angle-of-Attack Lower Engage Limit Table UA Entry 2
DBCBD	6	11	Angle-of-Attack Lower Engage Limit Table UA Entry 3
DBCCB	6	12	Angle-of-Attack Lower Engage Limit Table PA Entry 1
DBCCC	6	13	Angle-of-Attack Lower Engage Limit Table PA Entry 2
DBCCD	6	14	Angle-of-Attack Lower Engage Limit Table PA Entry 3
DCBBB	7	0	Impact Pressure Check Enabled
DCBBC	7	1	Impact Pressure Check Disabled
DCBBD	7	2	Reset Impact Pressure Parameters to Nominal Values
DCBCB	7	3	Impact Pressure Upper Engage Limit Table UA Entry 1
DCBCC	7	4	Impact Pressure Upper Engage Limit Table UA Entry 2
DCBCD	7	5	Impact Pressure Upper Engage Limit Table UA Entry 3
DCBDB	7	6	Impact Pressure Upper Engage Limit Table PA Entry 1
DCBDC	7	7	Impact Pressure Upper Engage Limit Table PA Entry 2
DCBDD	7	8	Impact Pressure Upper Engage Limit Table PA Entry 3
DCCBB	7	9	Impact Pressure Lower Engage Limit Table UA Entry 1
DCCBC	7	10	Impact Pressure Lower Engage Limit Table UA Entry 2
DCCBD	7	11	Impact Pressure Lower Engage Limit Table UA Entry 3
DCCCB	7	12	Impact Pressure Lower Engage Limit Table PA Entry 1
DCCCC	7	13	Impact Pressure Lower Engage Limit Table PA Entry 2
DCCCD	7	14	Impact Pressure Lower Engage Limit Table PA Entry 3
DDBBB	8	0	Static Pressure Check Enabled
DDBBC	8	1	Static Pressure Check Disabled
DDBBD	8	2	Reset Static Pressure Parameters to Nominal Values
DDBCB	8	3	Static Pressure Upper Engage Limit Table UA Entry 1
DDBCC	8	4	Static Pressure Upper Engage Limit Table UA Entry 2
DDBCD	8	5	Static Pressure Upper Engage Limit Table UA Entry 3
DDBDB	8	6	Static Pressure Upper Engage Limit Table PA Entry 1
DDBDC	8	7	Static Pressure Upper Engage Limit Table PA Entry 2
DDBDD	8	8	Static Pressure Upper Engage Limit Table PA Entry 3
DDCBB	8	9	Static Pressure Lower Engage Limit Table UA Entry 1
DDCBC	8	10	Static Pressure Lower Engage Limit Table UA Entry 2

Table B-3. Continued.

Sequence	Table Number	Row Number	Description
DDCBD	8	11	Static Pressure Lower Engage Limit Table UA Entry 3
DDCCB	8	12	Static Pressure Lower Engage Limit Table PA Entry 1
DDCCC	8	13	Static Pressure Lower Engage Limit Table PA Entry 2
DDCCD	8	14	Static Pressure Lower Engage Limit Table PA Entry 3
CBBBBB	9	0	Bank Angle Check Enabled
CBBBBC	9	1	Bank Angle Check Disabled
CBBBBD	9	2	Reset Bank Angle Parameters to Nominal Values
CBBBCB	9	3	Bank Angle Upper Engage Limit Table UA Entry 1
CBBBCC	9	4	Bank Angle Upper Engage Limit Table UA Entry 2
CBBBCD	9	5	Bank Angle Upper Engage Limit Table UA Entry 3
CBBBDB	9	6	Bank Angle Upper Engage Limit Table PA Entry 1
CBBBDC	9	7	Bank Angle Upper Engage Limit Table PA Entry 2
CBBBDD	9	8	Bank Angle Upper Engage Limit Table PA Entry 3
CBBCBB	9	9	Bank Angle Lower Engage Limit Table UA Entry 1
CBBCBC	9	10	Bank Angle Lower Engage Limit Table UA Entry 2
CBBCBD	9	11	Bank Angle Lower Engage Limit Table UA Entry 3
CBBCCB	9	12	Bank Angle Lower Engage Limit Table PA Entry 1
CBBCCC	9	13	Bank Angle Lower Engage Limit Table PA Entry 2
CBBCCD	9	14	Bank Angle Lower Engage Limit Table PA Entry 3
CBCBBB	10	0	Altitude Check Enabled
CBCBBC	10	1	Altitude Check Disabled
CBCBBD	10	2	Reset Altitude Parameters to Nominal Values
CBCBCB	10	3	Altitude Upper Engage Limit Table UA Entry 1
CBCBCC	10	4	Altitude Upper Engage Limit Table UA Entry 2
CBCBCD	10	5	Altitude Upper Engage Limit Table UA Entry 3
CBCBDB	10	6	Altitude Upper Engage Limit Table PA Entry 1
CBCBDC	10	7	Altitude Upper Engage Limit Table PA Entry 2
CBCBDD	10	8	Altitude Upper Engage Limit Table PA Entry 3
CBCCBB	10	9	Altitude Lower Engage Limit Table UA Entry 1
CBCCBC	10	10	Altitude Lower Engage Limit Table UA Entry 2
CBCCBD	10	11	Altitude Lower Engage Limit Table UA Entry 3
CBCCCB	10	12	Altitude Lower Engage Limit Table PA Entry 1
CBCCCC	10	13	Altitude Lower Engage Limit Table PA Entry 2
CBCCCD	10	14	Altitude Lower Engage Limit Table PA Entry 3
CCBBBB	12	0	Reset All Parameters to Nominal Values
CCBBBC	12	1	Enable All Limit Checks
CCBBBD	12	2	Disable All Limit Checks
CCCBBB	13	0	Ground Test Mode OFF
CCCBBC	13	1	Ground Test Mode ON - Disable Envelope Checks
CCCBBD	13	2	Ground Test Mode ON

Table B-3. Continued.

Sequence	Table Number	Row Number	Description
	14-19		Not Used
DBDBBB	20	0	Retrofit Gain Set No. 1 (Nominal), Trim Maneuver Mod. Disabled (= 0), Rudder Pedal Mod. Disabled (= 0)
DBDBBC	20	1	Retrofit Gain Set No. 2 (4/3 x Nominal), Trim Maneuver Mod. Disabled (= 0), Rudder Pedal Mod. Disabled (= 0)
DBDBBD	20	2	Retrofit Gain Set No. 2 (5/3 x Nominal), Trim Maneuver Mod. Disabled (= 0), Rudder Pedal Mod. Disabled (= 0)
DBDBDB	20	6	Retrofit Gain Set No. 1 (Nominal), Trim Maneuver Mod. Disabled (= 0), Rudder Pedal Mod. Enabled (= 1)
DBDBDC	20	7	Retrofit Gain Set No. 2 (4/3 x Nominal), Trim Maneuver Mod. Disabled (= 0), Rudder Pedal Mod. Enabled (= 1)
DBDBDD	20	8	Retrofit Gain Set No. 2 (5/3 x Nominal), Trim Maneuver Mod. Disabled (= 0), Rudder Pedal Mod. Enabled (= 1)
DCBBBC	21	1	Retrofit Control Only
DCBBBD	21	2	Retrofit Control Stand Alone Test (Ground Test only)
	22	0-12	FAIL R Stabilator Absolute Failures (not used)
DCCCCC	22	13	FAIL R Stabilator 0 deg Offset
DCCCCD	22	14	FAIL R Stabilator +1 deg Offset
DCCCDB	22	15	FAIL R Stabilator +2 deg Offset
DCCCDC	22	16	FAIL R Stabilator +3 deg Offset
DCCCDD	22	17	FAIL R Stabilator +4 deg Offset
DCCDBB	22	18	FAIL R Stabilator +5 deg Offset
DCCDBC	22	19	FAIL R Stabilator +6 deg Offset
DCCDBD	22	20	FAIL R Stabilator -1 deg Offset
DCCDCB	22	21	FAIL R Stabilator -2 deg Offset
DCCDCC	22	22	FAIL R Stabilator -3 deg Offset
DCCDCD	22	23	FAIL R Stabilator -4 deg Offset
DCCDDB	22	24	FAIL R Stabilator -5 deg Offset
DCCDDC	22	25	FAIL R Stabilator -6 deg Offset
	23	0-12	Retrofit - FAIL R Stabilator Absolute Failures (not used)
DCDCCC	23	13	Retrofit - FAIL R Stabilator 0 deg Offset
DCDCCD	23	14	Retrofit - FAIL R Stabilator +1 deg Offset
DCDCDB	23	15	Retrofit - FAIL R Stabilator +2 deg Offset

Table B-3. Continued.

Sequence	Table Number	Row Number	Description
DCDCDC	23	16	Retrofit - FAIL R Stabilator +3 deg Offset
DCDCDD	23	17	Retrofit - FAIL R Stabilator +4 deg Offset
DCDDBB	23	18	Retrofit - FAIL R Stabilator +5 deg Offset
DCDDBC	23	19	Retrofit - FAIL R Stabilator +6 deg Offset
DCDDBD	23	20	Retrofit - FAIL R Stabilator -1 deg Offset
DCDDCB	23	21	Retrofit - FAIL R Stabilator -2 deg Offset
DCDDCC	23	22	Retrofit - FAIL R Stabilator -3 deg Offset
DCDDCD	23	23	Retrofit - FAIL R Stabilator -4 deg Offset
DCDDDB	23	24	Retrofit - FAIL R Stabilator -5 deg Offset
DCDDDC	23	25	Retrofit - FAIL R Stabilator -6 deg Offset
	24	0-12	FAIL R Aileron Absolute Failures (not used)
DDBCCC	24	13	FAIL R Aileron 0 deg Offset
DDBCCD	24	14	FAIL R Aileron +5 deg Offset
DDBCDB	24	15	FAIL R Aileron +10 deg Offset
DDBCDC	24	16	FAIL R Aileron +15 deg Offset
DDBCDD	24	17	FAIL R Aileron +20 deg Offset
DDBDBB	24	18	FAIL R Aileron +25 deg Offset
DDBDBC	24	19	FAIL R Aileron +30 deg Offset
DDBDBD	24	20	FAIL R Aileron -5 deg Offset
DDBDCB	24	21	FAIL R Aileron -10 deg Offset
DDBDCC	24	22	FAIL R Aileron -15 deg Offset
DDBDCD	24	23	FAIL R Aileron -20 deg Offset
DDBDDB	24	24	FAIL R Aileron -25 deg Offset
DDBDDC	24	25	FAIL R Aileron -30 deg Offset
	25	0-12	Retrofit - FAIL R Aileron Absolute Failures (not used)
DDCCCC	25	13	Retrofit - FAIL R Aileron 0 deg Offset
DDCCCD	25	14	Retrofit - FAIL R Aileron +5 deg Offset
DDCCDB	25	15	Retrofit - FAIL R Aileron +10 deg Offset
DDCCDC	25	16	Retrofit - FAIL R Aileron +15 deg Offset
DDCCDD	25	17	Retrofit - FAIL R Aileron +20 deg Offset
DDCDBB	25	18	Retrofit - FAIL R Aileron +25 deg Offset
DDCDBC	25	19	Retrofit - FAIL R Aileron +30 deg Offset
DDCDBD	25	20	Retrofit - FAIL R Aileron -5 deg Offset
DDCDCB	25	21	Retrofit - FAIL R Aileron -10 deg Offset
DDCDCC	25	22	Retrofit - FAIL R Aileron -15 deg Offset
DDCDCD	25	23	Retrofit - FAIL R Aileron -20 deg Offset
DDCDDB	25	24	Retrofit - FAIL R Aileron -25 deg Offset
DDCDDC	25	25	Retrofit - FAIL R Aileron -30 deg Offset

Table B-4:Detailed Test Matrix

Test Point Number	Maneuver	Config-uration	Altitude (Feet Hp)	Airspeed (KCAS)	AOA (deg)	FSFCC Mode(2)		Remarks
						Failure(4,5) (Surface, mag)	RCLAWS	
1100	Integrated Test Set(1)	CR	20,000	235		None	Inactive	
1101	Integrated Test Set(1)	CR	20,000	235		None	Active	
1110	Integrated Test Set(1)	CR	20,000	235		Aileron, 0 deg	Inactive	
1111	Integrated Test Set(1)	CR	20,000	235		Aileron, 0 deg	Active	
1120	Integrated Test Set(1)	CR	20,000	235		Aileron, 15 deg	Inactive	
1121	Integrated Test Set(1)	CR	20,000	235		Aileron, 15 deg	Active	
1130	Integrated Test Set(1)	CR	20,000	235		Aileron, 30 deg	Inactive	
1131	Integrated Test Set(1)	CR	20,000	235		Aileron, 30 deg	Active	
1140	Integrated Test Set(1)	CR	20,000	235		Stab, 0 deg	Inactive	
1141	Integrated Test Set(1)	CR	20,000	235		Stab, 0 deg	Active	
1150	Integrated Test Set(1)	CR	20,000	235		Stab, 3 deg	Inactive	
1151	Integrated Test Set(1)	CR	20,000	235		Stab, 3 deg	Active	
1160	Integrated Test Set(1)	CR	20,000	235		Stab, 6 deg	Inactive	
1161	Integrated Test Set(1)	CR	20,000	235		Stab, 6 deg	Active	
1200	Guns Tracking	CR	20,000	235		None	Inactive	
1201	Guns Tracking	CR	20,000	235		None	Active	
1210	Guns Tracking	CR	20,000	235		Aileron, 0 deg	Inactive	
1211	Guns Tracking	CR	20,000	235		Aileron, 0 deg	Active	
1220	Guns Tracking	CR	20,000	235		Aileron, 15 deg	Inactive	
1221	Guns Tracking	CR	20,000	235		Aileron, 15 deg	Active	
1230	Guns Tracking	CR	20,000	235		Aileron, 30 deg	Inactive	
1231	Guns Tracking	CR	20,000	235		Aileron, 30 deg	Active	
1240	Guns Tracking	CR	20,000	235		Stab, 0 deg	Inactive	
1241	Guns Tracking	CR	20,000	235		Stab, 0 deg	Active	
1250	Guns Tracking	CR	20,000	235		Stab, 3 deg	Inactive	
1251	Guns Tracking	CR	20,000	235		Stab, 3 deg	Active	

Table B-4. Continued.

Test Point Number	Maneuver	Configuration	Altitude (Feet Hp)	Airspeed (KCAS)	AOA (deg)	FSFCC Mode(2)		Remarks
1260	Guns Tracking	CR	20,000	235		Stab, 6 deg	Inactive	
1261	Guns Tracking	CR	20,000	235		Stab, 6 deg	Active	
2100	Integrated Test Set(1)	PA	16,000		8.1	None	Inactive	
2101	Integrated Test Set(1)	PA	16,000		8.1(3)	None	Active	
2110	Integrated Test Set(1)	PA	16,000		8.1	Aileron, 0 deg	Inactive	
2111	Integrated Test Set(1)	PA	16,000		8.1(3)	Aileron, 0 deg	Active	
2120	Integrated Test Set(1)	PA	16,000		8.1	Aileron, 15 deg	Inactive	
2121	Integrated Test Set(1)	PA	16,000		8.1(3)	Aileron, 15 deg	Active	
2130	Integrated Test Set(1)	PA	16,000		8.1	Aileron, 30 deg	Inactive	
2131	Integrated Test Set(1)	PA	16,000		8.1(3)	Aileron, 30 deg	Active	
2140	Integrated Test Set(1)	PA	16,000		8.1	Stab, 0 deg	Inactive	
2141	Integrated Test Set(1)	PA	16,000		8.1(3)	Stab, 0 deg	Active	
2150	Integrated Test Set(1)	PA	16,000		8.1	Stab, 3 deg	Inactive	
2151	Integrated Test Set(1)	PA	16,000		8.1(3)	Stab, 3 deg	Active	
2160	Integrated Test Set(1)	PA	16,000		8.1	Stab, 6 deg	Inactive	
2161	Integrated Test Set(1)	PA	16,000		8.1(3)	Stab, 6 deg	Active	
2200	Waveoff	PA	16,000		8.1	None	Inactive	HILS only
2201	Waveoff	PA	16,000		8.1(3)	None	Active	HILS only
2210	Waveoff	PA	16,000		8.1	Aileron, 0 deg	Inactive	HILS only
2211	Waveoff	PA	16,000		8.1(3)	Aileron, 0 deg	Active	HILS only
2220	Waveoff	PA	16,000		8.1	Aileron, 15 deg	Inactive	HILS only
2221	Waveoff	PA	16,000		8.1(3)	Aileron, 15 deg	Active	HILS only
2230	Waveoff	PA	16,000		8.1	Aileron, 30 deg	Inactive	HILS only
2231	Waveoff	PA	16,000		8.1(3)	Aileron, 30 deg	Active	HILS only
2240	Waveoff	PA	16,000		8.1	Stab, 0 deg	Inactive	HILS only
2241	Waveoff	PA	16,000		8.1(3)	Stab, 0 deg	Active	HILS only
2250	Waveoff	PA	16,000		8.1	Stab, 3 deg	Inactive	HILS only

Table B-4. Continued.

Test Point Number	Maneuver	Configuration	Altitude (Feet Hp)	Airspeed (KCAS)	AOA (deg)	FSFCC Mode(2)		Remarks
2251	Waveoff	PA	16,000		8.1(3)	Stab, 3 deg	Active	HILS only
2260	Waveoff	PA	16,000		8.1	Stab, 6 deg	Inactive	HILS only
2261	Waveoff	PA	16,000		8.1(3)	Stab, 6 deg	Active	HILS only
3100	Integrated Test Set(1)	PA1/2	16,000		8.1	None	Inactive	HILS only
3101	Integrated Test Set(1)	PA1/2	16,000		8.1	None	Active	HILS only
3110	Integrated Test Set(1)	PA1/2	16,000		8.1	Aileron, 0 deg	Inactive	HILS only
3111	Integrated Test Set(1)	PA1/2	16,000		8.1	Aileron, 0 deg	Active	HILS only
3120	Integrated Test Set(1)	PA1/2	16,000		8.1	Aileron, 15 deg	Inactive	HILS only
3121	Integrated Test Set(1)	PA1/2	16,000		8.1	Aileron, 15 deg	Active	HILS only
3130	Integrated Test Set(1)	PA1/2	16,000		8.1	Aileron, 30 deg	Inactive	HILS only
3131	Integrated Test Set(1)	PA1/2	16,000		8.1	Aileron, 30 deg	Active	HILS only
3140	Integrated Test Set(1)	PA1/2	16,000		8.1	Stab, 0 deg	Inactive	HILS only
3141	Integrated Test Set(1)	PA1/2	16,000		8.1	Stab, 0 deg	Active	HILS only
3150	Integrated Test Set(1)	PA1/2	16,000		8.1	Stab, 3 deg	Inactive	HILS only
3151	Integrated Test Set(1)	PA1/2	16,000		8.1	Stab, 3 deg	Active	HILS only
3160	Integrated Test Set(1)	PA1/2	16,000		8.1	Stab, 6 deg	Inactive	HILS only
3161	Integrated Test Set(1)	PA1/2	16,000		8.1	Stab, 6 deg	Active	HILS only
3200	SSE Waveoff	SSE	16,000		8.1	None	Inactive	HILS only
3201	SSE Waveoff	SSE	16,000		8.1	None	Active	HILS only
3210	SSE Waveoff	SSE	16,000		8.1	Aileron, 0 deg	Inactive	HILS only
3211	SSE Waveoff	SSE	16,000		8.1	Aileron, 0 deg	Active	HILS only
3220	SSE Waveoff	SSE	16,000		8.1	Aileron, 15 deg	Inactive	HILS only
3221	SSE Waveoff	SSE	16,000		8.1	Aileron, 15 deg	Active	HILS only
3230	SSE Waveoff	SSE	16,000		8.1	Aileron, 30 deg	Inactive	HILS only
3231	SSE Waveoff	SSE	16,000		8.1	Aileron, 30 deg	Active	HILS only
3240	SSE Waveoff	SSE	16,000		8.1	Stab, 0 deg	Inactive	HILS only
3241	SSE Waveoff	SSE	16,000		8.1	Stab, 0 deg	Active	HILS only

Table B-4. Continued.

Test Point Number	Maneuver	Configuration	Altitude (Feet Hp)	Airspeed (KCAS)	AOA (deg)	FSFCC Mode(2)		Remarks
3250	SSE Waveoff	SSE	16,000		8.1	Stab, 3 deg	Inactive	HILS only
3251	SSE Waveoff	SSE	16,000		8.1	Stab, 3 deg	Active	HILS only
3260	SSE Waveoff	SSE	16,000		8.1	Stab, 6 deg	Inactive	HILS only
3261	SSE Waveoff	SSE	16,000		8.1	Stab, 6 deg	Active	HILS only

NOTES:

(1) Integrated Test Set consists of pitch doublets, pitch attitude captures, bank-to-bank rolls, and optional heading captures. Specific procedures for each maneuver are described in the DMOT.

(2) The FSFCC 1750A research processor will be engaged for all test points. The RCLAWS will be active where designated, and the Failure Sim module will be active where designated.

(3) Monitor sideslip when above 150 KCAS with RCLAWS active in PA Half or Full.

(4) Failure magnitudes are specified, but direction will be at the discretion of the test team.

(5) Test points may be inserted with intermediate failure magnitudes (Stab, 4 deg, for example) to provide additional buildup.

Table B-5: Flight Test Maneuver Descriptions and Tolerances

		Pitch Attitude Capture	Bank-to-Bank (Bank Angle Capture)
CR(1)	Smooth	Capture ±5° within ±1° (desired) or ±2° (adequate) with ΔNz>2g in 1 second	Capture ±30° within ±5° (desired) or ±10° (adequate) with ¼ stick in 1 second
	Aggressive	Capture ±5° within ±2° (desired) or ±3° (adequate) with ΔNz>2g in ½ second	Capture ±45° within ±10° (desired) or ±20° (adequate) with ½ stick in ¼ second
	Guns Tracking	Acquisition (coarse): stabilize within 1.5 heading carets within 2 seconds (desired) or 4 seconds (adequate) Tracking (fine): stabilize for 3 seconds (desired) or 1 seconds (adequate)	
PA(2)	Smooth	Capture ±5° within ±1° (desired) or ±2° (adequate) with ΔNz>2g in 1 second	Capture ±15° within ±2° (desired) or ±4° (adequate) with ¼ stick in 1 second
	Aggressive	Capture ±5° within ±2° (desired) or ±3° (adequate) with ΔNz>2g in ½ second	Capture ±30° within ±5° (desired) or ±10° (adequate) with ½ stick in ¼ second

(1) CR: 20,000 feet / 235 KCAS
(2) PA: 16,000 feet / 8.1 degrees AOA
Entry conditions for all maneuvers are straight and level, ±1000 feet altitude, ±10 KCAS airspeed, and ±2 deg AOA.

Appendix C: FCS DIFFERENCES

FCS CHANGES

Changes to the Flight Control System software between versions 10.1, 10.3, and 10.5.1 are described below and summarized in Table C-1.

VERSION 10.3 = V10.1 + the following:

a. Added a number of TACAN/VORTAC/INS waypoint coupled-steering modes.
b. Added a source-error correction table for use when airplane is configured with Recce nose.
c. Added Memory Inspect of Unpopulated 701e Memory, which corrects a lab-test only problem which caused all 4 FCC channels to go into a fault routine that equates to MECH/OFF/OFF mode (can be manually reset).

VERSION 10.5.1 = V10.3 + the following:

a. Takeoff Trim Button Stabilator Setting, which changes takeoff trim button setting from 4° TEU trim to 12° TEU trim.
b. Flight Control System Actuator Signal Recovery Logic, which changes FCS hydraulic pressure recovery logic from time-proportional resumption (5 seconds) of actuator command to rate-proportional command.
c. Air Data Sensor FCC Channel Tracking, which adds a PBIT test and BLIN codes to improve failure isolation of miss-track between two FCC channels for both Qc and Ps ADC data.
d. Uncommanded Yaw With Loss of Rudder Toe-In Due To Rudder Actuator Failure, which modifies the fade-to-zero rudder toe-in command schedule of good rudder to better match the time for the failed rudder to move to the faired position.
e. Jammed Angle-Of-Attack Probe Fault Detection, which changes flight-control AOA redundancy management to use an alternate AOA reference if a probe-split is detected while the aircraft is weight-on-wheels.

ENVELOPE CHANGES

There are no changes to the NATOPS flight envelope between FCS versions 10.1, 10.3, and 10.5.1.

APPLICABLE WARNINGS/CAUTIONS/NOTES

With FCS v10.3 and below, if an AOA probe split greater than 15.5 deg occurs, FCC AOA is set to the last valid value before the split occurred. During field takeoffs a single probe jammed at a large AOA can significantly delay nose wheel liftoff. Depending on the last average value selected by the FCC, the pilot may not be able to counter this FCC feedback, even with full aft stick. Aircrew should pay particular attention to projected nose wheel liftoff speed and maximum abort speed.

A warning was added to the test plan that states: “If the damaged/stuck AOA probe is stuck at greater than 30 degrees, the stabilators are commanded to full nose down and there is insufficient control stick authority to recover the aircraft”

Table C-1: Summary of 10.1/10.3/10.5.1 FCS Differences

Function	v10.1 to v10.3 changes	v10.3 to v10.5.1 changes
Inner Loop Control Laws	None	None
Redundancy/ Failure Management		Actuator signal recovery logic changed to resume actuator command when reset
		Added air data sensor channel tracking between partner channels
		Modified fade-to-zero rudder toe-in schedule to better match failed rudder
		Added AOA probe fault detection logic
Takeoff Trim		Takeoff trim setting changed from 4 degrees TEU to 12 degrees TEU
Source Error Correction (SEC)	New SEC table for RECCE nose	
Autopilot	Additional TACAN/VORTAC/INS waypoint-coupled modes	

For FCS versions 10.1 through 10.5.1, cross control inputs are prohibited above 150 knots with flaps FULL. This prohibition is due to the possibility of building sideslip. With the RCLAWS engaged, the FSFCC is capable of commanding a cross control situation above 150 KCAS, possibly violating this prohibition. For this reason, the project flight clearance allows cross control inputs above 150 KCAS with the ground team monitoring sideslip. The monitoring engineer will call knock-it-off in the event that sideslip meets or exceeds 10 degrees during any maneuver.

APPLICABLE EMERGENCY PROCEDURES CHANGES

For any in-flight or ground emergencies, disengage the FSFCC with the paddle switch and follow NATOPS procedures. In the event of a departure from controlled flight with v10.1, spin arrows may rapidly cycle left/right during highly oscillatory post-stall gyrations, spins, or spin recovery. If cycling of command arrows continues and a spin is confirmed, Spin Recovery Mode (SRM) should be manually selected. For both intermediate and high yaw rate spin mode recoveries, removal of the command arrows from the SRM display may be delayed a few seconds after spin yaw rate has stopped and the AOA warning tone is no longer present. Under these conditions, maintaining full lateral stick until the command arrow disappears may delay spin recovery, lead to a redeparture, and lead to excessive altitude loss (1000 to 2000 feet). When the pilot has confirmed that yaw rate has decreased to zero, anti-spin controls should be neutralized, even if a sustained command arrow is present. This minimizes altitude loss during recovery. Higher yaw rates lead to longer command arrow delays during spin recovery.

Appendix D: DETAILED METHOD OF TEST

FSFCC CHECKOUT

Each time the FSFCCs are installed, a set of BITs will be performed. The general procedure will be as follows:

1. Ensure the aircraft is free of flight control failures prior to the installation of FSFCCs:

   Prior to the installation of the FSFCCs, a Flight Controls pre-flight IBIT and a full Maintenance BIT will be run on the project aircraft. Any Flight Controls X's or BLIN codes will be recorded. The test team will analyze any BLIN codes to determine whether any FCS degrades will compromise the value of the rest of the checkout.
2. Verify proper FSFCC operation in the project aircraft using pre-flight Initiated BIT and Maintenance BIT prior to flight:

   The production FCCs will be removed from the project aircraft, and the FSFCCs will be installed. A flight controls Initiated BIT and Maintenance BIT will be performed. The operator will record any flight controls X's or BLIN codes and report them to the test team.

PREFLIGHT FSFCC CHECKS

The following checks will be performed by the pilot prior to each flight (DAF sequences are valid for FSFCC v3.1.6):

1. Verify MC OFP via the software configuration page.
2. Verify the FSFCC production software via the software configuration page. Both FCCA and FCCB should indicate 991.
3. Verify FSFCC research software version via memory inspect.
4. Enable DAF.
5. Enable FTFCS display.
6. Program the DAF push tiles "A", "B", "C", and "D" to command [table, row] numbers [1,1], [2,2], [3,3], and [4,4], respectively.
7. Attempt to arm the FSFCC mode "DDBCCB", right aileron fail to 30 deg TEU absolute. The FSFCC cannot be armed on the ground without using the Ground Test settings. The pilot will verify the fail to arm in the cockpit and the flight controls engineer at RTPS will verify the proper fail to arm indications are displayed at RTPS.
8. Enter FSFCC mode "CCCBBC", Ground Test Mode without envelope checks ON, and engage mode "A", Slimmed Replication mode. Both the pilot and engineers will verify they see the proper engage indications, and the engineers at RTPS will give a "Disengage" call. The pilot will press the paddle switch, and both the pilot and engineers at RTPS will verify the system disengages and the proper indications are provided.
9. Enter FSFCC mode "CCCBBB" to turn Ground Test Mode OFF.
10. Disable FTFCS display for takeoff.

TAKEOFF

Takeoff will be performed in accordance with NATOPS except for the addition of the following two steps.

1. Ensure stabilator trim is set to 12 degrees TEU.
2. Ensure production FCS page is displayed.
3. Above 50 KCAS during the takeoff roll, cross check the L/R AOA probe indications on the FCS display. Abort the takeoff if either left or right AOA is outside the range of ±10 degrees, or if the split between left and right exceeds 10 degrees.

FSFCC AUTOMATIC DISENGAGE LOGIC VERIFICATION PROCEDURE

During the first flight of the test program, the FSFCC automatic disengage logic will be verified prior to the execution of any test points. The disengage logic verification procedure may be accomplished enroute to the range area or after established in the range area at or above 15,000 feet MSL, at approximately 235 KCAS. The pilot will engage the FSFCC prior to each of the following steps in 1.0 g level flight and verify that the FSFCC disengages appropriately during each step. The disengage logic verification procedure will consist of the following:

a. Set Yaw Rate disengage limits to ±5 degrees/second and Nz disengage limits to +3.0/0.0 g.
b. Pedal Input (full rudder deflection to exceed ±5 degrees/second yaw rate disengage limit).
c. + 3.2 g steady state pull-up.
d. –0.5 g steady state pushover.
e. Modify disengage parameters as required for first test point.

TEST MANEUVERS

Integrated Test Set

Description:
1. Pitch Doublet
2. Pitch Attitude Capture
3. Bank-to-Bank Rolls
4. Heading Capture (may or may not be performed based on test team's assessment of value added)

All maneuvers are described below.

Pitch Doublets

Description:
1. Establish the specified initial conditions.
2. Perform a ¼ stick (<1-g disturbance) sinusoidal longitudinal stick doublet and allow subsequent motions to subside or pitch oscillation amplitude to double before making any further control inputs.

3. If motion is controllable and well damped, repeat with ½ stick input (<1-g disturbance).

Success Criteria:
- Maneuver begins within 5 KCAS or 0.02 Mach and 1,000 feet of specified initial conditions.
- Stick doublet input symmetric within 1/4 in.
- Total doublet time is greater than 1/2 second.
- Less than 1-g disturbance.
- Motions subsided when either damped to less than 2% of disturbance, fifth oscillation, or motion results in angle twice that of released condition.

Purpose:
- Controllability
- Magnitude of longitudinal/lateral/directional coupling
- Longitudinal stability

Rationale:
- Buildup maneuver to check longitudinal characteristics.

Flying Qualities Criteria:

Desired:
- No yaw or roll coupled motions.
- No PIO tendency.

Adequate:
- Yaw or roll coupled motions are minor and predictable.
- Bounded PIO damps immediately if input is relaxed.

Controllability:
- Any unexpected or unpredictable normal acceleration or pitch rate response which requires full stick to counter.
- Any divergent PIO.
- Any bounded PIO which diverges after input is relaxed.
- Uncontrollable coupled roll or yaw response.

Pitch Attitude Capture

Description:

1. Establish the specified initial conditions.
2. Using a fixed pipper-type reference on the HUD and in a smooth, non-aggressive manner ($\Delta g \leq 2$ g in 1 second) attempt to acquire a ± 5 degrees pitch attitude change.
3. Re-establish the initial trim conditions.
4. In a moderately aggressive manner ($\Delta g \leq 2$ g in $\leq {}^{1}/_{2}$ second) attempt to acquire a ± 5 degrees pitch attitude change.

   Note: Pitch attitude captures should only be performed in a wings level attitude. The tendency for PIO must be explored by aggressively zeroing the error between pipper and desired pitch attitude. If stabilization or PIO problems develop, lowering the input rate is allowable but should be cited as pilot compensation and described.

Success Criteria:
- Maneuver begins within 5 KCAS or 0.02 Mach and 1,000 feet of specified initial conditions.

Purpose:
- Pilot Induced Oscillation (PIO) tendencies.

Rationale:
- Pitch attitude changes of ± 5 degrees are appropriately accomplished with smooth inputs defined in terms of a $\Delta g \leq 2$ g in 1 second onset rate. Faster pitch attitude changes ($\Delta g \leq 2$ g in $\leq {}^{1}/_{2}$ second) also need be evaluated, but large, fast inputs are unreasonable with a degraded flight control system.

Flying Qualities Criteria:

Desired:
- Acquire target pitch attitude within ± 1 degrees for smooth inputs and within ± 2 degrees for more aggressive inputs
- No yaw or roll coupled motions.
- No PIO tendency.
- Overshoots do not exceed 4 degrees.

Adequate:
- Acquire target pitch attitude within ± 2 degrees for smooth inputs and within ± 3 degrees for more aggressive inputs
- Bounded PIO damps immediately if input is relaxed.

Controllability:
- Any unexpected or unpredictable normal acceleration or pitch rate response which requires full forward stick to counter.
- Any divergent PIO.
- Any bounded PIO which diverges after input is relaxed.
- Uncontrollable coupled roll or yaw response.

<u>Bank-to-Bank Rolls</u>

Description:
1. Establish the specified initial conditions.
2. Smoothly roll the aircraft and attempt to capture a 30 degrees bank angle (15 degrees in $PA^{1}/_{2}$ or PA).
3. Smoothly roll the aircraft and attempt to capture the opposite 30 degrees bank angle (15 degrees in $PA^{1}/_{2}$ or PA).
4. Smoothly roll back to the wings-level attitude and re-establish the initial conditions.

5. Aggressively roll the aircraft and attempt to capture a 45 degrees bank angle (30 degrees in PA$^1/_2$ or PA).
6. Aggressively roll the aircraft and attempt to capture the opposite 45 degrees bank angle (30 degrees in PA$^1/_2$ or PA).
7. Aggressively roll back to the wings-level attitude and re-establish the initial trim condition.

Note: Roll attitude should be acquired and maintained using the same input rate used to start the roll to zero any error between desired and actual roll attitude. Smooth input implies ≈ 1 second to reach $^1/_4$ stick input. Aggressive input implies a $^1/_2$ lateral stick input in ≤ $^1/_4$ second. After the initial input, any error should be corrected by the pilot in the minimum time possible. If stabilization or PIO problems develop, lowering the input rate is allowable but must be cited as pilot compensation and described. The HUD and the outside visual scene should be used jointly to judge the roll angle.

Success Criteria:
- Maneuver begins within 5 KCAS or 0.02 Mach and 1,000 feet of specified initial conditions.
- Specified lateral stick within $^1/_4$ second for abrupt inputs.

Purpose:
- Roll mode characteristics
- PIO tendencies

Rationale:
- Mission representative flying qualities task.
- Smooth lateral stick inputs are normal for small bank angle changes while aggressive lateral stick inputs are common for large bank angle changes.

Flying Qualities Criteria:

Desired:
- Acquire specified bank angle within ± 5 degrees (± 2 degrees in PA$^1/_2$ or PA) for smooth inputs and within ± 10 degrees (± 5 degrees in PA$^1/_2$ or PA) for aggressive inputs.
- No PIO tendency.
- No coupled pitch motion.

Adequate:
- Acquire specified bank angle within 10 degrees (± 4 degrees in PA$^1/_2$ or PA) for smooth inputs and within ± 20 degrees (± 10 degrees in PA$^1/_2$ or PA) for aggressive inputs.

Controllability:

- Any roll acceleration after roll input is removed which requires full opposite stick to counter
- Any bounded PIO which diverges after input is relaxed
- Uncontrollable coupled pitch response
- Uncontrollable coupled yaw response
- Divergent PIO

Heading Capture

Description:

1. Establish the specified initial conditions.
2. Smoothly initiate a level turn at 30 degrees bank angle (15 degrees in PA$^1/_2$ or PA).
3. Smoothly roll out of the turn to capture the desired heading.

Note: Smooth input implies ≈ 1 second to reach $^1/_4$ stick input. If stabilization or PIO problems develop, lowering the input rate is allowable but must be cited as pilot compensation and described.

Success Criteria:

- Maneuver begins within 5 KCAS or 0.02 Mach and 1,000 feet of specified initial conditions.

Purpose:

- Roll mode characteristics
- PIO tendencies

Rationale:

- Mission representative flying qualities task.

Flying Qualities Criteria:

Desired:

- Acquire intended heading within ± 3 degrees (± 2 degrees in PA$^1/_2$ or PA)
- No PIO tendency.
- No coupled pitch motion

Adequate:

- Acquire intended heading within ± 5 degrees (± 3 degrees in PA$^1/_2$ or PA).

Controllability:

- Any bounded PIO which diverges after input is relaxed
- Uncontrollable coupled pitch response
- Divergent PIO

TRACKING TASK

Guns Tracking Exercise

Description:

1. Direct the target aircraft to establish 230 KCAS in straight and level flight at 20,000 feet Hp and then establish a position approximately 3,000 feet in trail of target.
2. Verify "speed and angels set" then direct the target to commence a 1.5 to 2.0 g level turn.
3. Establish the test aircraft in a guns tracking position and then direct the target aircraft to begin mild vertical maneuvering, maintaining 200 to 250 KCAS and a pitch attitude within ±15 degrees of horizon while the test aircraft attempts to maintain a guns tracking solution.

Success Criteria:

- Test team satisfaction with maneuver set-up and conduct.

Purpose:

- Evaluation of high-gain task, applicable to aerial refueling.

Rationale:

- Mission representative task

Flying Qualities Criteria:

Desired:

- On acquisition, stabilize the heading caret within one and one-half carets (about 25 mils) of the target within 2 seconds of initial input.
- For fine tracking maintain pipper anywhere on the target aircraft for more than 3 seconds on each attempt.
- No PIO Tendencies during acquisition or fine tracking.

Adequate:

- On acquisition stabilize the heading caret within one and one-half carets (about 25 mils) of the target within 4 seconds of initial input.
- Maintain pipper on the target aircraft for more than 1 second on each attempt.
- No PIO Tendencies.

Controllability:

- Any undesired, unexpected, or unpredicted aircraft response.
- Any PIO which diverges when input is relaxed.
- Divergent PIO.

SIMULATED LANDINGS

Waveoff

Description:

1. Establish On-speed AOA and a -4 degrees flight path angle at the top of the test altitude band.

2. Commence the waveoff by advancing throttles to MIL and maintaining On-speed AOA without re-trimming until reaching 10 degrees pitch attitude in a positive rate of climb.

Variation:
Repeat, but advance throttles to MAX.

Success Criteria:
- Initial approach AOA stabilized ± 0.3 degrees ($^1/_4$ E-bracket)
- AOA held within ± 1.2 degrees (E-bracket) throughout waveoff maneuver

Purpose:
- Flying qualities on approach and waveoff.
- PIO tendencies

Rationale:
- Standard V_{PA} approach.
- A 1.2 degrees AOA variation corresponds to top and bottom of the HUD E-bracket.

Flying Qualities Criteria:

Desired:
- AOA maintained within $^1/_2$ E-bracket
- No objectionable pitch attitude transients or oscillations
- Roll attitude maintained ± 1 degree
- No roll/yaw coupled motion
- No PIO tendencies

Adequate:
- AOA maintained within E-bracket
- Pitch transients ≤ 1 degree and easily damped
- Roll attitude maintained ± 3 degrees
- Any roll/yaw coupled motions bounded ≤ 3 degrees and well damped

<u>Simulated Single Engine Waveoff</u>

Description: Waveoff from Simulated Single-Engine Approach:

1. Establish On-speed AOA and a -4 degrees flight path angle at the top of the test altitude band with either engine at FLIGHT IDLE in the SSE configuration.
2. Commence the waveoff by selecting MIL thrust on the operating engine, maintain approach AOA and heading with no more than 5 degrees bank angle into the operating engine until reaching 10 degrees pitch attitude in a positive rate of climb.
3. Terminate maneuver by lowering AOA and reducing the throttle on the operating engine to FLIGHT IDLE (match the simulated failed engine thrust setting).
4. Match throttles at PLF.

Variation:
Repeat with MAX thrust.

Success Criteria:

- Approach AOA within $^{1}/_{2}$ E bracket
- Roll attitude ≤ 5 degrees
- Inputs maintained until positive rate of climb established (performance allowing)

Purpose:

- Emergency maneuver technique
- Flying qualities evaluation

Rationale:

- Maintain heading and/or control lateral drift critical during shipboard waveoff maneuvers.
- Approach AOA range realistic for emergency recovery conditions.

Flying Qualities Criteria:

Desired:

- AOA maintained within $^{1}/_{2}$ E-bracket
- No apparent pitch attitude transients or oscillations
- Roll attitude maintained ± 1 degree
- No roll/yaw coupled motion
- No PIO tendencies

Adequate:

- AOA maintained within E-bracket
- Pitch transients ≤ 1 degree and easily damped
- Roll attitude maintained ± 3 degrees
- Any roll/yaw coupled motions bounded ≤ 3 degrees and well damped

Controllability:

- Any PIO oscillations bounded and damp out when control input is relaxed
- Roll attitude maintained within ±10 degrees
- Roll/yaw coupled motions easily controlled
- Sideslip ≤ 10 degrees

Vita

Lieutenant Matthew Doyle was born in Lemoore, California. He graduated from Coronado High School in 1993 and was accepted into the Mechanical Engineering program at the University of Southern California. In December 1997, he earned a degree in Mechanical Engineering and was commissioned as an Ensign in the United States Navy through the Naval Reserve Officer Training Corps (NROTC). After graduation, Matt went on to naval flight training and was designated a Naval Aviator in April 2000. From there he went to the F/A-18E/F Fleet Replacement Squadron at NAS Lemoore, California and was subsequently assigned to Fighter Attack Squadron (VFA) 115. During this time he completed a deployment on the USS Abraham Lincoln, in support of Operation Enduring Freedom, Operation Southern Watch and Operation Iraqi Freedom. While flying combat missions over Iraq and Afghanistan, Matt earned two Strike Flight Air Medals, one individual Air Medal with Combat V, two Navy Commendation Medals with Combat V and the Navy Achievement Medal. Following his first tour he was selected to the United States Naval Test Pilot School at NAS Patuxent River, Maryland and graduated in December of 2004 and was assigned to Air Test and Evaluation Squadron (VX) 23. He is currently serving as the F/A-18E/F and EA-18G air vehicle project officer and F/A-18E/F NATOPS officer. He has accumulated over 1600 flight hours, over 250 carrier arrested landings and piloted more than 25 different fixed and rotary wing aircraft. He currently resides in Patuxent River, Maryland with his wife, Kara.