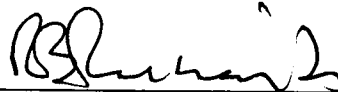


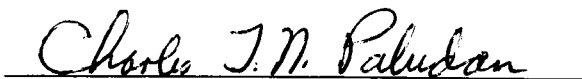
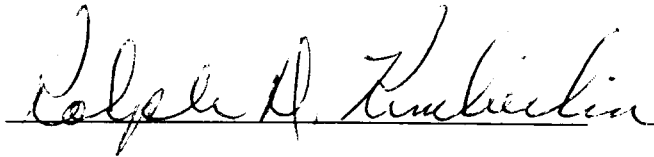
To the Graduate Council:

I am submitting herewith a thesis written by Francis D. Morley entitled "Performance Developmental Flight Testing of the F/A-18E/F Super Hornet". I have examined the final copy of the 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.



Mr. R. B. Richards, Major Professor

We have read this thesis
and recommend its acceptance



Accepted for the Council:



Associate Vice Chancellor
and Dean of the Graduate School

DEVELOPMENTAL PERFORMANCE FLIGHT TEST PLANNING AND
PROCEDURES FOR THE F/A-18E/F SUPER HORNET

A Thesis

Presented for the

Master of Science Degree

The University of Tennessee, Knoxville

Francis D. Morley

December 1996

DEDICATION

This Thesis is dedicated to the 450 members of the F/A-18E/F Integrated Test Team, whose hard work and untiring devotion has made not only this thesis possible, but has given the United States Navy a new strike-fighter aircraft for decades to come.

ACKNOWLEDGMENTS

I would like to thank my academic advisor, Mr. R. B. Richards for his guidance. I would also like to thank the other committee members, Dr. Ralph Kimberlin, Dr. Ted Paludan, and Dr. Frank Collins. I would also like to mention several of my colleagues who have provided invaluable guidance and assistance over the past year, to include, CDR Bob Wirt, CDR Rob Niewoenher, LCDR Tom Gurney, and Mr. Les Doud.

I would especially like to thank my wife Elizabeth, whose support, patience, and understanding has made the completion of this thesis possible.

ABSTRACT

This research attempted to consolidate most of the variables and considerations required when conducting a major Engineering, Manufacturing and Development (EMD) flight test program. Specifically, this research concentrated on performance testing of the F/A-18E/F Super Hornet, in which the author was a test pilot.

The F/A-18E/F is a massive upgrade to the current F/A-18C/D, a fighter/attack aircraft used by the U.S. Navy, Marine Corps, and several foreign militaries. This upgrade incorporates an aircraft which is 25% larger, with new and modified control surfaces, new engines, completely new flight control laws, two additional weapons stations, survivability enhancements, and highly modified electrical, hydraulic, and fuel systems. The EMD flight test program consists of seven flight test aircraft and will cover a period of three years. At the time of writing this paper, the program is only in its first year of flight test. Each flight test aircraft was specifically built to accomplish specific types of flight testing. The performance/propulsion flight test aircraft is the second F/A-18E/F built and flown, referred to as E2. The aircraft is highly instrumented specifically for obtaining performance and propulsion flight test data. The intricate test plans, flight test hazards, and massive personnel and logistical support required for each test flight are

presented in order to identify the multiple aspects of EMD flight testing. In addition, test points flown and results (at the time of writing) are presented.

EMD flight test programs for major military acquisition programs are few and far between due to the expense of modern military aircraft. This research has hopefully provided some insight to the conduct of such a program. The analysis and conclusions are the author's and not the U.S. Government's or the Naval Air Warfare Center's.

PREFACE

"This Hornet, a new and better Hornet, will be the force of the future, and our Naval Aviators will take this aircraft into the fight with improved capabilities and greater fighting power... It brings a certain combat capability to an increasingly uncertain world. It extends the saga of Naval Aviation well into the next century."

Source: Admiral Mike Boorda, Chief of Naval Operations, commenting on the F/A-18E/F during its rollout ceremony on 18 September 1995.

TABLE OF CONTENTS

CHAPTER		PAGE
1.	OVERVIEW.....	1
	<u>INTRODUCTION</u>	1
	<u>F/A-18E/F BACKGROUND</u>	2
	<u>F/A-18E/F ENGINEERING, MANUFACTURING</u> <u>AND DEVELOPMENT</u>	4
	THE ORGANIZATION.....	5
	FLIGHT TEST AIRCRAFT.....	7
	SPECIFIC TEST OBJECTIVES.....	16
2.	DESCRIPTION OF THE F/A-18E/F.....	19
	<u>GENERAL DESCRIPTION</u>	19
	<u>AIRCRAFT SYSTEM SPECIFICS</u>	21
	POWER PLANT SYSTEMS.....	21
	HYDRAULIC SYSTEMS.....	23
	ELECTRICAL SYSTEM.....	24
	FUEL SYSTEM.....	25
	FLIGHT CONTROL SYSTEM.....	26
	AIR DATA SYSTEM.....	36
3.	PERFORMANCE FLIGHT TEST METHODOLOGY.....	39
4.	DESCRIPTION OF THE PERFORMANCE/PROPULSION.....	47
	TEST AIRCRAFT	
	<u>GENERAL</u>	47
	<u>AIRCRAFT E2 CONFIGURATION</u>	48

	<u>SPECIAL FLIGHT TEST INSTALLATIONS</u>	50
	<u>SPECIAL FLIGHT TEST AVIONICS HARDWARE</u>	56
5.	IN-FLIGHT THRUST DETERMINATION.....	63
6.	PERFORMANCE TEST PROGRAM.....	71
	<u>PERFORMANCE TEST PREREQUISITES & INTERDEPENDENCIES</u>	71
	<u>TEST APPROACH</u>	75
	<u>STANDARD TEST PROCEDURES AND CONVENTIONS</u>	86
	<u>AIR DATA CALIBRATION VERIFICATION</u>	90
	<u>PERFORMANCE MANEUVERS</u>	91
	LEVEL FLIGHT PERFORMANCE.....	92
	MANEUVERING FLIGHT.....	96
	EXCESS POWER CHARACTERISTICS.....	98
	DESCENTS.....	101
	DYNAMIC MANEUVERS.....	102
	ADDITIONAL PERFORMANCE MANEUVERS.....	106
	STALLS.....	110
	MANEUVER ACCEPTABILITY.....	112
	<u>DATA REQUIREMENTS, REDUCTION, AND ANALYSIS</u>	113
	REAL TIME DATA REQUIREMENTS.....	113
	POST FLIGHT DATA REQUIREMENTS.....	114
7.	SPECIFIC FLIGHT TEST HAZARDS.....	118
8.	TEST TEAM AND TEST CONDUCT.....	127
	<u>THE TEST TEAM</u>	127
	<u>FLIGHT CONDUCT</u>	133

PRE-FLIGHT PROCEDURES.....	133
IN-FLIGHT PROCEDURES.....	136
POST-FLIGHT PROCEDURES.....	142
9. RESULTS AND CONCLUSIONS.....	143
BIBLIOGRAPHY.....	152
APPENDIX A. FIGURES.....	156
VITA.....	165

LIST OF FIGURES

- 1 F/A-18E/F CONTROL SYSTEM COMPONENTS
- 2 F/A-18E/F SURFACE DEFLECTION AND RATE OF MOVEMENT
- 3 F/A-18E/F CONTROL STICK
- 4 F/A-18E/F LONGITUDINAL CONTROL STICK SCHEMATIC
- 5 F/A-18E/F LATERAL CONTROL STICK SCHEMATIC
- 6 F/A-18E/F RUDDER PEDALS SCHEMATIC
- 7 LEVEL FLIGHT DRAG
- A-1 AIRCRAFT TEST PROGRAM SUMMARY
- A-2 F/A-18E/F NET PROPULSIVE FORCE
- A-3 EARLY METHODOLOGY TEST POINT SUMMARY
- A-4 FLAP PARAMETRIC TEST POINT SUMMARY
- A-5 COMPLETED AND SCHEDULED PERFORMANCE DATA ANALYSIS
- A-6 PITOT STATIC MACH VARIANCE
- A-7 PITOT STATIC ALTITUDE VARIANCE
- A-8 EARLY OPERATIONAL ASSESSMENT CRUISE PERFORMANCE

LIST OF ABBREVIATIONS AND NOMENCLATURE

A/B	Afterburner
ACLS	Automatic Carrier Landing System
ADEPT	Aerospace Data Editing and Processing Tool
ADF	Air Data Function
ADS	Air Data System
AFRS	Aircraft Fault Reporting System
AGL	Above Ground Level
ALTS	Aircraft Laser Tracking System
AMAD	Airframe Mounted Accessory Drive
AOA	Angle of Attack
AOSS	Angle of Side Slip
APCS	Approach Power Compensation System
APU	Auxiliary Power Unit
ARS	Aerial Refueling Store
ATC	Autothrottle Control
ATEF	Aircraft Test and Evaluation Facility
ATF	Altitude Test Facility
Blisks	Bladed disks
BMA	Body Mounted Accelerometer Package
Buddy store	Aerial Refueling Store
CAS	Control Augmentation System
CATM	Captive Air Training Missile
CG	Center of Gravity

DAF	Dial-A-Function
Daft	Afterbody Drag
DATM	Dummy Air Training Missile
DDAS	Digital Data Acquisition System
D/delta	Referred Drag
Decshx	ECS Heat Exchanger Drag
Dramp	Inlet Ramp Bleed Drag
Dspill	Inlet Spill Drag
ECS	Environmental Control System
EFAP	Empirical Force-Area-Pressure
EFD	Engine Fuel Display
EGT	Exhaust Gas Temperature
EMC	Electro-Magnetic Compatibility
EMD	Engineering, Manufacturing, and Development
EOA	Early Operational Assessment
EPGS	Electrical Power Generating System
EW	Electronic Warfare
FADEC	Full Authority Digital Engine Control
FAP	Force/Area/Pressure
FCC	Flight Control Computer
FCS	Flight Control System
FE	Fighter Escort
FFRR	First Flight Readiness Review
FLIR	Forward Looking Infrared
FMC	Full Mission Capable

FN	Net Thrust
FNP	Net Propulsive Force
FPA	Flight Path Angle
FPAS	Flight Performance Advisory System
fpm	feet per minute
FQTY	Fuel Quantity
ft.	feet
FTE	Flight Test Engineer
g	Load Factor, as measured by force of gravity
GE	General Electric
GVT	Ground Vibration Tests
hot-pit	Engine running ground refueling
HUD	Heads Up Display
IFT	Inflight Thrust
INS	Inertial Navigation System
IOE	Instrumentation Operations Engineer
IST	Initial Sea Trials
ITT	Integrated Test Team
JBD	Jet Blast Deflector
K	1000 feet
KCAS	Knots, Calibrated Airspeed
kt	knot
KVA	Kilovolt Ampere
lb.	pounds
LD	Low Drag

LEF	Leading Edge Flap
LEX	Leading Edge Extensions
LVDT	Linear Variable Differential Transducers
M	Mach
MAC	Mean Aerodynamic Chord
MAX	Maximum Power
MC	Mission Computer
MDA	McDonnell Douglas Aerospace
MDI	Multi-purpose Display Indicator
MIL	Military Rated Power
min.	Minute
MPCD	Multi-Purpose Color Display
MSL	Mean Sea Level
MUX	Memory Unit
NAS	Naval Air Station
NAVAIR	Naval Air Systems Command
NAVFLIR	Navigational Forward Looking Infrared
NAWC	Naval Air Warfare Center
N/FPA	Noseboom Flight Path Accelerometer
NGC	Northrop Grumman Corporation
NIU	Noseboom Interface Unit
NT	New Technology
NWS	Nose Wheel Steering
Nz	Normal Acceleration
OML	Outer Moldline

PA	Power Approach (gear and flaps down config.)
PLF	Power for Level Flight
PMG	Permanent Magnet Generators
psi	Pounds per square inch
RSRI	Rolling Surface to Rudder Interconnect
RTB	Return to Base
RTPS	Real-Time Telemetry Processing System
SEC	Source Error Correction
sec	second
SEROC	Single Engine Rate of Climb
SMI	Structural Mode Interaction
SMS	Stores Management System
SOFT	Safety-of-Flight-Test
TC	Test Conductor
TECH	Technician
TEF	Trailing Edge Flap
TISM	Test Instrumentation Support Module
TM	Telemetry
TPI	Test Point Index
TRA	Test Requirements and Analysis Officer
TRU	Transformer Rectifier Unit
UA	Up and Away (gear and flaps up configuration)
UFCD	Up Front Control Display
V _{mc}	Single engine minimum control speed
VV	Vertical Velocity

WCC	Wind Calibration in Climb
W/delta	Normalized Weight
W root T	Airflow root Temperature Method
WUT	Wind Up Turn

CHAPTER 1

OVERVIEW

INTRODUCTION

This paper details the overall Engineering, Manufacturing, and Development (EMD) program for the F/A-18E/F "Super Hornet". Specifically, it concentrates on the performance flight test program of the aircraft. The many variables, interdependencies, flight test maneuvers, hazards, and hardware and software aircraft modifications required for comprehensive performance flight testing are discussed. The initial performance flight test results are also presented. At the time of this writing (Fall 1996), the aircraft was nearing completion of the first of three years of flight tests. Because of this, some aspects of the program had been completed, some aspects were on going, and many aspects had not yet been started. The reader must keep this in mind. The author discusses all aspects of the program, including those aspects that were on going and not yet started at the time of this writing.

At the time of this writing, the author was the Navy's performance test pilot on the program. As such, the author

was intimately involved in all aspects of the program discussed in this paper. The author helped identify and write many of the items within the performance test plans, to include flight test maneuvers, required tolerances, safety of flight and safety of test measurands, and associated flight test hazards, preventative measures, and corrective actions. The author had flown all the performance test maneuvers presented in this paper, many of the prerequisite flight tests in other program flight test aircraft, and had collected a large portion of the current flight test results.

F/A-18E/F BACKGROUND

The F/A-18A entered operational service with the U.S. Navy in the early 1980's, replacing the A-7 Corsair, and the F-4 Phantom. In 1987, the aircraft was upgraded to the F/A-18C (F/A-18 B's and D'S are the two seat versions of the A and C, respectively). This was a standard upgrade that most Military aircraft experience during it's life cycle. More robust mission computers and systems were added to allow the aircraft to employ more advanced weapons systems, as well as correct deficiencies noted during operational use of the F/A-18A.

The success of the F/A-18A-D prompted a study request by then-Secretary of Defense Casper Weinberger in 1987. The study was conducted by the Naval Air Systems Command, McDonnell Douglas, and Northrop (now Northrop Grumman). Several potential upgrade approaches were defined. The F/A-18E/F represents the approach chosen. In June 1992, The Navy awarded McDonnell Douglas Aircraft (MDA) a \$3.1 billion (FY 90) 7 1/2 - year engineering, manufacturing, and development (EMD) contract for the F/A-18E/F. Under the contract, MDA was charged to build 10 test articles -- seven flying aircraft and three ground test aircraft. The flight test program was determined to be a three year program conducted mainly at the Naval Air Warfare Center (NAWC) at Naval Air Station (NAS) Patuxent River Maryland. Total value of the developmental program, including a separate contract with General Electric (GE) to develop the new engine, was estimated to be between 4 1/2 to 5 billion dollars (Personal Conversation with MDA Business Operations).

Design and manufacturing work for the aircraft was promptly started by MDA, Northrop Grumman Corporation (NGC), the prime sub-contractor, and GE. On 18 September, 1995, the first F/A-18E, designated E-1 was rolled out at the MDA manufacturing facility in St. Louis, Missouri. On that day, the Chief of Naval Operations, Admiral Mike Boorda, renamed the aircraft "Super Hornet". Slightly over two months later,

on 29 November, 1995, E-1 flew for the first time from Lambert Field, St. Louis. Within one month, the second aircraft, E-2 flew for the first time as well. In February of 1996, both E-1 and E-2 were ferried to NAS Patuxent River to begin the three year flight test program.

F/A-18E/F ENGINEERING, MANUFACTURING AND DEVELOPMENT

The primary objectives of the F/A-18E/F EMD flight test program are to develop the weapon system, demonstrate specification compliance, and provide opportunities for independent technical and operational evaluations by the Navy. How does the flight test team accomplish these goals on a new aircraft within three years? The intent of this paper is to present how this is accomplished; detailing the interdependencies of different flight test and aircraft technologies, and presenting the tasks required to determine overall aircraft performance. This paper will present the EMD performance test program for the F/A-18E/F aircraft. The structure of this program is the result of decades of experience, from both industry and the U.S. Navy, in performance testing of a new aircraft. Although this paper concentrates on one aircraft's test program, the reader would find many similarities in any present day major test program.

THE ORGANIZATION

The organization established for the F/A-18E/F program was an Integrated Test Team (ITT), made up of members of industry and government. Specifically, members of MDA, NGC, GE, other subcontractors, and the U.S. Navy (both Military and civil service) were integrated into one organization. Traditionally, the contractor would conduct initial flight tests with the Navy only observing. After a particular flying qualities and performance aircraft envelope had been determined by the contractor, the Navy would have a dedicated fly period where Navy Test Pilots and Engineers would evaluate the aircraft for the Government. This process would continue for the first year or two of any developmental program, before the contractor and the Navy integrated. The disadvantage to this process was that many test points were flown twice, once by the contractor, and once by the Navy.

The F/A-18A/B Full Scale Development Program followed this process, while trying to increase Navy involvement earlier in the program. This increased involvement was found to contribute significantly to Navy visibility into the developmental effort and provided for current and relevant Navy comments on contractor direction and progress (F/A-18A/B Full Scale Development Program Summary, p. 21).

In an attempt to work more efficiently, and incorporate and expand on the lessons learned from the F/A-18A/B program, the F/A-18E/F program was integrated from the very beginning. The ITT was a matrix organization, with the individual technologies interwoven with the particular project flight test teams. In addition, each team within the organization was manned by both industry and government personnel, working side by side. This organization was established early in the development phase of the aircraft, therefore, both sides had been equally educated and informed on aircraft progress. This same philosophy had been carried on within the flight test organization. The flight test organization was made up of five contractor test pilots and five Navy test pilots, as well as approximately 400 industry and government engineers working under one roof.

The result of such an integrated organization was that the entire program worked off of one overall test plan, not having to repeat test points in order for both industry and government to individually evaluate the aircraft (although occasional Navy only operational assessment periods would eventually be conducted with pilots outside the ITT). This approach was designed to allow for the EMD program to span only three years, in comparison to four years which would traditionally be required.

FLIGHT TEST AIRCRAFT

Each EMD flight test aircraft was equipped with the production aircraft equipment and special flight test instrumentation appropriate to its primary mission assignment. Each aircraft was assigned specific areas of the EMD program, and were specifically instrumented to accomplish this. The aircraft test program summary is presented in Figure A-1. In addition, some of the aircraft were designated to fulfill a backup roll in the event of a loss of another aircraft. Aircraft with back-up or alternate mission assignments include provisions for those special installations or production equipment required, should the aircraft assume its alternative role. Provisions typically included inaccessible wiring and mounting provisions, and inaccessible instrumentation. Some production systems were omitted from earlier aircraft when there was no impact to their mission assignment.

The following is a brief synopsis of each individual flight test aircraft as stated in the F/A-18E/F Master Test Plan, chapter 3.

E1: The primary missions assigned to aircraft E1 were flying qualities envelope expansion, flight control system development and aeroelastic envelope clearance (flutter testing). Additional tests, many of which were accomplished in addition to the aircraft's primary missions, included aircraft systems air data system checkout, initial propulsion system tests, controls and displays evaluation, noise and vibration assessments, and production air data system and noseboom source error correction development.

Prior to first flight of aircraft E1, a number of on-aircraft ground tests were conducted during the manufacturing cycle. These included structural tests such as proof loads, Ground Vibration Tests (GVT), Structural Mode Interaction (SMI), checkouts of the various aircraft subsystems and crew systems, and Electro-Magnetic Compatibility (EMC) tests. Low, moderate and high speed taxi tests were the final ground tests prior to flight. These tests were required to ensure flight readiness. The results of these tests were assessed as part of the First Flight Readiness Review (FFRR) process.

Following the initial series of checkout flights, a series of GVT's and SMI tests with external stores would eventually be conducted. These tests were prerequisites for the stores

flutter testing to be conducted during the second half of the aircraft E1 flight test program.

The flight test program on aircraft E1 was planned to encompass 350 developmental and demonstration test flights. No dedicated Navy test periods were planned for this aircraft. This aircraft was the first F/A-18E/F to fly.

E2: The primary missions assigned to aircraft E2 were the developmental and demonstration of propulsion and secondary power systems, engine/inlet integration, and aircraft performance demonstrations. Aircraft E2 was also involved in the flight envelope expansion process. As aircraft E1 expanded the flying qualities and aeroelastic stability (flutter) flight envelopes, aircraft E2 followed closely behind performing the required propulsion engine/inlet compatibility tests needed to provide an engine operating envelope for the other test aircraft. The system and Aerial Refueling Store (ARS) demonstrations were also performed by aircraft E2.

Prior to first flight of aircraft E2, ground tests were performed to checkout the extensive engine instrumentation and document the baseline performance of the test engines. Ground tests were also performed to the fuel system and

secondary power systems for instrumentation checkout and specification compliance demonstrations. Taxi tests were also conducted prior to first flight.

The flight test program on aircraft E2 was planned to include 345 developmental and demonstration flights. The aircraft was scheduled to be used for two dedicated Navy test periods.

F1: The primary mission assigned to aircraft F1 (the first two seat model) was carrier suitability, including the first actual shipboard arrestments and catapults (Initial Sea Trials). The largest effort under the carrier suitability umbrella was the catapult and arrestment demonstrations. Other activities related to carrier suitability included Approach Power Compensation System (APCS) development, Automatic Carrier Landing System (ACLS) development, catapult and arrestment aircraft vibration, Jet Blast Deflector (JBD) thermal and acoustic environment, and carrier Full Mission Capable (FMC) qualification.

Aircraft F1 had a number of other mission assignments, including crosswind landing evaluation and Environmental Control System (ECS) development and demonstration, air data calibration, wingfold system demonstration, and "F" model

flying qualities including high angle-of-attack. Controls and displays were evaluated conjointly.

The flight test program on aircraft F1 included 300 developmental and demonstration flight tests. Two Navy developmental evaluation periods were also scheduled. The Navy planned to utilize the first period, Initial Sea Trials (IST) to evaluate the clean configuration in the carrier environment. The second period was scheduled to evaluate the aircraft with external stores in the carrier environment, as well as the Navy Technical Evaluation of the aircraft.

E3: The primary mission assigned to aircraft E3 was flight loads demonstration testing. Aircraft E3 was involved in the envelope expansion process in that the other test aircraft are limited to 80% design limit loads until aircraft E3 had completed the 100 % loads demonstrations. It was also assigned the dynamic stores release (g-jump) tests, and airframe buffet evaluation. Additional tasks, many of which were accomplished concurrently with the primary missions, included controls and displays evaluation, and flying qualities development tests.

Prior to the first flight of E3, an extensive airframe loads calibration was conducted to prepare the aircraft for loads

flight testing. This calibration took place during the manufacturing cycle, as well as control surface and wingfold freeplay and rigidity checks.

The flight program on aircraft E3 was scheduled to encompass 265 developmental/demonstration test flights. No Navy test periods were planned.

E4: The primary missions assigned to aircraft E4 were the high angle-of-attack (AOA) build-up and demonstration test program, and the spin evaluation. The primary mission assignments gave this aircraft a role in the envelope expansion process. The other EMD test aircraft had AOA and maneuvering limits until aircraft E4 had performed its high AOA envelope expansion. Aircraft E4 had several additional assignments. These included flight tests for the emergency recovery system which had to be completed before initiation of the high AOA testing, and a significant role in the flying qualities and flight control development and demonstration testing. Aircraft E4 was also assigned a role in the controls and displays evaluation, which was performed conjointly with its primary mission.

On-aircraft ground test activities with the emergency recovery system were accomplished during the manufacturing

cycle prior to first flight. These included the spin chute installation proof load test, the emergency recovery system evaluation, and aircrew egress checks with the modified aircrew restraint system utilized in this aircraft.

The flight test program on aircraft E4 was scheduled to include 285 developmental and demonstration flights. No dedicated Navy test activities were planned.

E5: The primary mission assigned to aircraft E5 was weapon separation build-up and demonstration testing which accounted for two-thirds of its planned test activity. The aircraft had several other significant assignments which were; gunfire, noise and vibration, new technology assessment, and several avionics systems evaluations including controls and displays evaluation, antenna pattern tests, countermeasures evaluations and demonstrations, and interior/exterior lighting evaluation. Aircraft E5 was also assigned some of the flying qualities and flight control developmental test activities.

Aircraft E5 was dependent on the envelope expansion activity of the earlier aircraft to provide a flight envelope for many of its tests, including weapon separation and noise and vibration. The testing conducted on aircraft E5 was crucial

to the operational flight clearance required for this aircraft.

Prior to first flight, an EMC Safety-of-Flight-Test (SOFT) was performed. This was required due to avionics systems configuration differences between aircraft E5 and its predecessors.

The flight test program on aircraft E5 was scheduled to encompass 262 developmental and demonstration flights. The aircraft was also scheduled to be used for two dedicated Navy test periods.

F2: The primary missions assigned to aircraft F2 were weapon separation build-up and demonstration testing, and weapon accuracy testing. As with aircraft E5, the weapons testing accounted for a large portion of its testing. However, it had additional assignments to include; avionics systems evaluations including controls and displays and antenna pattern tests, F-model flying qualities and flight control development and demonstrations, and the electrical system evaluation and demonstration and the lighting system flight evaluation and demonstration.

Again, as with aircraft E5, F2 was dependent on the envelope expansion activity of the earlier test aircraft to provide a flight envelope for many of its activities including weapon separation and the F-model flying qualities evaluations. The testing conducted on aircraft F2 was crucial to the operational flight clearance required for this aircraft.

Prior to first flight, several on-aircraft ground tests were performed. These tests satisfied specific requirements for the last EMD aircraft (ground vibration test, control surface and wingfold freeplay and rigidity); and to evaluate baseline electrical system performance and checkout the associated instrumentation.

The flight test program on aircraft F2 was to include 160 development and demonstration test flights. The aircraft was also to be used for several dedicated Navy evaluations.

The interdependencies of all seven flight test aircraft were key. Each aircraft was dependent on other aircraft to clear out a particular part of the overall envelope in order to complete specific flight tests. The timing of all seven aircraft, which was built first, order of flight tests, etc. had been carefully planned out.

SPECIFIC TEST OBJECTIVES

The overall objective of the performance flight test evaluation was to obtain performance data necessary to build a credible aerodynamic database. Guaranteed performance was to be calculated from the database built from the data obtained during these tests. The objective of performance tests with stores was to define the aerodynamic increments associated with the specification fighter escort and interdiction store loadings. High lift performance tests were to be performed to determine approach speed and angle of attack, single engine rate of climb, and field takeoff and landing performance.

The F/A-18E/F Performance Test Work Description states the objectives for the performance test program. Listed below is a synopsis of these objectives, as identified and stated in the F/A-18E/F Performance Test Work Description Document, p. 1 - 2.

- Verify noseboom source error correction for use during performance testing.

- Develop and refine a performance flight test and data reduction methodology for the performance flight evaluation.

-Verify or optimize baseline flap schedules and rudder positioning and scheduling (toe-in/flare) for the fighter escort and interdiction configurations.

-Determine in-flight thrust, lift and drag at subsonic, transonic, and supersonic Mach numbers, as applicable, with the loadings required to evaluate performance guarantees and missions.

-Quantify performance impact of configuration changes throughout the EMD flight test program.

-Quantify the aerodynamic increment of the fighter escort configuration stores.

-Quantify the aerodynamic increment of the interdiction takeoff and return loadings.

-Field takeoff performance -- determine nose wheel lift off speed, takeoff speed, and ground roll distances for the fighter escort and interdiction configurations.

-Field landing performance -- determine landing ground roll distance for both configurations.

-Determine Single Engine Rate of Climb (SEROC) performance for both configurations.

-Determine approach speed and angle of attack for both configurations.

-Collect propulsion performance data necessary to evaluate installation effects and support in-flight thrust determination.

These were the overall program performance objectives. The flight test program was designed to complete all of these objectives during the three year EMD program. Despite the specific technical objectives, the overall objective was always to ensure the aircraft was going to be capable of accomplishing its intended mission; in this case, as a fighter and attack carrier airplane. The author, and other test pilots, utilized their previous experience as operational carrier pilots to ensure this objective was met.

CHAPTER 2

DESCRIPTION OF THE F/A-18E/F

GENERAL DESCRIPTION

As described in the F/A-18E/F Preliminary Flight Manual, p. I-1-1, the F/A-18E is a single-place (F/A-18F being two-place) fighter/attack aircraft built by McDonnell Douglas Aerospace. The airframe is a balance of conventional and composite materials and is powered by two General Electric F414-400 turbofan engines with afterburner. The aircraft features a variable camber mid-wing with extended leading edge extensions (LEX) mounted on each side of the fuselage from the wing roots to just forward of the windshield. The twin vertical stabilizers are angled outboard 20 deg from the vertical. The wings have hydraulically actuated leading edge and trailing edge flaps, ailerons, and LEX vents. The twin rudders and differential stabilators are also hydraulically actuated. Spoilers are mounted on the top of each LEX. The pressurized cockpit is enclosed by an electrically operated clam shell canopy. An aircraft mounted auxiliary power unit (APU) is used to start the engines. On the ground, the APU may be used to supply air conditioning or electrical and

hydraulic power to the aircraft systems. The F/A-18E/F Preliminary Flight Manual goes on to say that the aircraft is controlled by a digital fly-by-wire Flight Control System (FCS) through irreversible hydraulic flight control surfaces. Lateral control is provided by a combination of ailerons, trailing edge flaps, and asymmetric deflection of the all-moveable horizontal tail.

The aircraft has an approximate wing span of 44' 11''; a length of 60' 2''; and a height of 16' 0'' to the top of the vertical stabilizers and 10' 8'' to the top of the closed canopy (F/A-18E/F Preliminary Flight Manual, p. I-1-1). Empty weight of the aircraft is currently around 30,000 lb.

Major airframe upgrades for the F/A-18E/F include a lengthened fuselage, larger wings, stabilizers and control surfaces. The propulsion system is improved with higher airflow caret type inlets, higher thrust F414-GE-400 engines with Full Authority Digital Engine Controls (FADEC) and upgraded engine monitoring. Subsystem improvements and upgrades for the F/A-18E/F include quad redundant digital fly-by-wire flight controls, 3000/5000 psi dual pressure hydraulic system, hybrid electric and motive flow fuel system with 3,500+ lb. additional internal fuel capacity and tanker store ("buddy" store) compatibility. In addition, each external fuel tank carries approximately 3,000 lb. of fuel,

in comparison with 2,000 lb. found with the F/A-18A-D external tanks, and has provisions to carry a Maximum of five external tanks, compared to three in the older Hornet. Overall the aircraft is approximately four feet longer and has a wing span that is four feet greater than the F/A-18C/D.

Avionics and crew station displays are upgraded to include a high resolution, flat panel Multi-Purpose Color Display (MPCD), Up Front Control Display (UFCD) and new Engine Fuel Display (EFD). The existing (F/A-18C/D) Multi-purpose Display Indicators (MDI) will be used for the F/A-18E/F.

The F/A-18E/F has eleven weapon stations. A new wing station is provided just inboard of each wingfold and the centerline station is modified for carriage of the air refueling "buddy" store.

AIRCRAFT SYSTEM SPECIFICS

POWER PLANT SYSTEMS

The F414-GE-400 engine is a low bypass, axial-flow, dual rotor turbofan with afterburner. The three stage fan (low pressure compressor) is driven by a single stage turbine. The first stage of the fan has variable stator vanes and the

second and third stage rotors are bladed disks (blisks). Approximately one-third of the fan discharge air is bypassed to the afterburner for combustion and cooling. The seven stage high pressure compressor is also driven by a single stage turbine. The first two stages of the compressor are variable, with the third stage having a blisk. Bleed air is extracted from the third fan stage, and seventh stage compressor. A set of variable inlet guide vanes are mounted in front of both the fan and compressor to direct the inlet air at the best angle for the existing engine operation. Atomized fuel and compressor discharge air is mixed and ignited in the combustion chamber. These ignited gases then pass through the compressor and fan turbines and out the engine exhaust. Afterburner operation uses added atomized fuel mixed with the combustion discharge gases and the bypass fan discharge air to produce additional thrust. The uninstalled Military thrust (MIL) of each engine is approximately 13,900 pounds, with Maximum afterburner thrust (MAX) around 21,000 pounds. The engine thrust to weight is approximately 9 to 1. The engine accessory gearbox, driven by the compressor rotor, powers the lubrication and scavenge oil pumps, alternator, main fuel pump, afterburner fuel pump, and the aircraft secondary power system. (F/A-18E/F Preliminary Flight Manual, p. I-2-1)

HYDRAULIC SYSTEM

The Hydraulic System consists of two independent hydraulic systems. Each system is pressurized by a single, dual pressure (3000 psi and 5000 psi) variable delivery pump driven by an engine through an Aircraft Mounted Accessory Drive (AMAD). The system pressure is commanded by the Flight Control Computer (FCC) and is determined by dynamic pressure. Each pump is divided into two branches, providing four independent hydraulic circuits identified as 1A and 1B for the left system and circuits 2A and 2B for the right system. Reservoirs maintain a return side pressure of 85 psi at 3000 psi operating pressure and 145 psi at 5000 psi operating pressure. (Flight Control System Design Report, p. 4-1)

The utility system operates at 3000 psi only. Pressure reducers in System 2 regulate the pressure in the utility system to 3000 psi when the pump generates 5000 psi to satisfy flight control requirements. System 1 circuits, 1A and 1B, are dedicated to flight controls. Circuit 2A provides for flight control and utility functions. Circuit 2B supplies flight control functions and pressurizes the APU start accumulator, brake accumulator, arresting hook system, and emergency hydraulic functions. Emergency actuation of some utility functions is also provided by the APU and brake accumulators. (ibid, p. 4-1)

All flight control surfaces are powered by one circuit from each system. Some flight control surfaces are powered by dual system actuators while others are powered by a single system actuator with an upstream switching valve which connects a backup system in the event the primary system pressure is lost. The utility functions that are required only on the ground and for takeoff and landing are downstream of isolation valves. This decreases the vulnerability of the systems to internal failure and external damage. (ibid, p. 4-1)

ELECTRICAL SYSTEM

The electrical system provides AC and DC power to the aircraft. Primary AC electrical power is provided by two 50/65 Kilovolt Ampere (KVA) variable speed constant frequency electrical generating systems, powered by the Airframe Mounted Accessory Drive (AMAD). Each system has a 400 Hertz, 115/200 volt, three-phase output and is connected to a four wire, split bus distribution system. DC electrical power is provided by two 150 ampere, 28-volt Transformer Rectifier Units (TRU) which are connected in parallel through two current limiters. The flight control computers are provided power from dedicated, separate electrically isolated Permanent Magnet Generators (PMG). There are six PMG's

overall, three associated with each generator. One generator and its three PMGs are termed an Electrical Power Generating System (EPGS). Maintenance power is supplied by a 15 ampere-hour sealed lead acid battery. The maintenance battery furnishes power for aircraft starting and maintenance functions such as canopy operation and readout of ground maintenance information. The maintenance battery also provides keep alive power for all four FCC channels (Flight Control System Design Report, p. 5-1). External electrical power can be applied to the bus system on the ground. The electrical power system is redundant enough in that one EPGS and one TRU can supply all aircraft loads. (F/A-18E/F Preliminary Flight Manual, p. I-2-24)

FUEL SYSTEM

Fuel is carried internally in four interconnected fuselage tanks and two internal wing tanks. External fuel is carried in three (provisions for five) 480 or 330 gallon tanks. The internal wing tanks, tank 1 and tank 4, are transfer tanks. Tanks 2 and 3 are engine feed tanks. The tanks are arranged so internal fuel may gravity transfer (although at a reduced rate) if the transfer pumps fail. Regulated engine bleed air pressure transfers fuel from the external tanks and provides a positive pressure on all internal fuel tanks. The aircraft holds approximately 14,500 pounds (13,800 in the two seat

version) of JP-8 fuel, with each external tank holding approximately 3,000 pounds. (F/A-18E/F Preliminary Flight Manual, p. I-2-9)

FLIGHT CONTROL SYSTEM

The following flight control description is a synopsis from the F/A-18E/F Flight Control System Design Report, Volume I, system description, by McDonnell Douglas Aerospace:

The F/A-18E/F flight control system is a digital, quadruplex, fly-by-wire, full authority Control Augmentation System (CAS). All control law computations are performed by four digital computers working in parallel. It includes a built-in redundancy management system which detects and isolates control system component failures. Due to control system component redundancy, multiple like failures are required before a degradation in handling qualities or stability occurs. The F/A-18E/F does not contain any backup control modes (electrical or mechanical) where control of the actuators revert from CAS closed loop control to an alternate control function, as does the F/A-18A-D. Instead, CAS operation always continues following failures to provide degraded, but acceptable flying qualities. A diagram of the major control system components and associated redundancy is provided in Figure 1.

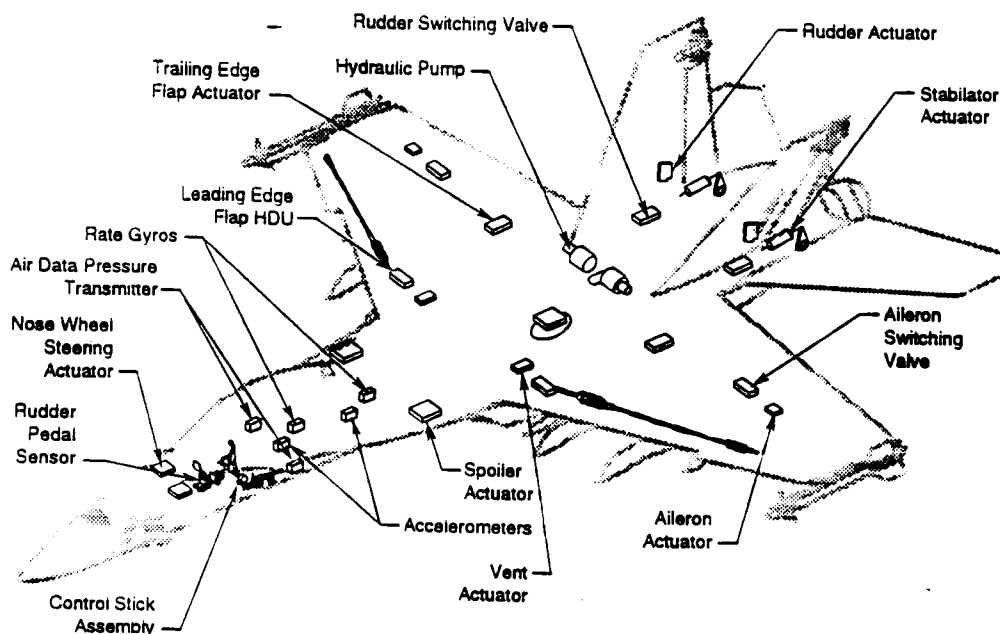


Figure 1

F/A-18E/F CONTROL SYSTEM COMPONENTS

F/A-18E/F Flight Control System Design Report. Volume 1.

St. Louis, Missouri: McDonnell Douglas Aerospace, July 1995.

There are 14 primary flight control surfaces on the F/A-18E/F, each of which is part of a left/right pair: stabilators, rudders, ailerons, leading edge flaps, trailing edge flaps, Leading Edge Extensions (LEX) vents, and spoilers. Maximum surface deflection and surface rate of movement are provided in Figure 2.

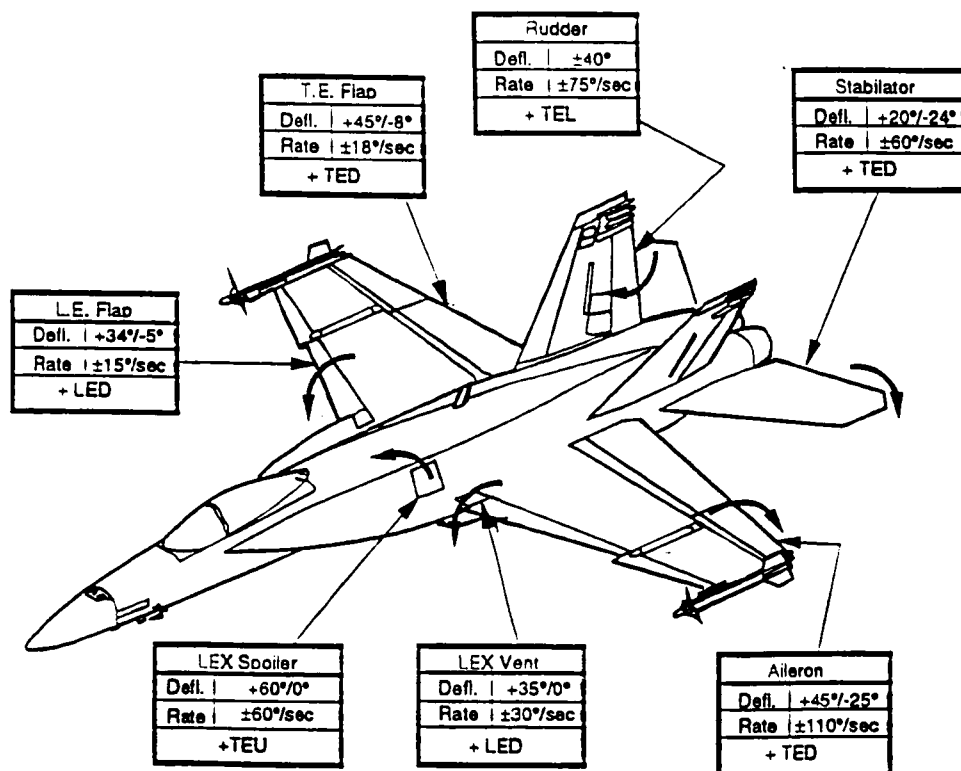


Figure 2

F/A-18E/F SURFACE DEFLECTION AND RATE OF MOVEMENT

F/A-18E/F Flight Control System Design Report. Volume 1.

St. Louis, Missouri: McDonnell Douglas Aerospace, July 1995.

Longitudinal control uses symmetric deflection of the stabilators, leading and trailing edge flaps, ailerons, and toe-in of the rudders. Lateral-directional control uses differential deflection of the stabilators, ailerons, leading and trailing edge flaps, and symmetric rudder deflection. In the takeoff and landing configuration, there is no differential deflection of the flaps. Flight control system

logic and gain schedules may limit surface deflection commands and rates to less than Maximum.

The major components of the flight control system include the flight control electronic set and electrohydraulic servoactuators. The flight control electronic set is comprised of the following:

- Two Flight Control Computers (FCC's), each containing two channels of digital and analog signal processing functions.

- Two rate sensor assemblies, each containing two pitch, two roll, and two yaw angular rate gyros.

- Two accelerometer sensor assemblies, each containing two normal and two lateral linear accelerometers.

- One (or two for two-place aircraft) rudder pedal sensor assembly, containing the rudder pedal feel spring and four transducers which measure the feel spring's displacement and hence pedal force.

Each flight control surface is driven by a fly-by-wire electrohydraulic servoactuator which is controlled by the flight control computers. The FCC's also control the nosewheel steering actuator, and the engine's FADECs' to modulate thrust during automatic throttle operation.

The control system includes the cockpit control stick and longitudinal and lateral feel springs. Quadruplex position transducers are mounted in parallel with longitudinal and lateral feel springs to provide the FCC's with electrical signals proportional to the control stick deflections.

A center stick configuration is used with nominal travel of 2.5 inches forward and 5.0 inches aft. Lateral travel is 3.0 inches to either side. The control stick is shown in Figure 3.

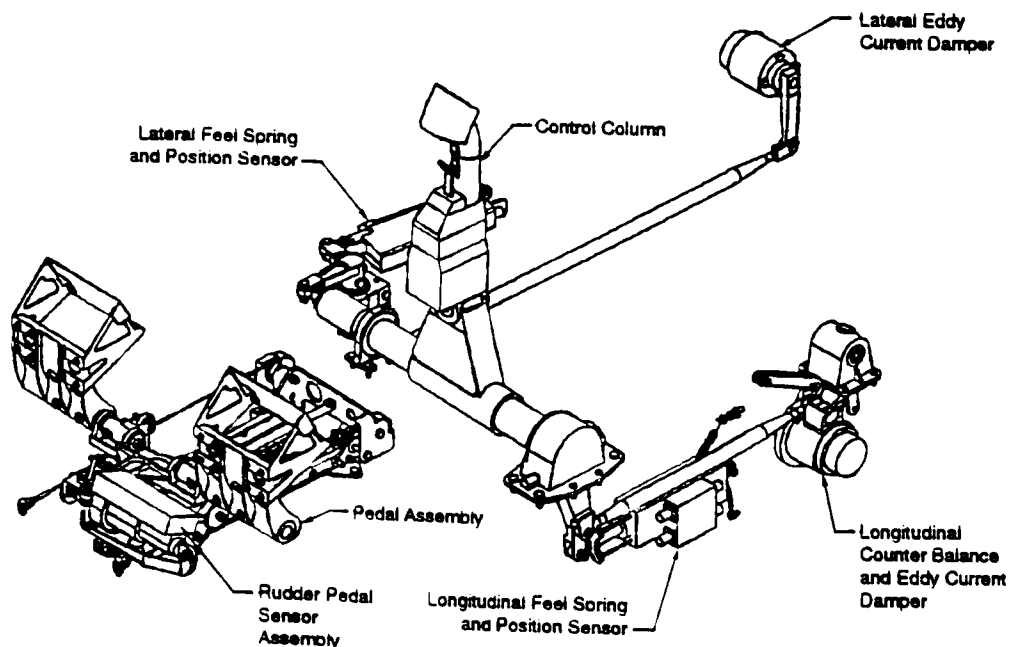


Figure 3

F/A-18E/F CONTROL STICK

F/A-18E/F Flight Control System Design Report. Volume 1.

St. Louis, Missouri: McDonnell Douglas Aerospace, July 1995.

The control stick transmits pilot fore and aft input commands through a direct mechanical linkage to a double acting feel spring assembly located beneath the cockpit floor. Quadruplex linear variable differential transformers are incorporated into the feel spring assembly to provide stick position inputs to the flight control computers. A mass counterbalance is coupled to the control stick via mechanical linkages to negate the forces acting on the control stick from longitudinal accelerations. Incorporated as part of the mass counterbalance is a longitudinal eddy current damper. The eddy current damper was added to the longitudinal control stick to improve aircraft longitudinal flying qualities. The feel spring cartridge requires two pounds of breakout force at the stick grip and provides an artificial feel force of seven pounds per inch of stick grip displacement. A schematic of the longitudinal control stick is shown in Figure 4.

The pilot's longitudinal stick inputs create symmetric stabilator commands. The leading edge flaps, trailing edge flaps, drooped ailerons, and toed-in rudders are air data scheduled to optimize lift, drag, pitching moment, and lateral-directional departure resistance.

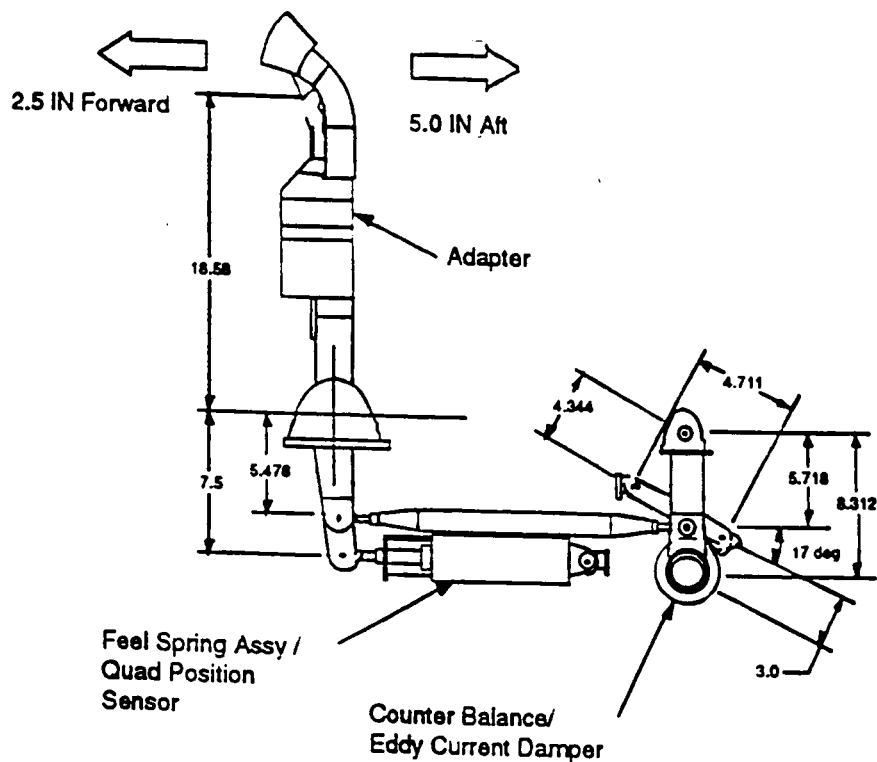


Figure 4

F/A-18E/F LONGITUDINAL CONTROL STICK SCHEMATIC

F/A-18E/F Flight Control System Design Report. Volume 1.

St. Louis, Missouri: McDonnell Douglas Aerospace, July 1995.

In Up-Auto configuration (UA - gear and flaps up), the LEX vents are opened above 20 deg AOA to reduce vertical tail loads and enhance directional stability. The LEX spoilers are used in the speedbrake function, to improve nose down

pitch acceleration from high AOA, and are partially deployed for engine bleed air at supersonic airspeeds. The rudders are toed-in at higher normal load factors in the supersonic region to reduce rudder hinge moments to allow more rudder authority for lateral-directional control. The rudders are flared out at high AOA to improve nose down pitch acceleration as well. The rudders are also flared out to increase drag for the speedbrake function.

In UA, the longitudinal stick commands load factor. The primary feedbacks are normal acceleration (normal load factor - measured by the force of gravity, "g", with 1 g equaling one unit of normal load factor.), pitch rate, and AOA. Above 376 KCAS, the only integral feedback is normal acceleration. Above 376 KCAS, the longitudinal control system is a load factor command system with a constant stick force of 3.5 pounds per g. Below 376 KCAS, pitch rate feedback is added to the integrator to increase the stick force per g to cue the pilot that the airspeed is decreasing and that less load factor is available. At these slower speeds, the control system is no longer a pure load factor command system, but rather a hybrid between load factor and pitch rate. Above 22 deg AOA, AOA feedback is added to the integrator as a stall warning cue, again increasing the stick force per g for high AOA maneuvering. At these higher AOA's, the longitudinal control system is still a hybrid, but very close to an AOA

command system since load factor and pitch rates are usually small.

In Power Approach (PA - gear and flaps down), the LEX spoilers are always retracted, and the speedbrake function is unavailable, other than the spoilers being capable of deployment with weight on wheels. The rudders are toed-in 40 deg for takeoffs to improve nose-up pitching moment. For more precise airspeed control, an AOA command system is used in PA. If the aircraft speeds up or slows down, the control system will change the stabilator command to maintain the commanded AOA. This provides airspeed cueing. The primary feedbacks for PA are AOA and pitch rate. Proportional AOA feedback primarily sets the short period frequency, proportional pitch rate sets short period damping, and integral pitch rate sets the phugoid (or long period) damping. Additional AOA feedback is added above 12 deg AOA to give a stall warning by requiring higher stick forces to get higher AOAs.

The control stick transmits pilot lateral input commands through direct mechanical linkage to a double acting spring cartridge located on the cockpit floor. The spring cartridge provides the pilot with artificial feel forces and contains integral quadruplex linear differential transducers. An eddy current damper reduces roll racheting for large lateral stick

inputs. The lateral feel spring cartridge requires one pound of breakout force at the stick grip and provides a stick gradient of four pounds per inch of lateral stick displacement. A schematic of the lateral control stick is shown in Figure 5.

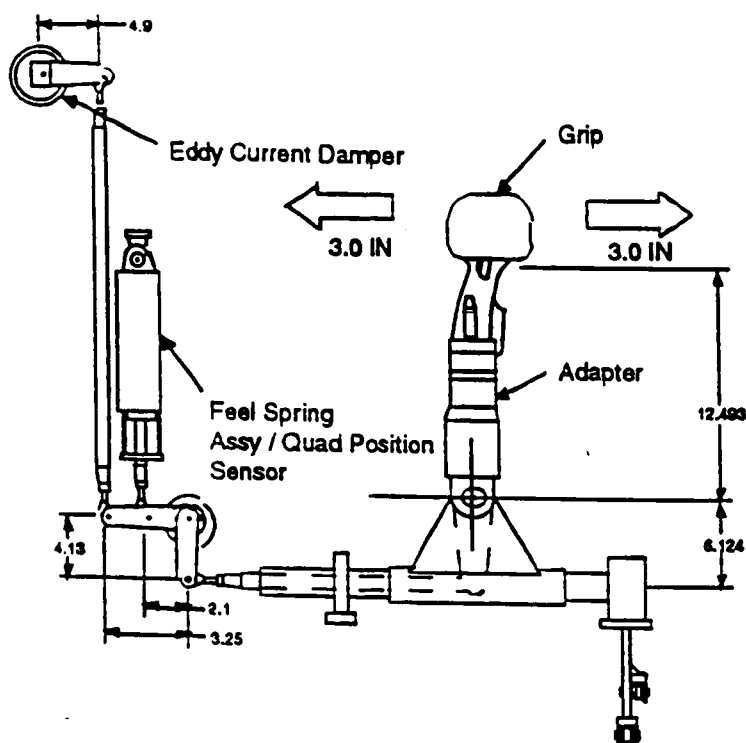


Figure 5

F/A-18E/F LATERAL CONTROL STICK SCHEMATIC

F/A-18E/F Flight Control System Design Report. Volume 1.

St. Louis, Missouri: McDonnell Douglas Aerospace, July 1995.

Directional control inputs are made through the rudder pedal assembly. A double acting spring cartridge provides the pilot with artificial feel forces through the pedals. The rudder pedal sensors, quadruplex linear variable differential transducers, are installed in parallel with the feel device so that they are responsive to the displacement of the device. The rudder pedal spring cartridge has a breakout force of 7.0 pounds at the pedal and a force gradient of 100 pounds per inch of pedal deflection. The entire pedal assembly is track mounted, allowing fore and aft adjustment. A Rolling Surface to Rudder Interconnect (RSRI) automatically coordinates roll maneuvers by commanding the rudders to remove the yaw generated by the lateral surfaces. A schematic of the rudder pedals is shown in Figure 6.

AIR DATA SYSTEM

The Air Data System (ADS) provides primary air data parameters to the FCC's, and externally to the Mission Computers (MC's) for primary flight data displays, navigation, weapons delivery, and other avionics functions. The production ADS consists of Angle of Attack (AOA) transmitters, pitot-static probes, total temperature sensors, pressure transmitter sets, and FCC's.

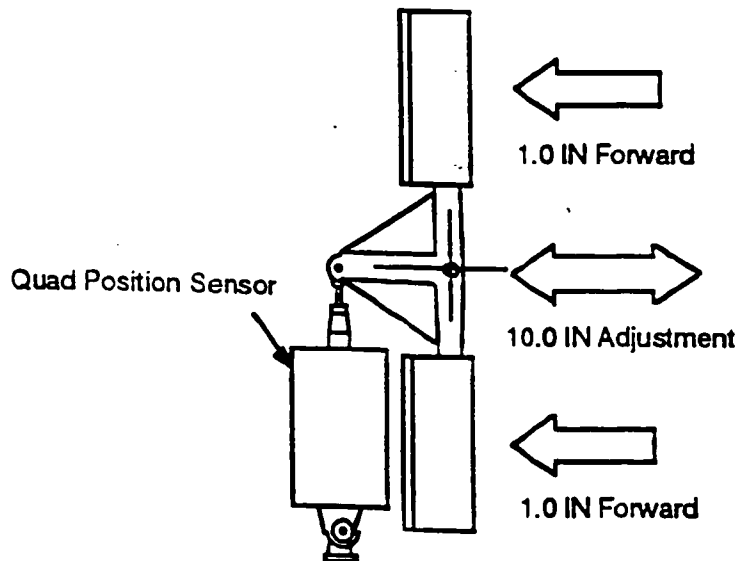


Figure 6

F/A-18E/F RUDDER PEDALS SCHEMATIC

F/A-18E/F Flight Control System Design Report. Volume 1.

St. Louis, Missouri: McDonnell Douglas Aerospace, July 1995.

The Air Data Function (ADF) is defined as the FCC hardware (internal to the FCC's) which interfaces with air data system sensors. The ADF provides interfaces to air data sensors and computes the air data parameters. Source Error Corrections (SEC) are performed by the ADF to correct for position or systematic error reflected in total pressure, static

pressure, angle of attack, and total temperature. The ADF also computes Mach, altitude, and airspeed. (Flight Control System Design Report, p. 3-27)

Pitot-static probes are located symmetrically on the lower forward fuselage. Each pitot-static probe has two static and one total pressure pneumatic outputs. The static pressure is pneumatically averaged prior to connecting to the pressure transmitter sets. Total temperature is measured by sensors which combine the total temperature sensor with the pitot-static probe. A single total temperature sensor is incorporated into each of the pitot-static probes. The total temperature signal is converted to a digital representation, with both FCC's receiving the same signal. (ibid, p. 3-29)

CHAPTER 3

PERFORMANCE FLIGHT TEST METHODOLOGY

According to the U.S. Naval Test Pilot School Fixed Wing Performance Flight Test Manual, aircraft performance generally can be defined as the flight maneuvers an aircraft must execute for successful mission accomplishment. Expected performance parameters must be an integral part of the aircraft design process. Given the user's performance expectations, the designer makes decisions regarding wing loading, power plant selection, airfoil selection, planform configuration, and other design considerations. All of these help tailor the design to give the aircraft the desired performance characteristics.

Actual aircraft performance characteristics are not always the same as the design or the predicted performance characteristics. Therefore, there is a need for performance flight testing to determine the actual performance. Performance flight testing is defined as the process of determining aircraft performance characteristics, or evaluating the energy gaining and losing capability of the aircraft. Determining aircraft performance depends upon

fundamental knowledge in several disciplines including: atmospheric science; fluid dynamics; thermodynamics; subsonic aerodynamics; and supersonic aerodynamics. Performance measurement requires knowledge of the propulsion system characteristics of the aircraft. The flight test team must be familiar with the theory and operation of turbine engines. They must understand the basic measurements, instrumentation techniques, and equipment to gather the data needed to determine the various elements of an aircraft's performance. The team uses these disciplines to form the basis for the flight test methods and techniques for performance flight testing. (USNTPS Fixed Wing Performance Flight Test Manual, p. 1.1)

Some of the basic questions that performance testing answers are (USNTPS Fixed Wing Performance Flight Test Manual, p. 1.2):

1. How fast will the aircraft fly?
2. How high will the aircraft fly?
3. How far and/or how long will the aircraft fly on a load of fuel?
4. How much payload can the aircraft carry?
5. How long of a runway is required for takeoff and landing?
6. How fast will the aircraft climb?

7. How expensive, regarding fuel consumption, is the aircraft to operate?

8. What is the aircraft's Maximum sustained turn rate?
The results of performance flight testing are used for several purposes (USNTPS Fixed Wing Performance Flight Test Manual, p. 1.2):

1. Determine mission suitability of the aircraft.
2. Determine if the aircraft meets specific contractual performance guarantees, or performance requirements as specified in the user's generated requirements.
3. Provide data to construct aircraft flight manuals for use by operational aircrews.
4. Determine techniques and procedures for use by operational aircrews to attain optimum aircraft performance.
5. Determine an aircraft's agility as measured by specific excess power and maneuverability.
6. Obtain research information to advance aeronautical science or to develop new flight test techniques.

There are three basic test conditions at which a pilot operates an aircraft while conducting performance testing. The USNTPS Fixed Wing Performance Flight Test Manual defines these conditions as stable equilibrium, unstable equilibrium, and nonequilibrium. Equilibrium test conditions are present when the aircraft is stabilized at a constant attitude, airspeed and altitude (It can be said that an aircraft is in

equilibrium while in a descent or climb, but for purposes of performance testing, equilibrium test conditions will mean stabilized altitude.)). A stable equilibrium condition is a condition in which the aircraft, if disturbed, returns to its initial condition. An unstable equilibrium test point is a point from which the aircraft, if disturbed, continues to diverge. A nonequilibrium condition is a condition during which there is a change in airspeed, altitude, and/or acceleration.

Stable equilibrium data points are obtained in both level and turning flight when operating at airspeeds greater than the airspeed for minimum drag (stable portion of the thrust or power required curve). The test technique for obtaining stable equilibrium data is to adjust altitude first. Altitude must be maintained precisely and thrust/power must not be changed once set. If this technique is followed, a time history of airspeed is used to determine when the equilibrium data point is obtained. For most tests, when the airspeed has changed less than 2 kts in the preceding 1 minute period, an equilibrium data point is considered to have been achieved. Stable equilibrium test conditions are obtained best by approaching them with excess airspeed. This approach usually ensures rapid convergence, whereas an accelerating approach may take much longer to converge. The flight test technique used in obtaining stable equilibrium

conditions is called the constant altitude or "front side method". (ibid, p. 1.13)

Unstable equilibrium data points are more difficult to obtain and require proper technique. For the unstable equilibrium points, indicated airspeed is held constant. Altitude, engine speed, or bank angle is adjusted as required by the test being conducted. Unstable equilibrium data points are associated with the unstable portion of the thrust or power required curve. To obtain data points under these conditions, the desired test airspeed is established first, then the throttle is adjusted to climb or descend to the desired test altitude. The vertical speed indicator is an important instrument in achieving equilibrium conditions. With throttle set, the vertical speed is stabilized while maintaining the desired test airspeed. A throttle correction is made and the new stabilized vertical speed is observed. A variation of this technique must be used in turning flight when the throttle is set at MIL or MAX power and cannot be used as the adjustable variable. In this case, bank angle (or load factor) is related to vertical speed in the same manner engine speed was related to vertical speed in the straight flight conditions. The flight test technique used in obtaining unstable equilibrium conditions is called the constant airspeed or "back side" method. (ibid, p. 1.13)

Nonequilibrium test points are usually the most difficult to obtain. They preclude stable conditions or the ability to trim to maintain constant conditions. The pilot does, however, have some schedule to follow in achieving a satisfactory flight path or flight test condition. Some nonequilibrium tests such as acceleration runs are performed at a constant altitude. Others, such as climbs and descents, are performed according to an airspeed schedule. Nonequilibrium test points require smoothly capturing, transitioning between data points, and maintaining a schedule. (ibid, p. 1.14)

The quality of a data point, whether it meets test requirements and test conditions, is determined by the test pilot/test team at the time the data are gathered (ibid, p. 1.15). Or, the quality of the point may be determined upon close examination of the data post flight. For performance testing, extremely narrow band tolerances are often present. Depending on whether the data point is a proof of meeting specifications, critical for defining performance curves, or simply a methodology test point, the band width of the tolerance may vary.

The concept of incremental build-up is one of the most important aspects of flight testing. Build-up is the process

of proceeding from the known to the unknown in an incremental, methodical pattern. Flight tests are structured in this manner. Testing begins with the best documented, least hazardous data points and proceeds toward the desired end points always conscious of the aircraft, pilot, and evaluation limits. There should be no surprises in flight test. In the event a data point yields an unexpected result or a series of data points creates an unexpected trend, evaluation stops until the results are analyzed and explained. (ibid, p. 1.17)

Because of these extremely narrow band tolerances, the author found performance work to be one of the most demanding types of test flying. Smoothness, extreme concentration, and above all, patience was required to be successful. Atmospheric conditions often precluded efficient performance flight test. With tolerances as constrained as ± 2 kts. and ± 50 ft. with not throttle movement, any change in air mass would disrupt the test point. The author found it extremely important to make the most accurate decision possible as to whether the data gathered was good data, meeting the required tolerances, immediately upon completion of a test point. This minimized unneeded repeating of a test point, as well as mistakenly accepting a test point which was outside required tolerances. Regardless of the decision made in flight however, the test

team would closely examine all data post flight to positively determine all data which could be used.

CHAPTER 4

DESCRIPTION OF THE PERFORMANCE/PROPULSION TEST AIRCRAFT

GENERAL

Each test aircraft was highly modified and specifically instrumented to accomplish the test objectives assigned each aircraft. There were configuration differences between aircraft E2 and the baseline production F/A-18E. Equipment or airframe components were eliminated or modified because they were not required to complete aircraft E2 test objectives. There were also special flight test installations required for data collection and for safe and efficient conduct of the flight test program. Since aircraft E2 was the performance and propulsion flight test aircraft, the majority of its instrumentation configuration was installed for performance and propulsion testing.

Individual aircraft configuration control and tracking during the EMD flight test program was maintained through an on-line Aircraft Fault Reporting System (AFRS). Configuration changes made to the aircraft were entered into the AFRS.

Additionally, individual flight reports included a configuration summary including changes to the aircraft configuration since the last flight. These procedures ensured the aircraft configuration was tracked and recorded for subsequent performance data reduction and reconciliation.

The following sections describe, as stated in the F/A-18E/F Performance Test Work Description, p. 3 through 5, aircraft E2 configuration changes to the baseline production systems and flight test modifications that were required for the testing.

AIRCRAFT E2 CONFIGURATION

Flight test modifications to aircraft E2's crew station included incorporation of the flight test Digital Data Acquisition System (DDAS) control panels as well as blank panel covers for removed avionics and cockpit controls.

Because aircraft E2 was not used for survivability flight testing, the "New Technology" (NT) coatings were maintained only to retain the external and air induction system moldline as required for the aircraft E2 performance flight test program. Deletion, significant repair or modification of any NT treatments, especially those that affected external

moldline or induction system, was approved by the test team due to the potential impact on aircraft performance. Maintaining aircraft moldline to production configuration was critical for the accuracy of performance data.

Differences between aircraft E2 and production airframe/systems were as follows;

A) Access doors were added in the aft fuselage growth area for access to flight test data acquisition equipment.

B) The production engine inlet ice detector was not installed.

The majority of the Electronic Warfare (EW) avionics equipment was not installed in E2, since their use was not required to accomplish E2's test objectives. However, all outer antenna installations were present to avoid any external moldline differences between E2 and the production configurations.

The following weapons systems modifications were made to aircraft E2:

A) Aircraft E2 had no test mission assignments which required weapons to be launched or released. For this

reason, aircraft E2 did not have a production Stores Management System (SMS) for normal carriage and release of weapons. However, E2 did have all launchers and bomb racks necessary for captive carriage of stores required to complete test objectives. A flight test emergency stores jettison release capability was installed.

- B) The gun system was not installed. An internal plug was installed in the production gun blast diffuser and the gun gas exhaust screens were internally sealed preventing airflow through the gun gas purge system. There was no airflow through the gun system when the gun was not operating, therefore the modified gun system as installed on aircraft E2 was aerodynamically representative of the production gun system configuration.

SPECIAL FLIGHT TEST INSTALLATIONS

The following flight test equipment installations were required for successful completion of the aircraft E2 test plan, as identified in the F/A-18E/F Performance Test Work Description, p. 5 through 8.

Aircraft E2 was equipped with a Digital Data Acquisition System (DDAS) for collection of flight test data. Certain data measurands were telemetered in real time for test mission monitoring. In addition, an onboard instrumentation data tape was used to collect data for post-flight analysis.

The core DDAS system was installed in radar and gun bay pallets in the aircraft nose. In addition, several growth areas throughout the aircraft were utilized for instrumentation.

A telemetry antenna was installed on the nose landing gear. An upper X-band tracking beacon and upper telemetry antennas were installed on the aft canopy fairing access cover, and a lower X-band tracking beacon antenna was installed on a panel adjacent to the nose landing gear drag brace fairing.

A flight test noseboom was installed on aircraft E2 to support performance, propulsion, flight controls, and flying qualities tests. The boom carried a pitot-static probe, total air temperature probes, angle of attack and angle of sideslip vane potentiometer assemblies. Unique to the aircraft E2 boom was the flight path accelerometer package required for performance tests. The flight path accelerometer package was fastened to the angle-of-attack

vane assembly to provide acceleration data along and normal to the flight path.

Noseboom total and static pressures were plumbed to special flight test transducers in the radome. Signal conditioning for the noseboom pressure transducers, potentiometers, and flight path accelerometers was provided by the Noseboom Interface Unit (NIU). The NIU provided noseboom data to DDAS for recording and to the mission computer via the avionics Memory Unit (MUX) talker unit for pilot displays.

The noseboom and mast were attached to a sheet metal flight test radome that replaced the production radome. Except for the noseboom attachment point, the production and flight test radomes had identical loft lines and were interchangeable.

A flight test emergency stores jettison system was installed on aircraft E2 for emergency stores release of wing and centerline external stores in the event of an in-flight emergency. The system was activated by pilot depression of the production emergency jettison button and provided normal jettison signals to the parent bomb racks in the wing pylon stations 2, 3, 4, 8, 9 and 10, and in the centerline pylon (station 6).

The emergency stores jettison system consisted of a relay panel that replaced the Stores Management System (SMS) processor and interfaces with the SMS wiring, connectors and mounting provisions. This relay panel simulated the SMS function when emergency jettison was commanded by the pilot and provided a response time and jettison sequence similar to the SMS. It also provided weight-off-wheels and landing gear handle up safety interlocks. Special adapter cables installed in the pylons replaced the SMS decoder functions and applied the firing voltage directly to the parent racks. This system did not provide a hung store indication to the pilot.

The F/A-18E/F Performance Test Work Description went on to state:

A flight test variable ballast system was installed in aircraft E2 to compensate for Center of Gravity (CG) differences between the production configuration and the unique test configuration of aircraft E2. Ballast was also used to set flight test unique forward or aft CG requirements.

The variable ballast system was located on the gun and radar bay flight test instrumentation pallets. The ballast material was lead bar and/or sheet and was removed or added to obtain an empty weight CG of approximately 35% Mean

Aerodynamic Chord (MAC). CG information was given to the Test Requirements & Analysis Engineer for real-time and post flight data processing whenever adjustments to weight and CG were made. Differences from the baseline empty weight were entered into the mission computer (MC) via the Stores Weight function.

The ballast configuration was changed only when specific off-nominal CG tests were required or when flight test configuration changes moved the CG from the desired position. When the aircraft was ballasted forward or aft of a nominal CG, fuel transfer management with the flight test fuel transfer control was used as required to maintain the actual CG within authorized limits (16.8% to 31.3% MAC).

Engine inlet rakes were installed in both inlets of aircraft E2 to determine inlet distortion and recovery during propulsion and performance tests. The engine inlet rake was a "wagon wheel" array of 40 total pressure probes extending into the inlet airflow. The rake was comprised of eight struts spaced at 45 degree intervals. Each strut contained five high-response total pressure transducers for measuring steady-state and dynamic total pressure. The production inlet ice detector was removed from the left inlet to accommodate the inlet rakes.

The inlet rake struts and mounts were designed to minimize aerodynamic disturbances and blockage. The inlet rakes had an infinite service life when operated within the permissible flight envelope and limits of the basic aircraft. Provisions were available to fly with the inlet rakes removed by replacing the strut with a plug.

The engines installed in aircraft E2 were instrumented and slightly modified to assist in determining engine/aircraft compatibility and performance. Three specific flight test engines were affected by these modifications. These three engines were also instrumented with performance, operability/compatibility, thermal, engine device and provisional instrumentation kits to provide engine operation and performance data.

A white yarn yaw string was installed on the fuselage centerline forward of the windscreen to provide additional Angle Of Side Slip (AOSS) information to the pilot. The yaw string was approximately two feet long originating from a point forward of the aft gun mount access cover. A special yaw string scale was painted on the fuselage to provide 0° and $\pm 5^\circ$ AOSS reference lines.

A laser reflector was at times installed on the aircraft (outboard tip of each vertical tail) to obtain takeoff and landing performance data from an Automated Laser Tracking System (ALTS).

The laser reflectors were to be installed for the initial field takeoff and landing tests. If an adequate correlation between Inertial Navigation System (INS) and ALTS data was established, the reflectors were to be removed and all subsequent takeoff and landing data was to be collected using the INS. The laser reflectors were not installed for any Up and Away (UA)/high speed performance tests.

The outer moldline (OML) of aircraft E2 was built and maintained to simulate the production configuration moldline and surface roughness as closely as possible. However, in some cases, flight test modifications and/or instrumentation affected the OML and were tracked for aircraft performance purposes.

SPECIAL FLIGHT TEST AVIONICS HARDWARE

Special avionics software was available and was utilized to support performance flight test data collection and test

conduct. The following sections, as described in the F/A-18E/F Flight Test System/Segment Design Document, briefly describe the capabilities and function of these software changes.

A Flight Test Heads Up Display (HUD) format was available to provide the pilot with additional flight condition data that was not normally displayed on the HUD. These data assisted the pilot in achieving test conditions and increased test efficiency. Display of the flight test HUD format and its symbols were controlled by the HUD reject control panel on the lower right main instrument panel.

The Test Instrumentation Support Module (TISM) in the MC software received flight test data via the avionics MUX talker unit for calculation and display to the pilot on the flight test HUD format. Air data from the noseboom, along with Flight Path Angle (FPA) and Normal Acceleration (Nz) from flight test accelerometers were used by the TISM to calculate and display the following parameters on the HUD:

- A) Noseboom angle of attack
- B) Mach number (from noseboom air data)
- C) Body-mounted normal acceleration
- D) Min & MAX acceleration tracking

- E) Time (minutes and seconds)
- F) Noseboom flight path acceleration (FPA)
- G) Noseboom angle of sideslip
- H) Calibrated airspeed (from noseboom air data)
- I) Rate of climb (differentiated noseboom pressure altitude)
- J) Pressure altitude (from noseboom air data)

The E/F Flight Test HUD format also incorporated two new status parameters; the Energy Cue (calculated FPA cue) and Auto throttle Control (ATC) AOA Reference. The ATC AOA Reference and the Energy Cue were calculated using INS and FCC data. The energy cue was very beneficial in increasing performance test point efficiency by indicating to the pilot when he was near an equilibrium condition.

Normalized weight was calculated by the mission computer using calculated aircraft weight and corrected noseboom static pressure and was used by the pilot to fly specific normalized weight (W/Δ) cruise performance tests. It was displayed in the upper right corner of the Fuel format and the In-flight Fuel Quantity/Transfer format.

Time was displayed on the MDI's for post test video playback. The time display was enabled/disabled by selecting the TISM button on the Engine format.

An INS 40 Hz Data function was enabled by a memory change (input change to aircraft mission computer), allowing the MC to read INS body axis rate and acceleration data at an increased 40 Hz update rate to support parameter identification and performance testing.

A FADEC flight test engine data function was enabled by a memory change, allowing the MC to read additional left and right FADEC data at 40 Hz so it could be recorded by the DDAS instrumentation system. The additional data was used to determine and evaluate engine performance.

An ECS airflow schedule function allowed the avionics, cabin and cabin cutback airflow schedules to be altered via a memory change. When the flight test ECS memory locations were non-zero, the MC sends the value to the ECS controller to change the baseline airflow schedules. ECS system performance directly effected performance data due to its relationship to engine bleed air.

The MC normally sent flap schedule discretes to the FCC based on the presence of external fuel tanks. A flaps schedule override memory change function provided the ability to override the MC determination of these discretes and manually

select one of three flap schedules to be sent to the FCC. This aided in flap parametric performance testing.

A stores weight function provided the ability to manually enter stores weight via the memory change function. This delta weight was then stored in the mission computer non-volatile memory. This function was intended primarily for the entry of stores weight because aircraft E2 did not have an SMS installed; however, it was also used for any delta weight requirements.

A delta fuel capacity function provided the ability to manually enter the fuel capacity of the external fuel tanks installed via the memory change function. This function was required in flight test aircraft which did not have a stores management system installed. This value was used to calculate the overall fuel capacity of the aircraft.

Aircraft E-2 possessed a flight test option to change, in flight, the Flight Control Computer (FCC) flight parameters. Predetermined and pre-tested alterations of selected constants in the FCC control law software were inputted. These were used to accomplish such tasks as flap schedule optimization, aerodynamic parameter identification, risk reduction, and enabling different automatic throttle

features. According to the Flight Test Features Brief Notes - F/A-18E/F Dial-A-Function Capability, there were 17 different areas, classified as tables, that Dial-A-Function was used. The first four tables were specifically designed for aiding performance flight testing. They were as follows:

Table 1: UA (Up and away -- gear and flaps up) performance optimization, adjusting LEF (Leading Edge Flap), TEF (Trailing Edge Flap), and aileron positioning.

Table 2: UA performance / loads / and nose-down control authority, adjusting the rudder positioning.

Table 3: PA (Power Approach -- gear and flaps down) performance optimization, adjusting LEF, TEF, and aileron positioning. It will also simulate TEF failures.

Table 4: PA performance / and nose down control authority, adjusting LEF, TEF, and Rudder positioning. This will also simulate rudder failures.

Any four of these tables could be programmed into the mission computer at one time. The mission computer could easily be reprogrammed, in flight by the pilot, to access additional table options, achieving even greater flexibility. The pilot easily and immediately disengaged from any of these functions when required. In addition, multiple interlocks were programmed in, to automatically disengage from the given function in the event of an actual flight control degrade or malfunction. This flight test option proved to be a very

valuable tool for both performance testing and flight control scheduling optimization.

CHAPTER 5

IN-FLIGHT THRUST DETERMINATION

The ultimate goal of the Performance Flight Test Program was to verify aircraft performance. This was to be achieved by:

- Providing a credible database for performance calculations; thrust, lift, and drag measured in-flight.

- Developing a clear understanding of airframe and propulsion system contributions to total vehicle performance; isolate responsibility for performance variance.

- Performing a limited performance demonstration (fallout of In-flight Thrust and Drag Test Flights) in order to verify calculated performance. (Performance Program Objectives Briefing, p.1)

A large part of accomplishing these objectives comes from successfully determining in-flight thrust. The reasons for requiring in-flight thrust are:

- Determination of aircraft drag.

- Problem rectification if aircraft performance is low.

- Interpolation of measured thrust and aircraft drag over a range of flight conditions by validation and development of analytical models.

-Establishment of a baseline for future aircraft and engine modifications. (In-Flight Thrust Determination and Uncertainty, p. i)

The determination of in-flight thrust can be a complex process. Success depends upon careful planning and meticulous attention to detail throughout the test program. It is important that the participants involved (engine and airframe manufacturers, Military service, government agency, etc.) agree at the outset on the definitions and the methods to be used for demonstration. Provision for flexibility and redundant methods is important to provide for unforeseen difficulties with a particular method. (ibid, p.1-1)

The in-flight forces acting on the installed propulsion system are sometimes difficult to define and are often even more difficult to evaluate. In distinguishing between in-flight thrust and drag forces, it is important that the definition of thrust is well understood by all concerned and that there is a proper accounting of all the forces acting on the propulsion system. (ibid, p. 2-1)

A basic premise in establishing a useful in-flight thrust methodology is to define propulsion system thrust and associated aircraft drag so they are equal in level, non-accelerating flight. The thrust definition should also

facilitate the determination of drag from excess thrust measurements in unsteady flight. To this end, the thrust of a propulsion system is defined as a force attributable to the installed engine in the absence of any losses in the external flow. Being a vector quantity, it will generally have components normal to and parallel to the flight path. The drag of a non-lifting body is entirely the consequence of energy dissipation in the external flow due to viscous effects resulting from skin friction, flow separation, and the formation of shock waves. In the absence of a propulsive flow, drag may be equated to a momentum defect at a station far downstream of the body where static pressures have returned to the freestream ambient value. It is the sum of drag consistent with this concept and of drag due to the generation of lift which equates to thrust in steady level flight. (ibid, p. 2-2)

It is when the propulsive force is added that the problem gets complicated. A mixing process begins at the conjunction of the internal and external flows at the exhaust nozzle exit, therefore prohibiting the thrust and the drag of a propulsion system from being defined mathematically without involvement of relationships defining the transfer of mass, momentum, and energy between the two flows (ibid).

Aircraft engine installations differ widely. Powerplant configurations include high-bypass-ratio commercial turbofans, which have fixed-geometry long and short duct nacelles, and highly integrated turbojet and low-bypass-ratio turbofans, which have variable geometry inlets and exhaust nozzles. Each propulsion system will have its own bookkeeping requirements and procedures. Despite this variety, force accounting procedures have much in common. For example, most will employ a well defined set of reference conditions, utilize wind-off engine calibrations, seek to achieve as unique a drag polar as possible, etc. The form of the basic propulsive force equation will be the same, although the terms may differ in important detail. (ibid, p. 3-1)

The F/A-18E/F Performance Flight Test Program utilized two different methods of in-flight thrust determination. The first method was the Force/Area/Pressure Method (FAP). In this method, gross thrust was obtained using a nozzle coefficient that was obtained from correlation's measured in an Altitude Test Facility (ATF) and represented as functions of nozzle pressure ratio and nozzle throat area, which was measured in flight (ibid, p. 4-23). Nozzle inlet pressure was determined by measurement of turbine discharge pressure adjusted by calculation for the pressure loss in the afterburner (ibid). The second method utilized was the W

Root T Method (with W being airflow and T being temperature), where specific gross thrust was obtained using nozzle coefficient that was obtained from correlation's measured in the altitude test facility and represented as functions of nozzle pressure ratio and throat area (ibid, p. 4-25). Nozzle inlet temperature was obtained from a heat balance calculation based upon engine inlet temperature, inlet airflow, bleed flow, and core and afterburner fuel flows (ibid).

The fundamental problem of in-flight thrust measurement was that the methodology employed was indirect; that is, measurements were made of indicators of thrust, rather than thrust itself (ibid, p. 4-1). Since gross thrust is all that can be indicated, all components of drag had to be identified and taken into account in order to determine net propulsive force.

For the F/A-18E/F, Net Propulsive Force (FNP) = Gross Thrust (FN) - Inlet Ramp Bleed Drag (Dramp) - Inlet Spill Drag (Dspill) - ECS Heat Exchanger Drag (Decshx) - Afterbody Drag (Daft). And FN is a function of engine cycle deck, flight condition, power setting, inlet recovery, horsepower extraction of utility systems, and compressor bleed (Propulsion System Performance Notes, p. 2). This is displayed in figure A-2.

The F/A-18E/F Performance Flight Test Program was governed by associated Military Specifications, as is any EMD program. The following statements are addendum's to the Military Specification, governing some of the requirements of this program.

"Performance tests when properly performed and documented are intended for use in the determination of compliance with contract performance guarantees and to provide early flight test data to show performance capabilities. In lieu of a formal performance demonstration, baseline aerodynamic characteristics (lift/drag/moment) will be developed and refined during the flight test program.... These characteristics shall be combined, where applicable, with the specification F414 engine performance... demonstrated aircraft weights, cg locations and fuel volume to calculate aircraft performance to show compliance with the contract guarantees...." (Aircraft Performance Flight Evaluation Briefing, p. 4).

"The variation of drag coefficient with lift coefficient shall be determined in flight at subsonic, transonic, and supersonic Mach numbers, as applicable, with the aircraft loadings required to evaluate performance guarantees.... Aerodynamic data will be derived from steady-state, quasi steady-state, and dynamic test maneuvers through measurement

of engine thrust and aircraft excess thrust. Evaluation of the vehicle aerodynamic characteristics in this manner requires that the net thrust of the installed engines be determined at the flight conditions. A primary and an alternate method for determining In-Flight Thrust (IFT) will be mutually agreed upon by the engine and airframe contractors and Naval Air Systems Command (NAVAIR). The methods developed shall establish performance responsibilities at the aerodynamic interface plane between the engine and the airframe. Engine altitude performance calibrations and gas path parameter measurements may be required to support IFT computation. To support the IFT computation methods, the performance flight test engines will be fully performance instrumented with gas path parameters. The methods utilized in this determination shall be as presented and approved.... The final baseline aerodynamic data shall evolve from integration of the flight test and "In-Flight Thrust Correlation" data to maximize accuracy and minimize data scatter. These baseline aerodynamic data will be determined by the contractor and supplied to NAVAIR. Incorporation of performance testing in flight test schedule at the earliest possible date is required to enhance validity for thrust/drag determination." (Aircraft Performance Flight Evaluation Briefing, p. 5).

"The thrust output developed by the turbojet engine in level flight shall be determined in conjunction with the performance and drag measurement tests specified.... The thrust shall be determined using applicable in-flight engine measurands. If the calculated net thrust of the engine is more than 5 percent above or below the installed values shown on predicted performance charts, the contractor shall consult with NAVAIR as to the action to be taken." (ibid, p. 6)

The extremely narrow band tolerances and the structure of the performance test program presented in the next chapter were a direct result of the requirements stated above.

CHAPTER 6

PERFORMANCE TEST PROGRAM

The performance flight tests defined were accomplished in conjunction with propulsion and flying qualities testing on aircraft E2. Performance tests required to develop test and data reduction methodology were accomplished first. Flap schedule parametrics testing followed and was completed to support the Build 2 software update availability in October 1996. Limited test matrices were to be performed as required throughout the EMD flight test program to quantify the impact of any configuration changes. Aerodynamic database documentation testing was to begin after the aircraft configuration stabilizes and the Flight Test Performance Working Group was confident in the test methodology results. Drag increments due to the interdiction store loadings were to be determined last due to interdependencies with aeroelastic stability and loads testing.

PERFORMANCE TEST PREREQUISITES & INTERDEPENDENCIES

Prerequisites and interdependencies were many in a large EMD program. Tests on one aircraft were dependent on tests from other aircraft. The proper planning and on time completion

of these interdependencies were absolutely critical for the flight test program to remain on schedule. The following paragraphs discuss the various program prerequisites and interdependencies required to complete the performance flight tests on aircraft E2, as identified in the F/A-18E/F Performance Test Work Description, p. 21 - 22.

Several tests on aircraft E2 were required before the performance flight evaluation could be completed. Weight and balance and fuel quantity gauging system calibration tests (including external fuel tanks) were accomplished prior to performance testing so that aircraft weight and center of gravity could be accurately calculated during performance maneuvers. Individual tank-by-tank fuel quantity gauging calibrations were not required for early methodology testing but were completed before database documentation tests.

Additionally, a thrust stand run was performed during the methodology development phase in the Patuxent River Aircraft Test and Evaluation Facility (ATEF) to verify operation of all engine and selected airframe instrumentation. Aircraft E2 was also participated in Phase 2 development of the air data system Source Error Correction (SEC) which was required before database documentation testing to ensure proper flap scheduling. Air refueling and engine running ground (hot-

pit) refueling tests were required, and completed early in the test program, to support extended performance flight operations and increase test efficiency.

Performance testing was to be accomplished within the established envelope and limits cleared by other EMD aircraft. Due to this approach, the following tests on other EMD aircraft expanded the aircraft operating envelope before the performance flight evaluation could be completed.

A) Aircraft E1 completed aeroelastic stability envelope expansion beyond the initial limitations in order to accomplish the supersonic test points and for clearance to carry fighter escort and eventually, interdiction store loadings.

B) Aircraft E3 was to complete loads testing required to clear the Nz envelope beyond the initial limitations for turn performance maneuvers with and without stores.

C) Aircraft E1, E2, and E4 were continuing to complete flying qualities tests to clear the maneuvering and AOA envelope required to verify stability and control during performance maneuvers.

D) Aircraft F1 was to complete the Brake/Skid Control System Performance Evaluation to verify functional operation of anti-skid under full brake application conditions.

The author performed test flights on some of the other aircraft in addition to E2. In many cases, these flights included many of the prerequisites for the performance test program. The author, as well as all program test pilots, stayed informed on the progress of all program aircraft.

The percentage of performance test points that required high Mach and high AOA clearances was relatively low. A large number of performance tests were completed within the initial flight clearance envelope.

High lift performance data gathered on aircraft E2 was necessary to support carrier suitability build-up for Initial Sea Trials. High lift performance tests were scheduled to occur after flap parametric testing in late 1996. Performance test interdependencies scheduled on aircraft E2 and other aircraft supported the test approach and schedule.

At the time of writing of this paper, some of the interdependencies had been fully completed, some had been partially completed, and some had not yet been started.

These interdependencies were woven throughout the entire three year EMD program.

TEST APPROACH

The objective of the performance flight test program was to verify guaranteed performance by developing a credible database for performance calculations through the measurement of in-flight lift and drag from a production-representative aircraft. Performance flight tests with stores were to define the aerodynamic increments associated with the specification loadings. These store effects, in conjunction with the database developed from a clean aircraft were to be used to calculate guaranteed performance. Steady-state in-flight thrust methodology was to be used to define the drag variation from zero lift to maximum lift across the Mach number range. Steady-state data (i.e. cruise and sustained turn) was to be used to anchor the database while quasi steady-state and dynamic maneuvers were to be used to extend and complete it. (F/A-18E/F Performance Test Work Description, p. 24)

Two primary methods which used the engine In-Flight Thrust (IFT) cycle deck were used for in-flight thrust determination (IFT cycle deck being the collection of thrust data obtained

through engine ground tests prior to first flight). Confidence in these methods was to be developed through the agreement of the derived aerodynamic coefficients as well as correlation in drag between extremes in power settings. Two additional IFT methods based on an Empirical Force-Area-Pressure (EFAP) calculation were also utilized. These methods were independent of the cycle deck. Repeat runs were employed to verify data quality. (ibid)

Maneuvers were to be flown with coordinated inputs, throttle fixed and the nozzle in the locked out position. To improve the bleed flow measurement accuracy, all of the bleed flow was extracted from one engine when practical. All performance testing was to be conducted using JP-5 fuel. (ibid)

The aircraft performance flight evaluation was to be conducted in eight phases at the conclusion of the dedicated air data verification flights. The eight testing phases are identified in the F/A-18E/F Performance Test Work Description, p. 24, and are as follows:

1. Early methodology development and verification
2. Flap parametrics
3. High lift performance

4. Interim configuration
5. Database documentation
6. Fighter escort store effects
7. Specification interdiction store effects
8. Climb & descent demonstrations

At the time of this writing, phases one, two, and three had generally been completed. Phase four was delayed, since no significant interim configuration change had occurred. The performance program was just starting phase five, database documentation.

The Military Specification required earliest possible performance testing to enhance the validity of thrust/drag determination. To accomplish this, the first phase focused on early methodology development and verification testing. The intent of this phase was to identify any issues that would require early resolution for the success of future testing. This was achieved through the demonstration of drag correlation between in-flight thrust methods and maneuver types over a range of operating conditions. It was also used to provide early assessment of fighter escort performance. Therefore, this phase was flown in the fighter escort configuration (two Dummy Air Test Missiles and two Captive Air Test Missiles, referred to here as DATM-9's and CATM-120's). (ibid, p. 24) The test matrix for this phase

contained a sampling of all the maneuver types to be used during subsequent testing as well as points to provide an early aircraft performance assessment at key performance specification points (ibid, p. 41)

The second phase consisted of flap parametric testing. Since the current flap schedule was developed from wind tunnel data, there was potential for it not to be optimum for the full scale aircraft, potentially resulting in a performance shortfall. In this instance, the testing was used to refine the flap schedule and yield a potential drag reduction without more costly moldline changes. This phase was also scheduled to include flap parametric tests with the interdiction takeoff and return loadings. The F/A-18E/F used a separate flap schedule when wing tanks were installed. Wind tunnel test data indicated the flap schedule was the same for both takeoff and return loadings (ibid, p. 24). Dial-a-function was used to set the control surfaces to discrete deflections.

Cruise points were flown at three Mach numbers at normalized weights (W/δ) corresponding to lift coefficients of 0.2, 0.4, and 0.5. For each Mach number and W/δ combination a flap parametric consisting of eight unique leading and trailing edge flap settings were performed. Cruise altitudes were greater than 5000 feet to avoid hinge moment alleviation

of flap schedules. Accelerations at an altitude of 35,000 feet with four flap deflection combinations provided data at lower lift coefficients than the cruise points and also provided supersonic data. These accelerations were all done at equivalent fuel states so the lift coefficient produced at each Mach number is nominally the same for all the accelerations. A limited rudder toe-in parametric was also conducted at a lift coefficient of approximately 0.4 with a 3/4 flap setting. All non-interdiction loading flap parametric tests were completed at the time of this writing, with no significant gain changes required. (ibid, p. 41)

High lift performance data gathered on E2 was used to support carrier suitability build-up testing on aircraft F1. High lift performance tests were performed during the third phase of testing to determine approach speed and angle of attack, single engine rate of climb, and field takeoff and landing performance. (ibid, p. 24)

Takeoff, approach, and landing data was recorded on different flights. Initial data was acquired to validate methodology. Additional data was to be acquired throughout the flight test program to assess interim configuration changes, and final database documentation data was to be acquired on the mature configuration. ALTS data was required for the dedicated takeoff and landing tests only. (ibid, p. 43)

The possibility of configuration changes existed throughout the EMD flight test program. In order to assess the performance impact resulting from these changes a limited test matrix was to be used. The total number of flights for this phase, the fourth phase, was to depend upon the number and type of configuration changes. Test plans for this phase were to be updated during EMD. When configuration development had been judged to be effectively complete and confidence had been established in the in-flight thrust methods and maneuver techniques, the performance flight evaluation progressed to the fifth phase, database documentation. This was a dedicated flight period devoted to developing a complete lift and drag database. (ibid, p. 24)

This database documentation matrix consisted of all maneuver types. Cruise testing will consisted of a Mach number series for five normalized weights. Included were four supersonic cruise points at 35,000 feet. Intermediate and Maximum afterburner thrust Maximum sustained turns were to be accomplished at two altitudes at the indicated Mach numbers. Accelerations were to be performed every 5000 feet up to an altitude of 40,000 feet at both intermediate and Maximum thrust. Decelerations were to be done every 10,000 feet commencing from the endpoint of the Maximum thrust acceleration. The power required for the decelerations was

specified. Constant Mach number climbs at intermediate thrust were to be flown from 5,000 feet altitude until rate of climb was less than 500 feet per minute. Maximum thrust climbs were to be executed at Mach numbers of 0.85 and 0.9. Constant Mach number descents were to be performed at the specified power setting. Roller coasters were flown at two test altitudes, 15,000 and 35,000 feet. Wind-up turns were to be performed at the same altitudes as the roller coasters with the addition of turns at 40,000 ft. A load factor of 1 (1g) stalls were to be used to aid in coefficient of Maximum lift determination. At the time of this writing, the database documentation phase had just started. (ibid, p. 42)

The fighter escort mission loading consisted of two DATM-9 wing tip missiles and two CATM-120 missiles mounted on the fuselage. The baseline aerodynamic database was developed from flights with a two DATM-9 loading. Therefore, the objective of the sixth phase was to define the aerodynamic increments produced by the addition of the CATM-120 missiles. Accurate data, such as that produced by cruise and acceleration maneuvers, were needed to define this increment. Dynamic maneuvers were not to be used since their resulting drag uncertainty spans the CATM-120 missile increment. In addition, wind tunnel data indicated that these effects were invariant with lift coefficient and flap deflection. (ibid)

The specification interdiction takeoff loading consisted of two DATM-9 wing tip missiles, Forward Looking Infrared (FLIR) and Navigational FLIR (NAVFLIR) pods mounted on the fuselage, two 480 gallon external fuel tanks mounted on inboard wing pylons, and four MK-83 Low Drag (LD) bombs individually on low drag pylons (mid-board and outboard stations). The return loading deleted the MK-83 bombs. The incremental drag, including interference, of the interdiction takeoff and return loadings relative to the two DATM-9 missile configuration were to be determined in the seventh phase. (ibid, p. 26)

This seventh phase matrix consisted of all maneuver types. Cruise testing consisted of a Mach number series for four normalized weights for both takeoff and return. Intermediate thrust maximum sustained turns were to be accomplished at the indicated altitudes and Mach numbers. Accelerations were to be performed every 5000 feet up to an altitude of 35,000 feet at both intermediate and Maximum thrust. Decelerations were to be done every 10,000 feet commencing from the endpoint of the intermediate thrust acceleration at idle power. Three constant Mach number climbs at intermediate thrust were to be flown from 5,000 feet altitude until rate of climb was less than 500 feet per minute complimented by three constant Mach number descents performed at a idle power. Roller coasters

were to be flown at two test altitudes, 10,000 and 35,000 feet. Wind-up turns were to be performed at the same test points as roller coasters with the addition of points at 0.85 Mach number. (ibid, p. 42)

Climb and descent performance demonstrations were scheduled to be conducted during the eighth and final phase. Minimum fuel climb and descent profiles were to be developed using the data obtained from previous phases and demonstrated in both the fighter escort and interdiction store loadings.

All test matrices previously mentioned were estimated to fit within the performance flight allocation for the EMD flight test program. Additional testing (designated as priority two) was desirable if required to satisfy the technical requirements of the Military Specification. The results of planned testing determined the extent of priority two testing needed to satisfy these requirements. Priority two testing was to be substituted for planned tests when required, performed if flight test program priorities and test efficiency permitted additional testing. (ibid, p. 43)

Some test points were available to demonstrate guaranteed performance. Aircraft performance specification compliance was to be verified based on performance calculations using

the aerodynamic characteristics and installation factors developed during this flight test program coupled with the specification minimum engine cycle deck, demonstrated aircraft weights, center of gravity locations, and fuel volume. (ibid, p. 24)

As previously mentioned, acquisition of valid performance data required all outer moldline surface features and geometry's to be fully representative of the baseline production aircraft as defined at the time of the performance flight. It was anticipated that configuration updates would be required during the performance flight test program to maintain commonalty with the production configuration. Special flight test installations were integrated such that external geometry features related to production equipment remained production representative. Detailed design definition was required for all exceptions to this requirement in order for the Flight Test Performance Working Group to assess compatibility with performance flight test objectives.

Critical measurands required for aircraft safety, or to achieve successful post-test data analyses are defined in the F/A-18E/F Performance Test Work Description, p 18 - 19. The author and test team members directed a significant amount of effort towards defining these measurands. The test pilot

defines most of the safety of flight and safety of test measurands, where as the technologists define the analysis critical and non-test specific measurands. These measurands are defined below:

Safety of Flight - "A safety of flight measurand is required to alert the aircrew of impending unsafe conditions regardless of the testing being conducted. Telemetry will be required during all flight operations. This Safety of Flight Measurand List applies to all test work descriptions on a specific aircraft and will be documented by a "living" memo per aircraft. Failure of a safety of flight measurand and any back-up will require Return to Base (RTB)."

Safety of Test - "A safety of test measurand is required to alert the aircrew of impending unsafe conditions. Telemetry will be required for the specific test only. The safety of test measurand list applies to specific tests on all aircraft. Failure of the measurand and any backup will require an RTB or proceeding with alternate, pre-briefed tests not requiring the failed measurands."

Analysis Critical - "An analysis critical measurand is required for real-time and/or post-flight analysis. Telemetry will be as required. The analysis critical

measurand list applies to specific tests on all aircraft. Failure of an analysis critical measurand and any backup will require RTB, proceeding with alternate, pre-briefed testing not requiring the failed measurand, or modification of the analysis critical measurand list real-time based on previous test results and/or changes in data requirements."

Non-Test Specific - "A non-test specific measurand is not required for flight or specific tests. This category is for measurands which are intended for other tests, back-up measurands for Category 3, contingency for troubleshooting, or are nice to have."

If questions arose concerning the health of any of these parameters based on calibration or data analysis, the E2 Test Team; aborted the flight if measurand was a Safety of Flight; omitted the test point if measurand was a Safety of Test; or decided and documented whether testing should proceed or whether the instrumentation should be repaired or replaced prior to resuming aircraft performance evaluation flights.

STANDARD TEST PROCEDURES AND CONVENTIONS

The following procedures were required to be performed prior to the beginning of testing, as defined and stated in the

F/A-18E/F Performance Test Work Description, p. 27 - 29. These pre-flight procedures were extensive, to ensure accuracy of the data, and took approximately three hours to complete.

An INS rotation table calibration was performed prior to performance testing to provide accurate angular information.

A misalignment test was required for the Body Mounted Accelerometer (BMA) Package accelerometers prior to performance testing to correct the accelerometer readings for any non orthogonality of the alignment or installation. This test, at times, had to be repeated during the test program when data anomalies occur. The Noseboom Flight Path Accelerometer (N/FPA) assembly alignment checks were performed before each flight and adjusted as required.

A theodolite survey was required prior to performance flight testing to document the flight test noseboom installation and aircraft control surfaces. The goals of the survey were as follows:

- A) To locate and mark on the aircraft the zero reference AOA and Angle Of Side Slip (AOSS) points.
- B) To document the locations and orientations (coordinates) of the following:

- 1) Noseboom AOA vanes
- 2) Noseboom AOSS vanes
- 3) Noseboom total temperature probes
- 4) Noseboom centerline
- 5) Production pitot-probes
- 6) Production AOA probes
- 7) Aircraft control surfaces including trailing edge flaps, ailerons, and stabilators.

If the noseboom/radome required removal, reference marks were required to ensure the validity of the original theodolite survey after the noseboom/radome is reinstalled. Noseboom angle of attack corrections for bending were analytically derived. However, to validate the inertial load bending corrections, weights were hung from the noseboom so the resulting deflection angles could be compared with results using the analytical model.

All aircraft surface positions, except the digital MUX Bus surface deflections, were calibrated using MDA supplied calibration procedures. These calibrations were "on aircraft" calibrations. This ensured that the information gathered from the instrumentation system was a true representation of surface position deflections.

A test to determine the time lags introduced by pneumatic instrumentation lines was required prior to performance flight testing. This testing was done on the aircraft where possible. If the testing had to be done in the lab, the pneumatic lines were equivalent in length and diameter and had the same connectors as those installed in the aircraft. Some of the instrumentation requiring this test were the noseboom total and static pressures, engine bypass duct pressures, compressor bleed boost venturi pressures, low pressure compressor and turbine pressures, and nozzle inlet pressures.

Prior to first flight, a noseboom pitot-static system leak check was required. This determined if there was a leak in the noseboom air data pneumatic tubing. This leak test was repeated when the noseboom pneumatic tubing was removed and reinstalled, before aerodynamic database documentation testing and when noseboom air data showed any anomalies.

Noseboom angle-of-attack and angle-of-sideslip potentiometers were calibrated while the noseboom was installed on the aircraft.

The aircraft was weighed prior to first flight and was weighed after every major configuration change or every two months, whichever was less.

External fuel tanks used for performance testing were subjected to a fuel calibration to improve the accuracy of aircraft weight determination. Additionally, mass properties (weight and CG) of all external stores carried on aircraft E2 were measured. This data, along with aircraft test weight and CG, were entered into the aircraft via the stores weight function and included in the onboard calculations.

AIR DATA CALIBRATION VERIFICATION

The forces acting on an aircraft in flight are a function of the temperature, density, pressure, and viscosity of the fluid in which the vehicle is operating. Because of this, the flight test team needed a means for determining the atmospheric properties. Measurements reveal the atmospheric properties have daily, seasonal, and geographic dependence; and are in a constant state of change. Solar radiation, water vapor, winds, clouds, turbulence, and human activity cause local variations in the atmosphere. The flight test team cannot control these natural variances, so a standard atmosphere was constructed. The standard atmosphere was used as the baseline atmospheric pressure, so that data could be collected independent of these atmospheric variations. (USNTPS Fixed Wing Performance Flight Test Manual, p. 2.2)

The purpose of pitot static (Source Error Correction) testing is to investigate the characteristics of the aircraft pressure sensing systems. The USNTPS Fixed Wing Performance Flight Test Manual, p. 2.1, defines the following objectives:

1. Determine the airspeed and altimeter correction data required for flight test data reduction.
2. Determine the temperature recovery factor.
3. Evaluate mission suitability problem areas.
4. Evaluate the requirements of pertinent Military Specifications.

A subset of noseboom air data source error correction tests was repeated on aircraft E2 to verify the source error correction developed on aircraft E1.

PERFORMANCE MANEUVERS

The development of the aerodynamic database used several maneuver types. They were classified into three types: 1) steady-state (to include the stable and unstable equilibrium points discussed previously), 2) quasi steady-state (the nonequilibrium points discussed previously), and 3) dynamic maneuvers. The following paragraphs detail the maneuver

procedures. Each maneuver provided a small piece of data which together, would eventually establish the aircraft's performance envelope. It was critical that each maneuver was performed precisely as specified, and within the required tolerances. The author flew all of these maneuvers, and helped refine the test techniques, in order to most efficiently execute the performance test program. Although many of these maneuvers were part of test phases not yet started at the time of this writing, all maneuvers were flown during the early methodology phase, which was completed.

The first class of maneuver was the steady-state maneuvers. Steady-state maneuvers were stabilized maneuvers performed at constant Mach number, altitude, and load factor where excess thrust was nominally zero (unaccelerated flight). These maneuvers yielded the most accurate data but required a large amount of flight time and airspace to define a small portion of the drag polar. The following maneuvers were considered steady-state maneuvers. (F/A-18E/F Performance Test Work Description, p. 34)

LEVEL FLIGHT PERFORMANCE

Aircraft level flight performance analysis is the process of determining standard day level flight characteristics from data obtained during nonstandard conditions. With jet powered

aircraft came the necessity of standardizing data for constant compressibility conditions, thus avoiding compressibility corrections. This type of data reduction is the pressure altitude method. The pressure altitude method is based on the concept of maintaining a constant pressure altitude and indicated airspeed, and correcting data for temperature to obtain standard day performance. (USNTPS Fixed Wing Performance Flight Test Manual, p.4.1)

Of specific interest are aircraft range and endurance. Aerodynamic forces acting on the aircraft, lift and drag, and engine parameters are presented as functions of easily measured parameters. These engine and aerodynamic functions are combined to complete the analysis. The final result provides a method to determine engine and airplane performance characteristics with minimum flight testing. The aircraft is in unaccelerated flight when the sum of the forces and moments acting upon it equal zero. Therefore, lift equals aircraft weight, and the net thrust parallel to the flight path equals the aircraft drag. (ibid)

With flight test efficiency being of utmost importance for both time and money reasons, determining aircraft level flight performance throughout its envelope is quite an undertaking. However, a method has been developed to simplify this process. By grouping the variables associated

with level flight performance, a simple relationship is formed, where Referred drag (D/δ) is simply a function of Mach and Referred weight (W/δ), where δ is defined as pressure ratio, as shown in Figure 7.

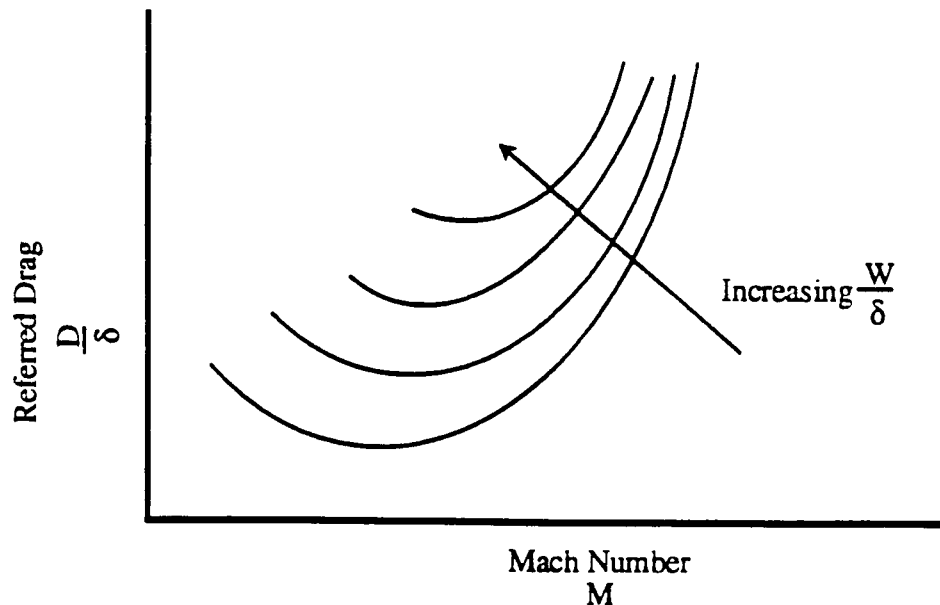


Figure 7

LEVEL FLIGHT DRAG

U.S. Naval Test Pilot School Flight Test Manual (Fixed Wing Performance). Patuxent River, Maryland: Naval Air Warfare Center Aircraft Division, September 1992.

This relationship allowed the test team to gather level flight data points at specific W/δ s and determine the level flight performance throughout the aircraft envelope.

Cruise data was obtained for specified normalized weights, W/delta. Each W/delta series was flown on the same flight, when possible, to remove flight-to-flight biases. The procedure for cruise testing was to stabilize at the target W/delta condition and maintain constant Mach number and altitude for one minute before starting the "data run". Use of the altitude hold feature of the autopilot was acceptable. The exact altitude was contingent upon weight but was ± 2000 ft. of the target altitude. The tolerances for the test point entrance conditions were:

<u>Parameter</u>	<u>Entrance Condition Tolerance</u>
Altitude	± 2000 ft.
Normalized Weight, W/delta	$\pm 2\%$
Mach Number	± 0.01

Procedures were to stabilize for three minutes in duration at constant Mach and altitude with fixed throttles. This duration was shortened if acceptable data was consistently collected in less time but was not be less than two minutes. Auto throttle was not acceptable due to induced oscillations in engine fuel flow. During data acquisition the following tolerances were maintained. (F/A-18E/F Performance Test Work Description, p. 34)

<u>Parameter</u>	<u>Data Acquisition Tolerance</u>
Mach Number	± 0.005 (± 2 KCAS)
Altitude	± 50 ft

MANEUVERING FLIGHT

An airplane in flight has a velocity vector which defines its speed and direction of flight. The capacity to change this vector is called maneuverability. Quantifying the maneuverability of an airplane involves documenting the acceleration, deceleration, and turning characteristics. These characteristics are not independent, however, they can be isolated. (USNTPS Fixed Wing Performance Flight Test Manual, p. 6.1)

Maximum Sustained Turns - The engines were preheated with an intermediate acceleration to target test Mach number and altitude conditions. With throttle fixed at rated power, a pull into a steady turn was conducted, varying load factor until attaining the normal load factor where $N_x=0$ in the wind axis. Mach number and altitude were held constant for 20

seconds. The following tolerances for the maneuver entrance point and data acquisition were maintained. F/A-18E/F Performance Test Work Description, p. 34)

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
Mach Number	± 0.01	± 0.01
Altitude	± 500 ft	± 200 ft

The second class of maneuver was the quasi steady-state maneuvers. Quasi steady-state maneuvers were those flown near a normal load factor of one with a fixed throttle position. Altitude or Mach number was held constant while the other became the primary variable. Net thrust and aircraft excess thrust varied as a result of the change in flight conditions. These maneuvers provided data for extremes in throttle setting. Quasi steady-state maneuvers increased uncertainty as compared to steady-state maneuvers. The following maneuvers were considered quasi steady-state maneuvers. (ibid, p. 35)

EXCESS POWER CHARACTERISTICS

Aircraft climb performance and level acceleration are really different aspects of the same characteristic. Aircraft performance is based on the balance that must exist between the kinetic and potential energy exchange of the aircraft, the energy dissipated against the drag, and the energy derived from the fuel (Energy Approach to the General Aircraft Maneuverability Problem, p. 187).

The specific excess power characteristics for the entire flight envelope of the aircraft can be determined from a series of level accelerations completed at different specified altitudes.

Accelerations to maximum Mach number at intermediate and maximum thrust were performed at constant altitude. The engines were preheated during a MIL power wind-up turn at the initial Mach and altitude until the engines were stabilized. A wind-down turn was often required to reduce Mach number to the target entry condition. Speedbrakes were also used in addition to or instead of a wind-down turn to maintain Mach during the preheat. MIL or MAX power was selected after the engines were stabilized while simultaneously rolling level to begin the acceleration at the target Mach number (allowing for afterburner (A/B) to light while rolling wings level).

Acceleration was at constant altitude and fixed throttle until the given endspeed. The following tolerances were maintained. F/A-18E/F Performance Test Work Description, p. 35)

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
Altitude	± 500 ft	± 200 ft
Load Factor	$1 \pm 0.1g$	$1 \pm 0.1g$

Decelerations were also performed at constant specified altitudes. After stabilizing at the specified initial condition for 30 seconds, thrust was reduced to idle power. Deceleration was at constant altitude until reaching desired airspeed. The following tolerances were maintained. The speedbrake function was not used to perform these decelerations. (ibid)

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
Altitude	± 500 ft	± 200 ft
Load Factor	$\pm 0.1g$	$\pm 0.1g$

Intermediate and maximum afterburner thrust climbs were performed at constant Mach number. The engines were preheated and stabilized at intermediate thrust before each climb began to allow the engine rotating parts to reach initial steady-state operating temperatures and design clearances. These test points were initialized from a MIL power acceleration to the target airspeed at approximately 1000 ft. Above Ground Level (AGL). Maximum power was selected for maximum thrust climbs upon reaching the initial condition. Climbs were at a constant Mach number and fixed throttle until rate of climb was less than 500 feet per minute. The climbs were sometimes performed in segments. However, some altitude overlap was required. The following tolerances were to be maintained: (ibid)

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
Mach Number	± 0.01	± 0.01

Climbs were also to be performed to verify the recommended schedules for the minimum fuel climb and the minimum time to climb for supersonic high altitude target interception. The profiles were to specified prior to performing these test points. The engines were to preheated and stabilized prior

to each test point. For the minimum fuel climb, airspeed variations of no more than ± 5 KCAS during the constant airspeed segments and ± 0.01 Mach during the constant Mach segments were to be allowed. These climbs were to be performed at MIL power. The altitude intercept climbs were to be performed at MAX power. (ibid, p. 36)

DESCENTS

For stabilized, level flight, engine thrust or power is adjusted to balance the aircraft's drag. If the thrust or power is reduced to zero, the power required to maintain the aircraft's speed comes from the aircraft's time rate of change of potential energy. The rate of energy expenditure varies directly with the rate of descent and linear acceleration. (USNTPS Fixed Wing Performance Flight Test Manual, p. 8.2)

A constant airspeed 250 KCAS continuous descent from 45,000 ft. to 5,000 ft. at idle power was to be performed. The aircraft was to be stabilized at the initial altitude and airspeed before initiation of the maneuver. Airspeed variations were not to exceed 5 KCAS.

Descents were to be performed at constant Mach number as well. After stabilizing at the specified initial condition for 30 seconds, thrust would be reduced to the specified power setting. The descent was to be at a constant Mach number and fixed throttle until reaching 5,000 ft. The descents could have been performed in segments; however, some altitude overlap was required. The following tolerances were to be maintained: (F/A-18E/F Performance Test Work Description, p.35)

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
Mach Number	± 0.01	± 0.01

DYNAMIC MANEUVERS

The third classification of performance maneuvers is dynamic. Dynamic maneuvers are characterized by variations in aircraft normal load factor and excess thrust with the engine throttles fixed and Mach number held constant. These maneuvers allow evaluation of the vehicle propulsion and aerodynamic characteristics covering a range of angles of attack that cannot be achieved easily through steady-state or quasi steady-state maneuvers. These maneuvers also have more

performance data uncertainty than either steady-state or quasi steady-state maneuvers. The following dynamic maneuver descriptions come from the F/A-18E/F Performance Test Work Description, p. 36 - 38.

Roller Coasters - The roller coaster (push-over/pull-up) maneuver was performed after stabilizing at the specified test conditions. The tolerances for the test point entrance conditions were:

<u>Parameter</u>	<u>Tolerance</u>
Mach Number	± 0.01
Altitude	± 500 ft

A 30 second steady-state cruise point was performed as a reference point from which to start the maneuver. Without a change in throttle setting, a push-over to approximately -0.2g was performed, followed by an immediate pull-up to a normal load factor of approximately 2g. The maneuver was performed with aircraft pitch changes in a smooth, steady manner over a duration of around 20 seconds. At lower Mach numbers it was acceptable to start this maneuver with a 2g pull started from a shallow dive followed by a -0.2g push ending at approximately level flight. This was the desired

definition and was performed whenever possible within the fuel system placards. Target nominal load factors were subject to the fuel system placards when applicable. Due to concerns with fuel system performance during early testing, the push-over target load factor was approximately +0.5g instead of -0.2g. During data acquisition the following tolerances were maintained.

<u>Parameter</u>	<u>Tolerance</u>
Mach Number	± 0.02
Altitude	± 2000 ft
Load Factor Onset Rate	< 0.25 g/sec

Constant Throttle/Mach Wind-up Turns - These maneuvers were performed at constant Mach number and throttle setting and were preceded by a stabilized trim point. The entrance condition tolerances were:

<u>Parameter</u>	<u>Tolerance</u>
Mach Number	± 0.01
Altitude	± 1000 ft

A 30 second steady-state cruise point was performed as a reference point from which to start the maneuver. Without a change in throttle setting, a turn was started, gradually increasing load factor to specified normal load factor limit. The maneuver was performed smoothly keeping pitch acceleration uniform and to a minimum. Mach number was maintained closely, trading off altitude for airspeed if required. During data acquisition the following tolerances were maintained.

<u>Parameter</u>	<u>Tolerance</u>
Mach Number	± 0.02
Load Factor Onset Rate	$< 0.25 \text{ g/sec}$

Wind-up turns starting at or below 25,000 ft. were sometimes performed in two parts to cover the desired AOA range. The first step was to perform a MIL-power constant-Mach wind-up turn from a MIL-power sustained level turn. This step covered the AOA range from the sustained Nz to the Nz limit. The second step was to perform a wind-up turn from 1g level flight at Power for Level Flight (PLF) to the sustained Nz.

ADDITIONAL PERFORMANCE MANEUVERS

Aerodynamic Database Development - Trimmed lift and drag was to be determined for an angle of attack range from 0 to +25 degrees. For each configuration, stabilized level flight at 5000 ft was to be achieved at target AOA, and the "data run" was to begin after engine thermal stabilization, as determined by the computed Exhaust Gas Temperature (EGT). "On condition" was to be maintained with fixed throttle for no less than one minute. Use of autopilot was acceptable. The autopilot was not to be used if during testing it was determined that the autopilot was unable to hold tolerances or induced large control inputs. Use of auto throttle was not acceptable due to induced oscillations in engine fuel flow. Test maneuver tolerances were: (F/A-18E/F Performance Test Work Description, p. 38)

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
AOA	$\pm 0.1^\circ$	As Required
Airspeed	As Required	± 2 KCAS
Altitude	± 200 ft.	± 50 ft.
N_z	1.0g	$1.0 \pm 0.1g$

Approach Speed Evaluation - The purpose of these tests were to collect high lift performance and approach speed data over the range of possible approach AOAs between 5,000 and 3,000 ft. The approach angle of attack for use during carrier landings was determined from carrier suitability tests.

In full flaps, with the landing gear down and the tail hook extended, the aircraft was stabilized on a 4.0 degree glideslope at angles of attack of 6.0, 7.0, 8.1, 9.0, and 10.0 degrees for 10 seconds prior to passing 5000 ft. Mean Sea Level (MSL). With throttles fixed, the stabilized descent was maintained for an altitude change of 2000 ft. or 2 minutes, whichever was less. The maneuver was performed with two different external store loadings. The maneuver was repeated with the aircraft in half flaps. The target weight was 42,900 lb. (± 1000 lb.). The maneuver was terminated at 3,000 ft. (ibid)

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
AOA	$\pm 0.1^\circ$	$\pm 0.2^\circ$
Flight Path	4.0°	As Required
Altitude	5000 ft. MSL	As Required
N_z	1.0g	$1.0 \pm 0.1g$

Field Takeoff Characteristics - The field takeoff performance characteristics of fuel used, ground roll distance, minimum nosewheel and main wheel liftoff speeds, and distance to clear a 50 ft. obstacle were to be determined for the specification fighter escort and interdiction store loadings. Atmospheric data including ground winds was to be required. Ground roll was to be determined using the Automated Laser Tracking System (ALTS). If an adequate correlation between INS and ALTS data was established, the laser reflectors were to be removed and all subsequent takeoff data was to be gathered using the INS. (ibid, p. 39)

Field Landing Characteristics - Field landing performance characteristics of ground roll distance was to be determined for the specification fighter escort, interdiction, and interdiction bring-back store loadings. Atmospheric data including ground winds were required. Like the field takeoff tests, initially, the ground roll was to be determined using ALTS. If an adequate correlation between INS and ALTS data was established, the laser reflectors were to be removed and all subsequent landing data was to be gathered using the INS. (ibid)

Simulated Single Engine - Single Engine Rate of Climb (SEROC) tests were performed to determine single engine climb

performance. The aircraft was stabilized for zero sideslip at the specified angle of attack in full flaps with the landing gear down at approximately 2000 ft. MSL. One engine was reduced to idle thrust and the other engine was commanded to MIL or MAX thrust. A climb was then initiated at the target angle of attack, and stabilized on the corresponding airspeed when passing through 3,000 ft. Stabilized rate of climb data was collected during a climb from 3,000 ft. to 5,000 ft. or 2 minutes, whichever occurred first. Total altitude change during the maneuver did not exceed 2,000 ft. Target AOAs were 0, 4, 8, and 12 degrees AOA. The maneuver was repeated with half flaps. A reduced test matrix was to be completed with the landing gear retracted (half and full flaps). SEROC points had been conducted in MIL and MAX power in the fighter escort configuration at a variety of gross weights, and were to be done in MAX power in the interdiction configuration at a variety of gross weights as well.

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
AOA	$\pm 0.1^\circ$	As required
Airspeed	As Required	± 1 KCAS
Altitude	3,000 ft. MSL	2Kft., 2 minutes
N _z	1.0g	1.0 $\pm$ 0.1g

No target test points had been, or were to be at or below single engine minimum control speed (V_{mc}) for the respective thrust settings as determined from analytical predictions or tests. (ibid, p. 40)

STALLS

The stall speed investigation documents the low speed boundary of the flight envelope of an airplane. In the classic stall, the angle of attack is increased until the airflow over the wing surface can no longer remain attached and separates. The resulting abrupt loss of lift causes a loss of altitude and, in extreme cases, a loss of control. Since stall speed represents an important envelope limitation, it is a critical design goal and performance guarantee for aircraft procurement and certification trials. Verifying the guaranteed stall speed is a high priority in the initial testing phases of an airplane. (USNTPS Fixed Wing Performance Flight Test Manual, p. 3.1)

While defining the boundaries of the performance envelope, it is not uncommon to face degraded flying qualities near the limits. The reduced dynamic pressure near the stall airspeed produces a degradation in the effectiveness of the flight controls in addition to a lift reduction. Maintaining lift

at these low speeds requires high angle of attack, which results in high drag and, frequently, handling difficulties. At some point in the deceleration, a minimum steady speed is reached which is ultimately defined by one of the following limiting factors:

1. Loss of lift. The separated flow is unable to produce sufficient lift.

2. Drag. Large increases in induced drag may cause high sink rates, compromising flight path control.

3. Uncommanded aircraft motions. These undesirable motions can range from a slight pitch over to a severe nose slice and departure.

4. Undesirable flying qualities. These characteristics include intolerable buffet level, shaking of controls, wing rock, aileron reversal, and degraded stability.

5. Control effectiveness. Full nose up pitch control limits may be reached before any of the above conditions occurs.

From the test pilot's perspective, the task is to investigate how much lift potential can be exploited for operational use, without compromising aircraft control in the process. The definition of stall speed comes from that investigation.

(USNTPS Fixed Wing Performance Flight Test Manual, p.3.2)

Erect stalls, at a load factor of 1, were performed in the cruise configuration. Trim was approximately 1.2 times the predicted stall speed. A steady 1 kt/sec deceleration was started at constant thrust by increasing the pitch attitude. A steady flight path was maintained, making all corrections smoothly to minimize Nz variations until a stalled condition was reached ($\approx 32^\circ$ AOA). (F/A-18E/F Performance Test Work Description, p. 40)

Tolerances

<u>Parameter</u>	<u>Entrance Condition</u>	<u>Data Acquisition</u>
dV/dt	1 kt./sec	1 kt./sec

MANEUVER ACCEPTABILITY

Data acquisition tolerances for the maneuvers were presented as guidelines to ensure useful data. Tolerances were exceeded and accepted occasionally for valid reasons (weather/cloud deck, variations in pilot technique, test point unattainable as defined) without impacting data quality. When tolerances were exceeded, the E2 Test Team decided real-time if the data was useful. In these cases, the test point was not reflown unless subsequent data analysis indicated it was necessary. This policy minimized unnecessary repeats and maximized test efficiency without

compromising data quality. (F/A-18E/F Performance Test Work Description, p. 43)

DATA REQUIREMENTS, REDUCTION, AND ANALYSIS

The data requirements given in the following paragraphs were arranged to satisfy the engineering requirements of these tests. Both real-time and post-flight data processing were required. The real-time data requirements were sometimes modified by the on-site test team as required. The onboard data recording system was the primary source for post-flight data reduction. The real-time telemetry data was recorded on the Telemetry (TM) tape, and was available for post flight processing if required. Pilot comments were documented throughout the test program and were recorded on tape.

REAL TIME DATA REQUIREMENTS

Safety of Flight, Safety of Test, and Analysis Critical parameters were monitored real-time to ensure test mission safety and to verify satisfactory test point completion. For test missions conducted at Patuxent River, MD, the Real-Time Telemetry Processing System (RTPS) ground station was used for in-flight telemetry monitoring. The basic RTPS station was comprised of ten stripchart recorders (8 channels per

chart), two digital displays (16 parameters per display), four color monitors, two user-interactive stations with graphics displays, and various hardcopy units.

The initial required telemetry setup included pilot's voice, range time, and parameters as identified by the test team. Stripchart data was used to select areas for post-flight data reduction, thus range time was required on the stripcharts. Telemetry setups were occasionally changed by the on-site test team as warranted by the test situation. (F/A-18E/F Performance Test Work Description, p. 114)

POST FLIGHT DATA REQUIREMENTS

It was critical to get the widest dissemination of the data as quickly as possible. Many of the engineers requiring the data were located in different regions of the country from where the flight test is occurring. Several processes were in place to aid in this task.

The MDA Flight Test Data Processing System (FT2001) was used to produce data from selected time slices. The flight test computer was loaded with the parameters after FT2001 data was reviewed for validity using a PC-based paperless review system (QuickView). Once loaded to the flight test computer, the data was viewed by using the Flight Test Aerospace Data

Editing & Processing Tool (ADEPT) or was made available to other computer analysis software. The flight test computer was accessed by cleared personnel at MDA St. Louis, NAS Patuxent River, Naval Air Systems Command, NGC, and GE. (F/A-18E/F Performance Test Work Description, p. 115) This process proved invaluable in distributing information throughout the E/F Flight Test Organization.

For instrumentation requiring initialization, a 10 second portion of the pre-flight hangar initialization record was processed. This was used to account for any parameter initial offset or bias. (ibid, p. 115)

Pseudo supplemental calculations were computations which were performed on raw measurands during post flight processing whose results were stored in the original measured sequence number. These computation included spike elimination, digital filtering, message coherency, time correction and sample rate decimation routines. Not all routines were performed on all measurands. (ibid)

The aircraft fuel specific gravity, viscosity and temperature was measured both pre- and post-flight. This information was utilized in the final data processing to convert the fuel flow from gallons/hour to pounds/hour. For each performance

test maneuver block, gross weight was initialized with the individual fuel tank quantities. After initialization, aircraft gross weight was computed for final data by integrating corrected engine fuel flow. (ibid)

A wind calibration was flown prior to each test maneuver for the computation of INS AOA and AOSS. The "Wind Calibration in Climb" (WCC) routine was utilized for maneuvers that exceeded altitude losses or gains of greater than 1500 feet. This routine built a table during the final data processing that maps and stores the winds as a function of altitude and was accessed for corresponding test points. The WCC wind calibration required designated test constants to be identified in the final data processing to be properly utilized. (ibid)

During the pre-flight for performance flights an FPA misalignment was determined and recorded. This misalignment was due to noseboom AOA vane misalignment. A correction in the final data processing was sometimes utilized to account for this misalignment angle. If the misalignment exceeded a load factor of ± 0.001 the vanes were re-aligned and the noseboom AOA was recalibrated. (ibid)

Laser tracker data from the test range was merged with aircraft data during post-flight processing of certain test points. If necessary, to avoid processing delays, the aircraft data was processed separately and reprocessed later to merge the laser tracker data. (ibid)

CHAPTER 7

SPECIFIC FLIGHT TEST HAZARDS

Identifying potential hazards to flight test is critical for any flight test program. It is essential that the flight test team clearly identify specific hazards, cause of hazard, resulting effect, preventative measures, corrective actions, hazard level, and residual risk. The author was intimately involved with the rest of the test team in defining all associated flight test hazards. These hazards were identified, with associated corrective action, long before any test flight was flown.

Hazard level, probability, and residual risk were categorized according to the following metric from the ITT Test Work Description Flight Test Guide, p. 18:

Hazard Severity:

- Catastrophic (I) -- Aircraft destroyed or fatality or permanent total disability to any personnel.

- Critical (II) -- Aircraft damage greater than \$1,000,000 or permanent partial disability to any personnel or a condition requiring immediate corrective action to avoid aircraft loss or death.

-Marginal (III) -- Aircraft damage greater than \$10,000 or major injury to any personnel or a condition resulting in a safety mission abort that must be corrected prior to next flight.

-Negligible (IV) -- Aircraft damage less than \$10,000 or a minor or first aid injury to any personnel or a condition that does not impact the safe completion of the mission.

Hazard Probability:

-Frequent (A) -- more than 10 occurrences per 100,000 flight hours.

-Probable (B) -- 1 to 10 occurrences per 100,000 flight hours.

-Occasional (C) -- 0.1 to 1 occurrences per 100,000 flight hours.

-Remote (D) -- 0.02 to 0.1 occurrences per 100,000 flight hours.

-Improbable (E) -- less than 0.02 occurrences per 100,000 flight hours.

These occurrences are calculated by system safety analysts that take into account predicted specific individual component lifetime, replacement schedule, failure predictions, and predicted component service lifetime.

Hazard Risk Index:

-Table 1, below, indicates the combination of Hazard Severity and Hazard Probability that results in a Hazard Risk of High, Medium, Low, or Very Low.

Table 1

HAZARD RISK MATRIX

PROBABILITY \ SEVERITY	Frequent	Probable	Occasional	Remote	Improbable
Catastrophic	High	High	High	Medium	Low
Critical	High	High	Medium	Low	Low
Marginal	Medium	Low	Low	Very Low	Very Low
Negligible	Low	Very Low	Very Low	Very Low	Very Low

The following hazards related to performance testing were identified by the test team prior to the start of any actual performance flight testing. These hazards are stated in the F/A-18E/F Performance Test Work Description, appendix H.

Hazard Description: Departure from controlled flight during high AOA maneuvering.

Cause: Insufficient control power to maintain control. AOA in excess of 32 deg.

Resulting Effect: Loss of aircraft control. Uncommanded pitch, roll and yaw.

Preventative Measures: High AOA envelope clearance to be performed by E1, E2, and E4 to ensure no unexpected flying qualities. Adequate buildup is incorporated into the matrix: stalls - high altitude and light weight before lower altitude and higher weights. Wind up turns (WUT) start in the middle of the envelope and progress at higher altitudes before lower altitudes. For each altitude block, perform at slower speeds before higher Mach conditions. Stalls will be approached at slow 1 kt/sec deceleration rate. WUTs will be approached at slow 0.25 g/sec rate.

Corrective Action: Recover in accordance with Flight Manual procedures.

Residual Hazard Level: II-D (critical-remote).

Residual Hazard Risk: Low.

Hazard Description: Loss of consciousness during high g maneuvers.

Cause: Insufficient g tolerance, anti-g system failure, and/or anti-g system disconnected.

Resulting Effect: Pilot loss of consciousness.

Preventative Measures: As part of the phasing maneuver, a 4g awareness turn will be conducted. Prior to flight, the pilot will test the g suit connection and manually test the anti-g system.

Corrective Action: If gray or red out condition occurs, immediately reduce commanded g levels.

Residual Hazard Level: I-E (catastrophic-improbable).

Residual Hazard Risk: Low.

Hazard Description: Hot brakes / brake fire.

Cause: Anti skid failure, heavy gross weight landings, or aborted takeoffs.

Resulting Effect: Aircraft structural damage or fire.

Preventative Measures: Brakes and tires will be visually inspected after each project flight. During landing performance testing, airplane gross weights will be limited by placard database. Hot brake checks will be conducted when required by standard operating procedures prior to entering flight line.

Corrective Action: If hot brakes or brake fire are suspected, emergency procedures will be conducted per standard operating procedures.

Residual Hazard Level: I-D (catastrophic / remote).

Residual Hazard Risk: Medium.

Hazard Description: Loss of control during single engine operations.

Cause: Asymmetrical thrust due to one engine being at a low power setting while the other engine is at a high power setting.

Resulting Effect: Uncontrollable yaw build-up and loss of directional control.

Preventative Measures: Do not slow below Vmc (minimum single engine controllable speed) recommended and cleared by flying qualities testing. Perform maneuvers no lower than 2000 ft.

Corrective Action: Reduce power on power setting engine and increase power setting on engine at idle. Control AOA until both engines are at nearly the same power setting and recover.

Residual Hazard Level: I-E (catastrophic-improbable).

Residual Hazard Risk: Low.

Hazard Description: Engine stall and/or flameout during high AOA maneuvering.

Cause: Inlet distortion exceeds surge margin. Engine combustor instability due to airflow disruption. Failure of engine to auto relight.

Resulting Effect: Engine damage. Loss of aircraft control during high pilot workload events.

Preventative Measures: Real time telemetry monitoring to detect engine instability and or impending flameout. Maneuvers conducted with fixed throttles.

Corrective Action: Emergency procedures as briefed. Advisory calls to pilot as required. Advisory calls to pilot during restart to ensure critical limits are not exceeded.

Residual Hazard Level: II-D (critical-remote).

Residual Hazard Risk: Low.

Hazard Description: Aircraft impacts water during low altitude operations or tower fly-by's for source error correction flights.

Cause: High pilot workload during tower fly-by's.

Resulting Effect: Possible loss of airplane and pilot.

Preventative Measures: Pilot will be briefed on the pattern, area, and procedures prior to tower fly-by's. Radar altimeter will be selected and displayed with altitude warning set at 110 ft AGL. This will be verified with ground personnel prior to commencing tower fly-by's. Engineers at RTPS will monitor radar altitude. Engineers will provide an "abort" call when altitude reaches 100 ft AGL. Engineers will also communicate altitude trends to the pilot between test points.

Corrective Action: If an abort call is made by the test conductor, immediately terminate test point and climb to a safe operating altitude.

Residual Hazard Level: I-D (catastrophic-remote).

Residual Hazard Risk: Medium.

Hazard Description: Bird strike during tower fly-by's.

Cause: Tower fly-by's are conducted at very low altitude over an area with high bird population.

Resulting Effect: Structural damage to airplane. Engine FOD. Possible loss of airplane and pilot.

Preventative Measures: A 250 kt / 500 ft pass will be conducted prior to 150 ft tower fly-by's to determine bird activity and to attempt to scare away birds. Engineers at the range tower or the pilot will call "abort" if birds are determined to be a hazard during tower fly-by's. During tests with the gear down, the landing light will be turned on.

Corrective Action: If a bird strike occurs the pilot will immediately, abort the test point, climb to a safe altitude, visually inspect for damage, perform a controllability check, and return to base.

Residual Hazard Level: II-C (critical-occasional).

Residual Hazard Risk: Medium.

Hazard Description: Damage to aircrew eye sight caused by laser tracking system.

Cause: Laser energy is directed into the crew station during landings and takeoffs.

Resulting Effect: Aircrew detects physical pain due to laser energy.

Preventative Measures: Place laser target (reflector) on the tail. Laser has an automatic power adjustment to a minimum level required to track and obtain data. Eye damage is most likely to occur if laser / eye contact occurs at a distance

less than or equal to 60 ft. (Laser at the runway intersection distance is 100 ft.)

Corrective Action: None.

Residual Hazard Level: II-D (critical-remote).

Residual Hazard Risk: Low.

Hazard description: Unacceptable handling qualities when operating Dial-A-Function (DAF).

Cause: Use of DAF results in turning off various flight control surfaces, modification of control law gains and lag times.

Resulting Effect: Aircraft departure from controlled flight. Pilot Induced Oscillation (PIO) generation.

Preventative Measures: Evaluate predicted handling qualities of each DAF table/option selection in a high fidelity simulation prior to flight tests. DAF table/option selections are programmed before flight. Aircrew cannot randomly select to turn off flight control surfaces. Verbally confirm that the DAF table/option is selected prior to flight test maneuver execution.

Corrective Action: Disengage DAF via paddle switch located on the control stick. If departed, recover in accordance with flight manual procedures.

Residual Hazard Level: II-D (critical-remote).

Residual Hazard Risk: Low.

CHAPTER 8

TEST TEAM AND TEST CONDUCT

THE TEST TEAM

The test team for each test flight was made up of several individuals, each with a specific purpose. The author, as the test pilot, worked closely with all these individuals on a daily basis. The following people were in the brief, debrief, and with the exception of the pilot and technicians, were located in the control room during test flights:

-Test Pilot

"The test pilot is proficient in the required flight skills to obtain accurate data. The pilot has well developed observation and perception powers to recognize problems and adverse characteristics. The pilot has the ability to analyze test results, understand them, and explain the significance of the findings. The test pilot understands the test aircraft in detail. The test pilot also clearly understands the aircraft mission, relying on past operational experience. The pilot knows the specific operational requirements the design was based on, and tasks required for

total mission accomplishment." (USNTPS Fixed Wing Performance Flight Test Manual, p. 1.5)

-Test Conductor

The Test Conductor (TC) led the flight test team, and was the head Flight Test Engineer on the team. The TC had general knowledge of the same items for which the test pilot was responsible for. In addition, the TC possessed sound knowledge of instrumentation requirements, planning and coordination aspects of the flight test program, data acquisition, reduction, and presentation, and technical report writing (USNTPS Fixed Wing Performance Flight Test Manual, p. 1.7). The TC controlled the schedule of the flight test aircraft in which he was assigned to. The TC produced the flight cards, decided which data points to fly, determined the aircraft's schedule, and decided when to fly and when to not fly in order to make required aircraft modifications for future testing. The TC was also the only member of the flight test team who talked to the test pilot during the test mission.

-Two Flight Test Engineers

The two Flight Test Engineers (FTE's) assisted the TC in all duties assigned.

-Test Requirements and Analysis Officer

The Test Requirements and Analysis Officer (TRA) was responsible for setting up the data station for the specific test mission. The TRA ensured all data strip charts

were assigned to display required data for the test flight. The TRA was also responsible for post flight processing of the recorded data, and ensured each technology engineer received their requested data. (Personal Conversation with FTE)

- Three Instrumentation Operations Engineers

- The Instrumentation Operations Engineers (IOE's) were responsible for the onboard aircraft instrumentation system, ensuring all instrumentation pre-flights had been successfully conducted, and noted any measurands that were inoperative (Personal Conversation with E2 FTE).

- Two Technicians

- The Technicians (TECH's) worked closely with the IOE's and were responsible for the actual maintenance of the onboard aircraft instrumentation system (ibid).

- Subsystems Engineer

- Propulsion Engineer

- At least one Performance Engineer

- Flight Controls Engineer

- Flying Qualities Engineer

- Avionics Engineer

Although the specific E2 test flight may have been specifically for performance or propulsion testing, all systems and technologies were present during the initial portion of the EMD program due to the unknowns associated

with a new and untested airplane. The TC, FTE's, TRA, IOE's, and Tech's were assigned to the specific aircraft, in this case, E2. The technology engineers, subsystems, propulsion, performance, etc. went from test aircraft to test aircraft monitoring their specific specialty. As confidence in and flight time on the aircraft increased, all the technologists were not present for every flight, only those specific to the type tests being conducted were present.

A typical flight briefing began with the TC ensuring all members of the test team are present. The TC ran the flight briefing. Referring to the MDA Briefing Checklist, the briefing then proceeded as follows:

Specific flight start, takeoff, and range times are covered and defined. The flight lineup is then identified to include the test pilot, chase pilot and aircraft, and possibly in-flight photographer. A brief description of primary and secondary mission is covered. Test aircraft instrumentation status and maintenance review is then covered, to include such things as; aircraft weight and CG, fuel load and weapons loading, aircraft software configuration, aircraft hardware configuration, maintenance performed since last flight, and instrumentation status. At this point specific aircraft placards are covered. Placards are critical and numerous to an EMD aircraft. The operating limits of each particular aircraft are ever changing, and it

is the responsibility of every member of the test team to keep on top of these limits. At this point, the specific flight test cards are briefed, covering every test maneuver in specifics. Applicable placards are restated at this point. The flight test cards are reviewed and approved by the test team, and supplied to the test pilot the day prior. Following the flight cards, predicted results of each test are covered by the technologists. Finally, pertinent flight test hazards, preventative measures, and corrective actions are covered. At this point, the brief is turned over to the test pilot, to cover specific mission requirements to include weather, chase aircraft responsibilities, and emergency procedures.

The entire pre-flight briefing usually took approximately 60 minutes.

The entire test team again gathered for the post flight debriefing. The first items covered were specific test aircraft or system anomalies including any required maintenance actions or aircraft instrumentation failures. The test pilot then conducted the majority of the debriefing, covering item by item each flight test card, discussing test objectives achieved or not achieved, any observed technical anomalies, and all pilot comments. This is where the author could make his largest impact on the program, by providing

his observations, opinions, and analysis. The author also submitted a detailed report concerning all results, data, and opinions from the flight the following day. The team would then briefly discuss the validity and confidence level of the data achieved. Any mission control room anomalies were identified in order to be corrected for next flight. Finally, attention was directed towards the next test mission, determining feasibility of next planned mission based on the results of the just completed mission. An action plan was created to get to the next mission, and the projected next mission date was identified. The flight debriefing varied in length based on duration and results of the given test mission, however, normally took approximately 60 minutes.

The frequency of test flights for each particular aircraft varied greatly, depending on type of tests being conducted, results achieved, and modification requirements for the aircraft. Program goal was to achieve 10 to 12 test flights per aircraft per month. At the time of this writing, the entire program was averaging 10 to 11 flights per aircraft per month.

FLIGHT CONDUCT

PRE-FLIGHT PROCEDURES

The following procedures were performed prior to and/or after each flight as designated, and are listed in the F/A-18E/F Performance Test Work Description, p. 29 - 30. Some of the instrumentation procedures are amplifications of standard test procedures mentioned earlier. Along with these procedures, a historical database of the pre-flight data values obtained from the pre-flight listings were maintained.

A) Noseboom Parameters Calibration Verification --

Procedures for pre-flighting the noseboom parameters (i.e. AOA, AOSS) were included in the general instrumentation pre-flight procedures and were performed prior to each flight to ensure that the noseboom parameters were functional and matched the previous calibration data.

B) Noseboom FPA Misalignment -- FPA misalignment due to the

noseboom AOA vane misalignment was recorded during every pre-flight. If the misalignment exceeded ± 0.001 g's the vanes were realigned and the noseboom AOA recalibrated.

C) Hangar Initialization Record -- A 30 second hangar initialization record was recorded on the onboard instrumentation data tape during pre-flight procedures. The record was performed in the hangar with engines off, no airflow in the ECS system or the engine bleed ducts, and with no avionics cooling supplied. This record was taken following a 15 minute power-up and stabilization period. This information was used for instrumentation initialization and validation for each flight. The aircraft was synchronized to range time prior to each ambient reading and the ambient times recorded were documented for data processing.

D) Noseboom Leak Check -- At selected times during the performance flight test program a leak check of the noseboom pitot-static system was conducted. This data was used to address any potential anomalies in measured air data parameters. A leak rate greater than 100 ft./min. or 3 kts./min. required the system to be repaired prior to conducting any further performance flight testing.

E) Aircraft Weighing -- At selected times during the performance flight test program the fuel quantity gauging system calibration was checked. The aircraft

was fueled to full internal (and external if external tanks installed) and then weighed on the ATEF scales.

Fuel samples were taken before (and after if air or hot-pit refueling) each flight and were used to measure fuel density, viscosity, and fuel heating value. The fuel densities were used to calculate fuel mass flow in post-flight data processing. Fuel heating value was necessary for in-flight thrust and was determined by test team laboratories for verification. Fuel samples were obtained as close to flight as possible following Flight Test Engineering Data Systems SOP. The samples were taken and sealed in air-tight containers until the laboratory analysis was complete and the data reviewed. A copy of the tracking log for the fuel supply source (tanker aircraft, hot-pit) was required for historical tracking. (F/A-18E/F Performance Test Work Description, p. 30)

Due to different fuel characteristics between fuel sources, in-flight or hot-pit, refueling was only permitted from a single source during a test mission. This procedure ensured accurate fuel flow data. This restriction was waived by the test team, on a case by case basis, when test efficiency was judged to outweigh the requirement for accurate fuel flow data.

Flight control cycles were performed and recorded on the onboard instrumentation data tape as part of the pre-taxi, post-flight, and shutdown procedures. These operations were used for telemetry parameter verification and post-flight instrumentation and data measurand validation. The cycles were as follows: (ibid)

- A) Longitudinal stick full forward and full aft
- B) Lateral stick full left and full right
- C) Full pedal left rudder and full pedal right rudder
(performed during taxi for nosewheel steering sweeps)
- D) Leading edge and trailing edge flap fully extended and fully retracted
- E) Speedbrake function extended and fully retracted

INS initialization data was required either prior to each takeoff, and after each landing or taxi data run. A ten second record was required from a stationary position. This data was used as an additional source for space position data to calculate takeoff and landing distances and rates. (ibid, p. 31)

IN-FLIGHT PROCEDURES

A phasing maneuver was performed and recorded on the onboard tape shortly after takeoff and prior to beginning in-flight tests. This phasing maneuver served as a final check of ground station and onboard data system polarities. The maneuver consisted of the following consecutive control inputs:

- A) Half left stick (30° left wing down)
- B) Half right stick (30° right wing down)
- C) Left rudder (half-pedal, aircraft nose left)
- D) Right rudder (half-pedal, aircraft nose right)
- E) Aft stick (2g pull-up)
- F) Forward stick ($-0.5g$ push-over)

Control input rates were not critical. The aircraft was returned to its initial attitude between each control input. The pilot called out each input to the ground station as it was applied. The phasing maneuver was usually performed at $10,000 \pm 500$ ft. and 0.6 ± 0.05 Mach for flight-to-flight comparison and historical tracking. The phasing maneuver altitude and Mach was occasionally adjusted due to primary mission requirements or weather if required. (ibid)

An engine health check was performed at 10,000 ft. and 0.6 Mach to monitor engine performance, deterioration trends, and check engine instrumentation. The aircraft was stabilized in 1g level flight and the bleed air knob was set to the non-test engine for this health check. Procedures were as follows:

- A) Stabilize 1g/level flight at 10,000 $\pm$ 500 ft. and 0.6 $\pm$ 0.05 Mach
- B) Set bleed knob to non-test engine (left or right)
- C) Set test engine to MIL power (non-test engine to maintain flight condition)
- D) Stabilize until engine stabilization parameter is within tolerance
- E) Repeat on opposite engine

The engine health check was performed on almost every flight during the methodology phase. As the performance flight test program progressed and the engine health tracking database was built, the frequency of the engine health check was reduced to approximately one in every five flights. (ibid)

Three sources of wind measurements were logged for takeoff and landing performance:

- A) As called from the control tower
- B) As measured with a hand held anemometer near the duty runway
- C) From the laser tracker equipment.

If agreement between tower called and hand held wind measurement was good, hand held measurements were often deleted at the discretion of the E2 Test Team.

Standard Wind Calibration - All test points performed on the aircraft when the flight test noseboom was not installed, and all test points that target AOA greater than 20° (noseboom installed) were preceded by a wind calibration so that INS AOA and AOSS could be calculated. The procedure is given below:

1. Select navigation master mode.
2. Trim wings for level flight.
3. Increment record number.
4. Fly wind calibration for a minimum of ten seconds with the following conditions:
 - (a) Zero AOSS (Yaw string centered and zero lateral acceleration).

- (b) Constant altitude (feet per minute vertical velocity (fpm VV), less than 60 fpm VV).
- (c) Constant airspeed (less than 2 kts change).
- (d) Wings level (less than 1 degree roll).
- (e) Subsonic (less than 0.85 Mach).

5. Momentarily selection of the wind calibration switch.

6. Proceed with maneuver.

This procedure froze inertial computed winds in the mission computer (MC) for computation of AOA and AOSS. It was also used for post-flight data processing. The validity of the wind calibration was decreased over time and distance and therefore needed to be updated (re-flown) prior to each test point requiring INS AOA and AOSS. This computation was valid only for the altitude at which the wind calibration procedure was flown. (ibid, p. 32)

Wind Calibration In Climb - For maneuvers that exceeded an altitude loss/gain greater than 1500 feet, the following "Wind Calibration In Climb" (WCC) procedure was flown prior to a block of test maneuvers. This method was intended to account for wind changes as a function of altitude to compute AOA and AOSS and was initiated at the beginning of a climb to test altitude. Procedures were as follows:

1. Increment record number.
2. Climb in area of tests (Begin climb at lowest test point minus estimated altitude loss).
 - (a) No Rapid Maneuvering (Navigational turns only).
 - (b) Low AOA (<10 degrees)
 - (c) Low rates (<2 deg/sec pitch/roll/yaw, <6000 fpm VV)
 - (d) Minimal AOSS (<1 deg, Yaw string centered).
 - (e) Gentle turns (<2 deg/sec)
 - (f) Subsonic (<.85M)
3. Climb at least 1000 feet above test altitude.
4. Increment record number.

The wind calibration in climb did not have to be performed as a single event. Multiple climb segments were permissible if they fully encompassed the test maneuvers. (ibid, p. 33)

Certain performance test points were preceded by an engine preheat maneuver or stabilization time. Engine preheat consisted of stabilizing at a fixed throttle setting until a calculated parameter indicates the engine had reached thermal stabilization. The engine stabilization parameter was calculated real-time and represented a "lagged" EGT. The time constant for the lag was derived from engine test data

and varied with flight condition and and/or power setting before the maneuver. When the lagged EGT was within a specified tolerance of the current EGT, the engine was considered thermally stabilized. (ibid)

POST-FLIGHT PROCEDURES

A post-flight ambient of 30 seconds in length was recorded on the onboard instrumentation data tape with all relevant and practical aircraft and avionics systems operating. This information was used for instrumentation initialization and validation.

It is apparent from the above discussion that a large amount of effort was directed towards ensuring data quality. High quality data was absolutely essential for accurate determination of aircraft performance and prediction verification. Since it was not economically possible to fly every performance point within the aircraft envelope, a cross section of points were selected and flown throughout the three year EMD program. These results were then combined with predictions and previously defined models in order to fully define the aircraft's performance window. Therefore, any error in the flight test data could be magnified when extrapolated out to the overall envelope.

CHAPTER 9

RESULTS AND CONCLUSIONS

At the time of this writing, approximately 15% of the F/A-18E/F performance testing had been completed. Although the majority of current results and data are still not releasable, the following results are from the Flight Test Performance Working Group #11 Conference on 28 Aug, 1996, and represents releasable results as of that date.

The majority of the testing from the Early Methodology Development and Verification phase and the Clean Wing Flap Parametric phase had been completed. The Early Methodology Development and Verification phase verified testing and analysis methodologies, as well as provided early assessment of Fighter Escort (FE) performance. The Clean Wing Flap Parametric phase verified trends observed in the previous years of wind tunnel testing, with no new flap schedules identified for drag reduction. The author found that the overall approach to the performance test program, including all test maneuvers, appeared to be capable of achieving the objectives of the performance test program set forth.

The early methodology testing was conducted in the FE configuration. Currently, 40 of 47 planned test points have

been completed, to include 27 of the 28 steady state, all of the nine quasi steady state, and four of the ten dynamic points. One planned test point had not yet been attempted, due to its predicted normal load factor (N_z) level being greater than current aircraft placard limitations. Six of the dynamic maneuvers still needed to be repeated. Figure A-3 provides a summary of the Early Methodology Test Points.

All the flap parametric testing thus far has been conducted in the clean configuration. At the time of this writing, all of the 39 Priority One points had been completed, to include 33 steady state points, and six quasi steady state points (MAX power accelerations at 35,000 ft). Nine of 27 Priority Two points had been completed, all of them being steady state. Figure A-4 provides a summary of the Flap Parametric Test Points.

Although actual numerical results were not releasable at the time of this writing, and full analysis of the collected data was not yet complete, all indications were that flight test performance was matching, very closely, wind tunnel and modeling predictions. Figure A-5 displays completed performance data analysis to date, and current scheduled analysis.

In order to have a standard against which to measure program progress, the ITT was primarily tracking test points completed, rather than flight time or flights. Each test plan had a documented number of test points, and the team took credit for a completed test point when it was flown and final data analysis verified it was acceptable. The program also tracked a Test Point Index (TPI), reflecting test points completed versus the plan. A facet of this was to rigorously track flight hours and flights required to complete particular types of testing. The data gathered from this TPI allowed the team to better track current program progress and predict future progress. In addition, at the end of the program, it was hoped that the data gathered from this TPI would be useful in developing a useful mathematical model to better forecast time requirements for future EMD programs. (F/A-18E/F Flight Test Update, p. 2)

Aircraft instrumentation, proved to be fairly reliable and predictable. The airplane had three different ways of determining actual control surface position; Linear Variable Differential Transducers (LVDTs, both digital and analog), Optical Encoders, and actual aircraft data recorded off the aircraft's internal memory unit (MUX). The LVDT output represented actuator position, with the analog data based on flight test calibration and the digital data based on mathematical function. The optical encoder measured control

surface deflection, and was based on flight test calibration as well. MUX data was found to be least accurate. The LVDTs were very accurate, however, the analog data did not include air loads effects. The optical encoders were useful in measuring actual control surface motion. No major reinstrumentation is planned or required at this point.

The aircraft was used for three weeks in order to determine individual fuel tank calibrations on all internal fuel tanks. Table 2 presents the results of this fuel calibration.

Table 2
FUEL CALIBRATION RESULTS

Fuel Type	Current	Predicted	Specification
Useable	14525	14871	14460
Drainable	143	101	-----
Trapped	225	133	255
Total	14895	15105	14715

Total fuel quantity was approximately 200 lb. less than predicted. The trapped and drainable fuel quantity was high. Useable fuel was above specification, but lower than predicted. Course of action was to minimize trapped and

unusable fuel in order to recover as much useable fuel as possible. Individual tank fuel quantity gauging accuracy had followed predicted trends.

Engine health tracking data points were taken each flight (alternating engines each flight) at 15,000 ft and 0.8 Mach. No significant performance trends were observed on any of the engines flown in E2. Engine performance was consistent and predictable. Engine performance was measured by charting low pressure turbine temperature, fan speed, nozzle throat area, and fan inlet calculated pressure versus flight number.

Although only 15% of the program was completed at the time of this writing, the two methods of determining In-flight Thrust, the Force/Area/Pressure (FAP) method and the Airflow root Temperature ($\sqrt{W \text{ root } T}$) method, were indicating similar numbers, with no divergence in results evident.

The aircraft had three sources of air data measurements; Inertial Navigation System (INS), flight test noseboom, and production air data. All three sources were in good agreement subsonically. Supersonically, Mach number and altitude values from the production air data had some variances. This was attributed to known source error correction limitations. Once all the source error correction test flights were completed, this was to be updated and

corrected. These errors made early attempts to achieve narrow band tolerance supersonic data points quite difficult. An example of the variance from the production system is presented in Figures A-6 and A-7.

All of the performance data quality was considered to be very good. No change in the instrumentation requirements, or go/no-go criteria was required. Test teams did an excellent job in maintaining maneuver tolerances and providing good quality maneuvers for data analysis. As stated earlier, the author found this type of flight testing to be quite challenging.

Lessons learned by the author regarding flight test maneuvers were as follows:

- Expand cruise altitude tolerance band from ± 50 to ± 100 ft. to allow additional altitude for maintaining Mach number tolerance of ± 0.005 Mach.

- Provide pilot with three digit Mach indications on HUD (e.g. .855) to allow increased efficiency in stabilizing for cruise points with tight Mach tolerance of ± 0.005 Mach.

- Eliminate rapid stick movements to maintain tolerance criteria in order to avoid unwelcome spikes in data.

- Roller Coaster maneuvers should be performed push-pull vice pull-push as originally called for, since most of the

interest is in the low lift coefficients data derived from the push.

Other programmatic lessons learned were as follows:

- Aircraft interdependency schedules were critical. If one airplane falls behind, it may affect other test aircraft schedules.

- Test point efficiency was critical. Cruise performance test points with extremely narrow band tolerances, or dynamic test points that require energy depletion were extremely hard to achieve, and cost flight test time and fuel.

- In-flight tanking support was critical. High Mach test points required refueling in as little as 20 minutes. Having to return to base each time to refuel would have been extremely inefficient.

- Additional test points derived from unexpected results were expected and are planned for in any flight test program, especially a major EMD program. The test team must strive to limit these new points as much as possible, or else risk falling behind schedule.

An Early Operational Assessment (EOA) was conducted very early in the flight test program in order to derive a quick look at aircraft cruise performance. The data was gathered on the second and third flights of aircraft E2. Standard normalized weight (W/Δ) test points were flown, with one W/Δ

test set being at a mission relateable cruise altitude of approximately 38,000 ft. MSL ($W/\Delta = 206,238$), and the other W/Δ test set conducted at approximately 10,000 ft. MSL ($W/\Delta = 61,107$).

The adjustments made to standard day specific range in order to account for test specific hardware were as follows: (F/A-18E Early Operational Assessment Performance Flight Evaluation Results, p. 3)

- Estimated noseboom drag.
- Excess Environmental Control System (ECS) bleed due to an intermittent avionics cooling air valve failure during these flights.
- Flap schedule errors resulting from uncalibrated production air data system.
- Noseboom impact on inlet recovery and flight test engine instrumentation.

The results from this assessment are presented in Figure A-8.

It is the hope of the author that this paper has given the reader some insight as to what is involved in conducting a major Engineering, Manufacturing, and Development (EMD) flight test program in general, and many of the variables involved with airplane performance testing in specific. The subject aircraft of this paper, the F/A-18E/F Super Hornet,

was conducting EMD flight test at the time of this writing. The efforts of this test team, described in part in this paper, will hopefully produce a carrier based strike/fighter aircraft which will be of value to the United States for many years to come.

BIBLIOGRAPHY

BIBLIOGRAPHY

- Aircraft Performance Flight Evaluation Briefing Notes (F/A-18 E/F). Los Angeles, California: Northrop Grumman Corporation, 31 October 1994.
- Aircraft Performance Flight Evaluation Briefing Notes (F/A-18 E/F). Los Angeles, California: Northrop Grumman Corporation, 7 September 1995.
- Aircraft Performance Optimization with Thrust Vector Control. Air Force Institute of Technology School of Engineering: Wright-Patterson AFB, Ohio, Fellows, Mark S., December 1985.
- Energy Approach to the General Aircraft Maneuverability Problem. Journal of the Aeronautical Sciences, Vol. 21, No. 3. Rutowski, E.S., March 1954.
- F/A-18A/B Full Scale Development Program Summary. Patuxent River, Maryland: Naval Air Test Center, August 1984.
- F/A-18E Early Operational Assessment Performance Flight Evaluation Results. St. Louis, Missouri: McDonnell Douglas Aerospace, February 1996.
- F/A-18E/F Flight Control System Design Report. Volume 1. St. Louis, Missouri: McDonnell Douglas Aerospace, July 1995.
- F/A-18E/F Flight Test Performance Working Group Meeting #4 Notes. Los Angeles, California: Northrop Grumman Corporation, 25 January 1994.
- F/A-18 E2 Flight Test Status Briefing. St. Louis, Missouri: McDonnell Douglas Aerospace, 28 August 1996.
- F/A-18E/F Flight Test System Segment Design Document. St. Louis, Missouri: McDonnell Douglas Aerospace, 1995.
- F/A-18E/F Flight Test Update. Patuxent River, Maryland: Madenwald-Sandberg-Niewoehner-Gurney, September, 1996.
- F/A-18E/F ITT Test Work Description Flight Test Guide. St. Louis, Missouri: McDonnell Douglas Aerospace, 1994.

F/A-18E/F Master Test Plan. St. Louis, Missouri: McDonnell Douglas Aerospace, November 1992.

F/A-18E/F Performance Test Work Description. St. Louis, Missouri: McDonnell Douglas Aerospace, August 1995.

F/A-18E/F Preliminary Flight Manual. St. Louis, Missouri: McDonnell Douglas Aerospace, October 1995.

Flight Path Reconstruction of Symmetric Nonsteady Flights. National Aerospace Lab Amsterdam: Wilt, M., May 1977.

Flight Test Features Briefing Notes - F/A-18E/F Dial-A-Function Capability. St. Louis, Missouri: McDonnell Douglas Aerospace, February 1996.

High Speed Aerodynamic Database Summary Briefing Notes. Los Angeles, California: Northrop Grumman Corporation, 7 September 1995.

Inflight Thrust Determination and Uncertainty. Warrendale, Pennsylvania: Society of Automotive Engineers, October 1986.

Inflight Thrust Installation Program Update. Los Angeles, California: Northrop Grumman Corporation, 30 April 1996.

Inflight Thrust Methodology Meeting Slides. St. Louis, Missouri: McDonnell Douglas Aerospace, 2 March 1993.

Personal Conversation with Flight Test Engineer. Patuxent River, Maryland: Kruenegel, Kirk, 22 August 1996.

Personal Conversation with MDA Business Operations. Patuxent River, Maryland: Renard, Rich, 26 July 1996.

Personal Notes, U.S. Naval Test Pilot School Airplane Performance Course, 1994.

Program Objectives Flight Test Performance Brief Slides. Los Angeles, California: Northrop Grumman Corporation, 5 August 1993.

Propulsion System Performance Notes. Los Angeles, California: Northrop Grumman Corporation, May 1994.

Test Conductor Guide. St. Louis, Missouri: McDonnell Douglas Aerospace, 1993.

- U.S. Air Force Test Pilot School Performance Phase Textbook.
Volume 1. Edwards AFB, California: April 1986.
- U.S. Naval Test Pilot School Airplane Performance Classroom
Notes. Patuxent River, Maryland: Powell, John W.
- U.S. Naval Test Pilot School Flight Test Manual (Fixed Wing
Performance). Patuxent River, Maryland: Naval Air
Warfare Center Aircraft Division, September 1992.
- U.S. Naval Test Pilot School Pitot-Static Systems Class
Notes. Patuxent River, Maryland: McCue, J.J., June
1982.
- U.S. Naval Test Pilot School Propulsion Systems Course
Textbook - The Jet Engine. Patuxent River, Maryland:
Powell, John W., July 1984.

APPENDIX

APPENDIX A -- FIGURES

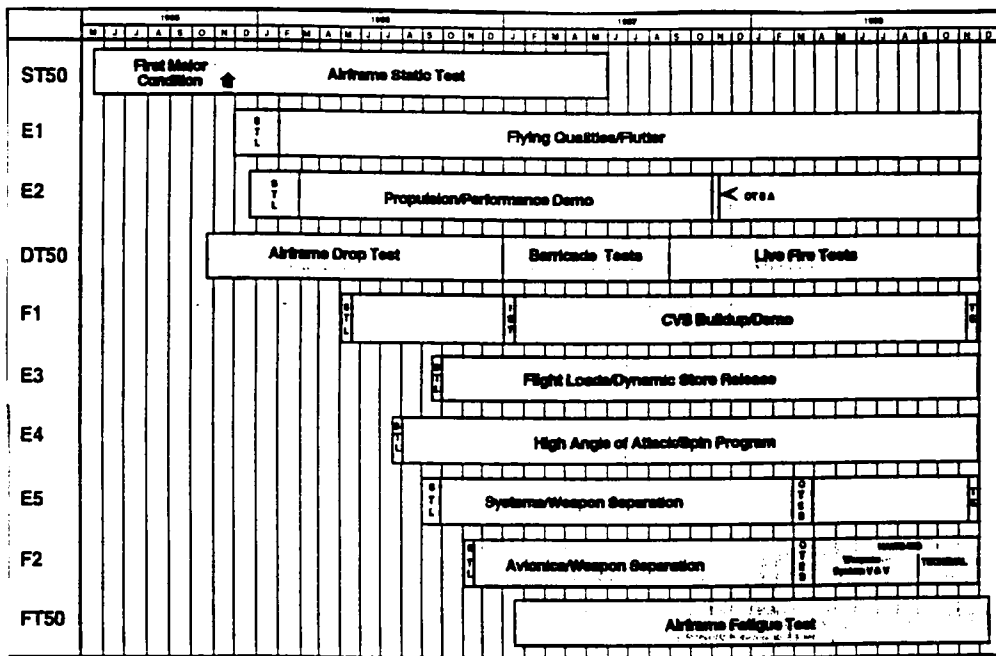
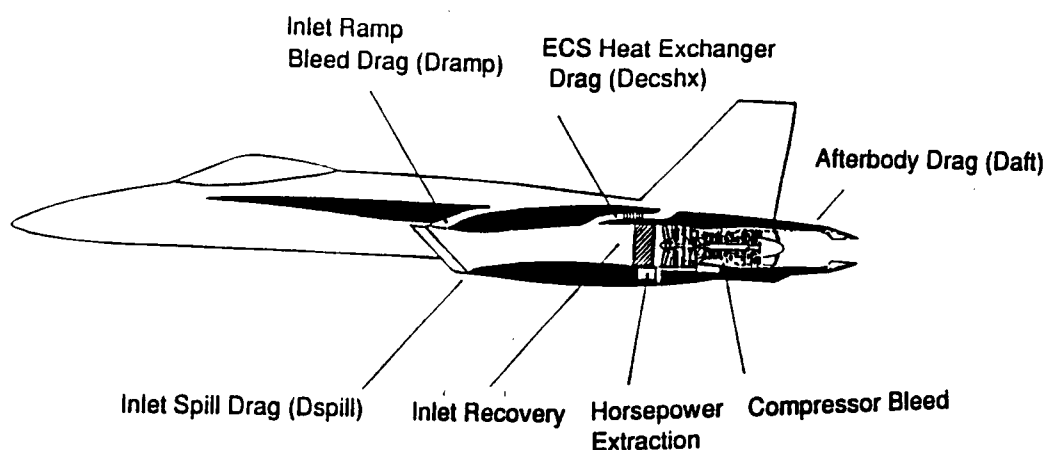


Figure A-1

AIRCRAFT TEST PROGRAM SUMMARY

F/A-18E/F Master Test Plan. St. Louis, Missouri: McDonnell Douglas Aerospace, November 1992.



$$\begin{matrix} \text{Net Thrust (FN)} \\ \text{Ram Drag (Dram)} \\ \text{Fuel Flow (WFT)} \end{matrix} = f \left(\begin{matrix} \text{Engine Cycle Deck, Flight Condition, Power} \\ \text{Setting, Inlet Recovery, Horsepower Extraction,} \\ \text{and Compressor Bleed} \end{matrix} \right)$$

$$\text{Net Propulsive Force (FNP)} = \text{FN} - \text{Dramp} - \text{Dspill} - \text{Decshx} - \text{Daft}$$

Figure A-2

F/A-18E/F NET PROPULSIVE FORCE

Propulsion System Performance Notes. Los Angeles, California:
Northrop Grumman Corporation, 1995.

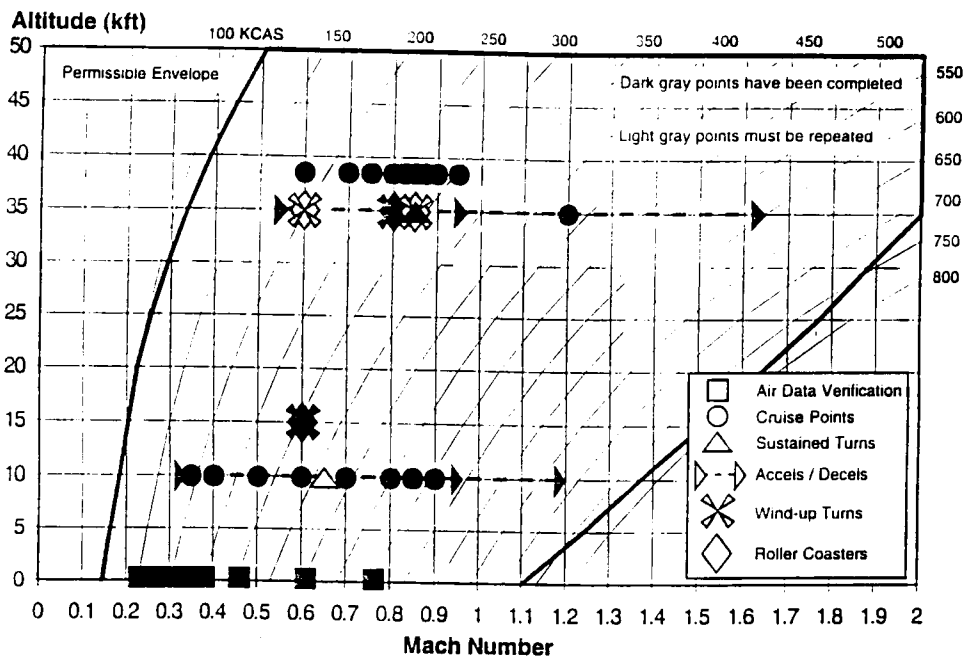


Figure A-3

EARLY METHODOLOGY TEST POINT SUMMARY

F/A-18E2 Flight Test Status Brief. St. Louis, Missouri:
McDonnell Douglas Aerospace, 28 August 1996.

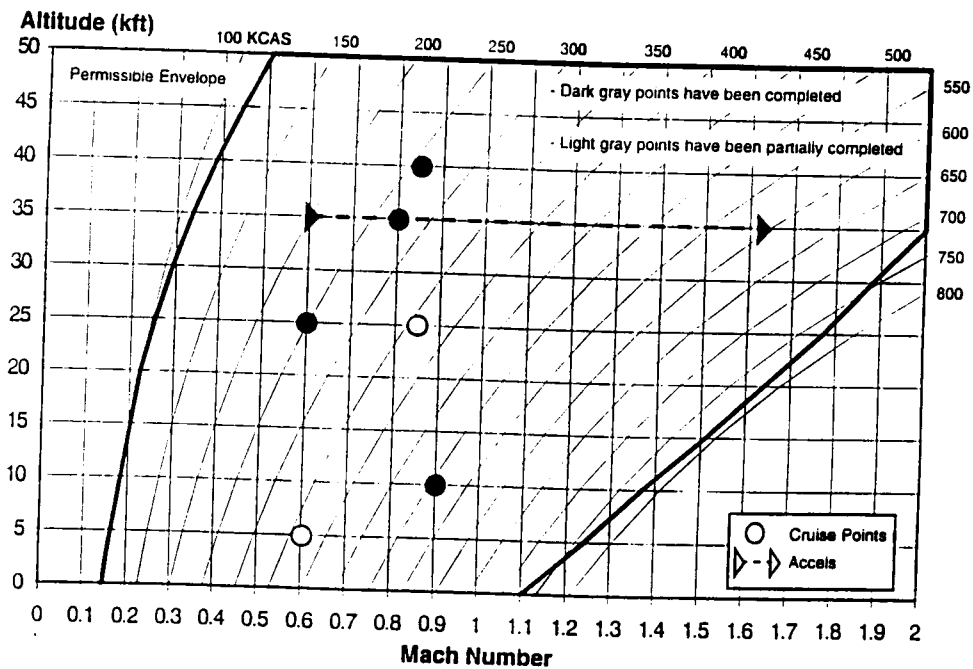


Figure A-4

FLAP PARAMETRIC TEST POINT SUMMARY

F/A-18E2 Flight Test Status Brief. St. Louis, Missouri:
McDonnell Douglas Aerospace, 28 August 1996.

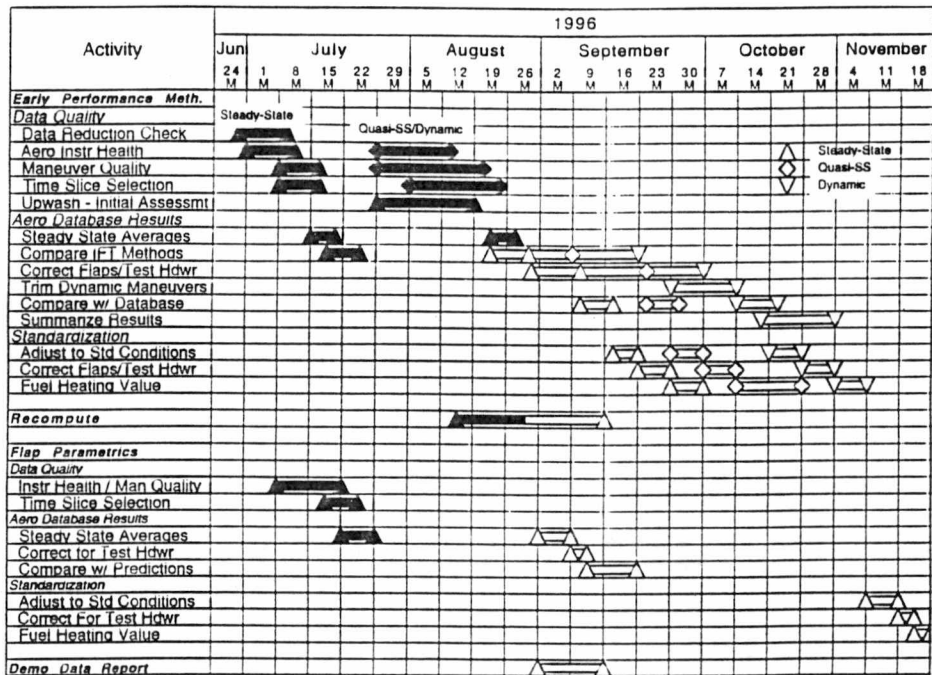


Figure A-5

COMPLETED AND SCHEDULED PERFORMANCE DATA ANALYSIS

F/A-18E2 Flight Test Status Brief. St. Louis, Missouri:
McDonnell Douglas Aerospace, 28 August 1996.

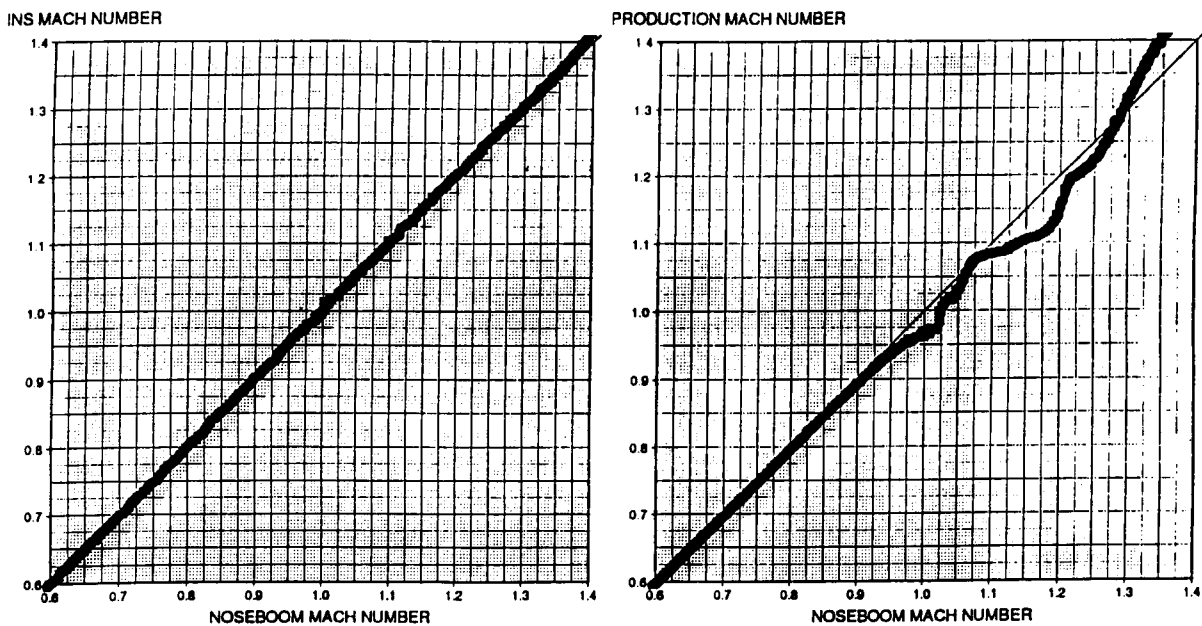


Figure A-6

PITOT STATIC MACH VARIANCE

F/A-18E2 Flight Test Status Brief. St. Louis, Missouri:
McDonnell Douglas Aerospace, 28 August 1996.

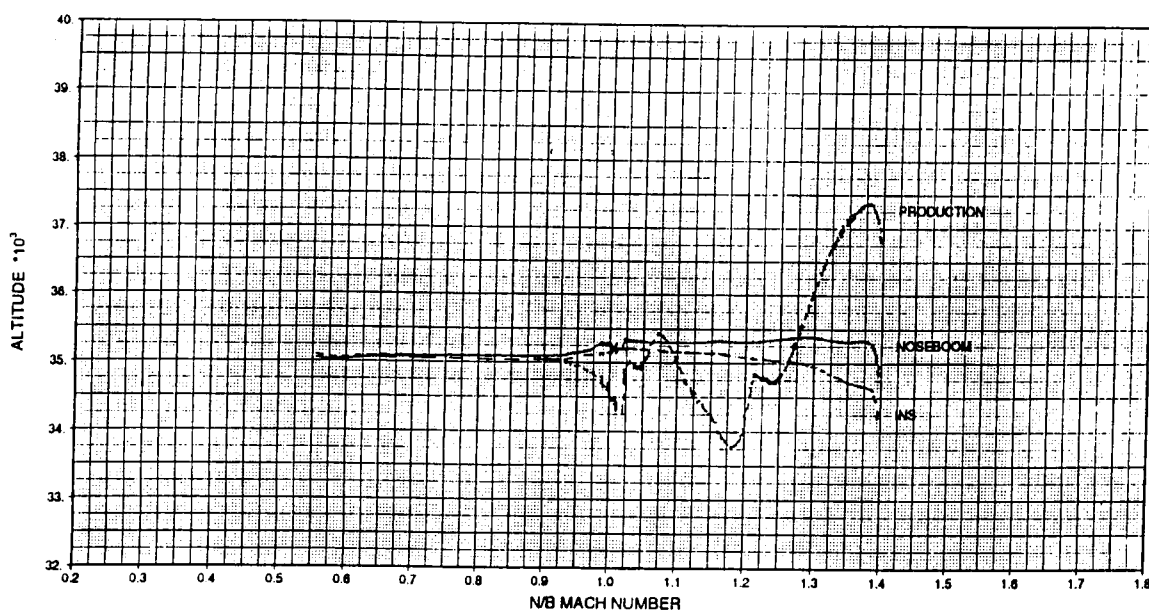


Figure A-7

PITOT STATIC ALTITUDE VARIANCE

F/A-18E2 Flight Test Status Brief. St. Louis, Missouri:
McDonnell Douglas Aerospace, 28 August 1996.

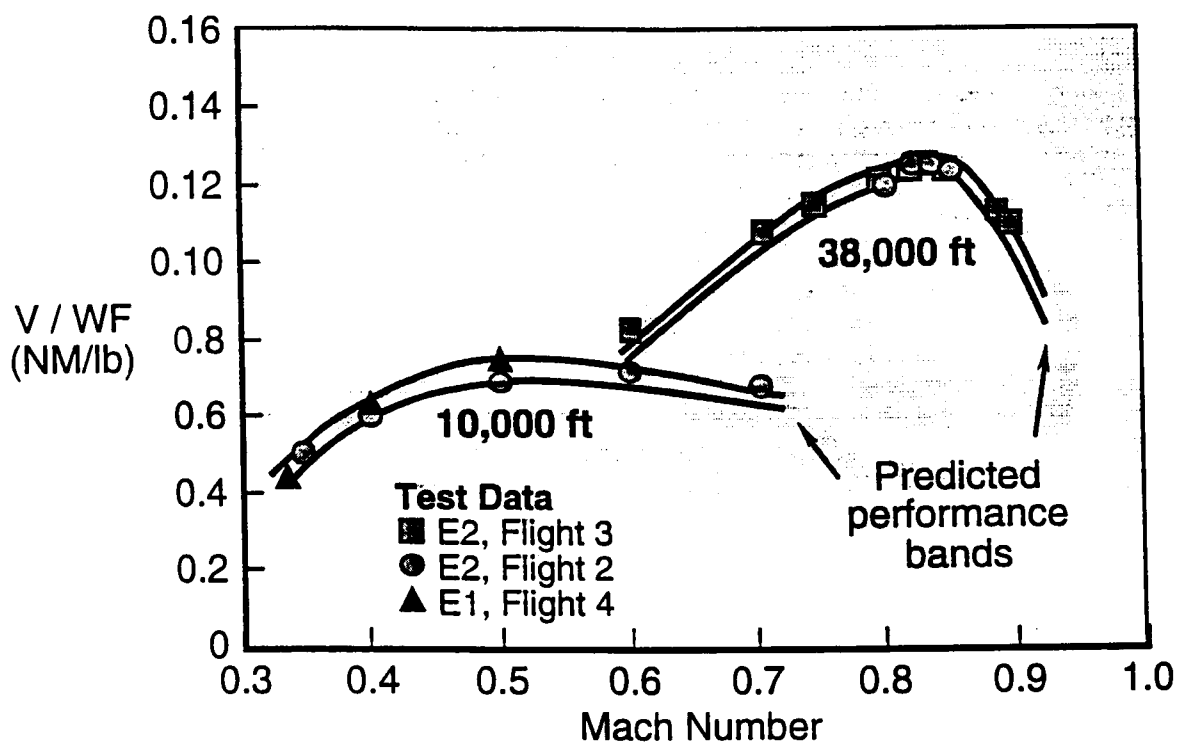


Figure A-8

EARLY OPERATIONAL ASSESSMENT CRUISE PERFORMANCE

F/A-18E/F Flight Test Update. Patuxent River, Maryland:
Madenwald-Sandberg-Niewoehner-Gurney, September, 1996.

VITA

Francis D. Morley was born in Miami, Florida on August 24, 1966. He graduated from Dobson High School in Mesa, Arizona in 1984. He attended San Diego State University with an NROTC academic scholarship, graduating in May of 1988 with a Bachelor of Science degree in Physics, and a minor in Naval Science. He was then commissioned as a Naval Officer on June 10, 1988.

He was designated a Naval Aviator in June of 1990, finishing first in his class, and receiving orders to fly the F/A-18 Hornet. After Hornet training, he was assigned to Strike Fighter Squadron 192, based in Atsugi, Japan, flying off the aircraft carrier USS Independence. He made two Persian Gulf deployments, and flew the first missions over Iraq in Operation Southern Watch. In March of 1994, he was selected to attend the United States Naval Test Pilot School. Following completion, he was assigned to the F/A-18E/F Flight Test Team, becoming the third Navy pilot to fly the "Super Hornet".

Francis Morley has logged over 1500 total flight hours in more than 30 different types of aircraft, including a flight evaluation of the MiG-29 "Fulcrum" conducted in Zukhovski, Russia. He is currently continuing flight tests on the Super Hornet, and is preparing to conduct the first carrier operations of the new aircraft.