

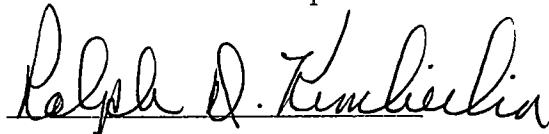
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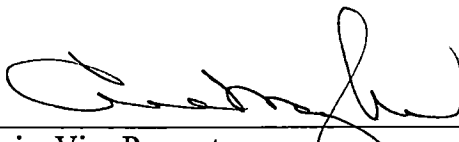


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F/A-18 SINGLE-ENGINE MINIMUM CONTROL AIRSPEED:
AN INVESTIGATION OF ANGLE-OF-ATTACK AND
LATERAL WEIGHT ASYMMETRY EFFECTS

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

David L. Woodbury
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DISCLAIMER

The results contained within this thesis were developed at the Naval Air Warfare Center, Aircraft Division, Patuxent River, Maryland. The discussion of the data, conclusions, and recommendations are the opinion of the author and should not be construed as an official position of the United States Department of Defense, Naval Air Systems Command, or the Naval Air Warfare Center.

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ABSTRACT

F/A-18 developers failed to identify the dependency of single-engine control on angle-of-attack and lateral weight asymmetry despite numerous test efforts and nearly twenty years of operational experience. This failure was the result of an over reliance on classic flight test techniques, a lack of understanding with regard to certain F/A-18 specific characteristics, and insufficient emphasis on constraints imposed by the shipboard environment

A discovery made during testing of the navy's newest aircraft, the F/A-18E/F Super Hornet, prompted another investigation into the single-engine control characteristics of the original Hornet. The test program used an innovative constant AOA technique to quantify a strong dependency of single-engine control on both angle-of-attack and lateral weight asymmetry. The nature of this relationship suggested that fleet F/A-18 pilots were being subjected to significant, unacceptable, and previously unknown hazards during catapult launch.

A systems based, problem solving approach using batch simulation and human factors studies yielded three products to mitigate the implications stemming from the test data. These included higher minimum catapult endspeeds, modified longitudinal trim settings, and redesigned emergency procedures. Together, these products combined to make the F/A-18 catapult launch environment significantly less hazardous

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GLOSSARY

ADC	Air Data Computer
AGL	Above Ground Level
ALB	Aircraft Launch Bulletin
AOA	Angle-of-Attack
AOB	Angle-of-Bank
ATEF	Aircraft Test and Evaluation Facility
BIS	Board of Inspection and Survey
CASTLE	Controls Analysis Simulation Test Loop Environment
CG	Center of Gravity
CRT	Combat Rated Thrust
CSV	Capacity Selector Valve
EPE	Enhance Performance Engines
FCS	Flight Control System
FOD	Foreign Object Damage
HUD	Heads Up Display
KCAS	Knots Calibrated Airspeed
LEX	Leading Edge Extension
MAC	Mean Aerodynamic Chord
MODSDF	Modular Six Degree of Freedom
MSL	Mean Sea Level
MRT	Military Rated Thrust
NATOPS	Naval Air Training and Operating Procedures Standardization
SQIDS	Super Quick Installation Data System
TEU	Trailing Edge Up
V_{mc}	Single-Engine Minimum Control Airspeed
WOD	Wind-Over-Deck

1. INTRODUCTION

The catapult launch environment provides significant challenges to those involved in the design and test of naval carrier aircraft. The practice of accelerating a twenty-five ton aircraft from standstill to flying speed in just over two seconds requires the combination of a host of engineering disciplines. The science of catapult launch is an amalgamation of aerodynamics, structural mechanics, thermodynamics, control theory, and human factors. Throughout America's impressive naval aviation history, carrier suitability engineers have worked constantly to advance this science. Accordingly, new theories, innovative approaches, and sophisticated flight test techniques have served to develop the science in parallel with the ships and aircraft for which it exists.

The F/A-18E/F Super Hornet, the U.S Navy's newest carrier based aircraft, underwent developmental testing from 1996 to 1999. The Super Hornet is a twin engine jet aircraft, larger and more capable than the original F/A-18 Hornet. Not surprisingly, a large portion of the Super Hornet flight test process focused on aircraft carrier suitability and, in part, the catapult launch environment. In that effort, the combined government-contractor test team developed a new method to investigate aircraft controllability in the event of single-engine failure. The innovative flight test technique isolated and quantified aircraft control characteristics that were unexpected. Most significant was the previously unknown and potentially hazardous dependency of single-engine controllability on aircraft angle-of-attack (AOA) and lateral weight asymmetry. These discoveries were most significant when considered in the context of an engine failure

during catapult launch; most specifically the aircraft's ability to fly away safely under single-engine power.

The discoveries made by the Super Hornet test team piqued the curiosity of those with years of experience working with the original F/A-18. Because of the similarity between the two aircraft types, would it be possible for the Hornet to possess the same, potentially hazardous single-engine characteristics as the Super Hornet, only to have them remain undiscovered during nearly 20 years of flight history? In response to this question, navy test pilots performed a rudimentary, qualitative assessment of the Hornet's single engine characteristics and confirmed similar tendencies to those exhibited by the Super Hornet. Thus, two teams of engineers were faced with a similar technical challenge, though a different sense of urgency. Super Hornet testers were dealing with a problem inherent to developmental flight test, while the heritage Hornet contingency was faced with an immediate reality: U.S. Navy and Marine Corps pilots around the world were being exposed to a significant hazard on every catapult launch.

In December 1997, a formal message was sent from the Naval Air System Command to all F/A-18 activities. The message warned of the potential hazards discovered during Super Hornet testing and related application to current F/A-18 operations. Pilots were warned that current procedures, in the event of engine loss during catapult, might not be enough to combat the failure. Commanding Officers were advised to exercise operational risk analysis when considering carriage of external ordnance, thus minimizing lateral weight asymmetry. The message also announced the initiation of a new flight test effort to quantify single-engine controllability while taking necessary steps to provide a reduced risk catapult launch environment

This thesis details the background, methods, results, analysis and conclusions of the flight test effort. As author of this document and test team leader, I was at the forefront of the effort throughout three distinct phases of execution. During pretest planning, I played a prominent role into the scrutiny of previous test results and the development of the eventual test methodology. I was one of three test pilots who participated in the flight test program, leading the team in flights and data collection. Finally, during the challenging post test analysis phase, I oversaw the complex and innovative problem solving process.

This thesis will demonstrate that previous F/A-18 flight test efforts with respect to single-engine controllability were critical flawed because of a disregard for lateral-directional control issues in a centerline thrust aircraft and an over reliance on classical flight test techniques. It will introduce an innovative flight test technique for isolating angle-of-attack and lateral weight asymmetry effects on single-engine minimum control airspeeds while validating the usefulness of a systems approach to technical problem solving.

2. BACKGROUND

Catapult Launch Basics

The function of a steam catapult is to provide a means to launch aircraft from carrier decks, day or night, in almost any kind of weather. The catapult launching engine, powered by steam from the ship's boilers, imparts energy sufficient to accelerate an 80,000 lb aircraft to 140 kts in a distance of just over 300 ft. Within the catapult engine, steam pressure acts on a piston below the flight deck, propelling it forward with rapidly increasing speed. Attached to the piston, is an above deck shuttle assembly which serves to connect the aircraft to the catapult. A launch bar, located on the nose landing gear structure, engages the shuttle. Upon launch initiation, the piston, shuttle, and aircraft travel together until the piston slams into a water brake assembly at the end of the catapult track and the aircraft separates from the shuttle, transitioning to forward flight.

The flyaway airspeed (also referred to as catapult endspeed) is the sum of the velocity imparted by the catapult and the headwind component. Generally, an aircraft carrier will steam into the natural wind to maximize headwind. Unfortunately, conditions occasionally preclude this action. In these cases, the catapult must generate the required airspeed for launch. Different types of aircraft require different flyaway endspeeds. Aircraft with higher required endspeeds will face greater accelerations and more significant aircraft loads during launch (for a given aircraft weight and headwind component). In parallel, wear and tear on the steam catapult system will increase with increased required endspeeds. As a result, minor changes in an aircraft's required endspeed can have major effects on the catapult launch system.

During carrier aircraft development, a set of minimum catapult launch endspeeds are determined. Each minimum airspeed correlates to a specific aircraft gross weight, with values normally assigned at 1,000 lb increments. For a given weight, the minimum endspeed represents the airspeed below which an unacceptable launch characteristic would be present. This determination is made using the following established criteria: Proximity to stall, proximity to the intersection of thrust available and thrust required (minimum level flight acceleration), adverse flying qualities, excessive sink-off-bow, unacceptable single-engine controllability, and flight control saturation. Minimum endspeeds for individual aircraft types may be determined by different criteria at different weights. For example, minimum endspeeds may be driven by single engine controllability at light weights, flight control saturation at medium weights, and sink-off-bow at heavy weights.

Once an aircraft's minimum catapult launch endspeeds are determined, an Aircraft Launch Bulletin (ALB) is published. This document is used by the carrier flight deck crew to properly set the catapult prior to launch. Contained within an ALB are the required Capacity Selector Valve (CSV) settings which control steam pressure and resultant catapult power. Prior to launch, aircrew indicate their aircraft's gross weight to catapult personnel. This weight, combined with the measured wind over the ship's bow and ambient temperature, is used to enter the ALB tables and determine the appropriate CSV setting. Normally, CSV settings are chosen to provide the launching aircraft with 15 kts excess airspeed above the designated minimum. In fact, if a situation dictates launching an aircraft with less than 10 kts excess, the Captain of the ship must personally

approve the decision and the pilot must be notified. An F/A-18 launch bulletin from the USS ROOSEVELT (CVN 71) is contained in figure A-1.

Single-Engine Controllability

All powered aircraft must be designed with consideration of engine failure. Such occurrences can have critical implications in many phases of flight. In the catapult launch environment engine failure is especially relevant. This reality is based on two factors. First, catapult launch leaves an aircraft 60 ft over the water, at slow speed and often fully loaded with fuel and ordnance; certainly a regime unforgiving of engine failure. Second, catapult launch tends to be an event which can trigger engine problems. It is the first time during a flight in which an engine is at full power, occasionally causing components to fail. Additionally, the proximity of men and machinery to a fully powered, rapidly accelerating aircraft can prove hazardous. It is not unusual for aircraft to occasionally ingest foreign objects into the engine intakes and, as a result, incur damage. Preventing Foreign Object Damage (FOD) takes the continuous effort of the ship's crew and, even then, all occurrences can not be eliminated.

Developers of twin-engine platforms must investigate the ability of their aircraft to fly with the loss of one engine. The determination of single-engine minimum control airspeeds, designated V_{mc} , is a critical part of this investigation. The minimum control airspeed is generally defined as the lowest airspeed at which control of the airplane is possible with the critical engine inoperative. The critical engine is that engine, the failure of which produces the most critical condition to the pilot. Minimum control airspeeds are typically determined for equilibrium (V_{mc} Static) and non-equilibrium (V_{mc} Dynamic)

conditions. V_{mc} Static is defined as the minimum airspeed achievable by the aircraft in a stabilized single-engine condition. V_{mc} Dynamic is the minimum airspeed at which the aircraft can experience an engine failure and still be controllable. V_{mc} Dynamic is normally the higher of the two minimums as lateral-directional rates and accelerations generated during the failure event typically degrade controllability.

Different test methods are used to determine the static and dynamic minimum control airspeeds. The U.S. Navy Test Pilot School Fixed Wing Stability and Control Manual describes classical techniques for both: V_{mc} Static is normally determined by simulating an engine out condition (pulling a throttle to idle in jet aircraft) at a relatively high airspeed, then decelerating slowly until one of several predetermined minimum control defining criteria is met. V_{mc} Dynamic is generally determined by simulating a dynamic failure at a given airspeed, analyzing controllability, and, if controllability is determined to be acceptable, repeating at a slightly lower airspeed. The lowest airspeed demonstrating acceptable control characteristics would be V_{mc} Dynamic.

A critical aspect of determining minimum control airspeeds is formulating criteria for which to define V_{mc} . For example, the inability to arrest yaw or roll rates, or the requirement of full stick or yolk deflection to maintain level flight would likely indicate unacceptable control characteristics. Often, altitude loss, sideslip angle, bank angle, or heading change limits will be specified for the purpose of the defining V_{mc} Dynamic. Different criteria are used for different aircraft based on, in part, flight control specifics, aerodynamic characteristics, performance, and operational regime. Control can also be defined qualitatively by the pilot performing the tests. For example, a pilot testing a carrier based aircraft may determine that the workload associated with the rates and

excursions experienced during a V_{mc} Dynamic test event would be unacceptable for the catapult launch environment.

F/A-18 Catapult Launch Specifics

The F/A-18 Hornet is a carrier based, fighter/attack aircraft originally built by McDonnell Douglas Aerospace. It is powered by two General Electric F404-GE-400 or F404-GE-402 (Enhanced Performance) turbofan engines with afterburner.

Distinguishing features include a moderately swept, variable camber mid-wing with leading edge extensions (LEX), twin vertical stabilizers angled 20 deg outboard from vertical, and twin horizontal stabilators. The wings have hydraulically actuated leading edge and trailing edge flaps and ailerons. The twin rudders and differential stabilators are also hydraulically actuated. The flight control system (FCS) is digital fly-by-wire using stick position sensors, rudder pedal force sensors, air data, and multiple feedback loops to generate control surface deflections. The F/A-18 is illustrated in figure A-2 while a flight control functional diagram is provided in figure A-3.

The F/A-18 is launched from the catapult at one of two power settings: MIL or MAX. MIL power (also known as Military Rated Thrust – MRT) is the highest power setting short of using afterburner and is typically used for light and medium weight launches. MAX power (also known as Combat Rated Thrust – CRT) uses full afterburner and generally is reserved for only the heaviest weight launches. It is common during medium weight MIL power launches for pilots to select MAX power upon first motion such that the afterburners are staged by the end of the catapult stroke (referred to as MIL-MAX).

During catapult launch, the design of the flight control system enables open loop ("hands off") rotation and capture of flyaway attitude. Following aircraft-shuttle separation, the FCS rotates the aircraft toward a commanded AOA while using pitch rate feedback to damp excessive pitch rates. As a result, the time history of a typical F/A-18 launch shows the peak pitch rate occurring less than 0.5 sec after launch with the AOA maximum following 1.0-1.5 sec later. Peak angle-of-attack values typically overshoot the commanded angle-of-attack by 1-2 deg then quickly decreases to below the desired AOA about a second later. The magnitude of the overshoot varies with such conditions as aircraft weight, longitudinal center-of-gravity (CG), airspeed, and desired AOA.

Pilots choose the target flyaway angle-of-attack by trimming the horizontal stabilator to a procedurally dictated angular position. The flight control system interprets this position as a request for a specific trim AOA. It is important to understand that the stabilators start moving as soon as the aircraft begins accelerating down the catapult track and, thus, the initial longitudinal trim setting becomes simply a means to communicate with the flight control computers. Note that the highest commanded angle-of-attack is 12 deg corresponding to stabilator position of 18 deg trailing edge up (TEU). Trimming above 18 deg TEU will result in increased pitch rate, more rapid AOA onset, and larger AOA overshoots, but will not change the 12 deg target AOA. The relationship between stabilator position and AOA is depicted in figure 1.

Longitudinal trim has significant effects on aircraft behavior during rotation. High trim settings command high pitch rates, quickly building AOA and, therefore, increasing lift. Low trim settings can result in under-rotation, insufficient lift, and

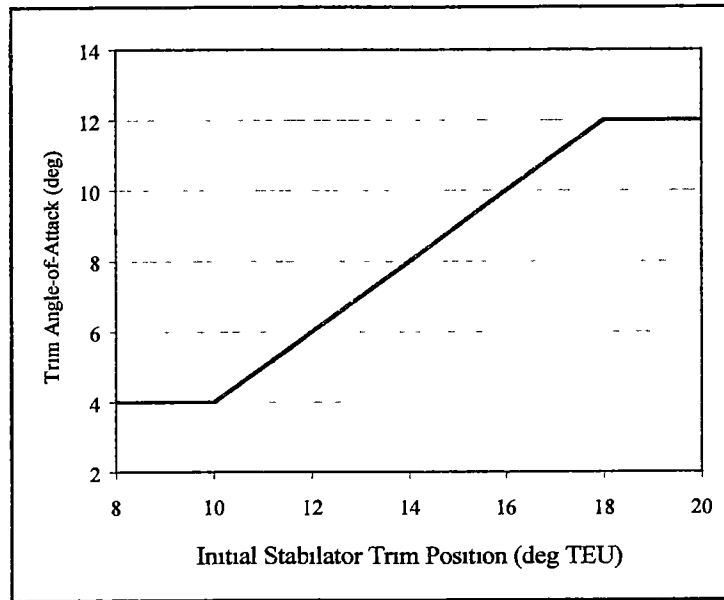


Figure 1
COMMAND ANGLE-OF-ATTACK

disconcerting sink-off-bow. In contrast, trim settings too high may result in over-rotation, uncomfortable pitch rates, and unacceptably high angles-of-attack.

F/A-18 pilots are instructed to set longitudinal launch trim as a function of aircraft CG and expected excess endspeed. Requirements are detailed in figure 2. Two significant flaws are evident in this diagram. First, the pilot has no way of knowing the difference between an 11-20 kt excess endspeed shot and a launch with more than 20 kt excess. The only case in which a pilot is informed of endspeed specifics is if less than 10 kts of excess is expected. Additionally, pilots are forced to calculate aircraft CG. This is not difficult, but time consuming. During training flights in which pilots may make multiple launches and landings, it is unrealistic to expect aircrew to calculate CG changes due to fuel burn and ordnance release. Accordingly, the diagram depicted in figure 2 has largely been ignored; replaced by unwritten rules-of-thumb.

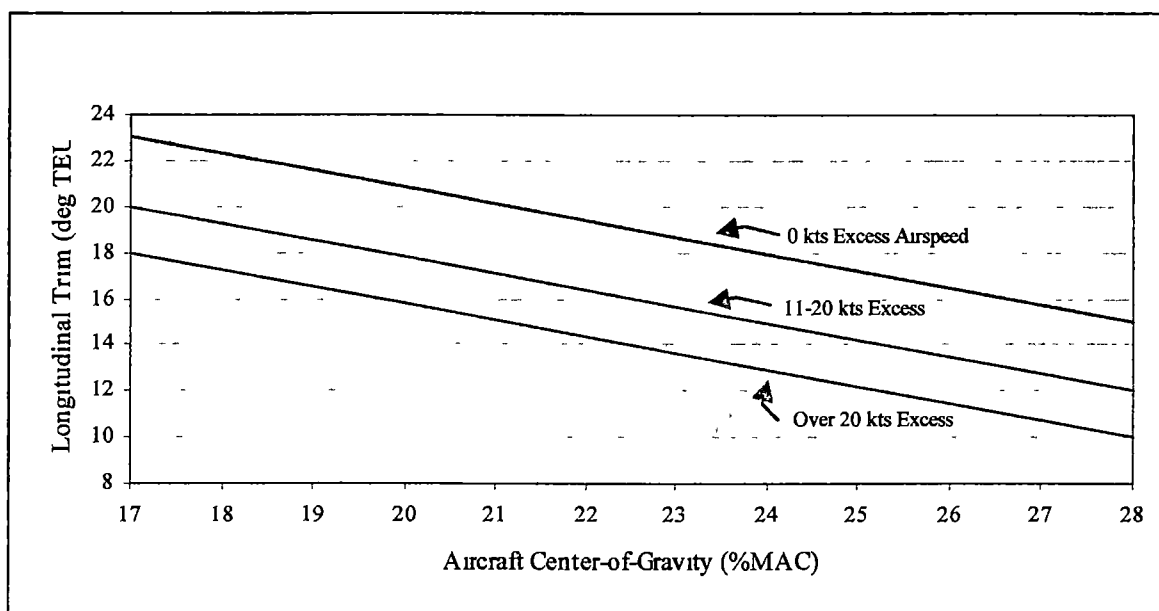


Figure 2
LONGITUDINAL TRIM REQUIREMENTS

F/A-18 Launch Bulletin History

Traditional test techniques were used to determine the original F/A-18 minimum endspeeds and develop resultant launch bulletins. Because of the near centerline location of the Hornet's two engines, no significant results with regard to single-engine controllability were expected. Because testing was conducted using classical test techniques, no significant results were discovered. A 1983 Board of Inspection and Survey (BIS) report detailing the initial F/A-18 single-engine controllability tests stated, "Since the Dynamic V_{mc} is well above any AOA or below any airspeed expected during shipboard catapult launches, Dynamic V_{mc} will not be a factor in determining safety or survivability in normal shipboard operations."

In the absence of single-engine concerns, an 18 ft sink-off-bow criterion dominated original F/A-18 launch bulletins. The minimum airspeeds for most gross

weights correlated with that which would result in an 18 ft descent in front of the ship prior to establishing a rate-of-climb. Only at the very lightest launch weights was single-engine controllability the determining factor for launch speed.

In 1991, the Navy tested the Enhance Performance Engines (EPE), designated F404-GE-402. Because the new engines were capable of producing about 2,000 lb more static thrust per side than their predecessors, much additional single-engine controllability testing was required. Once again, however, classic tests did not isolate any significant characteristics. As expected, the increased thrust created larger yawing moments and, as a result, a slightly higher MAX power V_{mc} Dynamic value

The existing F/A-18 launch bulletin can be graphically portrayed as a plot of minimum required airspeed as a function of gross weight. Figure 3 contains curves for both MIL and MAX power launches. Oblique sections of the MIL and MAX power curves represent aircraft weights at which sink-off-bow dictated the minimum endspeed. Horizontal sections correspond to weights at which single-engine control was the determinant criterion. From these curves, several characteristics are of note. First, the MAX power V_{mc} is 14 kts greater than that for MIL power. Accordingly, MAX power launches were prohibited below 37,000 lb. This legislation essentially removed the influence of MAX power V_{mc} Dynamic from launch bulletins. Additionally, the separation between the MIL and MAX power sink-off-bow curves above 38,000 lb is never greater than 3 kts (at a given weight). The MIL sink-off-bow curve was determined via flight test while the MAX power curve was formulated via analysis using the MIL power results.

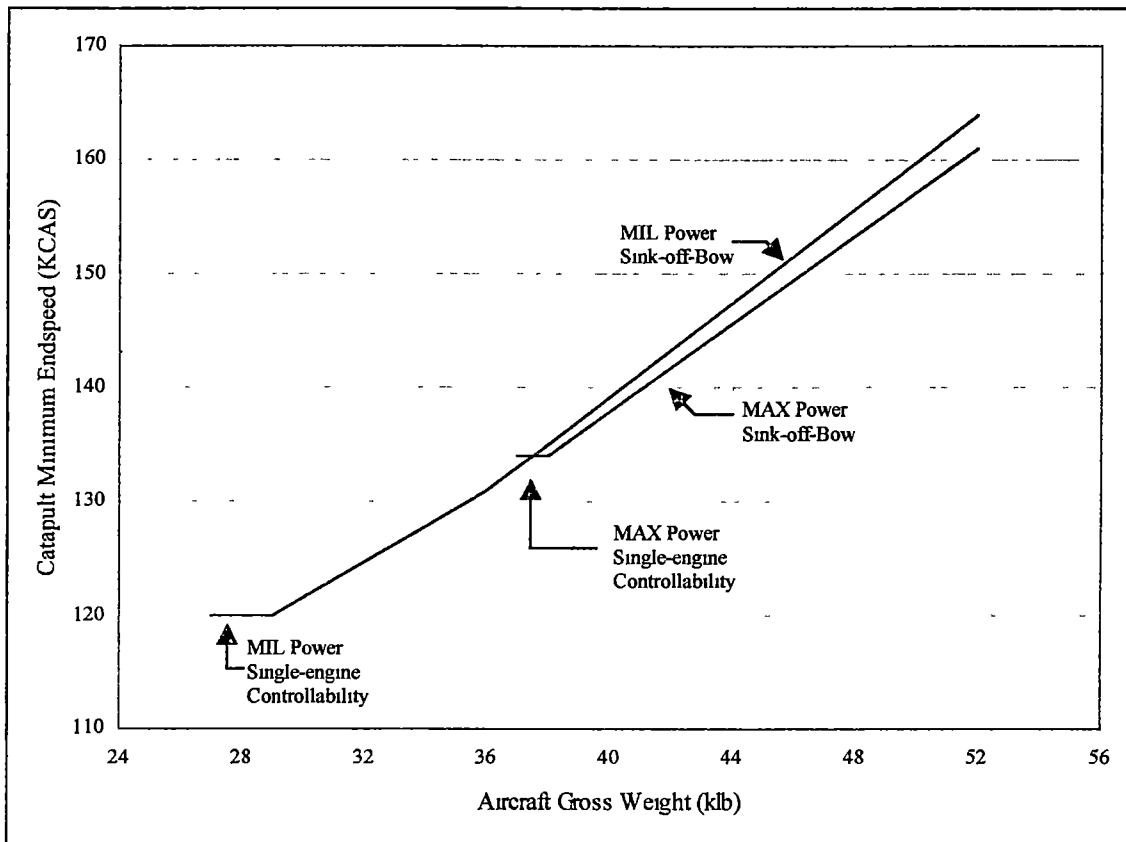


Figure 3
F/A-18 LAUNCH BULLETIN

Shortcomings of Early Tests

The two stages of F/A-18 testing described were unable to completely characterize the Hornet's single-engine controllability tendencies for several reasons. V_{mc} testing assumed the existence of a single dynamic minimum control airspeed for a given aircraft configuration. Accordingly, test conditions emphasized airspeed. AOA variations were not considered as a variable of the flight test and were allowed to fall out as a function of gross weight. This oversight would negatively affect the usefulness of the early flight test efforts. Figure 4 graphically portrays the classic, but in this case

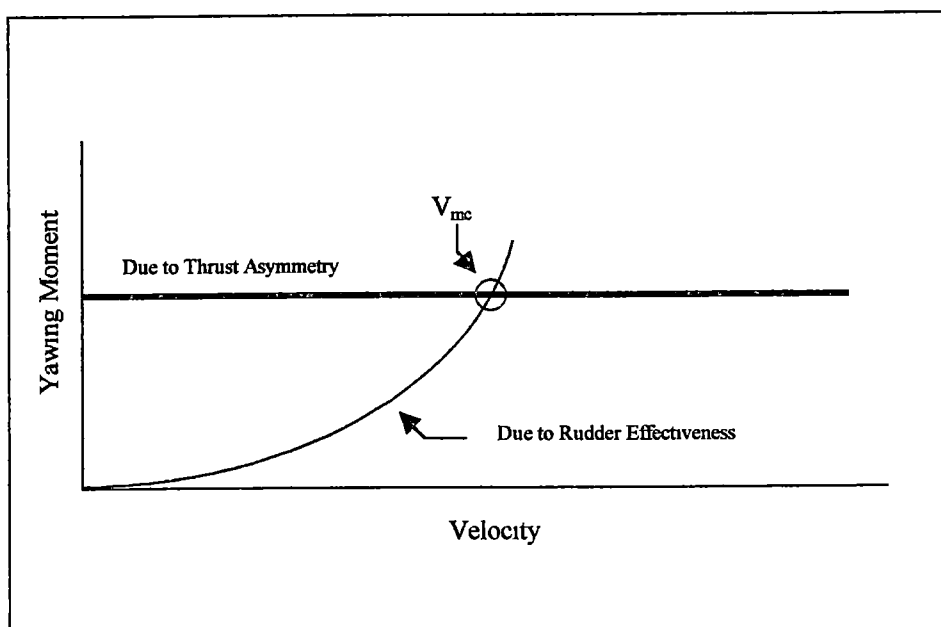


Figure 4
CLASSIC TEST TECHNIQUE ASSUMPTION

flawed test technique approach. Minimum control exists at the point where the asymmetric thrust yawing moment is equal to the restoring moment due to rudder.

The classical V_{mc} test technique assumed rudder effectiveness to vary only with airspeed and not with angle-of-attack. In the case of the F/A-18, this assumption is not valid. The yawing moment due to rudder does remain relatively constant up to 10 deg AOA. Above that value, however, rudder effectiveness gradually decreases. This phenomenon is illustrated in figure 5 with a plot of the non-dimensional "rudder control power" coefficient ($Cn_{\delta r}$) vs. angle-of-attack.

The degradation of rudder control power is especially significant in the catapult environment because most launches result in aircraft angles-of-attack above 10 deg. In

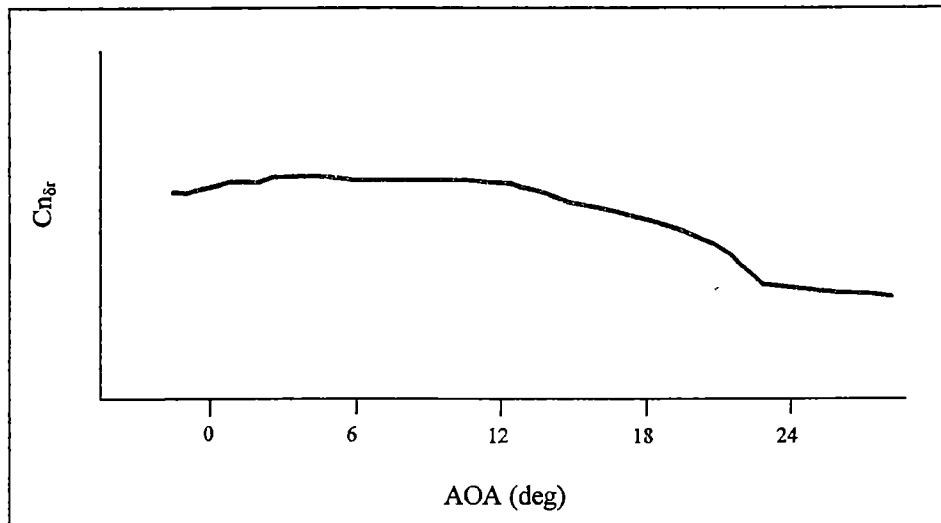


Figure 5
RUDDER CONTROL POWER

this regime, the classic V_{mc} assumption is replaced by a new theory that with each increase in AOA, V_{mc} also increases. The ramifications are significant. At a given airspeed, the aircraft may exhibit acceptable control characteristics, yet at a comparatively higher AOA (and the same airspeed), the aircraft would be uncontrollable.

The revised V_{mc} assumption is displayed in figure 6. From the same plot, another shortcoming of the early studies is illustrated. The recovery technique used for both test efforts allowed pilots to reduce aircraft AOA rapidly. The effect was, not surprisingly, immediate restoration of control. At the entry condition, the aircraft may have been below the minimum control airspeed for the entry AOA. As soon as AOA was allowed to decrease, however, the V_{mc} Dynamic airspeed shifted to the left. The flawed conclusion, therefore, was that at the entry airspeed, the aircraft was controllable. Such a reduction of AOA would not be significant if a similar reduction were possible in response to catapult emergencies. Unfortunately, F/A-18 catapult emergencies

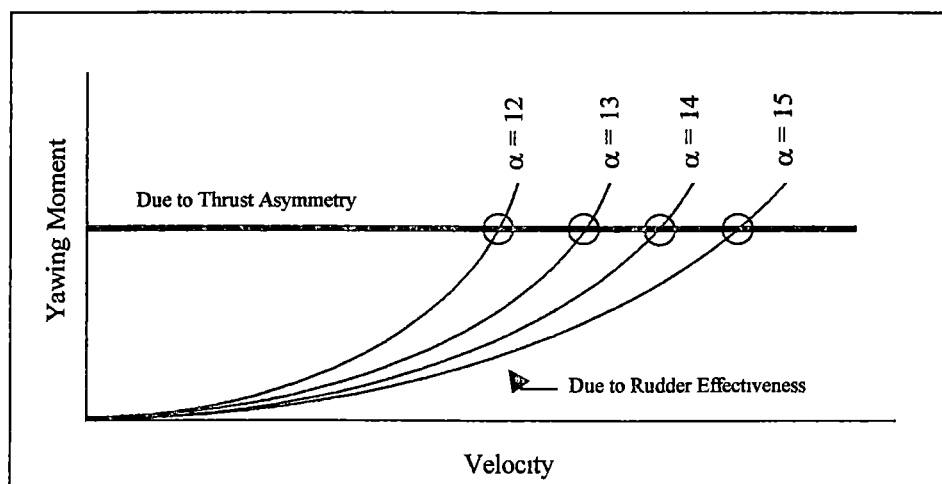


Figure 6
REVISED TEST TECHNIQUE ASSUMPTION

have not always allowed such action.

The final oversight of the early tests was the neglect of lateral weight asymmetry effects. The F/A-18 has nine external stations capable of carrying a variety of stores. As a result, asymmetric loads are commonplace with a catapult launch lateral weight asymmetry limit of 22,000 ft-lb. The original single-engine controllability tests did investigate asymmetric loads, but the inadequacy of the test techniques failed to isolate any effect. The EPE study chose not to examine any asymmetric loads. In defense of both programs, however, previous naval aircraft testing had not suggested the existence of lateral weight asymmetry effects on minimum control airspeeds

F/A-18 Catapult Emergency Procedure History

Because single-engine controllability was not originally considered relevant in the catapult environment, associated Hornet emergency procedures were correspondingly

lacking. In fact, the only related catapult emergency procedure contained in the F/A-18 Naval Air Training and Operating Procedure Standardization (NATOPS) manual was entitled "SETTLE-OFF-BOW". The procedure provided steps to be taken in the event of a dangerously large descent off the bow of the ship. Such a descent could be caused by a loss of aircraft thrust or insufficient catapult endspeed. The latter could be the result of catapult malfunction, improper communication of aircraft weight (and resultant improper CSV setting), or unexpected wind shift. Though aircraft settle is a very legitimate emergency, lateral-directional control issues were ignored.

The F/A-18 SETTLE-OFF-BOW procedure is listed in figure 7. Several important points are of note. First, pilots are told to control the longitudinal axis via pitch attitude, yet an additional longitudinal task is implied in the 15 deg AOA constraint. Second, stores jettison is given lower priority than power application and attitude control.

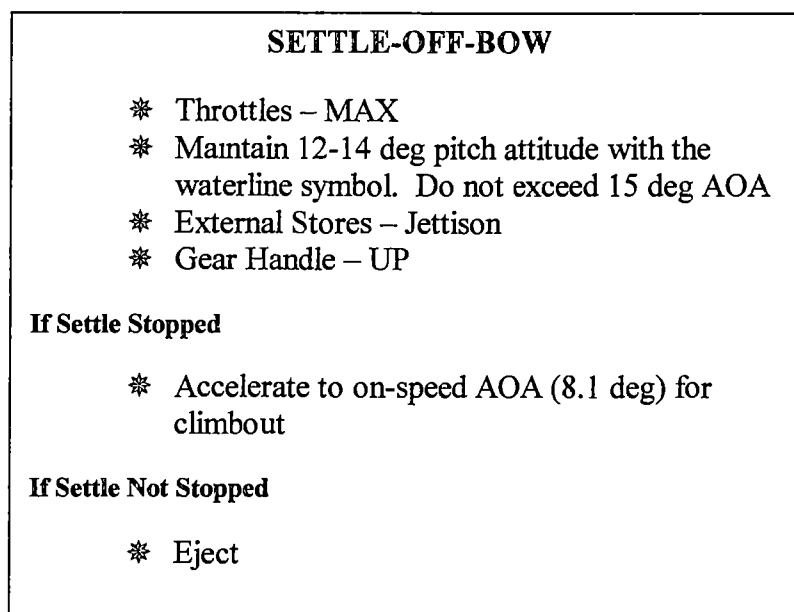


Figure 7
SETTLE-OFF-BOW EMERGENCY PROCEDURE

Stores jettison results in an immediate reduction of aircraft weight, drag, and lateral weight asymmetry and has proven in several cases to be the difference between successful recovery and aircraft loss. Review of actual F/A-18 catapult incidents has shown that pilots have been only moderately successful in accomplishing stores jettison, often failing to get past step two in the procedure. Finally, the procedure is devoid of lateral-directional control issues related to asymmetric thrust.

In choosing a flyaway attitude, emergency procedure developers used known, F/A-18 aerodynamic characteristics and a knowledge of the geometric relationship between critical longitudinal parameters. Angle-of-attack during catapult launch is essentially equal to the sum of pitch attitude and flight path angle. Thus, a settling aircraft with a descent angle of 1 deg and a pitch attitude of 12-14 deg, would experience angles-of-attack between 13 and 15 deg. The framers of the SETTLE-OFF-BOW emergency procedure chose a flyaway pitch attitude of 12-14 deg to put the aircraft in a maximum lift condition. Figure A-5 is a plot of the non-dimensional lift coefficient C_L vs. AOA. Note that 13-15 deg AOA represents a plateau at the end of the linear portion of the curve. Thus, the 12-14 deg pitch attitude choice was logical at the time considering controllability in this regime was presumed acceptable.

3. FLIGHT TEST

General

In January 1998, a limited scope test program was initiated at the Naval Strike Aircraft Test Squadron (NSATS) in Patuxent River, Maryland. Objectives of the effort were to investigate F/A-18 single-engine controllability and quantify angle-of-attack and lateral weight asymmetry effects. Potential products included new NATOPS procedures, modified Aircraft Launch Bulletins, and more restrictive asymmetry limits. The program was conducted in two phases: Phase I consisted of ground events to include engine thrust documentation, aircraft baseline measurement and calibration, and pilot training. Phase II consisted of flight test and was planned for 15 flights and 30 hours total flight time. Follow-on testing and simulation was considered likely pending the results of the flight test.

Test Aircraft

The test aircraft was an F/A-18C, Bureau Number 164869. The aircraft was equipped with Enhanced Performance Engines (F404-GE-402) which provided the largest thrust split for which to study engine out scenarios. Prior to the first flight, the aircraft was drained and weighed for baseline data purposes. The angle-of-attack system and Air Data Computer (ADC) were tested and calibrated. Ordnance to be used for external carriage underwent weight and balance baseline measurement.

Engine tests were conducted at the Patuxent River Aircraft Test and Evaluation Facility (ATEF) to document the comparative thrust characteristics of the engines. Test

matrix and results are listed in table B-1. Each engine was run individually through a variety of power settings using thrust cells for measurement. Results indicated that the difference between the two engines was approximately 1.5-2.5% at thrust settings greater than idle. The left engine was consistently higher in thrust than the right engine at high power settings with no clear trend at lower power settings. The small magnitude of the thrust difference, however, was considered inconsequential to flight test.

Flight Test Methodology

It was clear that for the F/A-18, V_{mc} Static would always occur at a slower airspeed than V_{mc} Dynamic. Accordingly, V_{mc} Static would have no influence on launch bulletin minimum endspeeds. Thus, the task facing the test team was quantification of V_{mc} Dynamic. This effort, however, required an innovative approach. The interdependency of angle-of-attack, airspeed, and aircraft gross weight made the isolation of individual effects difficult. A new test methodology, developed by the F/A-18E/F test team, presented a solution. The procedure entailed testing across a constant AOA line, allowing airspeed to vary with fuel burn. As aircraft gross weight decreased, airspeed for a given angle-of-attack decreased proportionally. Testing at a constant AOA, therefore, could be conducted at a 1.0 g load factor and with zero pitch rate. The approach is graphically depicted in figure 8.

The use of the constant AOA test methodology enabled efficient test conduct. The test aircraft would refuel in-flight just prior to V_{mc} Dynamic test initiation such to increase gross weight and proportionally increase the 1.0 g airspeed for any given AOA.

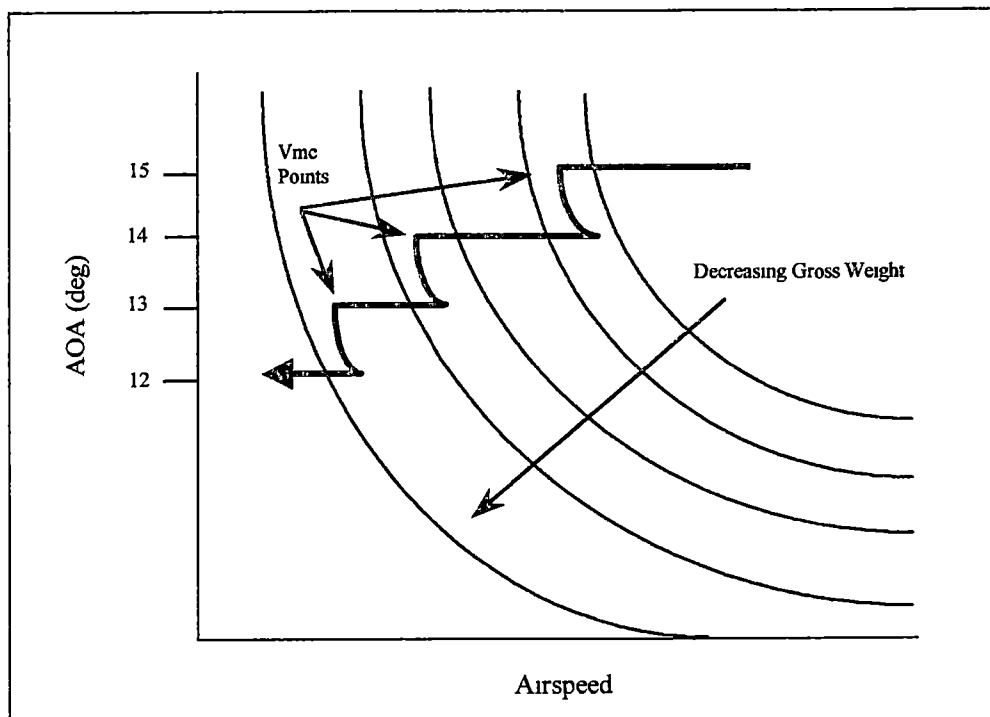


Figure 8
TEST METHODOLOGY

The highest target AOA was attempted first. At that AOA, a carefully chosen V_{mc} Dynamic test technique (to be discussed in detail later) was repeated, each time at a slightly slower airspeed due to fuel burn. When one of the specified adverse controllability criteria was met and, thus, V_{mc} determined, the next lowest target AOA was evaluated similarly. By decreasing AOA following a V_{mc} determination, the aircraft was ensured to be above the minimum control airspeed for the lower AOA.

During planning stages, the test team chose 12-15 deg as the AOA range in which to determine minimum control airspeeds. The width of this band, however, challenged the constant AOA methodology. For a given angle-of-attack, airspeed varies about 2.3 kts per 1000 lb of weight. Additionally, for a given weight, a reduction in AOA of 1 deg

results in a 3 kt airspeed increase. The cumulative effect of these two relationships is depicted in figure 9. To test across a 25 kt airspeed band while reducing AOA a total of three deg (assuming V_{mc} airspeeds were incrementally determined for the higher angles-of-attack), a gross weight change of 16,000 lb would be required. During test flights, available fuel burn was load dependant between 7,000 and 13,000 lb, thus available airspeed variance was insufficiently small.

To combat the narrow airspeed band, a two-for-one flight approach was chosen. One flight was conducted with numerous external stores to maximize the aircraft's zero-fuel gross weight, while a second flight was conducted using a relatively clean aircraft

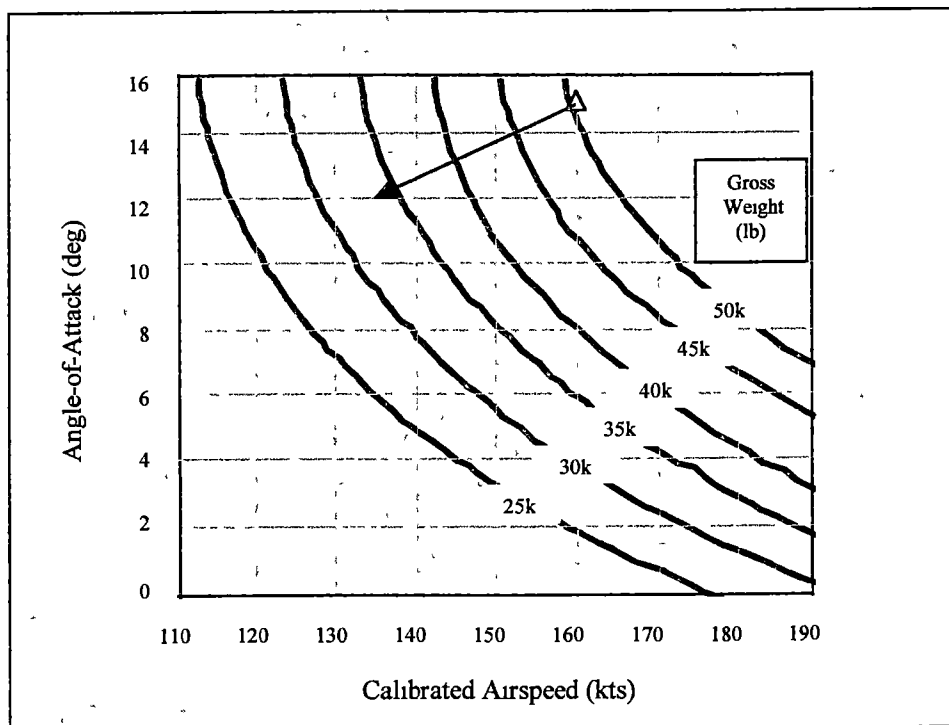


Figure 9
AIRSPEED AND AOA RELATIONSHIP

with a low zero-fuel gross weight. In combination, the effective gross weight change of the dual load approach was about 20,000 lb. The heavier aircraft was used to quantify V_{mc} Dynamic at the higher angles-of-attack, while the light aircraft tackled the lower AOA's. The choice of aircraft stores was considered critical, however, such to avoid introduction of new variables and contaminating effects.

External stores were used for more than just adjustment of zero-fuel gross weight. Since isolation of lateral weight asymmetry effects was a primary test objective, stores were also used to create varying asymmetry conditions. It was a goal of the test team to document V_{mc} Dynamic across the entire 22,000 ft-lb envelope, thus aircraft loads were chosen accordingly. Using a buildup approach, zero (symmetric), 6,000 ft-lb, 11,000 ft-lb, 15,000 ft-lb, 20,000 ft-lb, and 22,000 ft-lb target asymmetries were chosen. Generally, dual loads were planned. For example, there was an 11,000 ft-lb Heavy load and a 11,000 ft-lb Light load. Each used external stores to generate weight asymmetry, while the heavy load used additional external carriage to increase gross weight. Figure A-6 details test loadings.

Introduction of unwanted aerodynamic effects as a function of aircraft load complexity posed a problem. In an effort to identify such potential effects, the test team added a third load at zero lateral weight asymmetry. The other loads at zero lateral weight asymmetry (Symmetric Heavy and Symmetric Light) were both aerodynamically symmetric. The additional load matched Symmetric Light in gross weight and lateral weight asymmetry (zero), but added the variable of aerodynamic asymmetry. If the two

light loads produced different V_{mc} Dynamic values, an aerodynamic effect would be identified.

Critical Engine Determination

A symmetrically loaded F/A-18 was theorized to have no engine that, the loss of which, would be more critical to the pilot's ability to maintain control. The only variable, direction of engine core rotation, was expected to have negligible effect. An asymmetrically loaded aircraft, however, would likely have a critical engine. Remarkably, with nearly 20 years of F/A-18 experience, a debate existed as to which engine would prove critical under the influence of lateral weight asymmetry. The intuitive choice, as supported by classic stability and control theory, was that the engine on the heavy wing side would be critical. The alternative view argued that the lateral shifting of aircraft CG due to asymmetric loading would result in the lengthening of lateral-directional moment arms on the light wing side (and corresponding moment arm reduction on the heavy wing side), producing a reversed effect. The latter theory was substantiated by F/A-18 flight test data from GBU-24 (new, heavy weight, smart weapon) integration

The existence of the critical engine debate emphasized the established discountenance of F/A-18 single-engine concerns. Unfortunately, it also complicated test conduct. Instead of being able to begin with constant AOA V_{mc} dynamic testing, the critical engine had first to be established. This was done via a V_{mc} Static test technique. The aircraft was stabilized at a target airspeed considered well above that of minimum controllability. A throttle split was established with one engine being brought back to

flight idle and the other engine being advanced to MAX power, while initiating gradual deceleration (about 1 kt per second). With both engines stabilized, the aircraft pitch attitude was slowly increased to continue the deceleration. Lateral stick inputs were used to keep wings level, while full rudder was used on the side of the operating engine to generate heading change in that direction. V_{mc} static was determined as the airspeed at which the first of the following occurred:

1. Full lateral stick was required to keep wings level.
2. Heading reversal occurred.
3. 20 deg AOA or 10 deg sideslip (β) was reached.

The technique was then repeated reversing the direction of the throttle split. The condition that produced the higher minimum control airspeed identified the critical engine.

V_{mc} Dynamic Test Technique

Once the critical engine was identified, test conduct shifted to V_{mc} Dynamic determination. The pilot performed several practice V_{mc} Dynamic maneuvers at 10,000 and 5,000 ft AGL to build proficiency while getting a qualitative feel for aircraft behavior (the large variety of external stores combined with the varying degree of lateral weight asymmetry resulted in differing aircraft handling qualities from load to load). When ready, the aircraft was refueled in-flight, maximizing gross weight. Upon completion, the aircraft was flown to 2,000 ft AGL to begin V_{mc} Dynamic determination. The test altitude was chosen because it corresponded to the most mission representative flight

conditions of an actual catapult launch (60 ft AGL), without compromising test safety.

Corrections to Sea Level Standard Day would be made later.

Prior to executing the test technique, the aircraft was stabilized in wings level, steady heading flight at the following conditions:

1. Flaps – HALF
2. Landing Gear – DOWN
3. Thrust for Level Flight
4. Target AOA

While maintaining AOA, flight IDLE was selected on the critical engine while power on the opposite engine was immediately increased to MAX. After a 2 sec delay (to simulate pilot reaction time) or upon reaching a 20 deg bank angle, lateral and directional corrective inputs were applied to control aircraft attitude while maintaining target AOA. Recovery was initiated by simultaneously reducing AOA and matching throttle position (mid range power settings) if any of the following criteria was met:

1. 10 deg sideslip developed.
2. Uncomfortably rapid roll and/or yaw rates developed prior to corrective input application.
3. Corrective inputs failed to arrest roll or yaw rates.
4. Aircraft descended below 2,000 ft AGL.

Adverse controllability was defined (for a specific AOA) if any of recovery criteria 1, 2, or 3 was met or if aircraft attitude excursions during recovery were deemed incompatible with the catapult launch environment.

Aircraft Instrumentation

The test aircraft was equipped with a Super Quick Installation Data System (SQIDS). This system enabled onboard recording and real-time telemetry of MIL-STD-1553 databus parameters. Safety of flight and data critical parameters were monitored during test flights by project engineers. These parameters are listed in table B-2.

4. FLIGHT TEST RESULTS

General

Fifteen flights between 09 Feb and 13 March 1998 were flown totaling 31.6 hours of flight test. All objectives were met. Data were recorded to document AOA and lateral weight asymmetry effects on single-engine controllability. Test efficiency was smooth with only a few, minor weather delays temporarily inhibiting progress.

Critical Engine Determination

Critical engine determination provided interesting results. For symmetrically loaded aircraft, as anticipated, no engine was more critical than the other. In the case of aircraft loaded with lateral weight asymmetry, in all but a few cases, the engine on the heavy wing side proved critical. In cases where a GBU-24 was loaded on the aircraft, however, a curious result occurred. The engine opposite the GBU-24 (light wing side) was determined to be critical.

In response to the GBU-24 phenomenon, an additional loading was flown. The new load replicated the gross weight and lateral weight asymmetry of the 15,000 ft-lb Heavy load, however, it was done without use of a GBU-24. This new load exhibited the same characteristics as other non GBU-24 loads: The engine on the heavy wing side was critical. It was determined, therefore, that the "GBU-24 Effect" was of an aerodynamic nature rather than inertial. The test team theorized that the large aerodynamic control surfaces on the weapon's guidance section created lift and a resultant rolling moment

toward the opposite wing. At the angles-of-attack relevant to this study, the rolling moment proved strong enough to overpower inertial bias.

Fortunately, the "GBU-24 Effect," was the only aerodynamic influence of note. The symmetric (lateral weight) loads that exhibited significantly different aerodynamic characteristics demonstrated similar flying qualities, alike critical engine characteristics (no critical engine), and nearly identical V_{mc} Dynamic results. It was concluded, therefore, that aerodynamic effects were negligible in comparison with inertial (lateral weight asymmetry) except for the GBU-24 case. Upon this determination, flight test loads were modified slightly (figure A-6) to remove any GBU-24 influence.

V_{mc} Dynamic Results

V_{mc} Dynamic was determined at angles-of-attack between 12 and 15 deg as detailed in figure 10. From this plot, two trends were evident. First, V_{mc} Dynamic increased with increasing lateral weight asymmetry. Second, V_{mc} Dynamic increased with increasing AOA. Note that at lateral weight asymmetries above 15,000 ft-lb and at angles-of-attack of 14 and 15 deg, V_{mc} Dynamic was not determined. This result indicates that V_{mc} Dynamic for these angles-of-attack was in excess of the highest achievable 1.0 g airspeed. In other words, it was impossible to get the aircraft heavy enough, and therefore fast enough at 1.0 g, to stabilize above V_{mc} Dynamic at 14 and 15 deg AOA.

At lateral weight asymmetries of 11,000 ft-lb and below, motion predominated in roll with rates and bank angle changes developing rapidly after the throttle split.

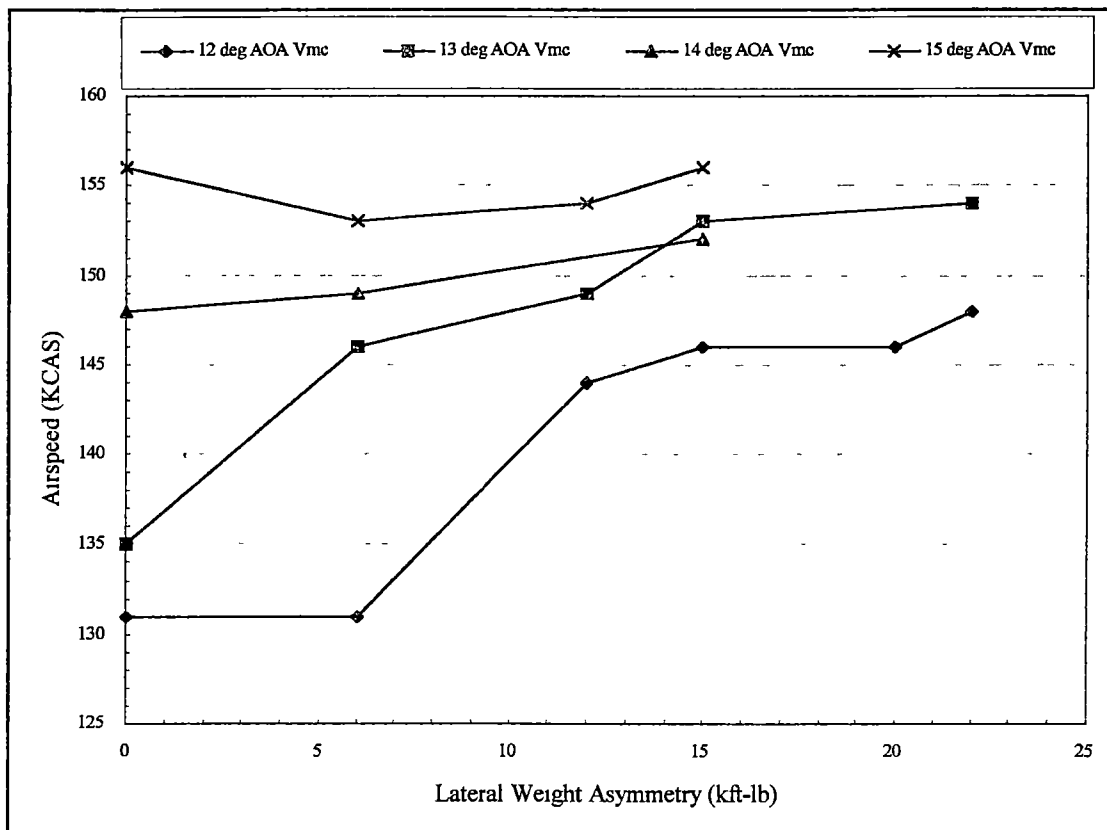


Figure 10
V_{mc} DYNAMIC AIRSPEEDS

When the roll excursions reached an objectionable level, adverse controllability was specified. A time history of a low asymmetry V_{mc} Dynamic point is included in figure A-7.

At lateral weight asymmetries of 15,000 ft-lb and above, motion was largely characterized by yaw. At airspeeds above V_{mc} Dynamic where rudder control power was sufficient to counter yaw, controllability was acceptable. Below V_{mc} Dynamic, however, the thrust split quickly generated yaw rates which could not be countered with full rudder. Accordingly, aircraft motion was similar to that experienced in a low yaw rate, flat spin. Adverse controllability was defined by either the inability to arrest yaw rate or

by reaching the test sideslip limit. A time history of a high asymmetry V_{mc} Dynamic point is included in figure A-8.

At all lateral weight asymmetries, controllability was sensitive to AOA. At higher asymmetries, the existence of an "AOA cliff" became apparent. For a given airspeed and weight, a specific AOA existed at which control became immediately and dramatically adverse. This point was often evidenced (in reverse) during recovery from a non-controllable event. Upon realization of the inability to arrest yaw rate with full rudder, the pilot would break AOA and initiate recovery. The slightest reduction of AOA would not only immediately arrest the yaw rate, but would restore rudder control power so thoroughly that a rapid heading reversal would be experienced.

Flying Qualities

During V_{mc} Dynamic testing, the pilot was required to control angle-of-attack precisely. A test point was only considered valid if AOA variance from throttle split to recovery remained below ± 0.5 deg. This tight tolerance proved challenging in the presence of dynamic thrust asymmetry and the resultant initiation of control inputs. In fact, so difficult was AOA control, especially at high lateral weight asymmetries, that over half the attempted test points were considered invalid as tolerances were exceeded. As an immediate result, test flights were long and arduous. A more pertinent result, however, was the realization that pinpoint AOA control in an actual catapult emergency is unrealistic.

While imprecise AOA control characterized the longitudinal axis, flying quality characteristics were also noted in the lateral-directional regime. In the presence of a

thrust split, rudder was clearly the most effective control input, with full pedal deflection opposite the “failed” engine utilized. If airspeed was above V_{mc} Dynamic, rudder input arrested both yaw and roll rates and immediately reduced sideslip. Often, rudder control input was enough to initiate bank angle reduction. A small lateral stick input in parallel with the rudder input worked well to counter roll and rapidly restore wings level flight. Large lateral stick inputs, however, introduced adverse yaw and served to further degrade controllability. This effect was more prevalent in certain aircraft loadings, but didn’t appear directly related to lateral weight or aerodynamic asymmetry.

Bottom Line

The flight test program was accomplished in a timely yet thorough manner, meeting all objectives. Angle-of-attack and lateral weight asymmetry effects were isolated and documented. Both parameters were shown to have clear and significant influence on single-engine controllability. The minimum control airspeeds determined were consistently above the minimum endspeed values listed in the existing F/A-18 launch bulletins, As such, the following ominous statement rang true:

Using current aircraft procedures and launch bulletins, F/A-18’s were being launched at airspeeds insufficient to guarantee controllability in the event of an engine failure

5. FOLLOW-ON TEST AND ANALYSIS

Systems Approach

Aircraft design consists of a series of tradeoffs; the success of the final product a function of the wisdom shown in choosing priorities along the way. Similarly, technical problem solving can lose effectiveness if the focus of an effort is allowed to get too narrow such to neglect the effect of change on the entire system. A myopic approach, therefore, risks the welfare of the larger system in favor of component sub-optimization. It was this kind of narrow approach that the test team sought to avoid while considering steps in reaction to the F/A-18 V_{mc} discovery.

Though the problem was to be attacked from a systems approach, requisite knowledge within individual disciplines was required. As a result, expert consultants were included early in the search for solutions: Catapult engineers advised of potential impact on ships' launching systems. Structural engineers provided aircraft fatigue studies. Propulsion experts evaluated potential effects on engine health and performance. Flying quality engineers studied aircraft behavior during rotation and flyaway. Simulation experts modeled and tested different scenarios. Catapult officers commented on procedural viability, while pilots provided insight on human factors and operational significance.

Carrier suitability engineers and pilots provided project leadership. This role included the task of promoting the flow of information to the distinct, non co-located disciplines. It also involved the responsibility of directing technical discussions; reminding all contributors of the project goals while avoiding inflexibility with regard to

established paradigms within specific fields of expertise. The leadership promulgated a clear set of goals to provide direction and vision:

- 1 Provide F/A-18 aircraft the ability to survive catastrophic engine failure during catapult launch.
2. Retain all current F/A-18 operational capability.

While the goals were clear and undisputed, the means of achieving the goals were not as obvious. An initial consideration was to increase the required catapult endspeeds such to provide margin above all minimum control airspeeds. The ramifications of this approach were significant. First, increased endspeeds would prove detrimental to catapult wear-and-tear and aircraft fatigue. Second, aircraft carriers would likely lose the ability to launch F/A-18's in no-wind or light wind conditions. Finally, a large increase in catapult endspeed would likely result in increased pitch rates following aircraft separation from the shuttle, over-rotation, and (as a result) pilot discomfort.

A second option was to reduce longitudinal trim settings during launch. The desired effect would be reduced AOA during rotation. Detrimental effects, however, would also be introduced. Lower trim settings would mean slower rotation and delayed lift generation. The result would be increased sink-off-bow. Lower trim settings would also seek a less than optimum angle-of-attack during catapult emergency flyaway. As such, the pilot's ability or inability to command a proper flyaway attitude would be more critical.

Two final options were similarly discussed. One possibility was to promulgate a dramatic reduction in the lateral weight asymmetry limit for catapult launch. This option was unacceptable operationally. The other possibility was to predicate catapult launch

CSV settings on lateral weight asymmetry. Instead of just communicating aircraft gross weight to catapult personnel, pilots would also communicate lateral weight asymmetry. A more complex variant of launch bulletin would then provide an appropriate CSV setting and govern the strength of the shot. This approach had merit, but resulted in complicated carrier deck procedures and still was affected by the aforementioned detriments to higher launch endspeeds.

Throughout the brainstorming phase, it became apparent that no single course of action was available – a combination of methods would be required. Each of the proposed solutions exhibited positive aspects, but each, if over emphasized, could be detrimental to the overall system. The key was to meld the different proposals together such to capture the good while mitigating the bad.

Angles-of-attack experienced during catapult launch and emergency flyaway had to be reduced. The current limit of 15 deg (with rotational excursions up to 20 deg) was no longer feasible in light of the new information concerning AOA sensitivity. In addition, some increases to minimum endspeeds would be required to protect against the AOA and asymmetry effects. The magnitude of these increases was hoped to be small, such to avoid far reaching effects. Finally, a concise, cohesive set of normal and emergency pilot procedures needed to be developed. Key to this effort would be the creation of new longitudinal trim settings which would provide optimum rotational and flyaway characteristics while remaining simple enough for pilots to interpret and follow.

The means to the end, however, was constrained by several factors. First, the fleet was operating in a potentially hazardous situation and, accordingly, resolution needed to be timely. Second, funding was not available for further flight test. Any

solution, therefore, could not significantly contradict standard operating procedures, historic flight test results, or resident technical expertise. Such a contradiction would likely be met with resistance in the absence of flight test data.

The next best thing to flight test is simulation. As such, simulation provided the foundation for follow-on test and evaluation. The test team decided upon a two-phase plan of attack. Phase I consisted of iterative, batch simulation in an effort to create new launch bulletins and better longitudinal trim settings. Phase II consisted of man-in-the-loop simulation for the development of normal and emergency pilot procedures.

Batch Simulation

Batch simulation was used to investigate the effect of independent variables such as longitudinal trim and aircraft CG on the critical dependent variables such as angle-of-attack. From these data, the test team proposed a modified launch bulletin with corresponding longitudinal trim settings. This proposal kicked off an iterative process. Dozens of simulated launches were conducted varying aircraft gross weight, CG, excess endspeed, and wind-over-deck. The results were graphically summarized and compared against the following set of limits:

1. Maximum 12 deg AOA
2. Maximum 12.5 deg/sec pitch rate
3. Maximum 3 deg/sec negative (nose-down) pitch rate
4. Maximum sink-off-bow of 18 ft

The test team analyzed any regime in which one or more of the limits was exceeded, then modified the trim settings and/or launch bulletins as required. These modifications were

then subjected to another batch matrix constrained by the same limits, thus continuing the process.

The test team chose the governing limits for the following reasons: The 12 deg AOA value represented a new, proposed maximum as a direct result of the V_{mc} testing. The values chosen to limit the pitch rates were in accordance with previous F/A-18 flight test maximums and were based on traditional standards. Excessive nose-up pitch rates during rotation or excessive nose-down corrective rates were considered undesirable because of their tendency to cause pilot discomfort. Maximum 18 ft sink-off-bow criterion was also in keeping with initial F/A-18 standards as well as in agreement with established carrier suitability practice

Simulator Assets and Correlation

The test team had the luxury of using two, independent simulator facilities. The first, located at Patuxent River and operated by the government, was the Controls Analysis and Simulation Test Loop Environment (CASTLE). The second, located in St Louis, MO and operated by the Boeing Company, was the Modular Six Degree of Freedom (MODSDF). Both used similar aerodynamic and engine thrust models, and identical flight control laws. MODSDF provided a slightly more sophisticated model with regard to aircraft nose gear strut compression and resultant effects on initial aircraft pitch rate following shuttle separation.

Simulator correlation was achieved using actual flight test data from F/A-18 LEX Fence sea trials conducted in 1988. Time history plots from catapult shots aboard USS INDEPENDENCE were compared with simulator predictions under the same conditions.

MODSDF consistently provided matching results while CASTLE yielded significant errors with regard to maximum pitch rates and angles-of-attack. To correct these deficiencies, CASTLE incorporated the Boeing nose gear model and correlation improved significantly. Figure A-9 is a catapult time history plot comparing flight test results with CASTLE, while figure A-10 compares MODSDF to CASTLE.

Sensitivity Studies

Initially, the test team sought to document the dependence of critical parameters on aircraft gross weight and CG at different longitudinal trim settings. This information would define specific relationships and provide a foundation from which to make intelligent proposals. Using the CASTLE simulator, a matrix was developed and tested. Sensitivity studies were repeated for both MIL and MAX power launches using a F404-GE-402 EPE thrust model.

To identify gross weight effects, simulated launches were conducted using a fixed, mid-range CG position while varying gross weight from 30,000 lb to 50,384 lb. Longitudinal trim settings were varied between 12 deg and 20 deg TEU. Catapult endspeeds were constant at 165 kts at and below gross weights of 45,000 lb, while endspeeds of 171 and 177 KCAS were chosen for 47,000 lb and 50,384 lb launches respectively. The 165 KCAS endspeed reflected 15 kts excess above the apex of the 12 deg AOA V_{mc} Dynamic curve (initial corrections to Sea Level Standard Day conditions increased the 148 KCAS point to 150 KCAS; more precise thrust corrections later yielded a value of 151 KCAS). The 171 and 177 kts endspeeds corresponded to 15 kts above the 18 ft sink-off-bow line in the existing MAX power launch bulletin.

Results from the gross weight sensitivity study are depicted in figure A-11 for the MAX power condition. From the data, several trends are evident. For any given longitudinal trim setting, maximum AOA during rotation varied about 2.5 deg across the entire weight band with the heavier aircraft experiencing greater angles-of-attack. Maximum pitch rate values varied about 3 deg across the weight band with lighter aircraft encountering higher pitch rates. Sink-off-bow at low trim settings (12 and 14 deg TEU) varied significantly and intuitively with weight as heavier aircraft were subject to larger deviations.

Sensitivity to longitudinal CG was investigated at aircraft gross weights of 36,000 and 45,000 lb. CG was varied between 17-27 % mean aerodynamic chord (MAC) representing complete flight envelope travel. The test team chose an endspeed of 165 KCAS for both launch weights to match the speeds used for gross weight sensitivity tests. Longitudinal trim varied from 12 deg to 23 deg TEU.

CG sensitivity results for the 45,000 lb, MAX power launches are illustrated in figure A-12. As in the case of gross weight dependence, all parameters varied linearly with longitudinal trim with the exception of sink-off-bow. Maximum AOA and maximum pitch rate both showed greater sensitivity to CG than gross weight with aft centers-of-gravity developing higher angles-of-attack and greater pitch rates.

From the sensitivity studies, several areas of concern were identified. First, light weight launches with aft centers-of-gravity were likely to generate pitch rates in excess of desired. Also, heavy weight launches with forward CG positions would potentially need high trim settings to minimize sink and, therefore, would be in danger of producing excessive maximum angles-of-attack. Finally, the non-linear relationship between sink-

off-bow and longitudinal trim was an indication of significant aircraft settle implications as a result of minor trim variations.

Launch Bulletin Development

During launch bulletin development, the test team decided to propose a single set of minimum endspeeds that would apply to both MIL and MAX power launches. At high gross weights the existing sink-off-bow lines were a maximum of three knots apart and only the MIL curve was based on actual flight test data. Also, a contradiction characterized the use of afterburner in response to emergencies. The first step in any catapult emergency was to apply as much power on the jet as possible such to get away from the water. As such, catapult endspeeds had to be sufficient to provide V_{mc} protection for the higher thrust asymmetry of a MAX split (one engine off, the other at MAX), even if the launch was conducted at MIL. Such protection was not assured using the existing launch bulletins. For example, if a 33,000 lb F/A-18 were launched at its minimum airspeed of 129 KCAS and experienced an engine failure, it would be below the 134 KCAS MAX power V_{mc} threshold. In theory, selection of afterburner would result in loss of control.

The test team prepared a rudimentary launch bulletin for use during the gross weight and CG sensitivity studies. As previously described, the bulletin was based on the 12 deg AOA V_{mc} Dynamic results at aircraft gross weights up to 45,000 lb and reflected the 18 ft sink-off-bow MIL power criterion at higher weights. This bulletin is depicted in figure 11 with the existing MIL and MAX power minimum endspeed curves. In theory,

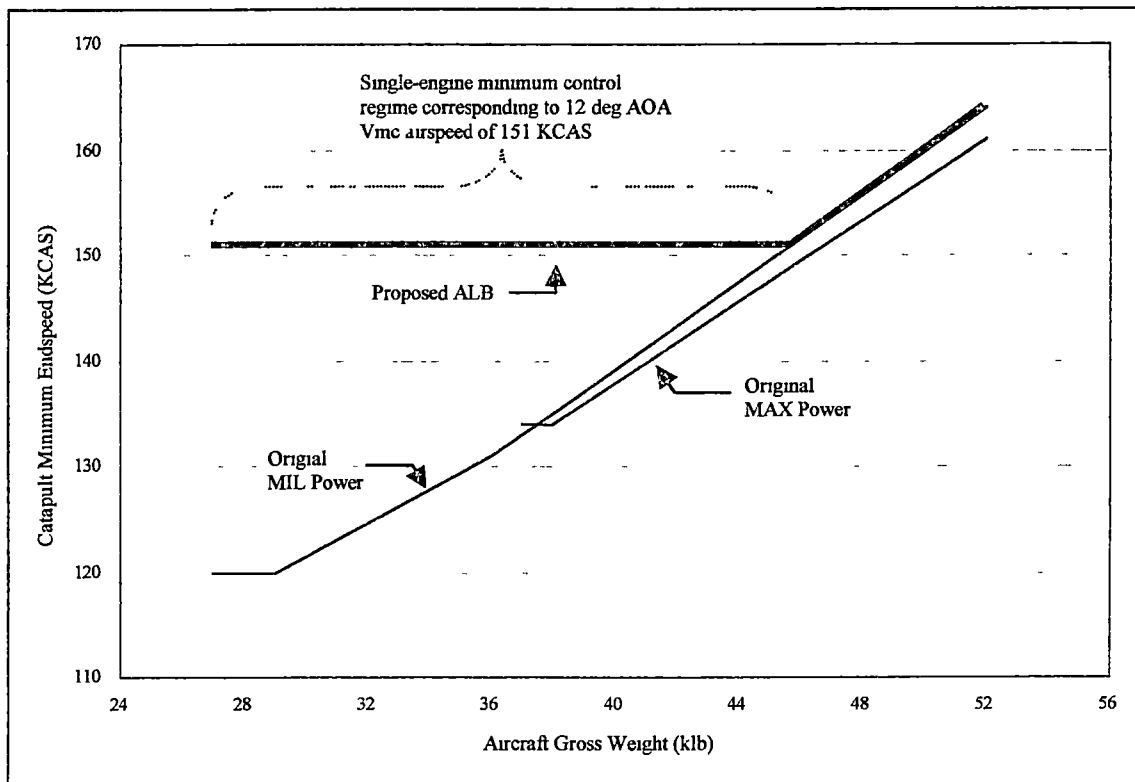


Figure 11
EARLY LAUNCH BULLETIN ATTEMPT

the new bulletin would provide safety margin for all launches at lateral weight asymmetries out to the existing limit of 22,000 ft-lbs. This statement, however, would only be true if AOA were kept at or below 12 deg throughout the launch sequence.

Even without thorough analysis, the initial launch bulletin proposal raised some obvious concerns; the most notable of these being the dramatic endspeed increase at light aircraft weights. The magnitude of the increases suggested significant impact on aircraft fatigue as well catapult wear-and-tear. Additionally, specific care would be required to avoid over-rotation as a result of the high flyaway airspeeds. In response to these concerns, the test team sought alternatives.

One alternative proposed the use of a stair step approach with regard to lateral weight asymmetry such to reduce required launch speeds at low weights. The theory was that, at light weights, only small levels of lateral weight asymmetry could be generated. The same weight that contributed to the asymmetric moment would also increase aircraft gross weight. A study of various normal aircraft loads and fleet operating procedures indicated that catapult launches almost never occur with gross weights below 37,000 lb and asymmetric moments in excess of 6,000 ft-lb. As a result, launches below 37,000 lb would only have to provide margin above the 6,000 ft-lb V_{mc} Dynamic minimum of 134 KCAS (Sea Level Standard Day). Thus, 17 kts could be trimmed from the minimum curves at aircraft launch weights below 37,000 lb. A formal NATOPS lateral weight asymmetry restriction would be required at these weights, however, the new limit would have no operational impact. The modified launch bulletin is depicted in figure 12.

Longitudinal Trim Setting Development

With the modified launch bulletin proposal ready, the test team next worked to develop accompanying longitudinal trim settings. The choice of settings would have strong influence on rotational and flyaway characteristics. Specifically, trim needed to be set such to maintain AOA at or below 12 deg during rotation, preclude undesirable positive and negative pitch rates, and manage sink-off-bow.

The existing NATOPS trim procedures had been essentially ignored by fleet pilots who chose to discard the tedium of CG calculations and instead rely on unofficial rules-of-thumb. This procedural shortcut was not considered a problem because single-

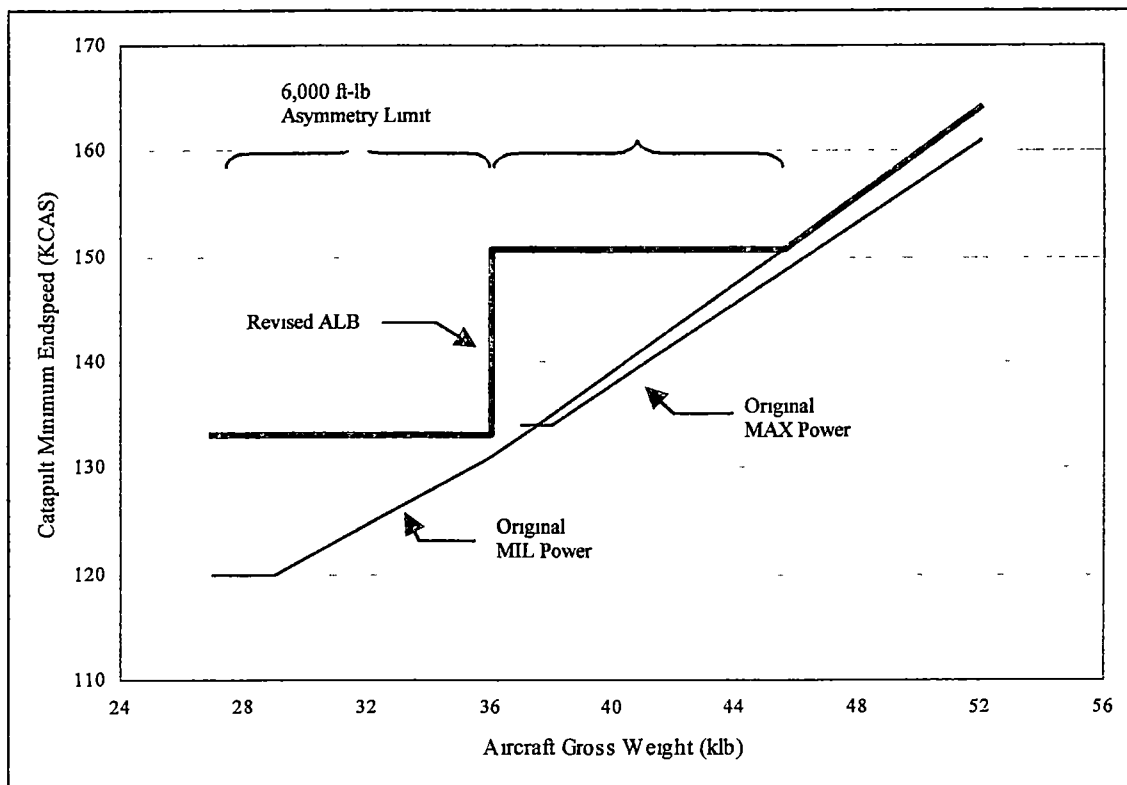


Figure 12
MODIFIED LAUNCH BULLETIN PROPOSAL

engine AOA issues were thought not to exist. In light of the new V_{mc} Dynamic understanding, adherence to longitudinal trim procedures was suddenly of great import. To promote adherence, simplicity was required. The procedural reliance on CG had to be removed

Sensitivity studies had shown the strong influence of CG on rotational characteristics to include AOA, pitch rate, and sink-off-bow. Discounting CG when choosing trim settings, therefore, seemed unwise. A relationship between CG and aircraft gross weight provided the solution. In general, F/A-18 center-of-gravity moves forward with increasing gross weight. Similarly, a light-weight aircraft will almost certainly have an aft CG. This relationship is shown in figure A-13. Basing trim settings

on gross weight would, therefore, retain the indirect influence of CG. Pilots communicate gross weight to catapult personnel prior to each launch and, as such, are acutely aware of this parameter

The test team had initially hoped a single trim setting of 16 deg TEU would work for all aircraft gross weights. This value corresponded to a trim AOA of 10 deg and, therefore, the 1-2 deg overshoots during rotation would remain at or below 12 deg AOA. Simulation quickly demonstrated that this setting was too low at heavy weights as excessive sink-off-bow was generated. The problem was addressed using a stair step approach. At gross weights above 45,000 lb, endspeeds were determined by the 18 ft sink-off-bow criterion. Accordingly, margin above the 12 deg V_{mc} Dynamic airspeed was introduced. From 45,000-48,000 lb, longitudinal trim could be increased to 17 deg without generating unacceptable AOA values. Above 48,000 lb, sink-off-bow minimums provided margin such to enable a trim setting of 19 deg TEU and acceptance of AOA excursions up to 13 deg.

The trim setting proposal is depicted in figure 13. Also shown are the existing NATOPS trim settings converted from a CG basis to a gross weight basis using the linear relationship introduced in figure A-13. Note that a single curve was hoped to replace three different trim lines. Also note that the proposed curve generally yields (in comparison to the existing NATOPS curves) lower trim settings for heavy weight launches and higher settings for light weight launches. The effect of these differences would be discovered during further batch simulation.

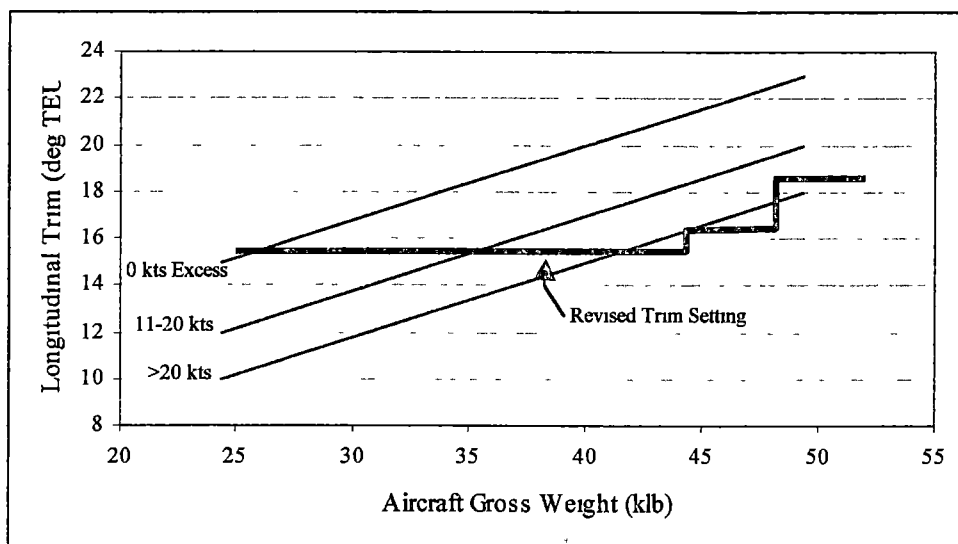


Figure 13
PROPOSED LONGITUDINAL TRIM REVISION

Final Simulation Results

The test team developed an analysis matrix to evaluate the proposed endspeeds and trim settings. The matrix was divided into three sections, each representing a different aircraft loading. The different loadings enabled testing across the entire aircraft gross weight envelope with representative CG travel. Tests were conducted using power settings of MIL, MAX and MIL-MAX (selection of MAX power during the catapult stroke). Three different excess endspeed curves were evaluated. These included launch at actual minimums (zero excess), normal fleet launch (15 kts excess), and high excess launch (30 kts excess). Engineers at both simulator sites were given leeway to conduct narrow scope sensitivity studies within regimes where undesirable characteristics were evidenced.

A summary of the simulation results for the light weight aircraft loading is provided in figure A-14 while a corresponding catapult launch time history plot is

included as figure A-15. From these data, two areas of concern became apparent. At high excess catapult endspeeds, pitch rates repeatedly surpassed the established criterion of 12.5 deg/sec nose-up, reaching values above 14 deg/sec at the lightest gross weights. During minimum launches (zero excess), peak AOA values exceeded the target 12 deg about 2.0 deg. These high AOA values, however, were deemed acceptable for several reasons. First, the duration of the AOA excursion was always less than 2 seconds with pitch rate feedback providing timely AOA reduction. Second, intentional low excess launches at light gross weights have proven to be extremely rare. Minimum endspeeds are low enough in this regime to enable no-wind and often tailwind launches while still providing the desired 15 kts excess endspeed.

As expected, sink-off-bow at light aircraft weights was not a concern. Accordingly, a longitudinal trim reduction, such to confront the remaining pitch rate issue, seemed logical. This course of action, however, was discarded for several reasons. First, an additional step in the longitudinal trim curve would further complicate procedures and entice fleet non-compliance. Additionally, the use of a trim setting less than 16 deg TEU would, following the dynamic excursions associated with rotation, result in flyaway angles-of-attack below optimum. As a result, pilots would have to manually increase aircraft attitude to avoid water impact during certain catapult emergencies. The 16 deg TEU longitudinal trim setting remained, therefore, the preferred choice for light weight launches. Further analysis would be required to solve the pitch rate problem.

A summary of the simulation results for the zero excess, MIL power, medium-weight aircraft loading is contained in figure A-16. The plots contain curves for zero and

25 kts wind-over-deck (WOD). The WOD difference does not equate to different rotational airspeeds, but instead specifies the means in which the aircraft reached the endspeed. Zero WOD represents a case in which endspeed is completely supplied by the catapult. In this case, the aircraft would experience higher nose strut compression and resultant higher initial pitch rates.

From the data in figure A-16, several trends are of note. First, all pitch rate and AOA criteria are met. Also of note is the excessive sink-off-bow at 44,000 lb. Clearly, a 16 deg TEU trim setting would not be sufficient for zero excess catapult launches at this weight. Heavy weight aircraft (45,000 lb and above) also exhibited unacceptable sink-off-bow as a result of zero excess launches. Figure A-17 illustrates this problem while also depicting compliance with AOA and pitch rate criteria.

Results of batch simulation were largely positive, however, two issues needed further resolution: Light-weight launches generated excessive pitch rates while heavy weight, minimum excess launches resulted in unacceptable sink-off-bow. Each problem was addressed separately.

Pitch Rate Paradigm Shift

Established carrier suitability doctrine identifies 10-12 deg/sec as the maximum comfortable pitch rate for catapult rotation. From this historical tolerance, a slightly higher, but similar 12.5 deg/sec F/A-18 criterion was specified during initial development. No testing, however, had ever been conducted to verify that the traditional pitch rate comfort zone applied to the Hornet. In fact, the digital flight control system

used by the F/A-18 has built-in functionality for the exact purpose of allowing high initial pitch rates during rotation.

During nominal F/A-18 catapult launch, the aircraft CG sinks a few feet during rotation. High pitch rates, required to arrest sink, also keep the pilot – seated several feet forward of the CG – from sensing the slight settle. The flight control computers combat over-rotation and excessive AOA excursions with the use of pitch rate feedback. Thus, it can be hypothesized that the excessive pitch rates identified by batch simulation may be acceptable in the context of an F/A-18 launch.

The test team received a chance to validate the F/A-18 pitch rate hypothesis in the form of the USS HARRY S. TRUMAN (CVN-75) catapult certification conducted in August, 1998. Catapult certification includes, among other things, high excess endspeed launches at light weights. During this particular certification effort, six pilots received a combined ninety catapult shots with excess airspeed varying from 22-68 kts over the existing launch bulletins. The minimum longitudinal trim setting used was 16 deg TEU.

Time histories from the CVN-75 launches (see figure A-18 for an example) revealed pitch rates routinely in excess of 12.5 deg/sec with peaks as high as 15 deg/sec. All six test pilots, however, reported no adverse handling qualities, objectionable pitch rates, or uncomfortable pitch attitudes. As a result, conclusive evidence in favor of accepting pitch rate excursions surpassing 12.5 deg/sec was available.

Heavy Weight Sink Solution

While the 12.5 deg/sec pitch rate criterion had been rendered inapplicable, no similar change of standards would characterize the sink-off-bow resolution. Sensitivity

studies conducted using the MODSDF simulator identified two possible courses of action. First, longitudinal trim could be increased for minimum excess launches. Second, endspeeds could be increased at heavy weights. A three deg increase in longitudinal trim would be required to meet the 18 ft sink-off-bow criterion above 42,000 lb. For the same aircraft weight band, a six knot endspeed increase would be needed to provide adequate settle protection. Figure A-19 depicts trim effects for the heavy weight aircraft loading, while figure A-20 illustrates endspeed relationship with sink-off-bow for a 51,900 lb aircraft.

The test team had avoided endspeed increases at weights above 44,000 lb and, in doing so, had avoided aircraft fatigue cycle implications and aircraft carrier operational impact. F/A-18 service life had been projected, in part, using a figure of 2700 catapult launches at gross weights of 47,000 lb and above. An endspeed change at these weights, unfortunately, would invalidate the initial service life projection and necessitate recalculation. Additionally, high gross weight launches are those which typically require wind-over-deck to provide a portion of the minimum endspeed. A six knot increase in minimum endspeed would translate to a six knot increase to the minimum WOD velocities for launch. The effect would be reduced operational flexibility in launching heavy weight F/A-18's.

With an aversion to higher endspeeds at heavy gross weights, the test team focused efforts on the longitudinal trim increase. A three degree increase applied to zero excess launches would reduce sink to acceptable limits. It would, however, also result in AOA excursions to 13.5 deg. Since launches at actual minimum endspeeds are very rare and occur only when operational necessity dictates, the risk associated with the minor

AOA excursions was accepted. A note, therefore, was added to the proposed longitudinal trim curve requiring a three degree increase for aircraft of 43,000 lb and above during intentional launches with less than 10 kts excess airspeed (pilot notification is required in these cases).

Summary of Batch Simulation

Upon completion of the batch simulation process, several products were developed. A single launch bulletin for all power settings had been developed with minimum endspeeds reflecting V_{mc} Dynamic test results. A simplified longitudinal trim curve based on aircraft gross weight provided optimum rotational characteristics and complemented the new endspeeds. These changes, however, were mostly applicable to the first few seconds of flight in which the pilot is largely along for the ride. To this point, human factors had been given little consideration. During catapult emergencies, however, human factors are paramount.

6. EMERGENCY PROCEDURE DEVELOPMENT

Human Factors

Anyone who has experienced a night catapult launch from an aircraft carrier will agree the capacity to recognize, identify, and react to anything out of the ordinary is miniscule. Hurtling into the blackness at the front of the ship humbles those with even the greatest of cognitive and physical abilities. This state of reduced capability, however, is sometimes forgotten. Formulators of catapult emergency procedures have commonly erred on the side of complexity. A tendency to over-engineer the human contribution during emergency flyaway has resulted in the existence of procedures that can be difficult to remember and harder still to execute.

During development of new catapult emergency flyaway procedures, the test team emphasized simplicity in an effort to produce an effective, executable formula. A review of previous F/A-18 catapult emergencies illustrated the frequent inability of pilots to complete critical steps such as external stores jettison. As such, the test team adopted a philosophy to include only those steps that were deemed absolutely necessary, and delete those which, if implemented properly, would have merely a secondary effect. It was these steps that added complexity without significant benefit

Power Application

Clearly, the first step in the catapult emergency flyaway procedure needed to the application of MAX power. Using all available thrust to create separation between the aircraft and the water is crucial, especially if one of the engines is damaged. Using the

new launch bulletins and trim procedures, MAX power could be applied on the good engine without fear of adverse lateral-directional control. In fact, pilots would be able to select MAX power during every launch while traveling down the catapult track. In the past, this practice had been prohibited at light weights. Now, pilots could leave the ship with afterburners engaged and, therefore, the first emergency action item completed. If a problem arose, executing the remaining steps would be that much easier.

Lateral-Directional Control

The existing "SETTLE-OFF-BOW" emergency procedure failed to consider lateral-directional control issues. Even at the lower angles-of-attack promised by the new launch bulletins and trim settings, lateral-directional control inputs would be required to counter thrust asymmetry. From the results of testing, rudder was the most effective control input. As such, countering roll and yaw with rudder became the second step of the new emergency flyaway procedure. A lateral stick limit of half deflection, to counter adverse yaw, would accompany the use of rudder

External Stores Jettison

Clearing the aircraft of its external stores has two effects. First, it instantaneously reduces the gross weight and drag of the aircraft. Second, it similarly negates lateral weight asymmetry. Accordingly, control characteristics improve and sink-off-bow is reduced. The importance of stores jettison, and therefore its inclusion into the emergency flyaway procedure, is clear.

Longitudinal Control

Using the new trim settings, the F/A-18 flight control system will command angles-of-attack between 10 and 12 deg depending on gross weight. These angles-of-attack are appropriate for either an engine-out emergency or sink-off-bow (insufficient endspeed) scenario. Accordingly, pilots can remain out of the longitudinal control loop during rotation as the aircraft seeks a good flyaway attitude on its own. After rotation, however, pilots need to actively control the longitudinal axis. This control is accomplished using pitch attitude because the digital AOA display in the HUD is insufficient to enable direct AOA control

The test team decided upon a flyaway pitch attitude of 10 deg nose-up for several reasons. First, 10 deg would command angles-of-attack near optimum for flyaway without sacrificing controllability. A two degree settle (flight path angle of minus two degrees) would produce an AOA of approximately 12 deg using the prescribed pitch attitude. In addition, the F/A-18 HUD displays an attitude line at 10 deg nose-up, making execution of the pitch control task less difficult.

Summary

The new Emergency Catapult Flyaway procedure is listed in figure 14. During development, the test team evaluated each step in the F/A-18 simulator. Test pilots agreed the technique was effective and easily executable. Accordingly, the new emergency procedure, revised launch bulletins and modified trim settings could now be combined as a three part solution, providing F/A-18 pilots with a reduced risk catapult launch environment.

EMERGENCY CATAPULT FLYAWAY

Simultaneously

- * Throttles – MAX
- * Rudder – Against Roll/Yaw
- * Emergency Jettison Button - Push

After Rotation Complete

- * Maintain 10 deg Pitch Attitude with the Waterline Symbol. Do Not Exceed Half Lateral Stick Deflection

If Unable to Arrest Roll/Yaw Rates or Stop Settle

- * Eject

Figure 14
EMERGENCY CATAPULT FLYAWAY PROCEDURE

7. CONCLUSION

F/A-18 developers failed to identify the dependency of single-engine control on angle-of-attack and lateral weight asymmetry because classic flight test techniques were either inadequate to isolate the variables or were unrepresentative of the actual flight environment. The flawed flight test approach was enabled as a product of a flawed perspective. Early F/A-18 studies were conducted under the belief that a twin-engine, centerline thrust, jet aircraft would not be subjected to significant lateral-directional control issues as the result of engine loss. As such, tests were unknowingly biased toward expected results. Data supporting the hypothesis were embraced while other data, hinting at unanticipated phenomena, were discounted.

Dependency of V_{mc} Dynamic on both angle-of-attack and lateral weight asymmetry makes single-engine controllability a very real hazard to F/A-18 pilots, especially in the catapult launch environment. With an increase in either AOA or lateral weight asymmetry, minimum-control airspeed increases similarly. This relationship was quantified only after the development of an innovative, specifically tailored test technique using AOA as an independent variable. At the heart of new technique is the understanding that catapult emergencies are not always tolerant of rapid AOA reduction and that test controllability criteria must reflect this reality.

Risk reduction in the catapult environment required balancing angle-of-attack reduction, sink-off-bow tolerance, and pitch rate allowance. During analysis, the use of a goal oriented, systems approach provided focus, balance, and diversity. Test pilots and engineers combined to provide an appropriate blend of operational experience and

technical expertise. Sub-optimization tendencies were combated with sensitivity studies, risk hazard analysis, and compromise. Iterative, batch simulation proved highly successful in isolating relationships and evaluating potential remedies. Paradigms, often based on many years of flight test experience, were questioned and discarded when appropriate

In February 1999, F/A-18 pilots received an urgent NATOPS flight manual update while, at the same time, aircraft carriers received a new F/A-18 launch bulletin. Mechanized for simultaneous release, the documents together implemented the products of the Hornet V_{mc} study. New trim settings, increased minimum endspeeds, and simplified emergency procedures were at the heart of the package. Fleet introduction of these products signaled completion of a successful test program while serving as a testament to the benefits of an innovative, unbiased systems approach to technical problem solving.

8. RECOMMENDATIONS

1. Developers must ensure classic test techniques remain applicable to modern aircraft and constraining operational environments and be willing to discard or modify those which have lost relevancy.

2. A constant angle-of-attack technique should be used for the determination of V_{mc} Dynamic airspeeds on fixed-wing aircraft intended for shipboard catapult launch. Tests need to include the variance of lateral weight asymmetry throughout the intended launch envelope.

3. The results of this study should be made available to Ship Suitability Department at Patuxent River Naval Air Station and to the U.S. Navy Test Pilot School.

9. FINAL WORD

On the evening of 23 May 1999, an F/A-18 was launched from the USS CONSTELLATION (CV-64) during operations about 500 miles north of Hawaii. While accelerating down the deck, the aircraft impacted several sections of rubber catapult seal (used to cover the catapult track while not in use) that had mistakenly been left in the catapult track. A 30 ft section of the rubber was ingested into the left intake, entirely destroying that engine. Several smaller sections were ingested into the right engine, causing significant, but not catastrophic damage. From the cockpit, the pilot experience was dramatic:

As the cat fires, I stage the blowers and am along for the ride. Just prior to the end of the stroke there's a huge flash and a simultaneous boom! And my world is in turmoil. My little pink body is doing 145 kts or so and is 60 ft above the black Pacific.

Amidst the shock and confusion, the pilot was successful in executing the new Emergency Catapult Flyaway procedures. He selected afterburner during the launch, maintained lateral-directional control in the asymmetric thrust condition, and jettisoned 4500 lb of external stores. During flyaway he maintained a pitch attitude which ensured controllability and provided for a gradual climb away from the water.

In addition to his piloting skills, this aviator had several other factors in his favor. As a result of the new launch bulletins, he was launched 9 kts faster than he would have been just four months earlier. He was also using a new, longitudinal trim setting which allowed the aircraft to quickly establish lift while avoiding dangerous angles-of-attack during rotation. It will never be known if the products of the V_{mc} study were directly

responsible for the survival of this aircraft and its pilot. The evidence, however, suggests a strong relationship.

During the early days of the flight test program, skeptics questioned the allocation of time and money to an issue that had not definitively reared its head during nearly twenty years of operational flight. Proponents of the program, however, responded with a hypothetical question: How would you feel if, a year from now, an aircraft and pilot are lost during catapult launch, and we had done nothing? Fortunately, this question has remained hypothetical.

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REFERENCES

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APPENDICES

APPENDIX A
FIGURES

SIGN CONVENTIONS

Flight parameters and flight control displacements are displayed on the following figures using generally accepted sign conventions. To avoid confusion, however, the following specifics are provided:

<u>Parameter</u>	<u>Positive (+)</u>	<u>Negative (-)</u>
Stabilator Position	Trailing Edge Down	Trailing Edge Up
Rudder Pedal Force	Right	Left
Yaw Rate	Right	Left
Sideslip	Left	Right
Roll Rate	Right	Right
Bank Angle	Right	Left
Pitch Rate	Nose Up	Nose Down
AOA*	Nose Up	Nose Down
Theta/Flight Path Angle	Up	Down
Sink-Off-Bow	Away From Water	Toward Water

* Aircraft telemetry plots show two angle-of-attack curves depicting separate MIL-STD-1553 databus sources. For the purpose of this study, the curve labeled O2A2705 should be considered the best reference of true AOA.

C13-1 CATAPULTS ABOARD CVN 71

80 DEGREE DAY**F/A-18A/B/C/D HALF FLAPS CRT**

WOD FOR
15 EXCESS > 30 32 34 36 38 40 42 44 46 48

WT/1000	CSV SETTING										MIN A/S
.0											0
.0											0
.0											0
.0											0
37.0	140	136	132	128	122	118	114	110	106	102	137
38.0	142	138	134	130	124	120	116	112	108	104	137
39.0	144	140	136	132	128	122	118	114	110	106	138
40.0	150	146	142	138	134	130	124	120	116	112	140
41.0	156	152	148	144	140	134	130	126	122	118	142
42.0	160	156	152	148	144	140	136	132	128	124	144
43.0	166	162	158	154	150	146	142	138	134	130	146
44.0	170	166	162	158	156	152	148	144	138	134	148
45.0	176	172	168	164	160	156	152	148	144	140	150
46.0	180	176	172	168	166	162	158	154	150	146	152
47.0	188	182	178	174	170	166	162	158	156	152	154
48.0	194	188	184	180	176	172	168	164	160	156	156
49.0	200	196	190	186	182	178	174	170	166	162	159
50.0	206	202	196	192	188	182	178	174	170	166	161
51.0	214	208	204	198	194	190	184	180	176	172	163
51.9	220	214	208	204	198	194	190	184	180	176	164

MAXIMUM EXCESS AIRSPEED = 50 KNOTS OFF-CENTER SPOTTING = 12 INCHES
 CRT LAUNCHES BELOW 45000 LBS ARE FOR POST MAINTAINENCE CHECK FLIGHTS ONLY.

Figure A-1
 SAMPLE AIRCRAFT LAUNCH BULLETIN

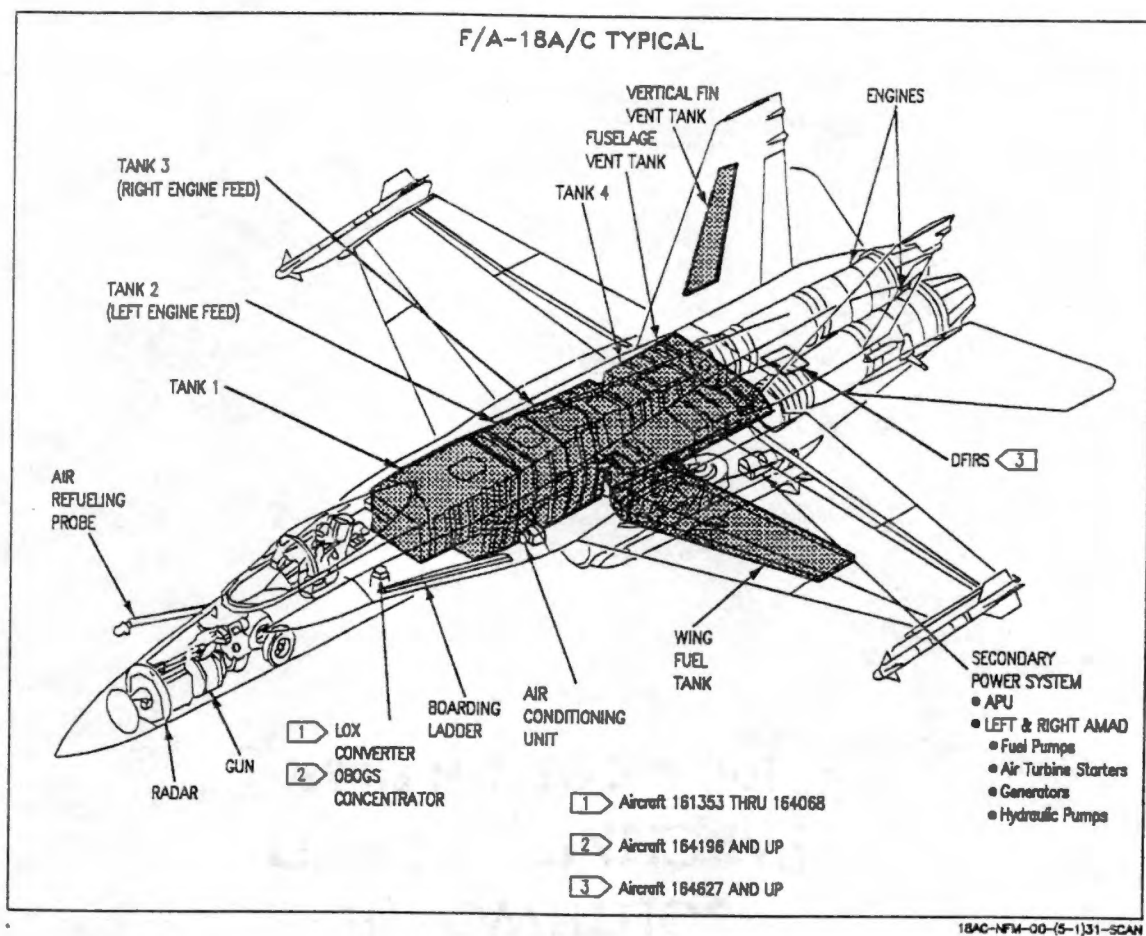


Figure A-2
F/A-18 HORNET

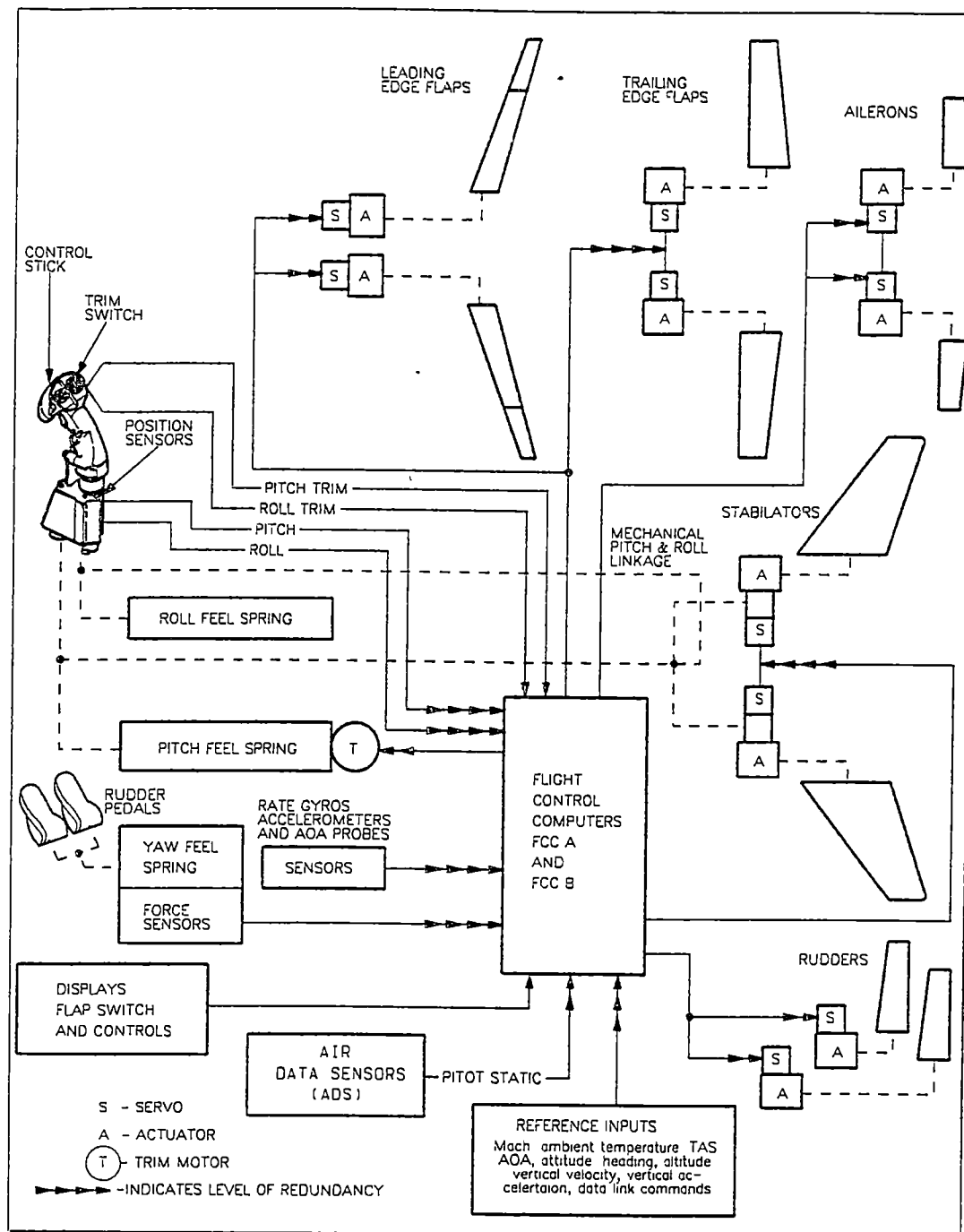


Figure A-3
FLIGHT CONTROL FUNCTIONAL DIAGRAM

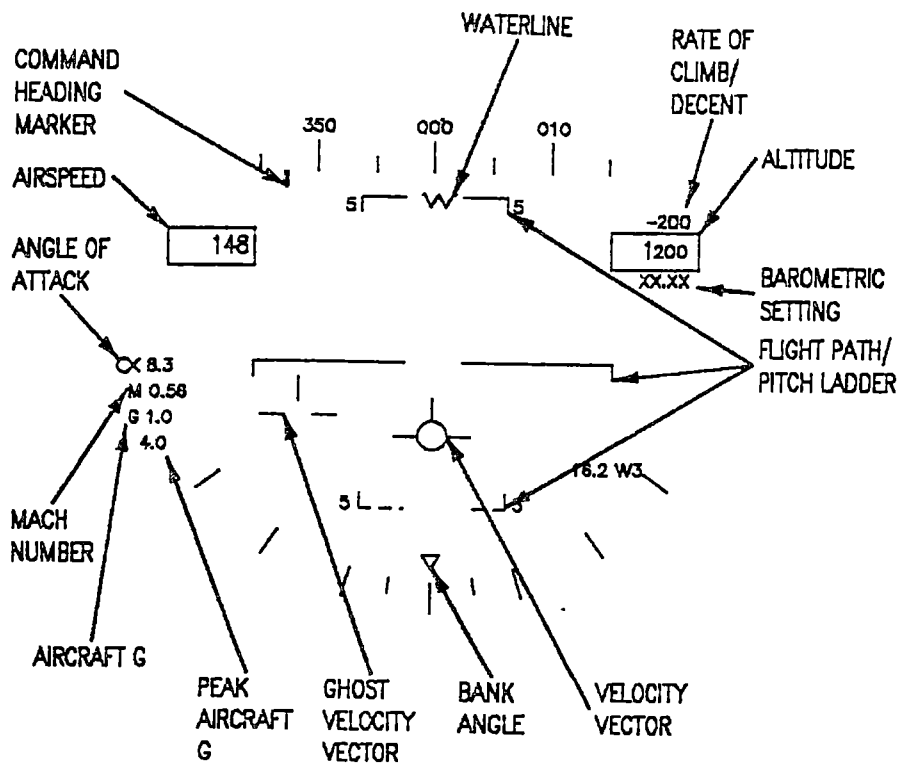


Figure A-4
HEADS UP DISPLAY

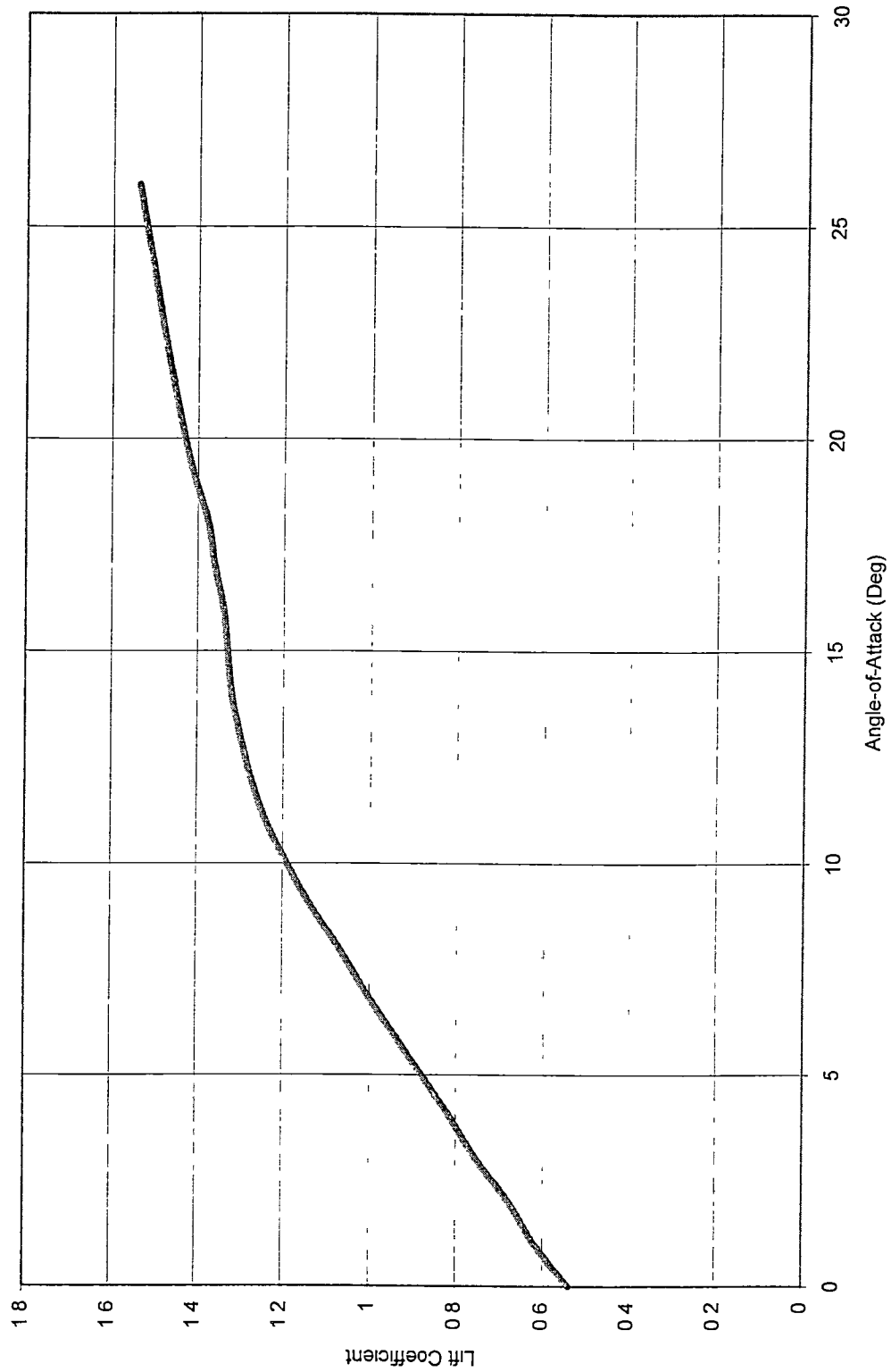
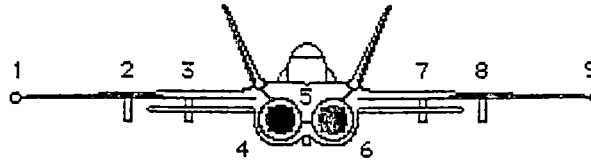


Figure A-5
LIFT CURVE SLOPE



Planned Aircraft Loads

LOAD	Aircraft Stations									ASYM (ft-lb)	Gross Weight (lb)	
	1	2	3	4	5	6	7	8	9		Max	Bingo
Sym H	AIM-9	GBU-24	FUEL	AIM-7	FUEL	AIM-7	FUEL	GBU-24	AIM-9	0	51710	36699
Sym L					FUEL					0	40439	29899
Sym L				AIM-7	FUEL		TANK			296	41248	30708
6K H	AIM-9	MK84	FUEL		FUEL	AIM-120	FUEL	GBU-24	AIM-9	6011	50587	35567
6K L				AIM-7	FUEL		TANK	MK82		6064	41763	31223
11K H	AIM-9	MK83	FUEL	AIM-7	FUEL	AIM-7	FUEL	MK84	AIM-9	11032	49882	34862
11K L				AIM-7	FUEL		TANK	MK83		11328	42223	31693
15K H	AIM-9	MK83	FUEL	AIM-7	FUEL	AIM-120	FUEL	GBU-24	AIM-9	15156	50112	35092
15K L					FUEL	AIM-7	TANK	MK83		15102	42233	31693
20K H	AIM-9	GBU-24			FUEL	AIM-7	BLST	GBU-24	AIM-9	20422	48670	38130
20K L					FUEL	AIM-7	BLST			20422	43488	32948
22K	AIM-9			AIM-7	FUEL		BLST	GBU-24	AIM-9	21419	48244	37704

Test Loads Flown

LOAD	Aircraft Stations									ASYM (ft-lb)
	1	2	3	4	5	6	7	8	9	
Sym H	AIM-9	GBU-24	FUEL	AIM-7	FUEL	AIM-7	FUEL	GBU-24	AIM-9	0
Sym L				AIM-7	FUEL		TANK			296
6K H	AIM-9	GBU-24	FUEL	TFLIR	FUEL		FUEL	MK-84	AIM-9	6064
6K L				AIM-7	FUEL		TANK	MK-82		6064
11K H	AIM-9	MK84	FUEL	AIM-7	FUEL	AIM-7	FUEL	MK83	AIM-9	11032
11K L				AIM-7	FUEL		TANK	MK83		11328
11K M			TANK	AIM-7	FUEL	AIM-7	FUEL			11169
15K H	AIM-9	GBU-24	FUEL	TFLIR	FUEL	AIM-7	FUEL	MK83	AIM-9	15211
15K L					FUEL	AIM-7	TANK	MK83		15102
15K H2	AIM-9	MK82	FUEL	TFLIR	FUEL		FUEL	MK84	AIM-9	15001
20K H	AIM-9	MK84			FUEL	AIM-7	BLST	MK84	AIM-9	20422
22K	AIM-9			AIM-7	FUEL	AIM-7	BLST	MK84	AIM-9	22198

TANK – Empty Fuel Tank

FUEL – External Fuel Tank with Normal Transfer

BLST – Full External Fuel Tank with Transfer Inhibited

Figure A-6
TEST LOADINGS

F18 A/C 164869 Flight 0223/00 Task 01D0890855 Run 049

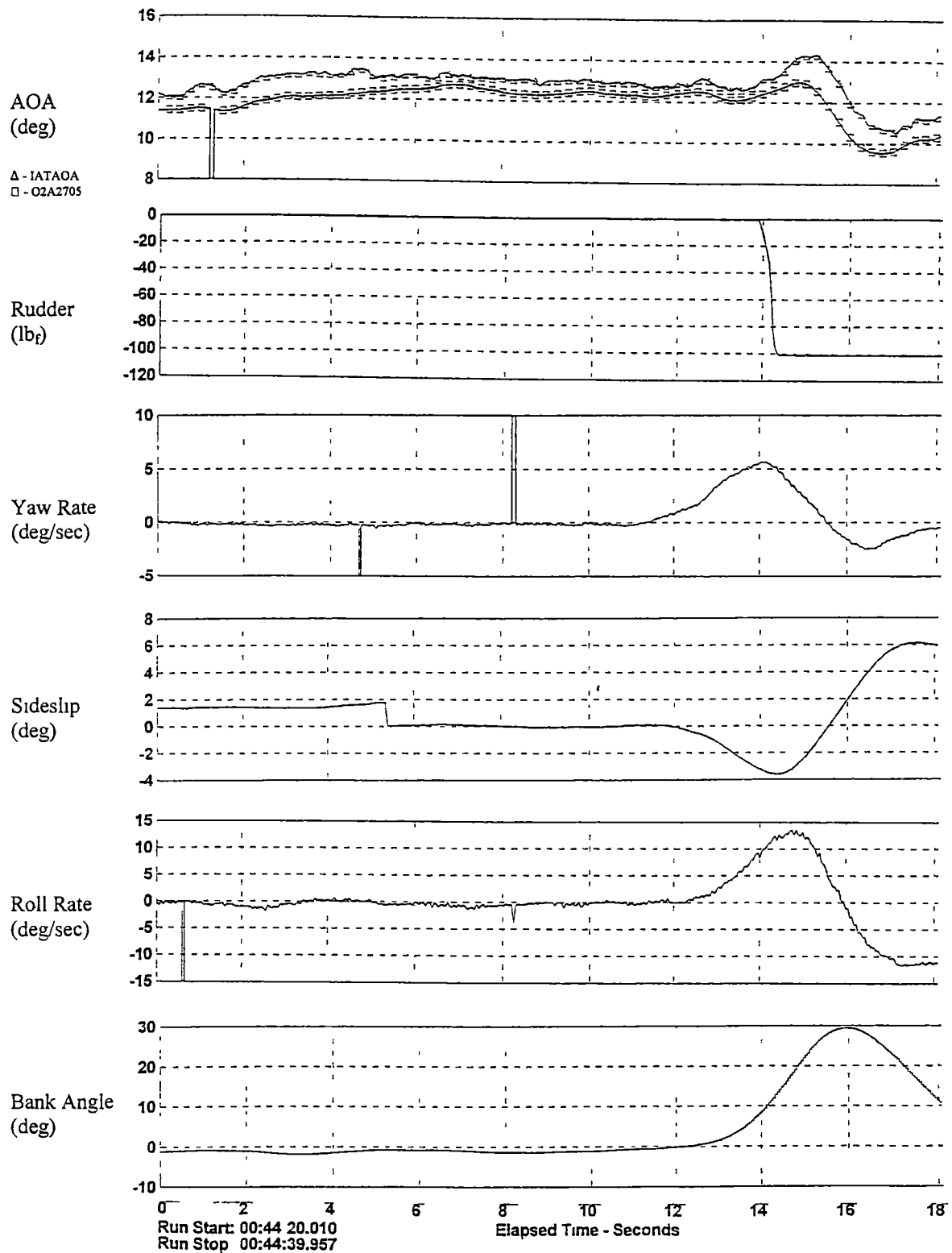


Figure A-7
 LOW LATERAL WEIGHT ASYMMETRY TEST POINT

F18 A/C 164869 Flight 0229/00 Task 01D0890908 Run 043

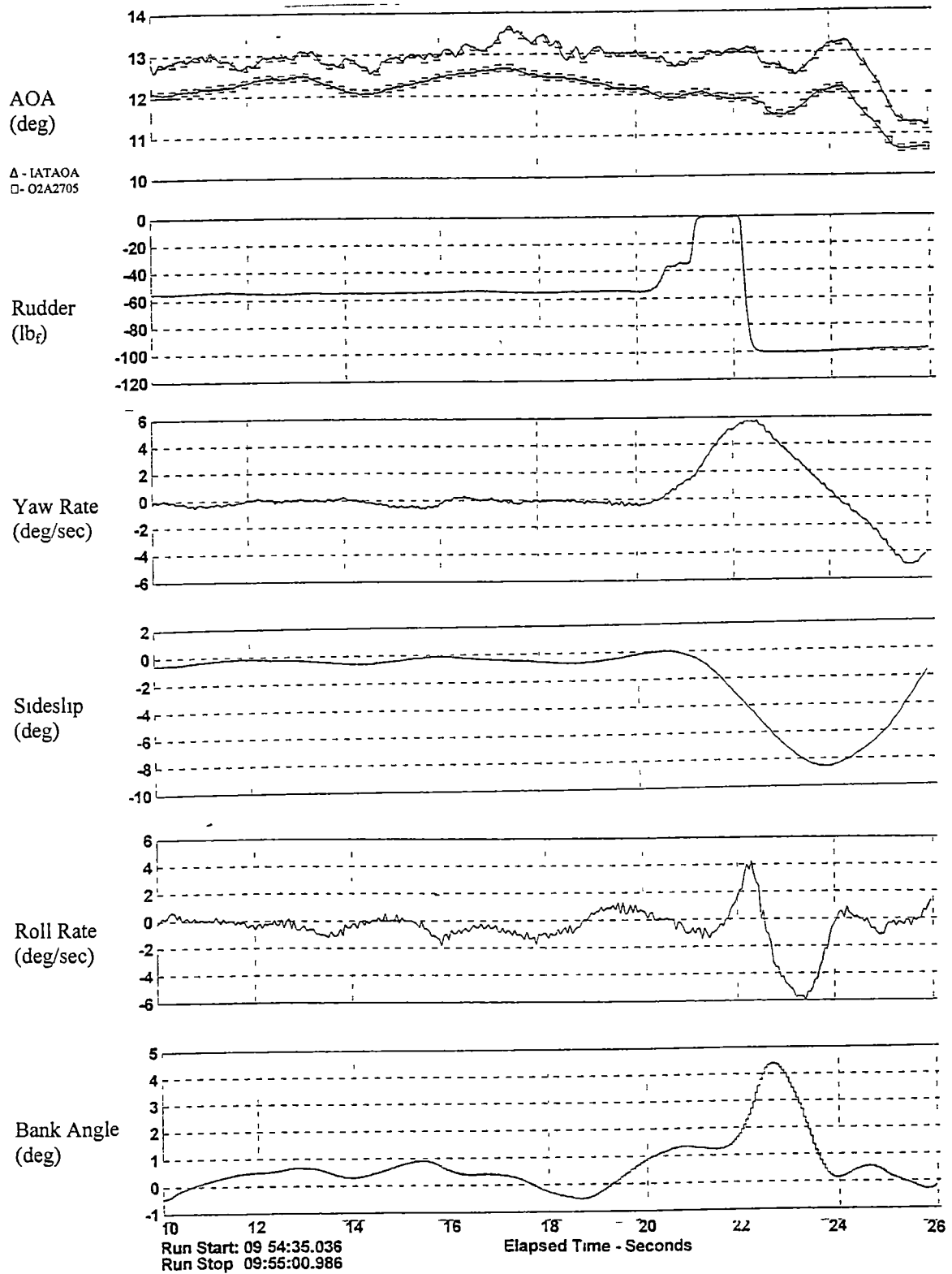


Figure A-8
 HIGH LATERAL WEIGHT ASYMMETRY TEST POINT

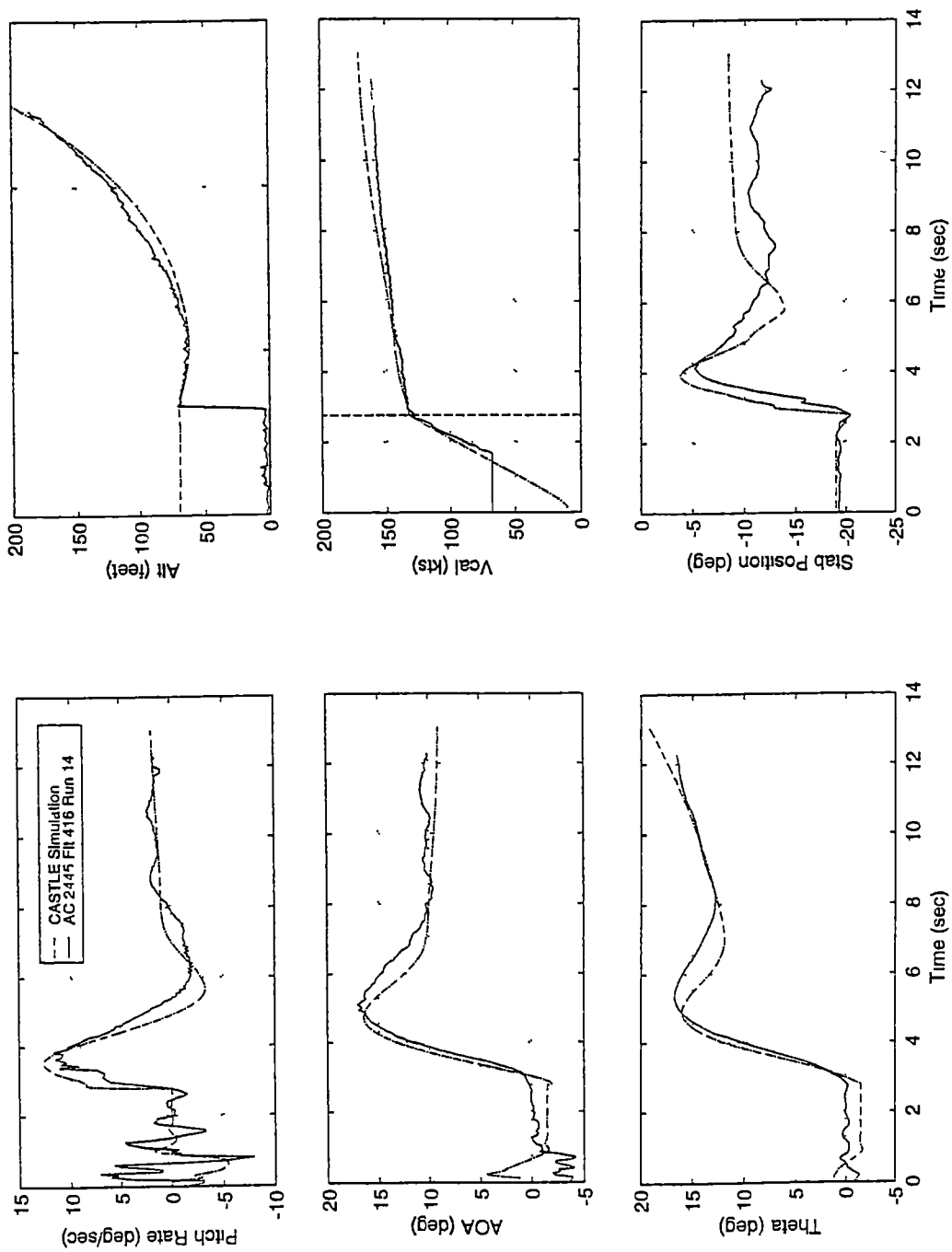


Figure A-9
CASTLE CORRELATION WITH FLIGHT TEST

F/A-18C: GW = 34,000 lbs, CG = 23.8%, -402 Engines, MIL Power; V_{end} = 126 kts, WOD = 5 kts

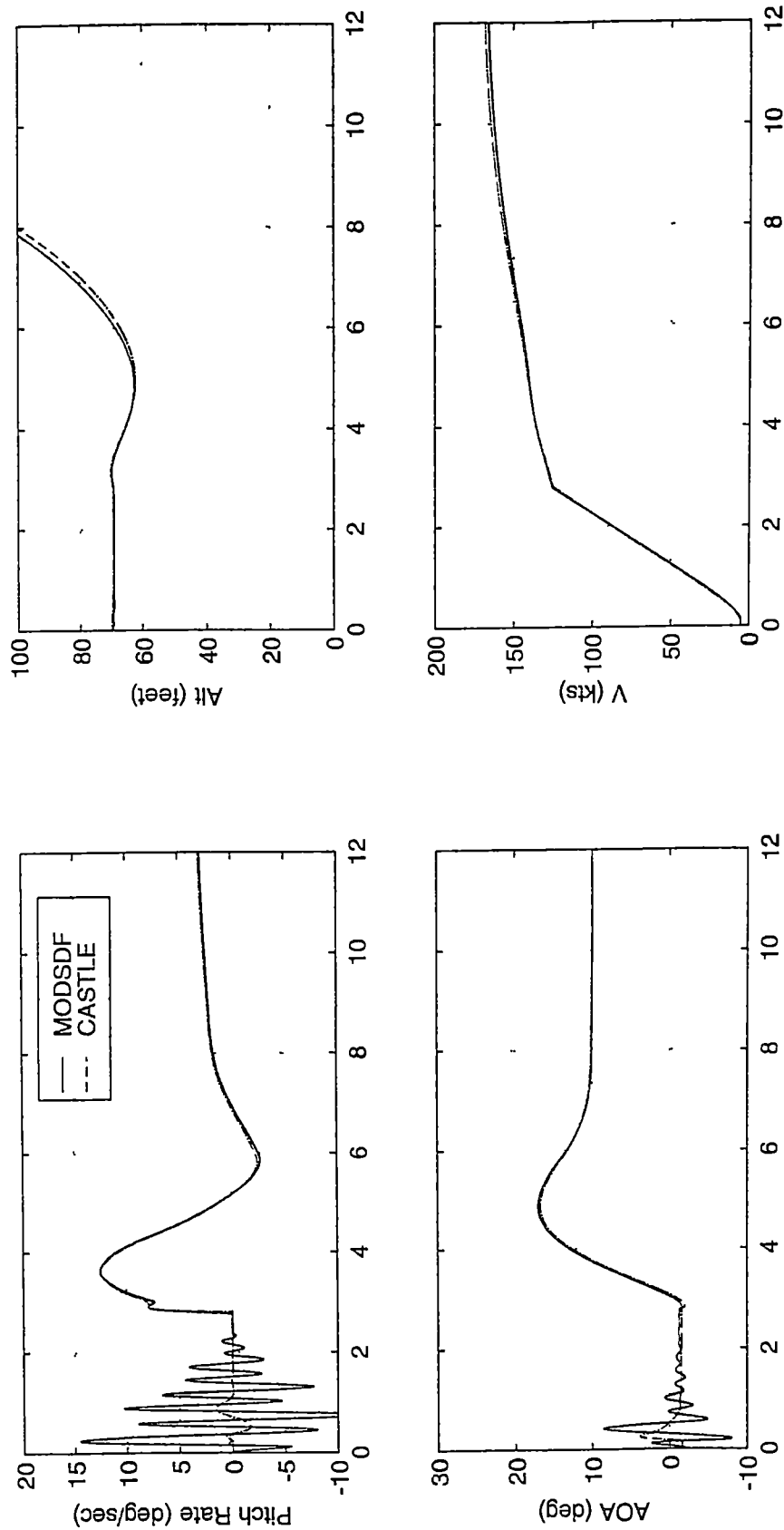


Figure A-10
CASTLE CORRELATION WITH MODSDF

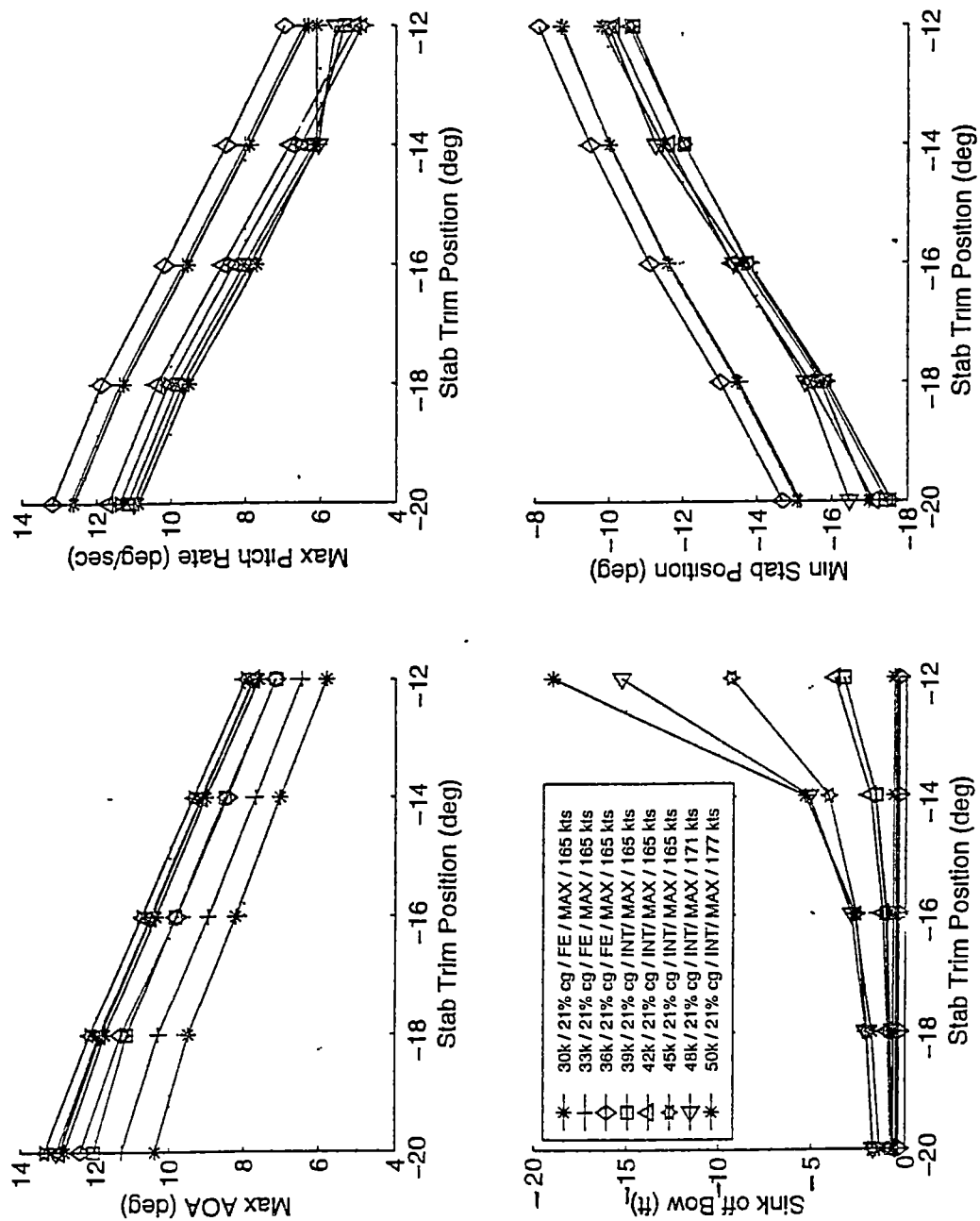


Figure A-11
GROSS WEIGHT SENSITIVITY STUDY

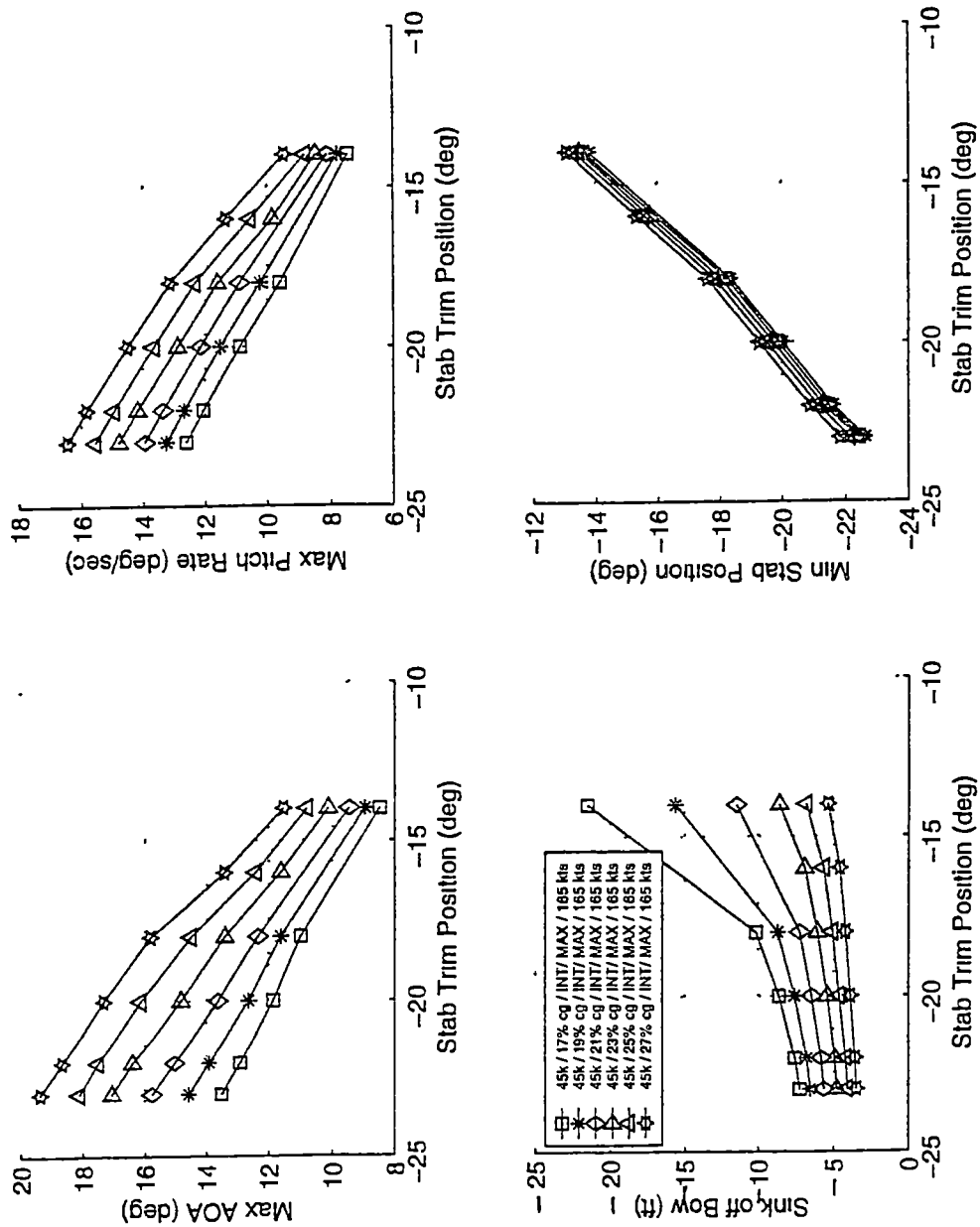


Figure A-12
CG SENSITIVITY STUDY

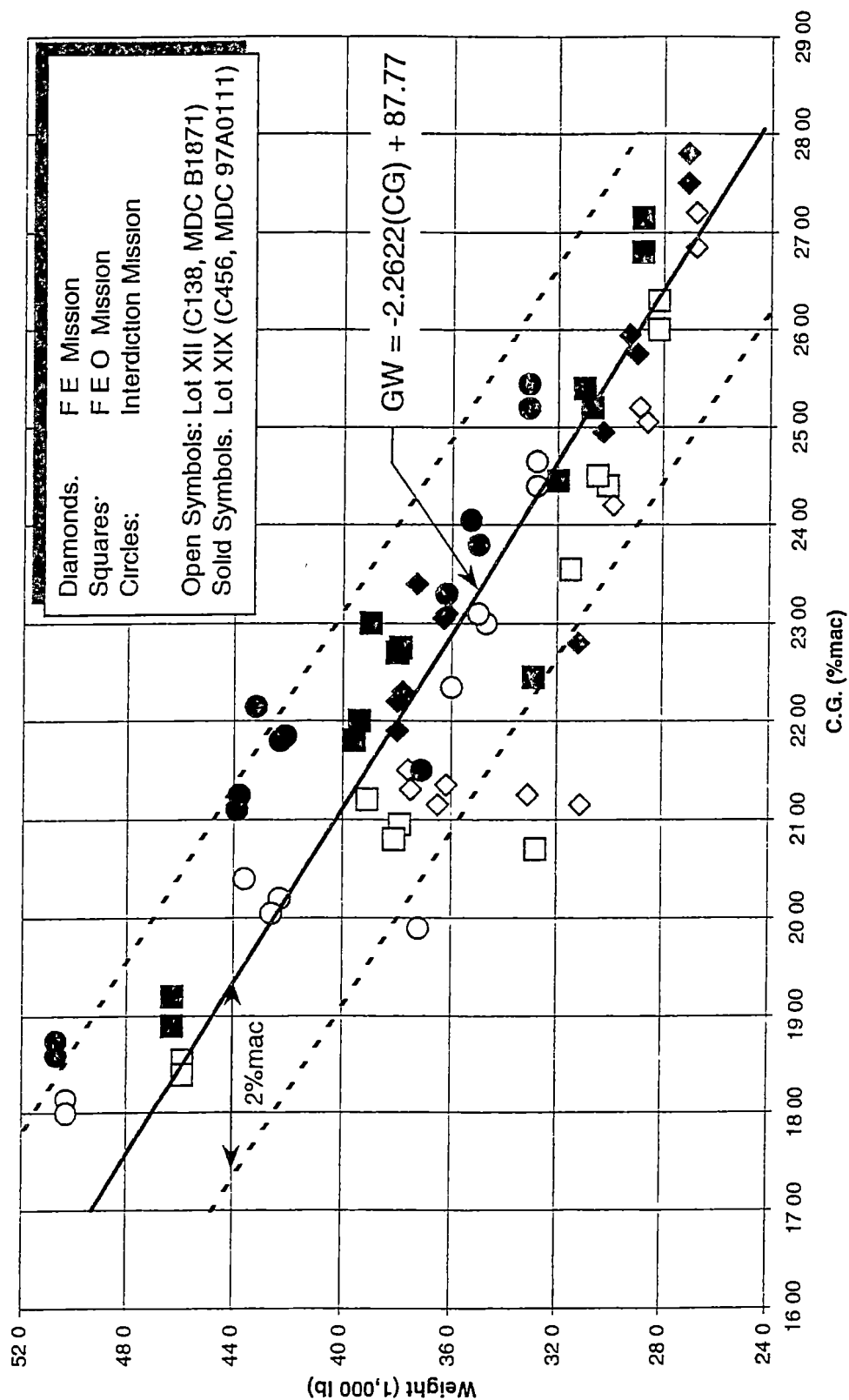


Figure A-13
CG TRAVEL WITH GROSS WEIGHT

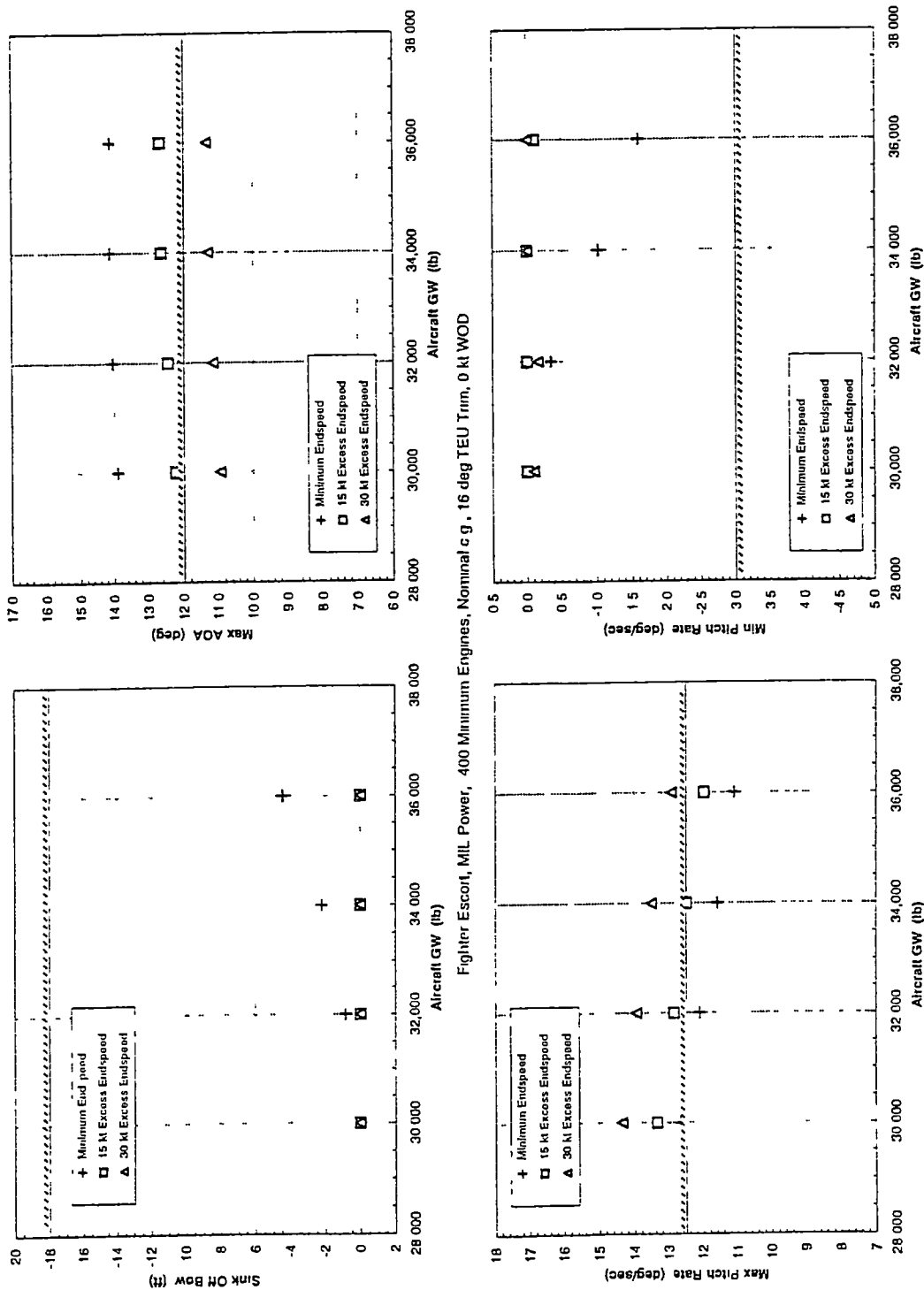


Figure A-14
LIGHT WEIGHT SIMULATOR RESULTS

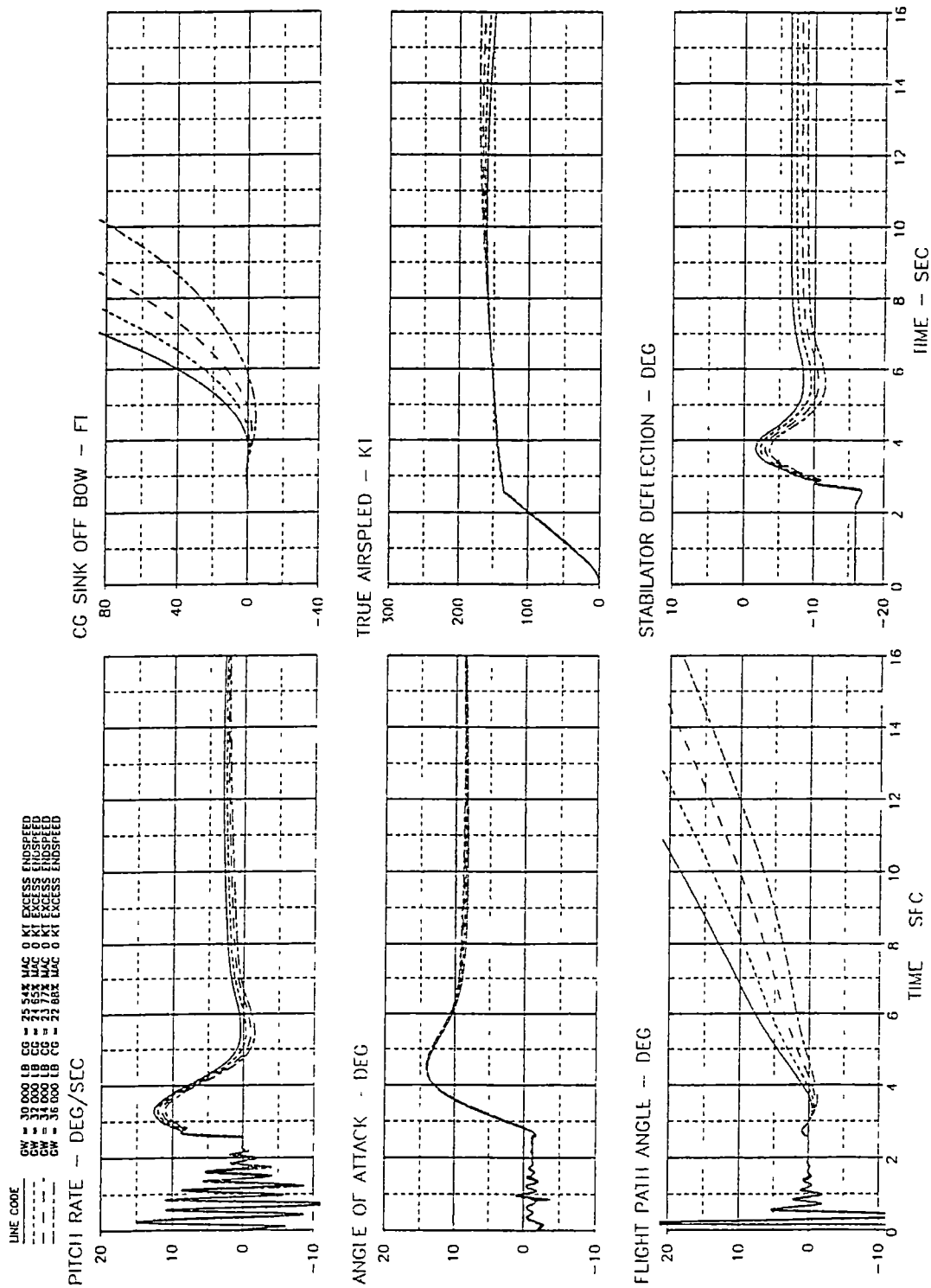


Figure A-15
 LIGHT WEIGHT AIRCRAFT TIME HISTORY

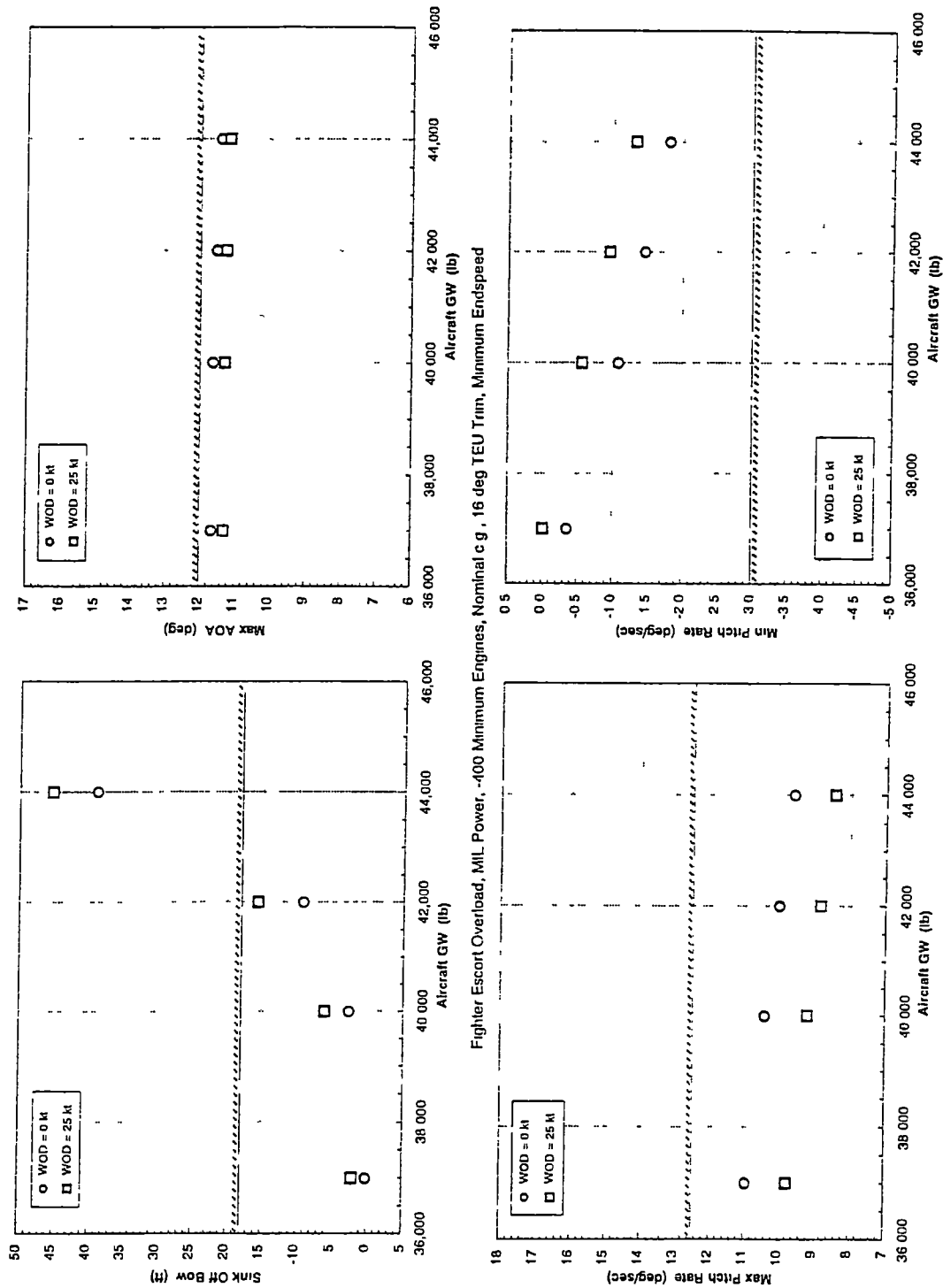


Figure A-16
MEDIUM WEIGHT SIMULATOR RESULTS

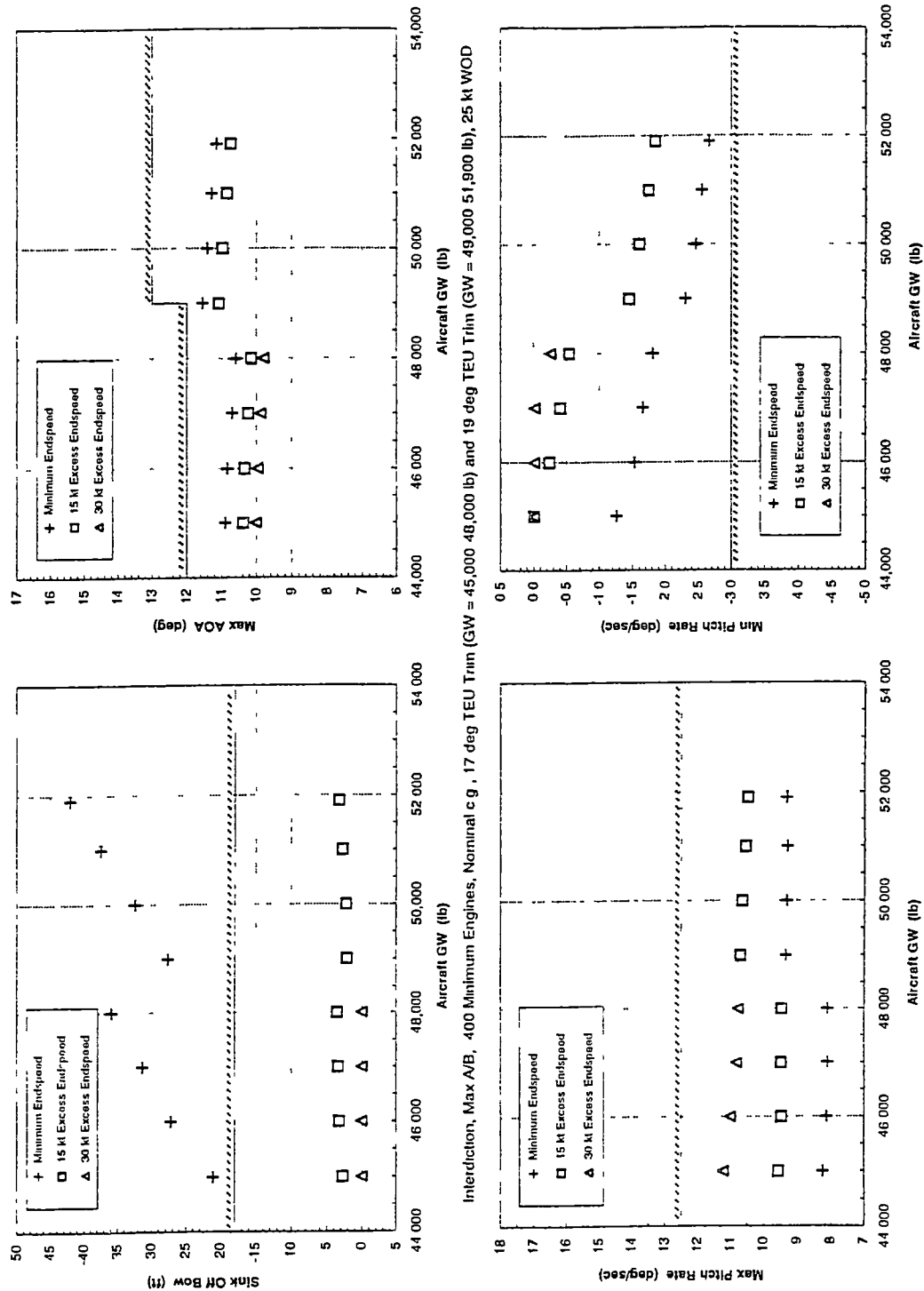


Figure A-17
HEAVY WEIGHT SIMULATOR RESULTS

F/A-18C Cat Shot | A/C #110 | CVN-75 (Truman) | 14 August 1998 | Event 3

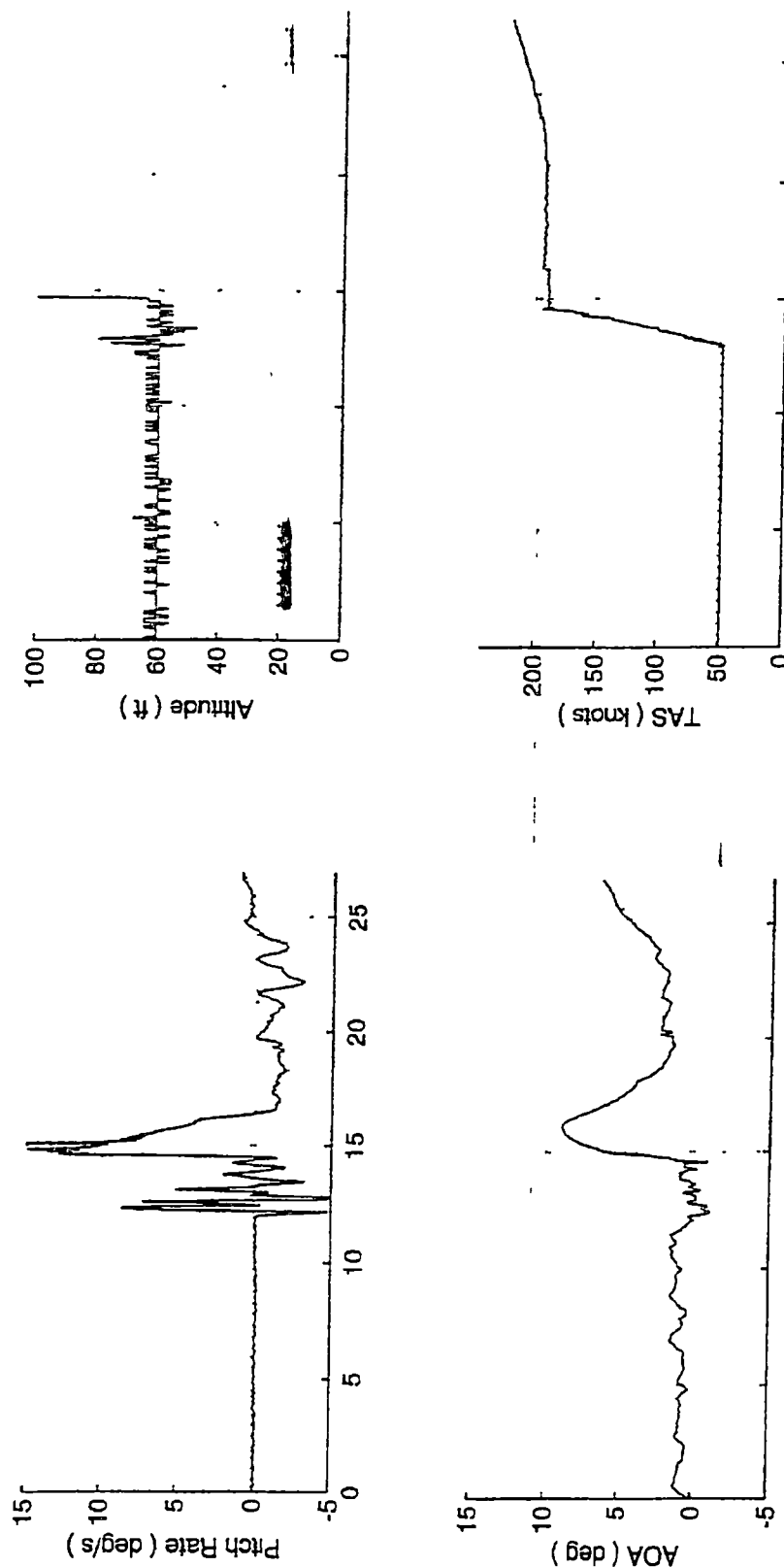


Figure A-18
HIGH EXCESS TIME HISTORY

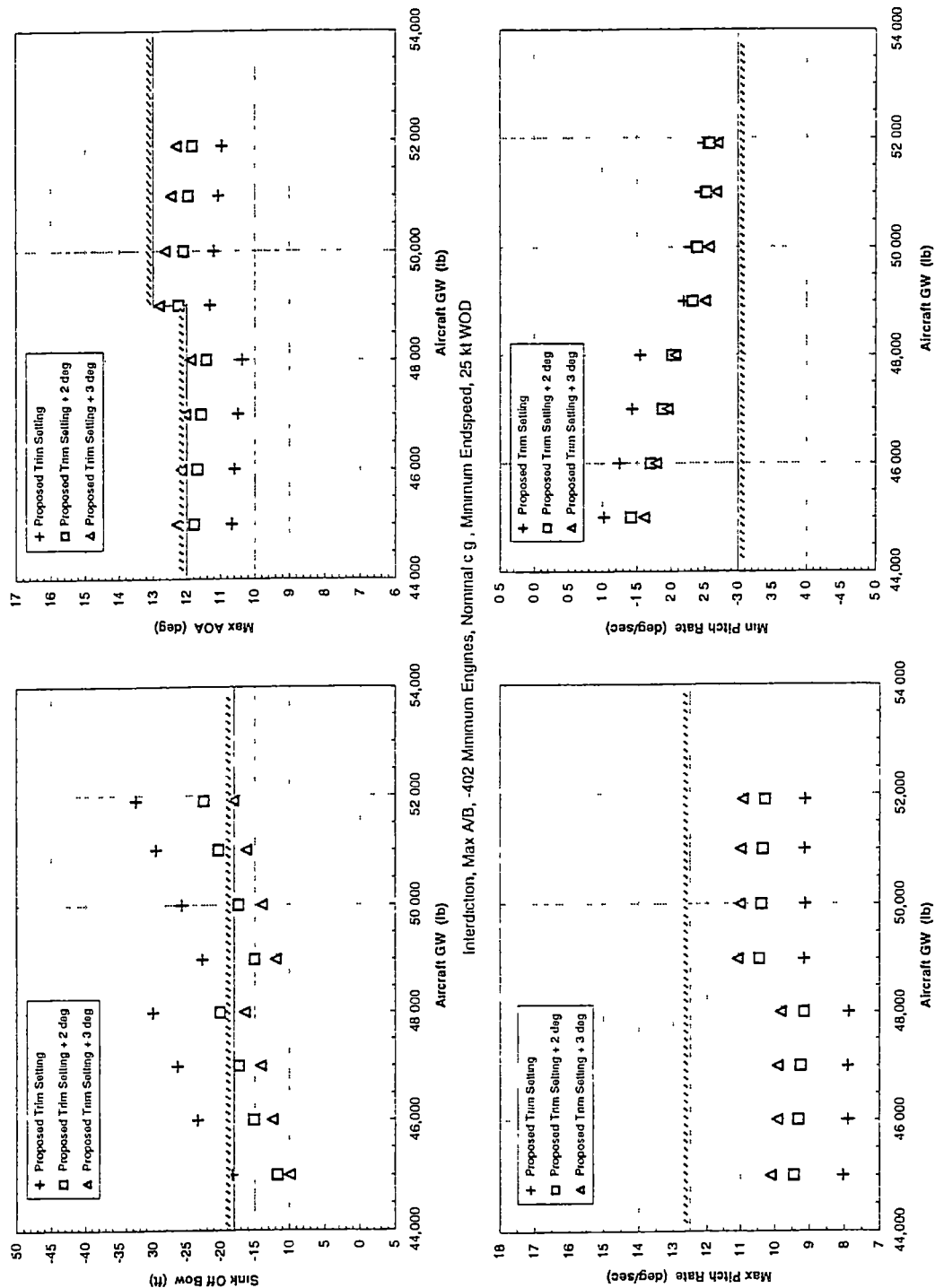


Figure A-19
HEAVY WEIGHT TRIM STUDY

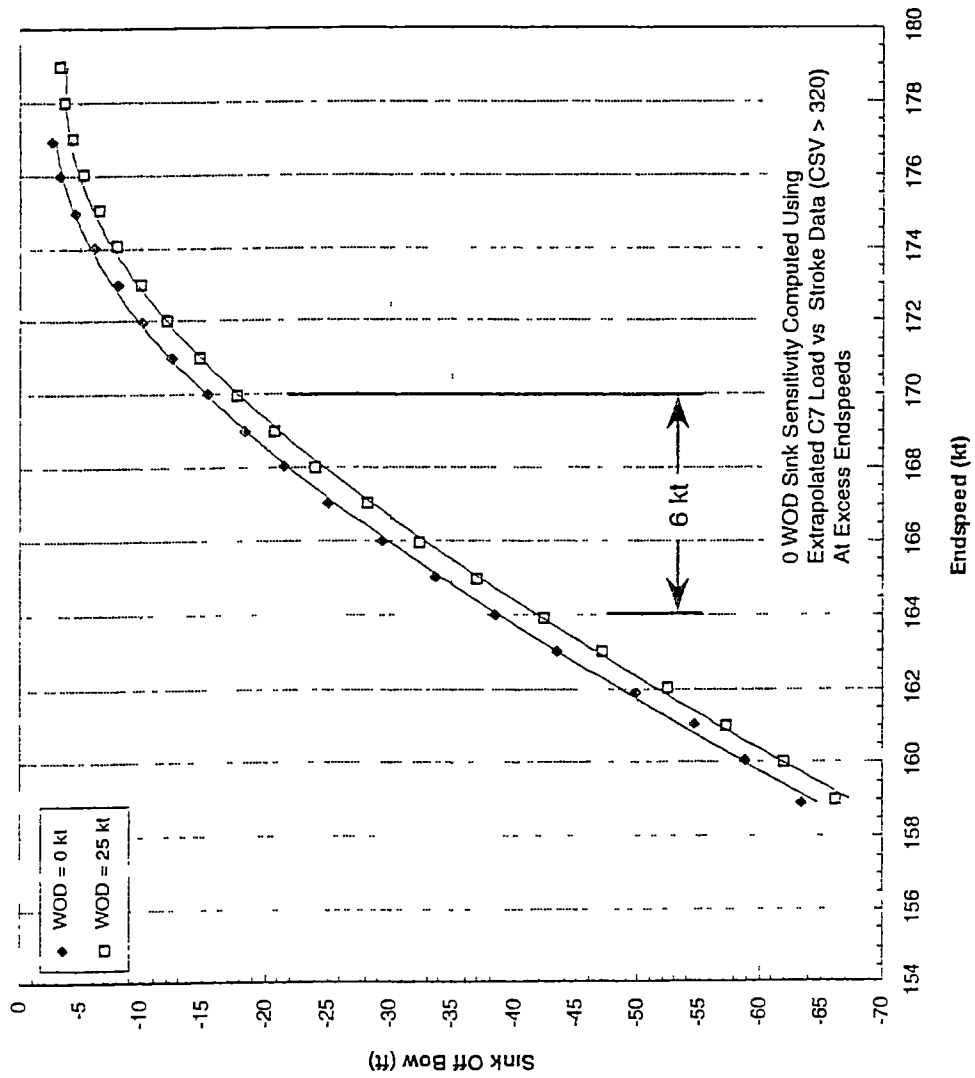


Figure A-20
REQUIRED ENDSPEED STUDY

APPENDIX B

TABLES

Table B-1
PROPULSION TEST MATRIX

Test Point	Left Engine	Right Engine	Test Engine Bleed	Ambient Temperature (deg F)	Ambient Pressure (in Hg)	Thrust lb _f
Test	OFF	OFF	NORM	36	30.28	-
1	GI	OFF	NORM	46	30.24	180
2	MIL	OFF	NORM	38	30.21	9800
3	MAX	OFF	OFF	38	30.21	NA
4	MAX	OFF	OFF	38	30.21	15400
5	MIL	OFF	NORM	37	30.21	10600
6	MIL	OFF	NORM	36	30.20	10100
7	94%	OFF	NORM	37	30.20	9500
8	88%	OFF	NORM	38	30.21	6150
9	82%	OFF	NORM	46	30.23	3400
10	76%	OFF	NORM	46	30.25	1680
11	73%	OFF	NORM	50	30.25	1070
12	64%	OFF	NORM	49	30.24	170
13	76%	OFF	NORM	50	30.23	1760
14	88%	OFF	NORM	38	30.21	6600
15	OFF	MIL	NORM	41	30.19	9550
16	OFF	MAX	NORM	41	30.19	14200
17	OFF	MAX	OFF	42	30.19	15070
18	OFF	MIL	OFF	40	30.20	10390
19	OFF	MIL	NORM	39	30.19	9900
20	OFF	94%	NORM	40	30.19	9300
21	OFF	88%	NORM	45	30.19	6150
22	OFF	82%	NORM	42	30.20	3460
23	OFF	76%	NORM	48	30.22	1660
24	OFF	73%	NORM	49	30.23	1100
25	OFF	64%	NORM	50	30.24	130
26	OFF	76%	NORM	46	30.21	1790
27	OFF	88%	NORM	41	30.17	6700
28	80%	80%	NORM	41	30.17	5550

Table B-2
DATA PARAMETERS LIST

Parameter	Safety	Data Critical	Parameter	Safety	Data Critical
Roll Att	X	X	Calibrated A/S	X	X
Pitch Att	X	X	Indicated A/S		
True Heading	X	X	Pressure Alt	X	X
Roll Rate		X	Radar Alt	X	X
Pitch Rate		X	OAT		X
Yaw Rate		X	Ambient Temp		X
INS Normal Accel			Total Temp		
INS Normal Accel			Static Press		
INS Long Accel			Total Press		
AOA	X	X	Mach Number		
AOSS	X	X	Bingo Fuel Qty		
Long Stick Posn	X	X	Fuel Tank 1 Qty		X
Lat Stick Posn	X	X	Fuel Tank 2 Qty		X
Rudd Pedal Force	X	X	Fuel Tank 3 Qty		X
L/R Aileron Posn	X	X	Fuel Tank 4 Qty		X
L/R TEF Posn	X	X	C Ext Fuel Qty		X
L/R In LEF Posn	X	X	L Ext Fuel Qty		X
L/R Out LEF Posn	X	X	R Ext Fuel Qty		X
L/R Rudd Posn	X	X	Fuel Qty Total		X
L/R Stab Posn	X	X	LW Fuel Qty		X
L/R N1		X	RW Fuel Qty		X
L/R N2		X	Gross Weight		X
L/R EG Temp		X	INS North Vel		
L/R CD Press		X	INS East Vel		
L/R TD Press		X	INS Vertical Vel		
L/R TD Temp		X	INS North Wind		
L/R Nozzle Posn		X	INS East Wind		
L/R Fuel Flow		X	INS Vertical Wind		
L/R PLA		X	Gear Down		
L/R Eng Inlet Temp		X	Nose Gear Down		
L/R Fuel Inlet Temp		X	R/L MLG Down		
L/R T1		X	Pitch Trim Integ		
Air Temp		X	Roll Trim Integ		
			Yaw String		X

VITA

David Woodbury was born in Ithaca, New York on November 12, 1965. At a young age he moved with his family to Missoula, Montana where he grew up and attended schools in the local public system. He was selected for the United States Naval Academy in Annapolis, Maryland and graduated with the class of 1988, earning a Bachelor of Science degree in aerospace engineering. After receiving his commission in the U.S. Navy, he attended flight school and was designated a Naval Aviator in March, 1990. After two years as a flight instructor in the A-4 Skyhawk, he received training in the F/A-18 Hornet and was transferred to Strike Fighter Squadron 195 based in Atsugi, Japan. He made two deployments to the Persian Gulf aboard USS Independence (CV-62), before being selected to the U.S. Navy Test Pilot School in Patuxent River, Maryland. Following test pilot training, he was assigned to the Naval Strike Aircraft Test Squadron where he served as project officer for numerous aircraft carrier suitability and weapon development test programs.

Lieutenant Commander Woodbury is currently flying with Strike Fighter Squadron 82 based in Beaufort, South Carolina. He recently returned from his third Persian Gulf deployment, this time aboard USS John F. Kennedy (CV-67). He has accumulated over 2700 flight hours in more than 25 different aircraft.