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Minimum control airspeed testing of the F/A-18 E/F airplane

Henry Melton III

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To the Graduate Council:

I am submitting herewith a thesis written by Henry Melton III entitled "Minimum control airspeed testing of the F/A-18 E/F airplane." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

R. B. Richards, Major Professor

We have read this thesis and recommend its acceptance:

Ralph D. Kimberlin, U. Peter Solies

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

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Interim Vice Provost and Dean of the
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MINIMUM CONTROL AIRSPEED TESTING OF THE F/A-18 E/F AIRPLANE

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

Henry Melton III
August 2001

DEDICATION

This thesis is dedicated to my family and friends for their encouragement and support that has allowed me to complete this research.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Mr. Bret Marks of the Boeing Company for his professionalism, engineering expertise and tireless efforts, which resulted in our successful completion of this flight test program. Together we were able to make this task an enlightening and enjoyable program.

ABSTRACT

The minimum control airspeed for an airplane has been classically defined based upon theory and methodology applicable to multi-engine, propeller-driven and low thrust-to-weight engine airplanes. This testing has traditionally been performed assuming aerodynamic characteristics remain constant throughout the test angle of attack (AOA) range, and controllability was primarily a function of dynamic pressure. For these airplanes, thrust level, thrust degradation and the interdependencies with the single engine minimum control airspeed were simple to flight test and analyze, as the results could be linearly extrapolated to a reference, sea level, standard day, condition. These extrapolations to reference conditions are critical to shipboard operations as these airspeeds are used as a basis to establish minimum catapult takeoff airspeeds during shipboard operations. Once established, safety margins over-and-above these airspeeds are applied to ensure controllability of the airplane is maintained in the event of a catastrophic engine failure during the critical catapult takeoff flight phase.

For the modern high thrust-to-weight fighter airplane, V_{mcA} is largely dependent on atmospheric conditions and the classical test techniques are no longer valid and are unsafe. During the F/A-18 E/F Engineering and Manufacturing Development (EMD) program, flight test results revealed additional V_{mcA} dependencies on AOA, and lateral weight asymmetry. As a result, the test techniques and analysis of the results were significantly more complex to analyze. This thesis discusses the methodology used to

establish and normalize the single engine minimum control airspeed flight test data for the F/A-18 E/F airplane, carrier environment, shipboard launching process, and the flight test demonstration requirements for airplanes which are catapult launched from ships. These discussions also include operational considerations, which must be made relative to operating in the shipboard environment.

PREFACE

The flight test results contained within this thesis were obtained during a United States Department of Defense sponsored Naval Air Systems Command project conducted by the Naval Air Warfare Center, Aircraft Division, Patuxent River, MD. The discussion of the data, conclusions and recommendations presented are the opinions of the author and should not be construed as an official position of the United States Department of Defense, the Naval Air Systems Command, or the Naval Air Warfare Center, Aircraft Division, Patuxent River, MD.

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GLOSSARY

A_x	Longitudinal Acceleration
A_z	Normal Acceleration
AGL	Above Ground Level
AOA	Angle-of-Attack
CG	Center of Gravity
EMD	Engineering and Manufacturing Development
FADEC	Full Authority Digital Electronic Control
FCS	Flight Control System
FE	Fighter Escort
ft^2	Square Feet
g	Gravitational Acceleration
H_p	Pressure Altitude
INT 3	Interdiction with (3) Three 480 Gallon Fuel Tanks
INT 3-15	INT 3 with 15,000 ft-lb lateral weight asymmetry
INT 3-22	INT 3 with 22,000 ft-lb lateral weight asymmetry
INT 3-30	INT 3 with 30,000 ft-lb lateral weight asymmetry
KCAS	Knots calibrated airspeed
KEAS	Knots equivalent airspeed
kft-lb	1,000 foot-pound
lb	Pound
LEX	Leading Edge Extension
LPQ	Limited Production Qualified

MAX A/B	Maximum Afterburner Thrust
MFHS	Manned Flight Hardware Simulator
MIL	Military Rated Thrust
NATOPS	Naval Air Training Operations Manual
PA	Power Approach
PFQ	Pre-flight Qualified
PLF	Power for Level Flight
ROC	Rate of Climb
SL	Sea Level
SOB	Sink off Bow
TEM	Transient Engine Model
VEN	Variable Exhaust Nozzle
V_{mcA}	Dynamic Minimum Control Airspeed
WOD	Wind Over Deck

CHAPTER I

INTRODUCTION

BACKGROUND

The F/A-18 A/B was designed in the late 1970s as a U.S. Navy, carrier based replacement for the F-4 Phantom II and A-7 Corsair II airplanes with multi-mission capability for the air-to-air fighter and air-to-ground strike missions. Throughout the 1980s the airplanes were upgraded with night vision compatible devices that included improvements in avionics and software and were designated as the F/A-18 C/D. By the late 1980s the F/A-18 C/D became gross weight limited, as the airplanes no longer had additional growth capability for future technological improvements.

Due to these limitations, the U.S. Navy pursued an evolutionary upgrade to the F/A-18 C/D, improving the range and endurance, payload capability, bring back capability, survivability, and allowance for future growth. This airplane was designated as the F/A-18 E/F.

As part of the overall F/A-18 E/F EMD program, the single engine minimum control airspeed (V_{mcA}) needed to be determined in order to develop the aircraft carrier launch bulletins for the airplane. It is in this high lift and thrust, transitioning flight phase where engine failure during takeoff can be catastrophic. More importantly the catapult launch bulletins incorporate a 15 knot airspeed margin above the established minimum safe airspeeds that guarantees controllability in the event of an engine failure.

Traditionally V_{mcA} testing has been performed using an assumption that the controllability of the airplane is predominately proportional to dynamic pressure. It was determined during testing with the F/A-18 E/F that the lateral-directional controllability in a single engine scenario may in some cases be more directly tied to AOA. Also, methodologies used to correct the flight test data to a sea level (SL) reference condition were based upon assumptions, that the dependency upon thrust and lateral-directional control power remained constant throughout the test envelope. Based upon these assumptions, linear extrapolations to SL conditions were made to the flight test data. While these data reduction methodologies accounted for variations of thrust, true airspeed and air density variations with altitude, they did not adequately account for the significant variations in thrust as a function of ambient temperature.

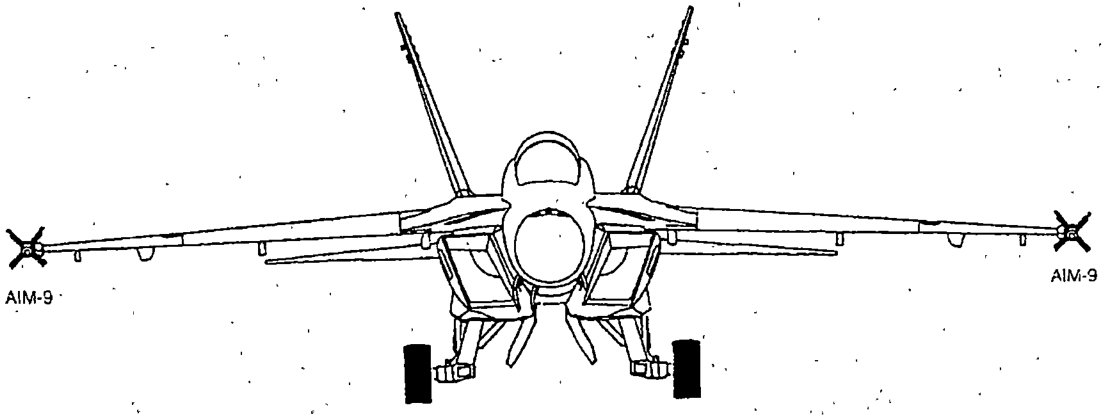
As a result, a new flight test technique and methodology for normalizing the flight demonstrated V_{mcA} data was used for the F/A-18 E/F. This approach employed a normal load factor of one, constant AOA technique that was considered representative of the airplane attitudes observed during carrier takeoff. The data reduction methodology used computer simulation to allow the flight test data, collected over a three year period, to be corrected to a reference SL, standard day condition. Correction of the flight test data was required since operational launches will be performed based upon these results.

SCOPE OF THESIS

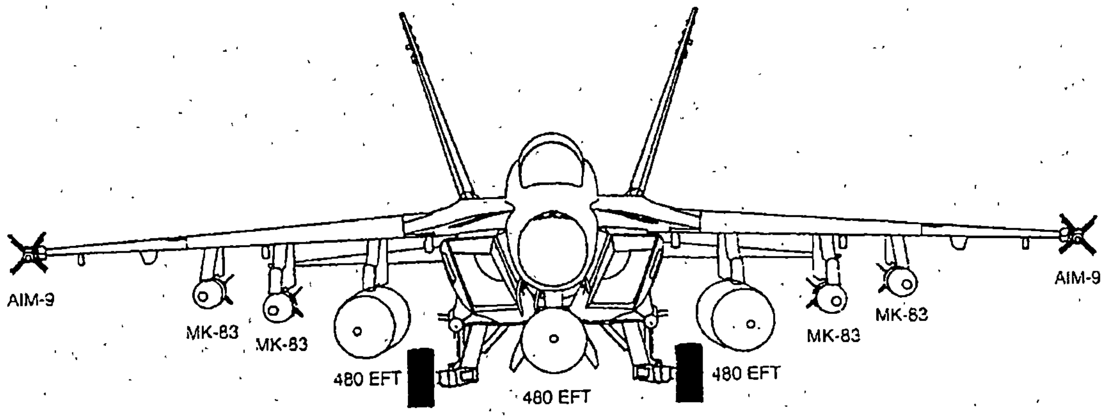
The EMD test airplanes E1, E3 and F1 were used throughout the flight test program to establish the V_{mcA} characteristics of the airplane. The term V_{mcA} used throughout this paper refers exclusively to the dynamic V_{mcA}. The V_{mcA} were determined for the full and half flap positions in both military (MIL) and maximum afterburner thrust (MAX A/B) power settings. The variation of V_{mcA} with both symmetrical and asymmetrically pylon mounted stores were also assessed. The tests were conducted from March 1996 through June 1999.

TEST LOADINGS

The flight demonstrated V_{mcA} were established for the symmetric and asymmetric store loadings and are presented in figures 1 and 2, respectively. These loadings were selected based upon wind tunnel data that were available for computer simulation and similarity to operational loadings that were used during shipboard testing. The symmetric loadings were defined as Fighter Escort (FE), and Interdiction with three 480-gallon external fuel tanks (INT3). The asymmetric loadings were a baseline from the interdiction loading with 15,000, 22,000 and 30,000 ft-lb of lateral weight asymmetry. These loadings were designated INT3-15, INT3-22 and INT3-30, respectively.



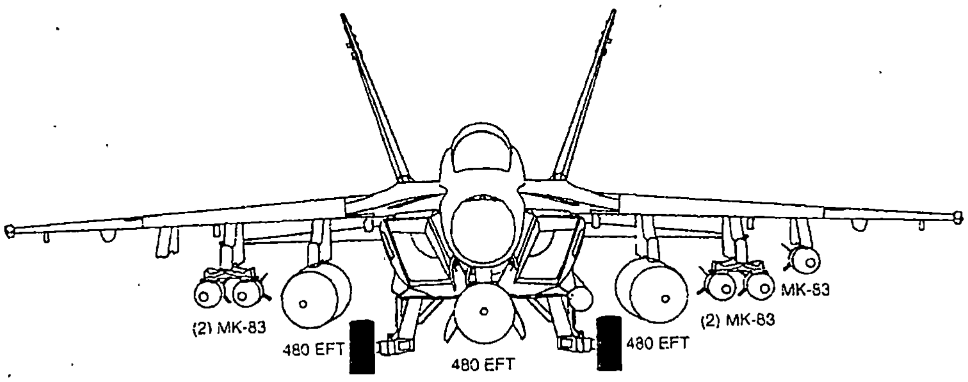
Clean Loading



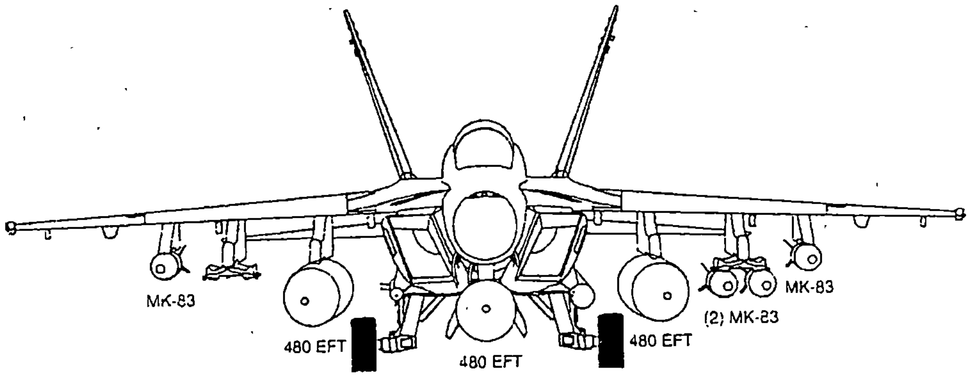
Symmetric Interdiction Loading

Figure 1. F/A-18 E/F Symmetric Test Loadings

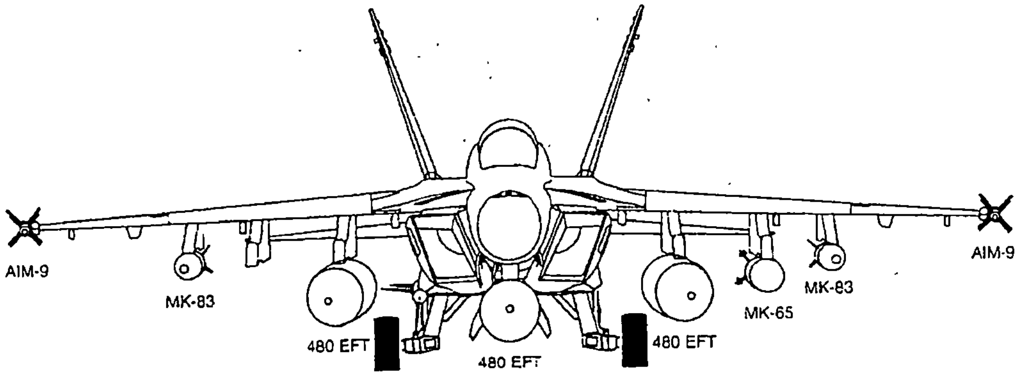
Source: Manned Flight Hardware Simulator Report, F/A-18 E/F-341C-6976, The Boeing Company, 1999.



15,000 ft-lb Asymmetry



22,000 ft-lb Asymmetry



30,000 ft-lb Asymmetry

Figure 2. F/A-18 E/F Asymmetric Test Loadings

Source: Manned Flight Hardware Simulator Report, F/A-18 E/F-341C-6976, The Boeing Company, 1999.

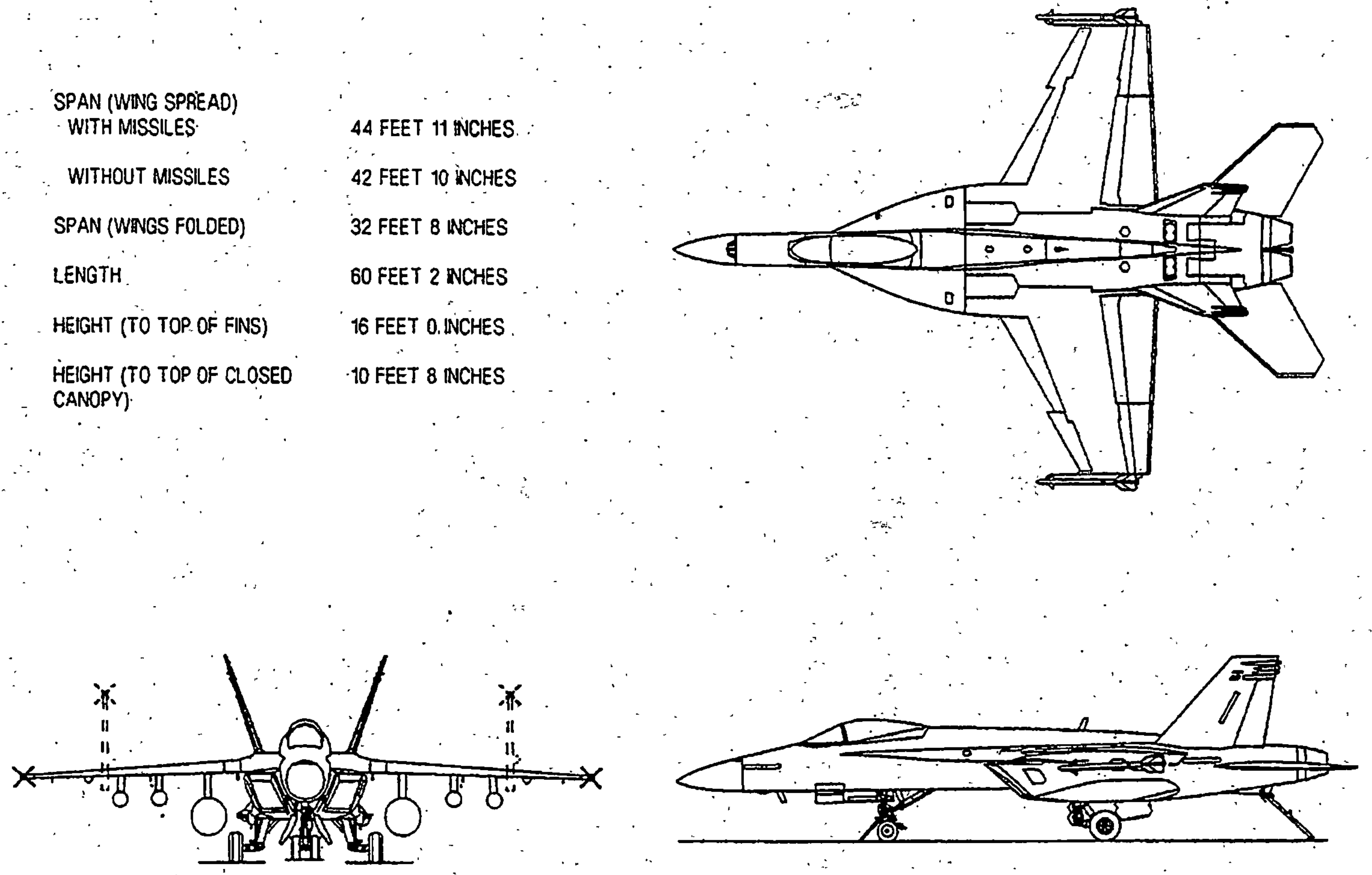
CHAPTER II

DESCRIPTION OF F/A-18 E/F AIRPLANE

GENERAL[1]

The F/A-18 E is a single seat fighter/attack airplane built by The Boeing Company along with the two-place, tandem-seat F/A-18 F shown in figure 3. The airplane features a variable camber mid-wing with leading edge extensions (LEX) mounted on each side of the fuselage. The wing area is approximately 500 ft^2 with the LEX area approximately 75 ft^2. The wings incorporate hydraulically actuated, full-span leading edge maneuvering flaps, trailing edge flaps, drooped ailerons and LEX vents. The airplane incorporate twin vertical stabilizers, hydraulically actuated that are canted outboard 20 degrees from the vertical of the airplane. Also, the airplane incorporates hydraulically actuated stabilators that can be positioned differentially allowing for increased roll rates. Spoilers are also mounted on the top of each LEX vent. The airplane wing span is approximately 45 feet and incorporates eight wing weapon stations for a total of eleven airplane weapon stations.

The F/A-18 E/F is powered by two General Electric F414-GE-400 turbofan engines, which each produce approximately 22,000 lb. of thrust in afterburner at uninstalled, static, sea level, standard day conditions. A Full Authority Digital Engine Control (FADEC) unit that is mounted on each engine case maintains engine control via



SPAN (WING SPREAD) WITH MISSILES	44 FEET 11 INCHES
WITHOUT MISSILES	42 FEET 10 INCHES
SPAN (WINGS FOLDED)	32 FEET 8 INCHES
LENGTH	60 FEET 2 INCHES
HEIGHT (TO TOP OF FINS)	16 FEET 0 INCHES
HEIGHT (TO TOP OF CLOSED CANOPY)	10 FEET 8 INCHES

Figure 3. F/A-18 E/F Three View Drawing
Source: U.S. Navy, F/A-18 E/F Preliminary Naval Air Training and Operations (NATOPS) Manual, 1 March 1999

throttle commands that are electrically transmitted from the throttles in the cockpit. The engines employ low bypass, two spool turbofans with afterburners and Variable Exhaust Nozzle (VEN) geometry.

FLIGHT CONTROL SYSTEM[2]

The F/A-18 E/F was designed with relaxed static stability and is controlled by a four channel digital, fly-by-wire Flight Control System (FCS) through hydraulically actuated, irreversible flight control surfaces. The flight control surfaces are ailerons, twin rudders, leading edge flaps, trailing edge flaps, LEX vents, LEX spoilers and differential spoilers. The leading edges of the wing incorporate a snag to increase outboard wing area and increase roll authority in the approach and landing configuration.

Longitudinal control of the airplane is obtained primarily through use of stabilators but rudder toe-in or flare and LEX spoilers are used for longitudinal control in several different flight configurations and conditions. The longitudinal control augmentation system uses a blend of air-data-scheduled pitch rate, normal acceleration, and AOA feedback. Proportional pitch rate, proportional AOA, and proportional and integral normal acceleration feedback improve aircraft stability and flight path control, and are most effective in the high dynamic pressure flight regimes.

The lateral control system uses roll rate feedback that is scheduled with dynamic pressure to provide increased roll damping at low-to-mid dynamic pressure. The roll control surfaces include ailerons, stabilators, and leading and trailing edge flaps.

The directional control system uses yaw rate feedback for increased directional damping and lateral acceleration feedback for increased directional stability. In the power approach (PA) configuration, a beta dot (rate of change of sideslip) estimator is used to increase the directional damping and stability. A rolling surface-to-rudder (aileron and differential stabilator) interconnect, scheduled with AOA is used for roll coordination.

CHAPTER III

CARRIER LAUNCH ENVIRONMENT

An aircraft carrier is a unique operating environment for an airplane where catapult takeoffs are performed by accelerating the airplane from rest to a flyaway airspeed in approximately 300 feet[3]. Solely, the catapult can be used to attain the required launch airspeed, if within the catapult capacity and airplane structural limitations (tow load and longitudinal acceleration). Alternately, the required launch airspeed can be attained through a combination of catapult performance and wind, measured over the flight deck of the carrier. This wind measurement is called wind over deck (WOD), and is required for takeoff if the required launch airspeed is greater than the available catapult capacity. A typical catapult launch envelope for a carrier airplane is presented in figure 4.

As illustrated in the diagram, the wind over deck shown to perform a maximum gross weight takeoff is the difference between the launch airspeed and available catapult performance. The catapult launch envelope is bounded by the required launch airspeed, limit catapult capacity and airplane structural limitations, and is presented as the shaded region of the diagram.

As depicted in figure 5, the F/A-18 is a nose gear launch airplane. As the catapult is fired, the airplane is accelerated to flyway airspeed by towing the airplane by the

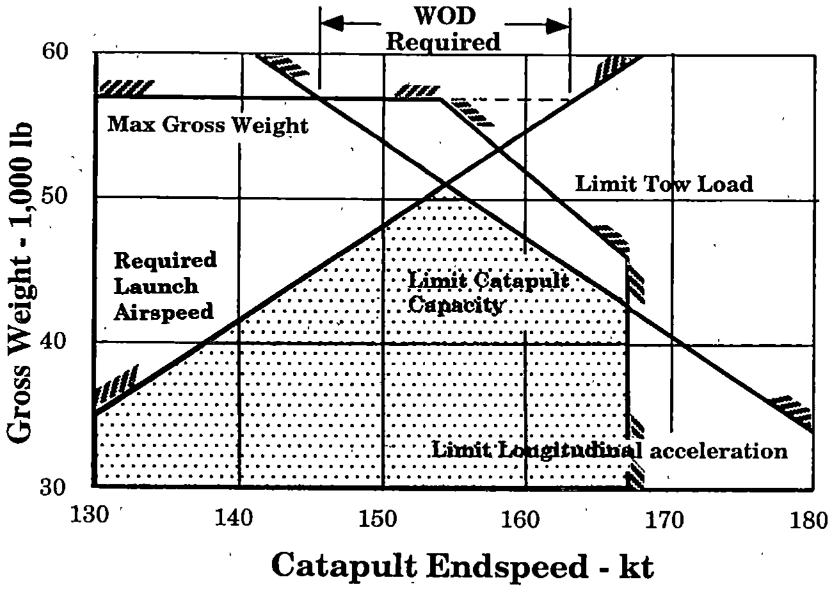


Figure 4. Typical Airplane Catapult Launch Envelope

Source: Naval Air Warfare Center – Aircraft Division, SA-FTM-01, *Carrier Suitability Testing Manual*, Revision 2, 30 September 1994.

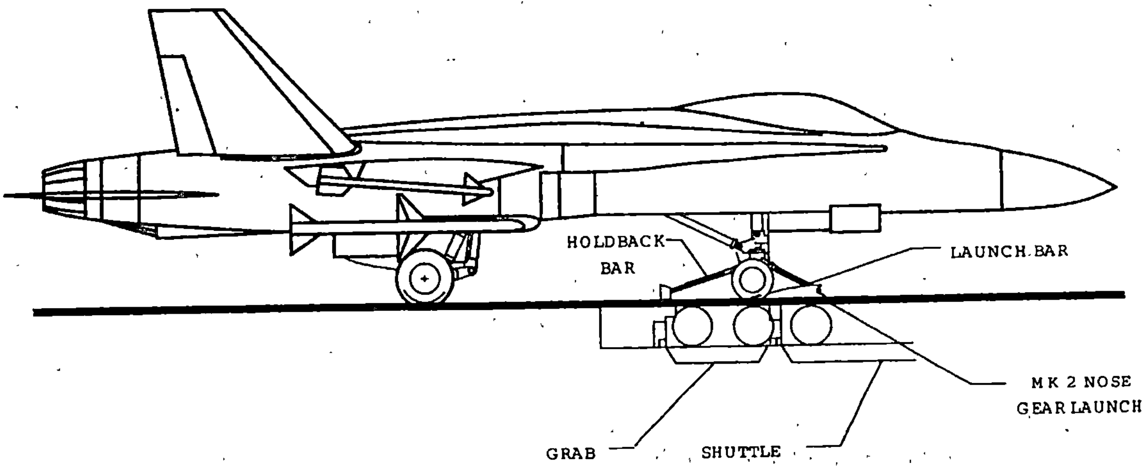


Figure 5. F/A-18 E/F Nose Tow Launch Assembly

Source: Zirkel, J., Nace, K. and Ziem, C., *Aircraft Carrier Reference Data Manual*, Revision D, Naval Air Warfare Center Aircraft Division, Lakehurst, New Jersey, 1 November 1997.

launch bar that is attached to the nose wheel strut. The tow load limit was established during the preliminary design of the airplane and is a function of the airplane takeoff gross weight and A_x. The launch A_x is directly proportional to the catapult endspeed required for takeoff.

Due to these characteristics, establishing the minimum catapult launch end airspeed as low as possible has considerable operational significance and advantages[4]. These advantages are:

1) Minimizing the required wind over deck for takeoff, which increases the operational flexibility of the aircraft carrier and airplane by lowering the ship steaming speeds necessary for launching.
2) Decreasing the catapult loads imparted on the airplane, which increases the fatigue life of the airframe.
3) Decreasing the catapulting energy requirement, which reduces the aircraft carriers fuel and water usage.

The minimum takeoff airspeeds for an airplane are determined based upon the following six criteria; high AOA flying qualities, proximity to or warning of impending stall, minimum level flight acceleration, airplane altitude loss measured at the center of gravity of the airplane when launched from the bow of the ship (sink off the bow), V_{mcA} and automatic flight control sensitivities[3]. In considering the criteria, the intent was to establish the lowest end airspeed that the airplane could be safely launched from the carrier. The minimum end airspeed is the lowest airspeed that satisfies all of these criteria. For the F/A-18 E/F, the V_{mcA} and sink off the bow established the minimum end airspeeds for the airplane. At light to medium gross weights, where the sink off the bow airspeeds were low due to the high lift wing, V_{mcA} limited the launch airspeeds. At the heavier takeoff gross weights, above V_{mcA}, sink off the bow established the takeoff airspeeds.

Since the airplane sink off the bow airspeeds are established during shipboard testing, the V_{mcA} had to be established prior to these tests to ensure controllability of the airplane in the event of an engine failure during takeoff. In the event of an engine failure, airspeed margin above the minimum allows the pilot to safely execute emergency procedures, and eject from the airplane, if necessary.

CHAPTER IV

MINIMUM CONTROL AIRSPEED (V_{mcA})

GENERAL

The V_{mcA} is the slowest airspeed below which, following sudden engine failure, recovery controls could not contain angle of bank (AOB) below 20 degrees and/or angle of sideslip (AOSS) below 10 degrees[5]. Also, V_{mcA} was reached if the pilot determined that the roll and/or yaw rates were of such magnitude that recovery to controlled flight would not be possible. Recovery controls were applied two seconds after initiation of the thrust asymmetry as specified by the airplane specification[5].

MANEUVER DEVELOPMENT

Prior to flight test, the Boeing Manned Flight Hardware Simulator (MFHS) was used to develop a test technique that quantified the V_{mcA} interdependencies with AOA and lateral weight asymmetry. The goal of the simulator evaluation was to develop a technique that not only quantified the results, but also was accurate, repeatable and operationally representative of the attitudes and AOA's observed during carrier takeoff.

The technique that was developed was based upon the "classical" technique, and a revised flight test technique referred to in this paper as technique A, that was developed during the F/A-18 A/B and F-18 C/D flight test programs.

"CLASSIC" TECHNIQUE

The "classic" V_{mcA} test technique assumes that the lateral-directional control of the airplane is dependent upon dynamic pressure and the aerodynamic characteristics of the airplane do not vary within the test AOA range[6]. For most "classic" airplanes, single engine flight does not reach the large pitch attitudes and AOA's due to the low thrust-to-weight ratios in these configurations. Using this test technique, the thrust asymmetry was established by the pilot by performing a "throttle chop" on the "critical" engine. A "throttle chop" is performed by advancing both throttles symmetrically to MIL or MAX A/B power, as specified by the test condition, followed by a rapid retard of a single throttle to flight idle, at the target airspeed. This maneuver is performed from a stabilized, high power, symmetric thrust condition. The critical engine was defined as the throttle chopped engine that resulted in the highest V_{mcA}. Once initiated, airspeed was maintained with pitch attitude adjustments and lateral-directional recovery controls were applied following a lapse of two seconds. This time period lapse was intended to simulate the pilot's engine failure recognition and response time as specified by the detail specification for the airplane.

Attempting to establish the low airspeed, high power setting condition in the F/A-18 A/B and F/A-18 C/D resulted in the airplane being in an unusually high pitch attitudes and AOA's. During this testing, pitch attitudes and AOA's upward of 20 degrees were obtained[7]. This condition was unsafe and was not mission relatable to the catapult takeoff environment, since the range of AOA during catapult takeoff is from zero to fifteen degrees. The stall warning in the F/A-18 A/B/C/D and F/A-18 E/F is initiated at 15 degrees AOA and 14 degrees AOA, respectively[8,1].

TECHNIQUE A

Due to the high pitch attitudes and AOA's observed while using the "classic" test technique a modified technique was developed during testing with the F/A-18 A/B. This test maneuver was initiated from a 20 degree AOA and power for level flight (PLF) condition that was below the target throttle chop airspeed. Once established, the throttles were symmetrically advanced to MIL or MAX A/B as required by the test condition, while the pitch attitude was lowered to 14 degrees AOA. For this testing, a pitch attitude of 14 degrees was chosen as this was the upper bound of the F/A-18 A/B NATOPS 'Aircraft Settling Off Catapult' emergency procedure. As the airplane accelerated, the throttle chop was performed at selected airspeeds, and repeated with build down until V_{mcA} was identified. These tests were repeated with throttle chops on both engines.

Performing this maneuver in the F/A-18 A/B and F/A-18 C/D yielded a low AOA (8 to 10 degrees), low induced drag recovery with high flight path accelerations that were representative of a failed engine scenario during an approach or waveoff. Approach AOA is significantly lower than the range of peak AOA typically observed during catapult takeoff and flyaway. For the F/A-18 series, the approach AOA is 8.1 degrees and performing single engine, maximum power waveoff results in a rapid, 2 to 4 knot per second increase in airspeed. During this testing, the flight path acceleration was so rapid that the airplane typically recovered from the throttle chop, prior to the pilot applying recovery controls. Also, no 'critical' engine was identifiable using this technique.

Testing with this technique was initially repeated on the F/A-18 E/F and also produced low AOA recoveries. Also, the test technique was not instinctive for the pilot to fly and the maneuver was not representative of an actual catapult launch trajectory since the pilot was pushing forward on the control stick to capture pitch attitude, while reducing AOA. In executing technique A, the timing of the pitch capture, the throttle chop, and the application of recovery controls were critical since flight path accelerations were even greater than what had been previously observed during testing on the F/A-18 A/B and F/A-18 C/D. This produced a maneuver that was very difficult for the pilot to fly and resulted in a significant amount of data scatter.

A time history depicting the technique A, V_{mcA} flight maneuver is provided in figure 6. As illustrated, during the two seconds between the throttle chop and the initiation of recovery controls, AOA was significantly reduced. As AOA was reduced the airplane rapidly accelerated, which was not representative of a catapult launch trajectory where AOA (and drag) is increasing following main wheel lift-off. The end result was that this technique produces an artificially low V_{mcA} that masks the airplanes true dependency on AOA and lateral weight asymmetry.

TECHNIQUE B

A new flight technique was required that was safe, accurate and repeatable. Also,

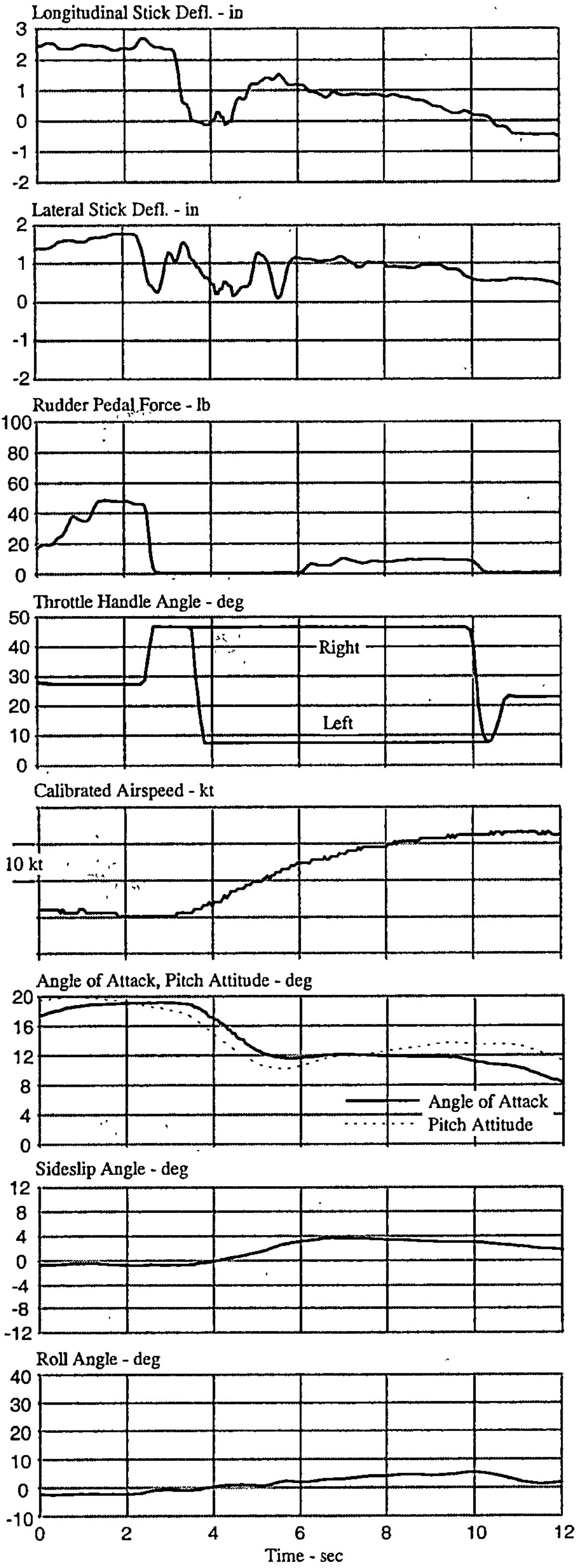


Figure 6. V_{mcA} Time History (Technique A)

it was important to develop a technique where the attitudes were representative of the actual takeoff trajectory. This new technique, referred to as "technique B", was a normal load factor of one, constant AOA technique with an initial condition of both engines at power for level flight. This technique allowed AOA to be maintained throughout the maneuver with entry airspeed being controlled by varying gross weight. Thrust asymmetry was established by performing a throttle "split" versus throttle chop from power for level flight. This approach was easier for the pilot to initiate and was deemed acceptable as the FADEC controlled F414-GE-400 engines exhibit rapid transient response characteristics. Figure 7 depicts thrust response to representative left and rights throttle motions as calculated by the Boeing transient engine model (TEM). As figure 7 illustrates, the transient response characteristics of the F414-GE-400 engines are such that the throttle split used with technique B results in higher asymmetry levels than technique A during the first two seconds following the throttle split.

Performing this maneuver was simpler for the pilot to fly than technique A in that AOA and airspeed were either constant or nearly constant. The only variable during the maneuver was the time delay, where 2 seconds was used as the simulated pilot reaction time between the throttle split and the application of recovery controls. This length of time was critical as roll and yaw rates were building through this period and recovery controls had to arrest these rates before a stable flight condition could be reacquired.

Several sessions in the Boeing MFHS were required to not only develop and refine technique B, but to establish predicted V_{mcA} variations with external store loading

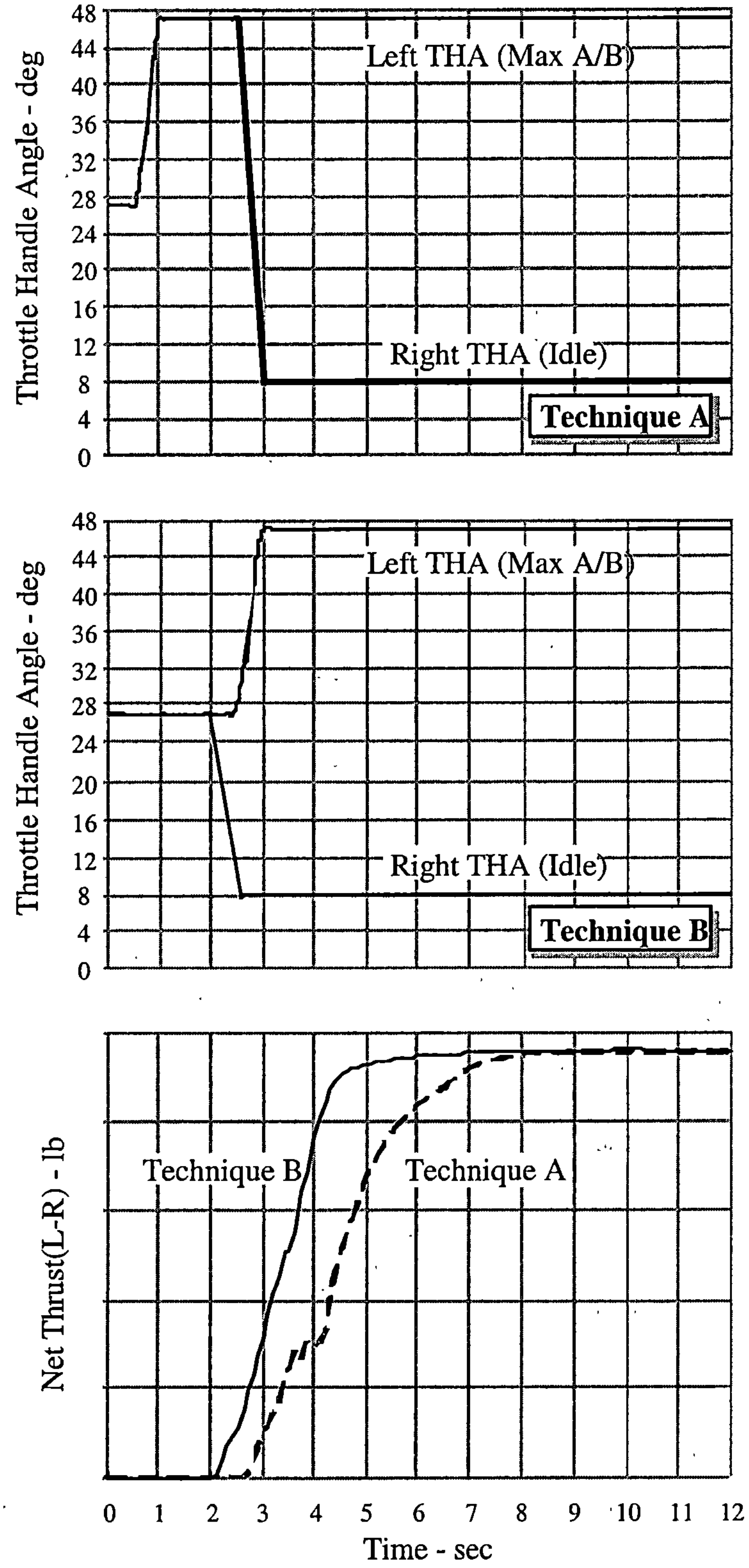


Figure 7. Simulated Engine Thrust Response to Throttle Split

and lateral weight asymmetry. The resulting technique is described as follows:

1) With the airplane configured to the appropriate test configuration, stabilize in wings level, steady heading flight at the specified initial conditions:

  a) On-speed AOA (8.1 degrees, full chevron illuminated on AOA indexer).

  b) Landing gear extended, full or half flaps.

  c) Test altitude plus 500 to 1,000 ft pressure altitude (H_p).

  d) Longitudinal and lateral trim as required.

2) Slowly decelerate to target AOA (and airspeed), dual engine thrust required for slow rate of descent (~500 to 1,000 ft/min).

3) While maintaining wings level, steady heading flight and passing through target altitude, perform "throttle split". The "throttle split" is performed by first reducing power on the critical engine to flight idle (simulated engine failure), immediately followed by increasing power on the opposite engine to the thrust level defined in the test matrix, either MIL or MAX A/B.

4) Maintain initial AOA within 0.5° and with neutral directional controls. Lateral inputs required to maintain a wings level condition are permitted.

5) Apply recovery controls (rudder to oppose yaw, lateral stick to arrest roll rate) after 2 seconds has elapsed (simulated pilot reaction time) or one of the following factors has

been reached:

a) 20° AOB change

b) 10° AOSS change

c) Pilot concern of yaw / roll rates

d) Full rudder deflection does not result in reversal in yaw acceleration

6) Re-acquire steady heading flight using up to 5° AOB into the operating engine.

Dynamic V_{mcA} was defined as the airspeed (actual throttle split airspeed) below which recovery controls could not contain AOB, AOSS or yaw / roll rates within the limits defined in Step 5.

RECOVERY MANEUVER

Forward stick was the primary control input for performing a safe recovery from test points below V_{mcA}. Breaking AOA had an immediate and positive effect on controllability, typically requiring less than a 5 degree AOA change. Matching the throttles at a medium range position was the final step in completing the recovery. In no case did altitude lost during recovery exceed 500 ft.

Technique B proved to be a reliable test technique that revealed the airplanes true lateral/directional control dependency on AOA and lateral weight asymmetry. Flight test time histories depicting technique B are provided in figure 8.

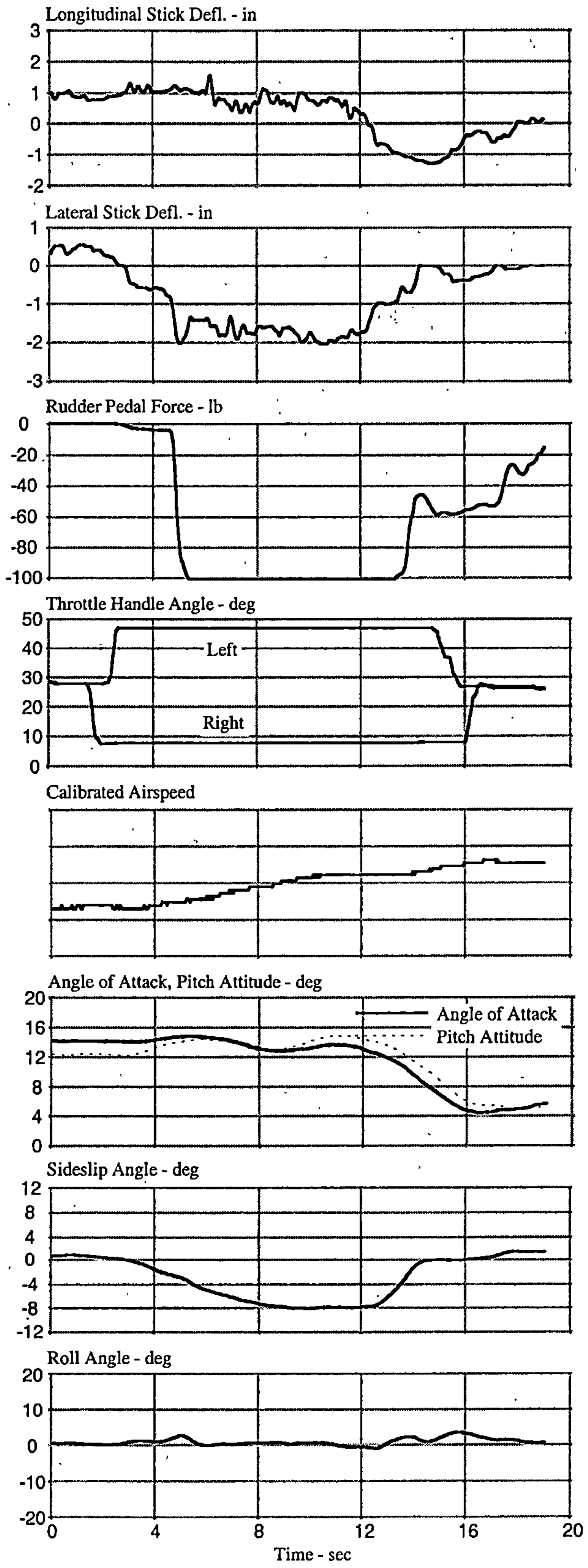


Figure 8. V_{mcA} Time History (Technique B)

CHAPTER V

FLIGHT TEST METHODOLOGY

Based upon results from the MFHS a test technique and flight test demonstration plan was developed that allowed the V_{mcA} interdependencies to be quantified. The MFHS was also used to practice and perfect the test technique and to establish a high level of confidence in the ability to recover from an inadvertent departure. Based upon these results a departure recovery technique and minimum safe altitude for testing were established at 2,000 ft AGL. To perform this testing as efficiently as possible, initial V_{mcA} maneuvers were flown at pressure altitudes of 5,000 and 10,000 ft to validate the lateral-directional characteristics, which were predicted in the simulator. After verifying these results, all testing was conducted at a pressure altitude of 2,000 ft. The demonstration matrix was defined to establish MAX A/B and MIL power V_{mcA} in both the full and half flap configurations at 15, 14, 12 and 10 deg AOA. Lateral weight asymmetries to 30,000 ft-lb were also evaluated.

Figure 9 illustrates the approach used for this test. In this example, more than one store loading was required to evaluate the gross weight range necessary to cover the desired airspeed range. Testing was initiated at 15 degrees AOA at the heaviest weight achievable for a given test store loading. If the V_{mcA} success criteria were satisfied, the maneuver was repeated. As fuel was used and the airplane became lighter, the stabilized airspeed in wings level flight at a given AOA was reduced. Consequently, the maneuver

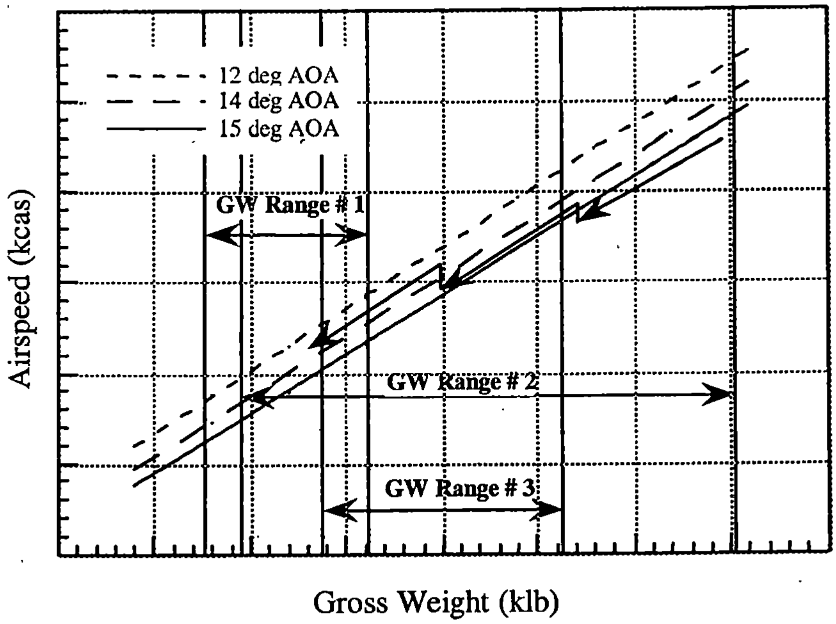


Figure 9. Typical V_{mcA} Test Approach, Constant AOA, Trim Airspeed

was repeated at successively lighter weights and lower airspeeds until V_{mcA} was established. Once V_{mcA} was established for a particular AOA, the test AOA was reduced to the next lowest value in the test matrix and the process was repeated. An inherent shortfall in using this test approach is that the test airspeed range for a particular AOA is dependent upon the airplane gross weight, which require testing to be performed in several test loadings.

CHAPTER VI

DATA REDUCTION AND CORRECTION METHODOLOGY

Since V_{mcA} data were collected over a broad range of ambient conditions, the ability to correct the flight test data to a reference condition was required. To accomplish this task, high fidelity computer simulation models were used to quantify V_{mcA} sensitivities with AOA, pressure altitude (H_p), temperature and lateral weight asymmetry. Once established, adjustments to the flight test data allowed the results to be corrected to a SL, standard day condition. To perform this computer analysis, the following databases and models were used.

AERODYNAMIC DATABASE

The F/A-18 E/F aerodynamic database was developed based upon results from the wind tunnel and the flight test programs. The wind tunnel database was developed using a 15% scale model where the wing outer moldline and high lift geometry design tolerances were held to tolerances of +/- 0.001 inches. Testing was conducted in the wind tunnels at up to 45% of the full scale Reynolds number.

THRUST MODELING

In addition to a significant dependency on pressure, the thrust produced by the FADEC controlled F414-GE-400 engines is strongly dependent on ambient temperature, as illustrated in figure 10. To quantify these results a Boeing transient engine model

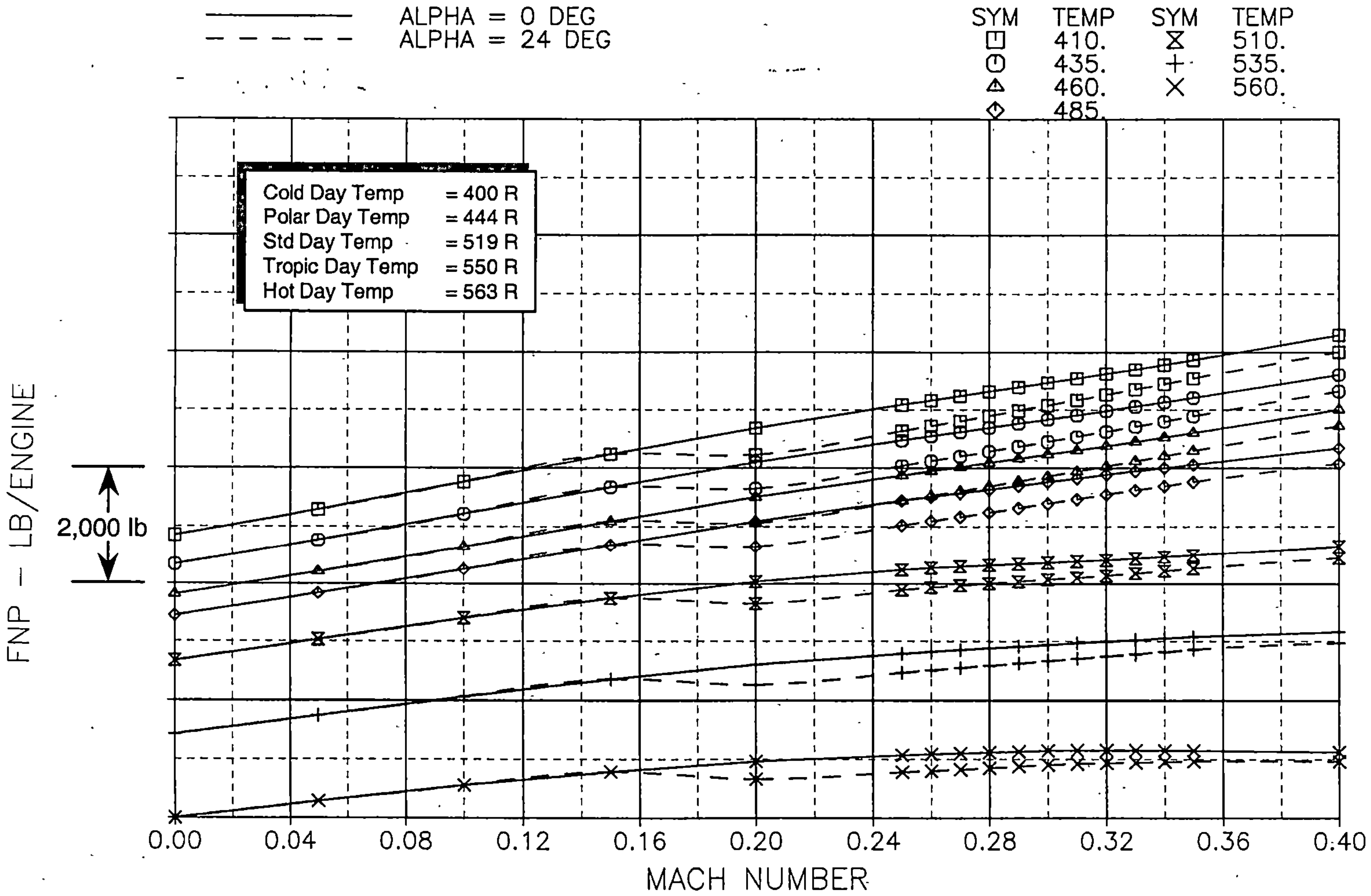


Figure 10. F414-GE-400 Static Thrust Variation With Ambient Temperature

(TEM) was used to duplicate the rapid thrust response to large throttle split inputs that were command by the pilot while performing the flight maneuver. The TEM was a simplified second order computer model that duplicated results from engine cell and ground testing with the airplane. The thrust levels used for the development of these models were based upon pre-flight qualified (PFQ) new engine performance and limited production qualified (LPQ) 1,000 hour engine performance. Since testing was performed on several test assets (airplanes and engines) over a range of engine hours, the sensitivity to engine deterioration was assessed. Based upon results from the computer simulation the V_{mcA} sensitivity to engine deterioration was negligible.

FLIGHT CONTROL SYSTEM (FCS)

A six degree of freedom model was used to duplicate the airplane control surface response to pilot control inputs and aircraft motion. The FCS response was verified by duplicating actual flight test maneuvers as presented in figure 11. As depicted, the predicted airplane trajectories for both the PFQ and LPQ engine models match the actual flight test maneuver. Based upon these results, the FCS response for use as an analysis tool was accurate.

PILOT MODEL

To perform V_{mcA} sensitivity and trend analysis, a pilot model was developed to perform precise, repeatable computer simulation of the flight test maneuver at the various flight conditions. To establish the pilot model, an AOA of 14 degrees was selected as the

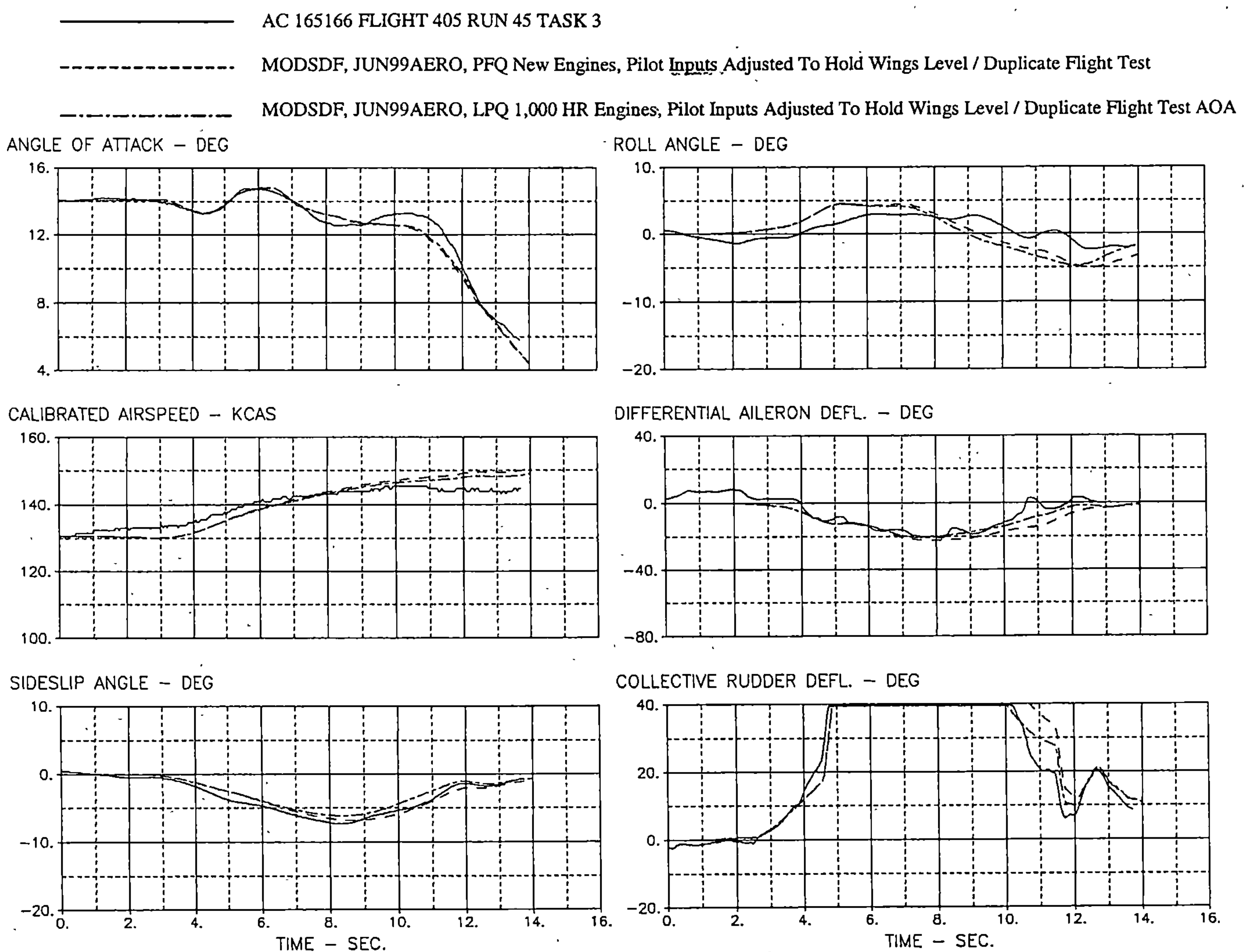


Figure 11. Predicted vs. Flight Demonstrated V_{mcA} Characteristics (1 of 4)

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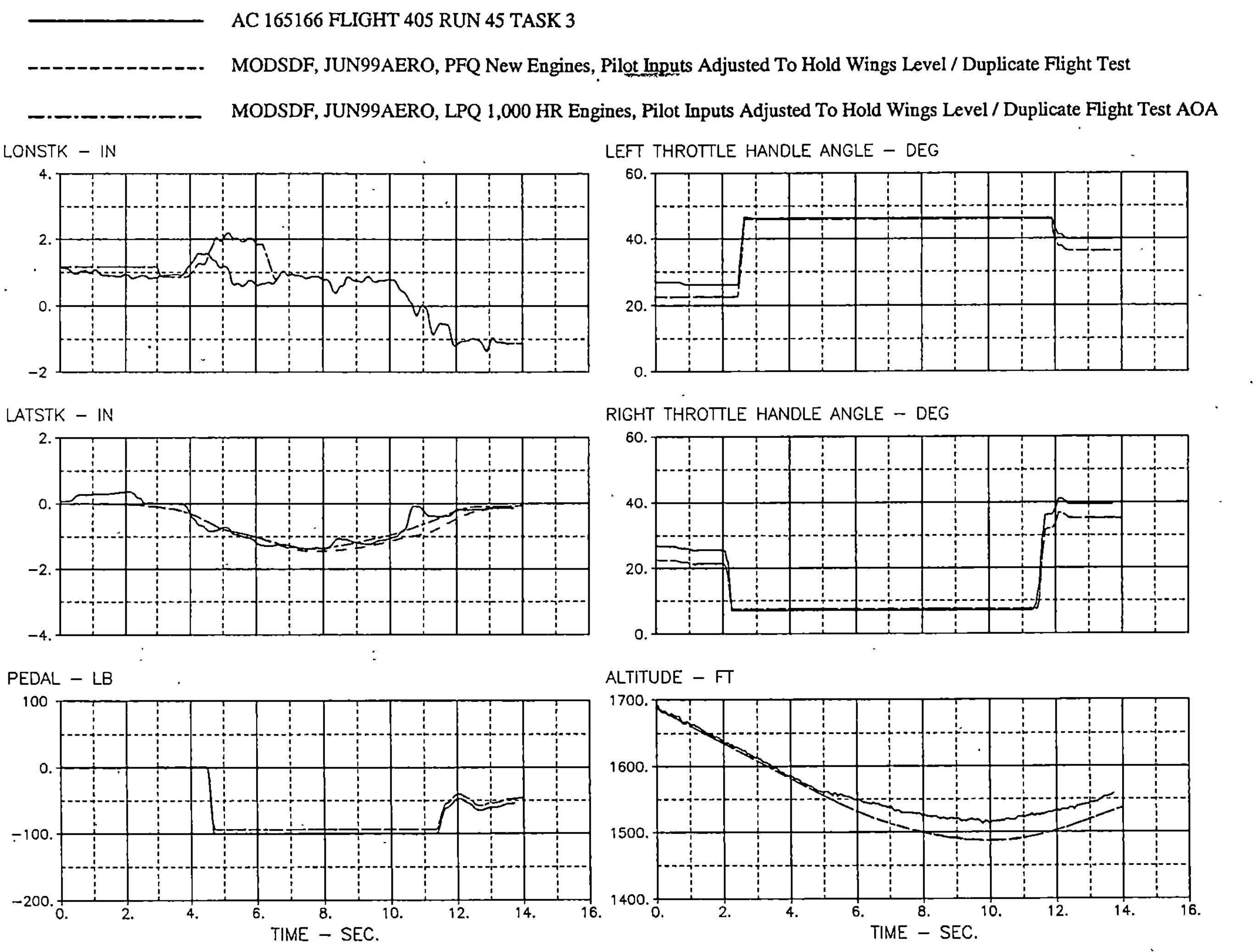

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Figure 11 (continued). Predicted vs. Flight Demonstrated V_{mcA} Characteristics (2 of 4)

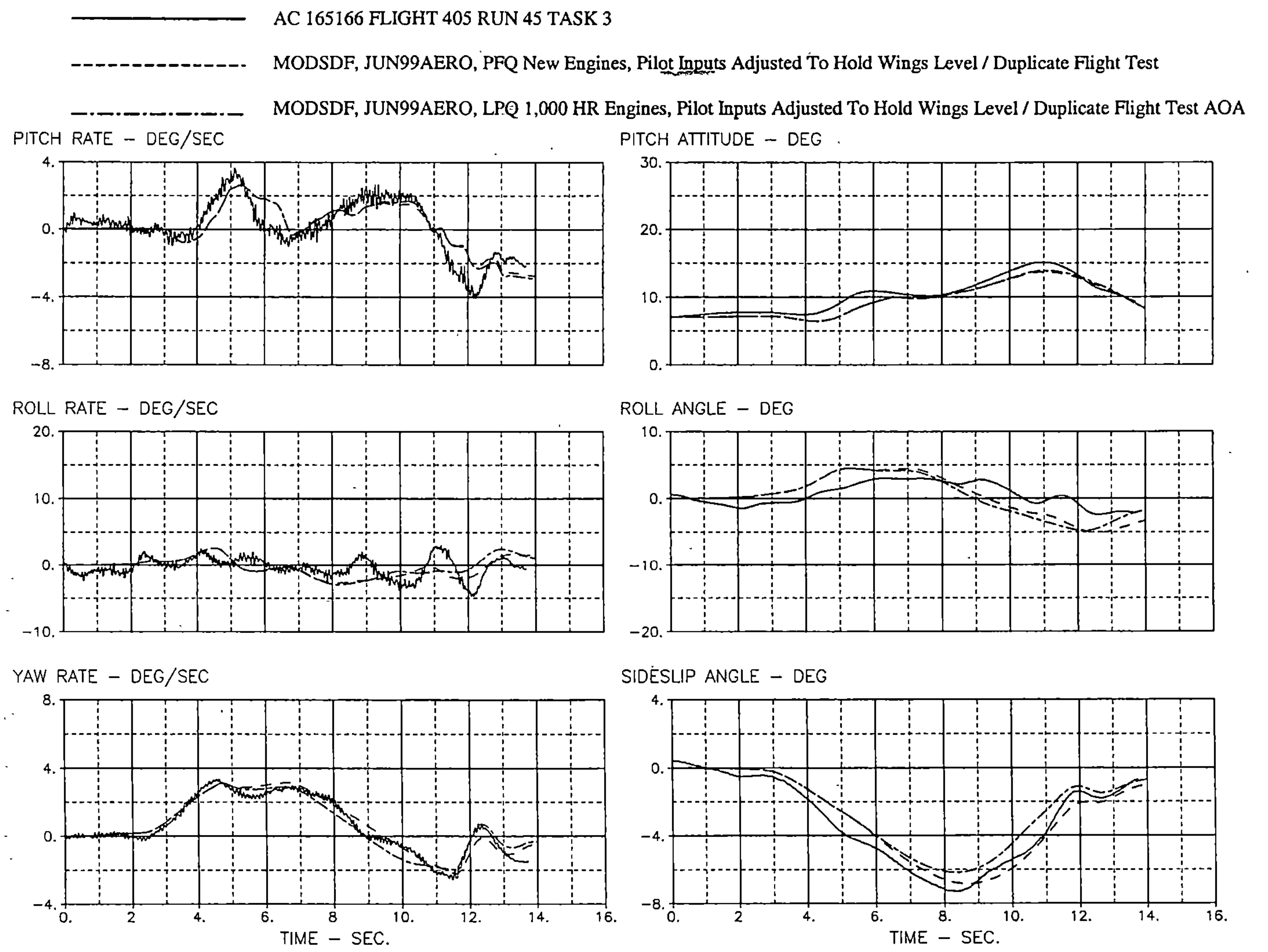

Figure 11 (continued). Predicted vs. Flight Demonstrated V_{mcA} Characteristics (3 of 4)

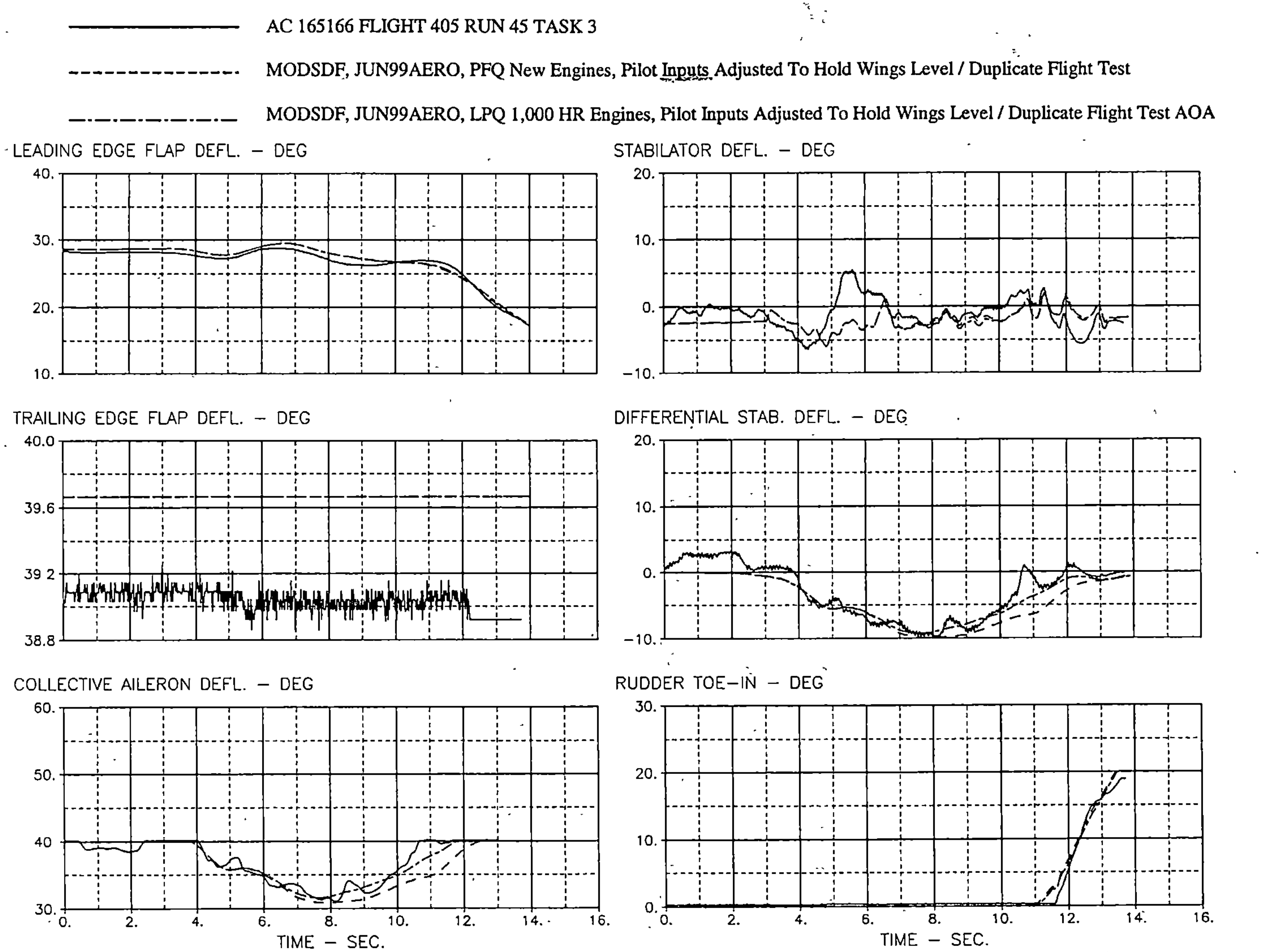

Figure 11 (continued). Predicted vs. Flight Demonstrated V_{mcA} Characteristics (4 of 4)

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initial reference AOA for analysis since this was the condition for stall warning in the takeoff and power approach configurations. Once the maneuver was initiated, longitudinal stick displacements were input as required to maintain the AOA within ± 0.5 degrees. Figure 12 presents the V_{mcA} pilot model that was used to perform the analysis. Once established, the maneuver was repeated for variations in atmospheric pressure and temperature, AOA and lateral weight asymmetry. For symmetrically loaded configurations, the simulation was performed and it was verified that neither engine was the critical engine. However, for asymmetrically loaded configurations, the simulation was performed and it was found that the critical engine was on the wing-heavy side of the airplane. The critical engine was on the wing-heavy side of the airplane due to the additional aileron deflection required to balance the lateral weight asymmetry.

As illustrated in figure 12 of the pilot model, the computer simulation model replicated the flight test maneuver by performing the initial throttle split and applying full directional recovery controls following a time delay of two seconds. This time delay was used to account for the delays in recognizing and reacting to a sudden engine failure. As demonstrated in-flight, lateral stick inputs were allowed to maintain wings level flight with no more than 5 degrees of AOB into the operating engine. To simulate a worst case scenario for the analysis, lateral stick inputs were initiated following a time delay of two seconds while attempting to capture 5 degrees of AOB into the operating engine. The magnitudes of the lateral stick inputs were allowed to vary to counter the initial roll rates of the airplane.

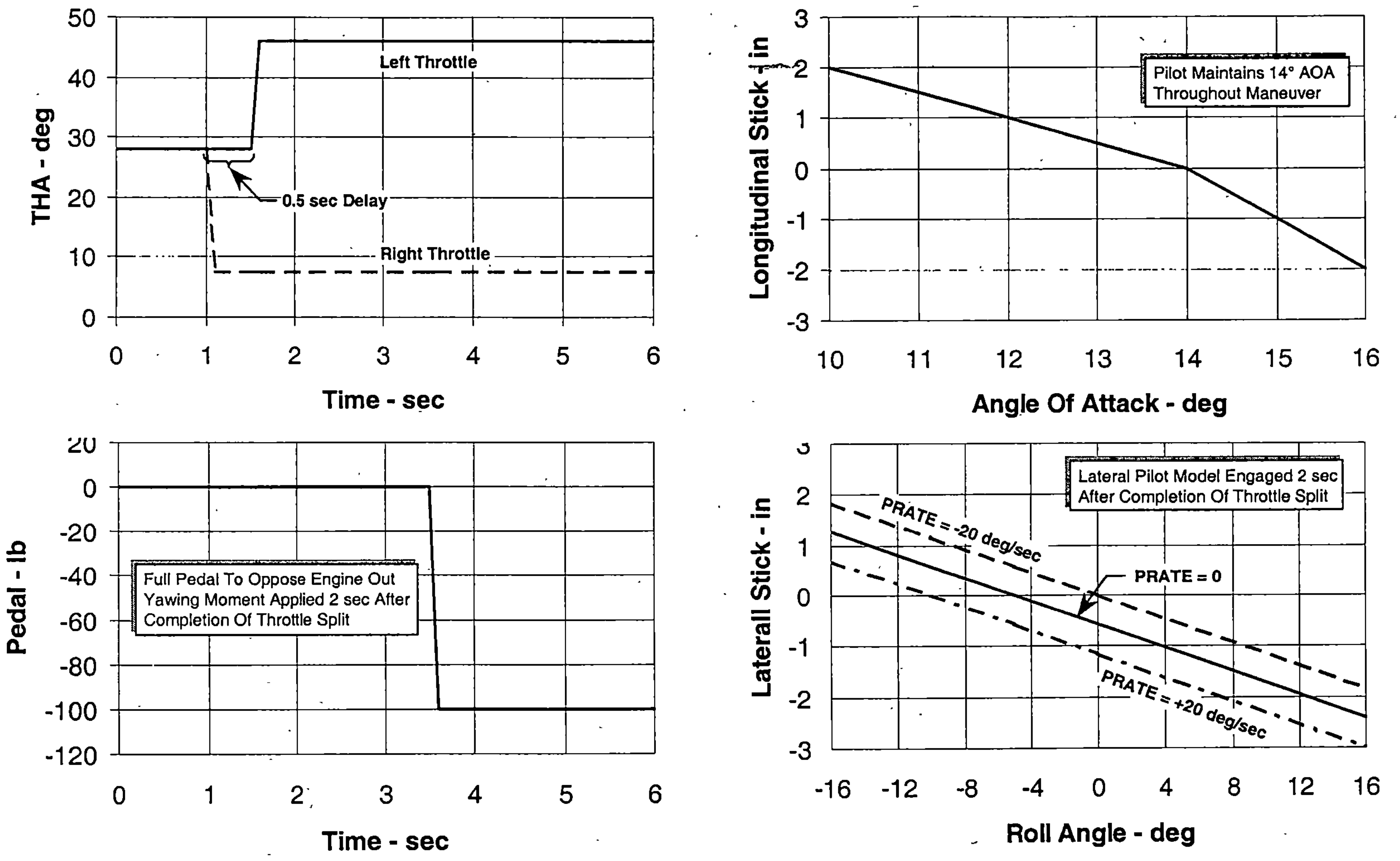
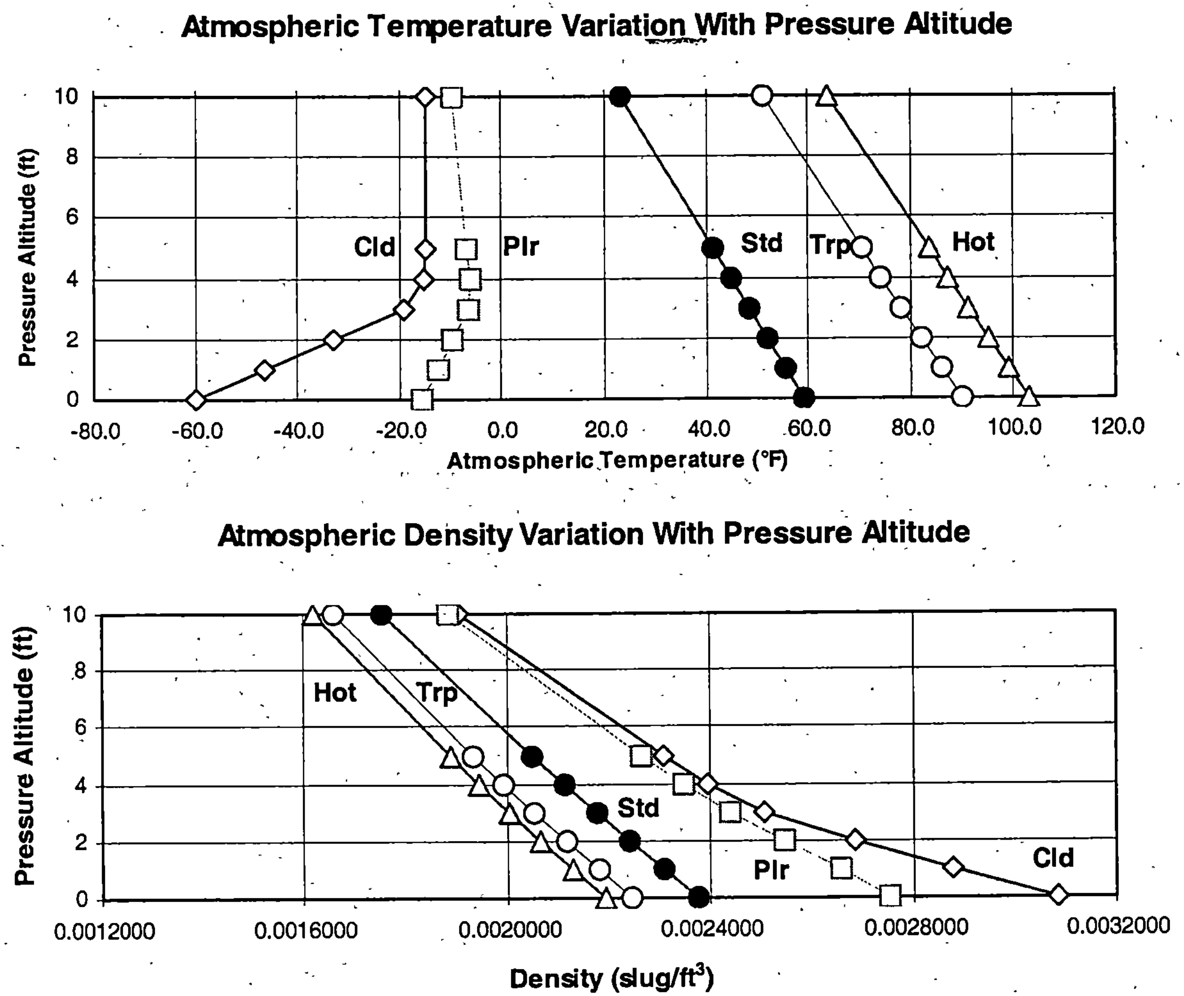


Figure 12. Dynamic V_{mcA} Pilot Model

Once the simulation models were developed, performing comparisons with actual flight test data validated the models. As illustrated in figure 12, the airplane attitudes and rates predicted by the simulation were nearly identical to the flight test results.

Subsequently, the computer simulations were conducted at pressure altitudes of 200, 1,000, 2,000, 3,000, 4,000 and 5,000 feet. At each altitude, temperatures and air density corresponding to cold, polar, standard, tropic and hot day, were simulated[9]. A graphical representation of the atmospheric models used for the analysis is provided as figure 13. For each of the simulation conditions, the build-down approach and technique were identical to what was performed during the flight test. To establish the maneuver entry speeds for each condition the aircraft gross weight was varied and the corresponding center of gravity and inertias were used based upon a nominal fuel burn sequence. Figure 14 presents a V_{mcA} condition where recovery controls are unable to contain AOSS within the 10 degree limitation. As illustrated, the gross weight and thus maneuver entry airspeed are incrementally reduced and the maneuver repeated until the V_{mcA} is obtained.

As illustrated in figure 15, the V_{mcA} sensitivity to both pressure altitude and temperature was generated using the methodology described within this chapter. Based upon these results the flight test data were corrected by applying an airspeed increment to the measured V_{mcA}, at corresponding atmospheric pressure and temperature. These results are illustrated in figure 16. As presented in figure 16, the flight test data can be


Atmospheric Temperature Variation With Pressure Altitude

Atmospheric Density Variation With Pressure Altitude

Figure 13. Computer Simulation Atmosphere Model

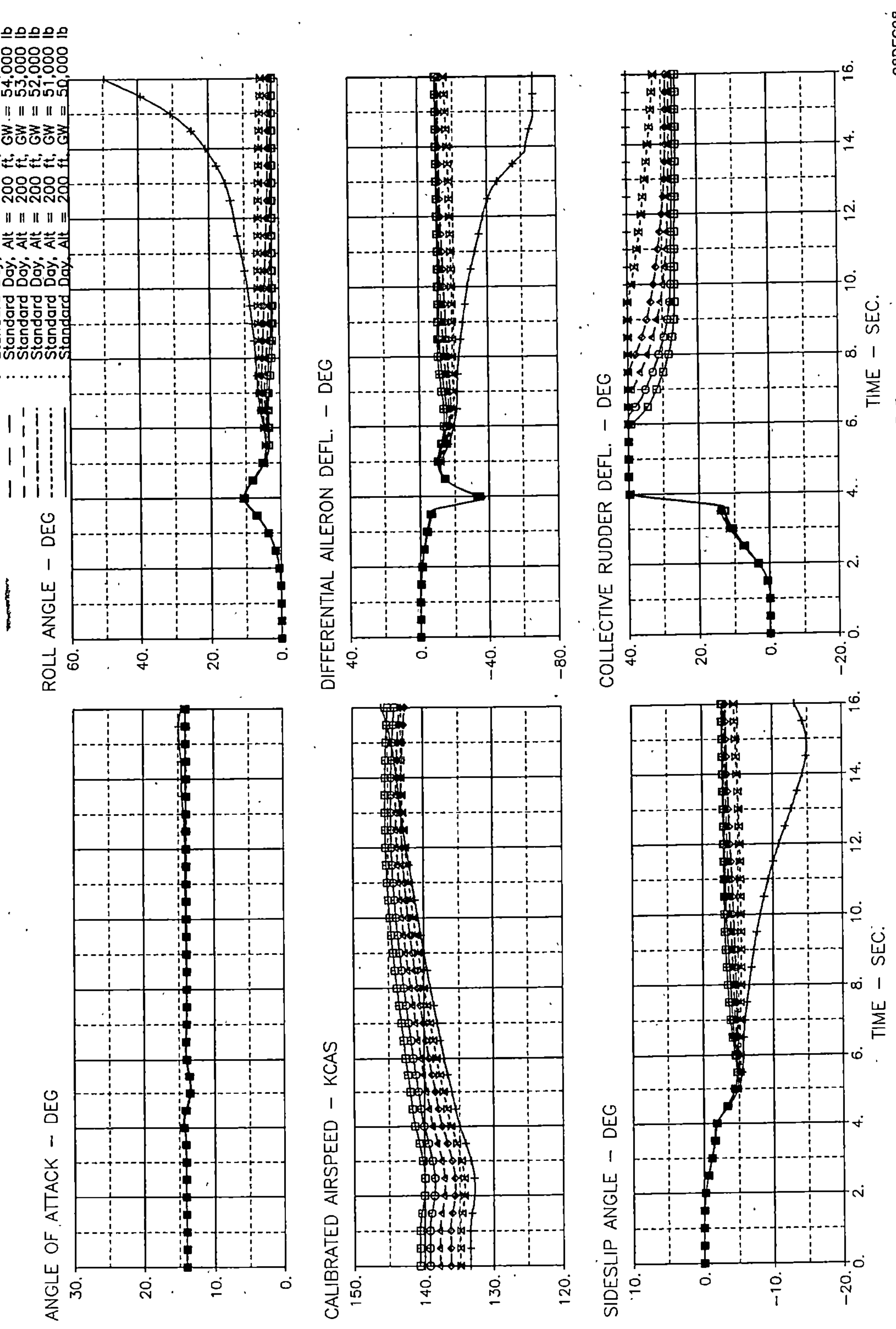


Figure 14. Computer Simulation of Dynamic V_{mcA} Maneuver

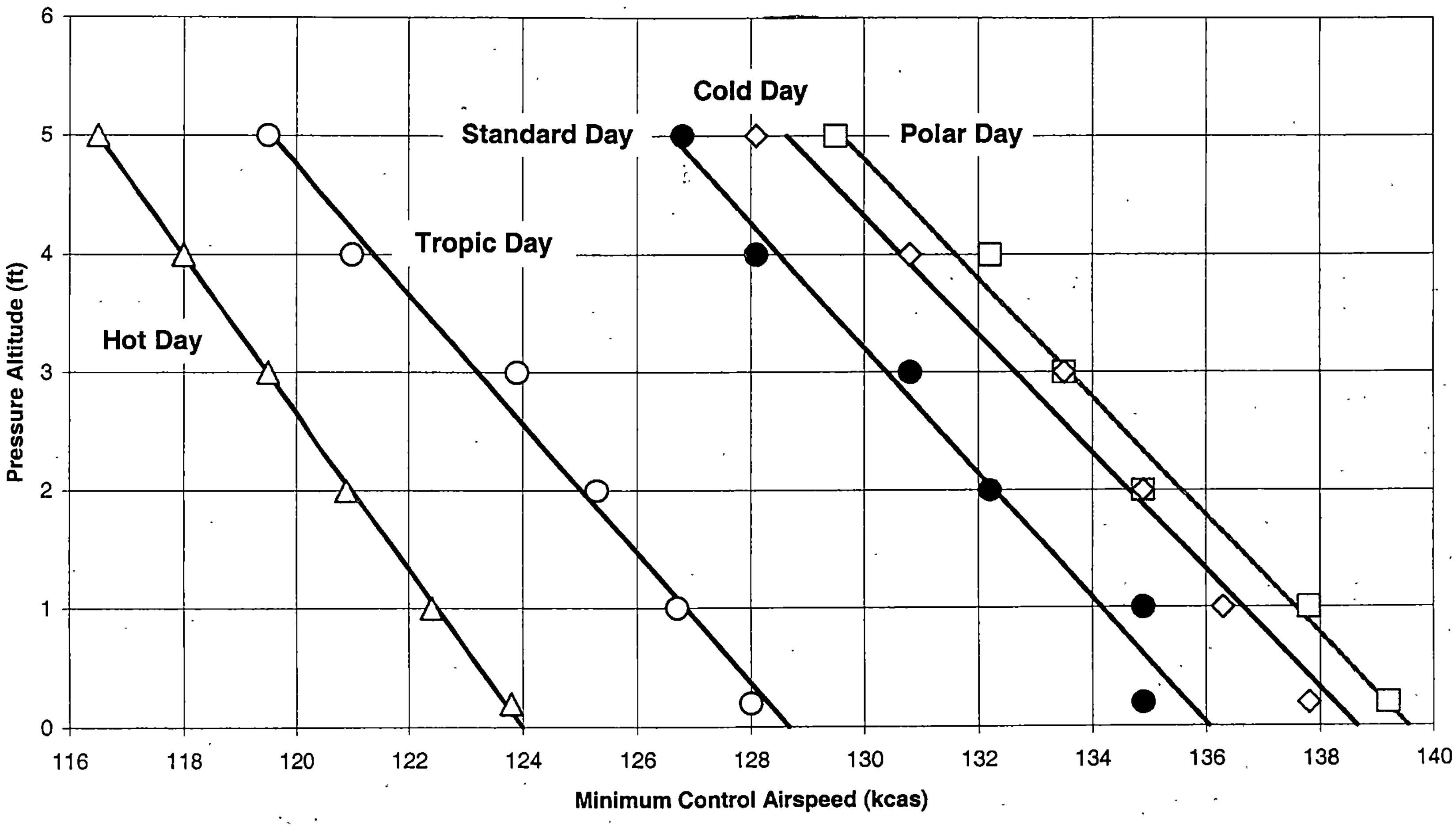
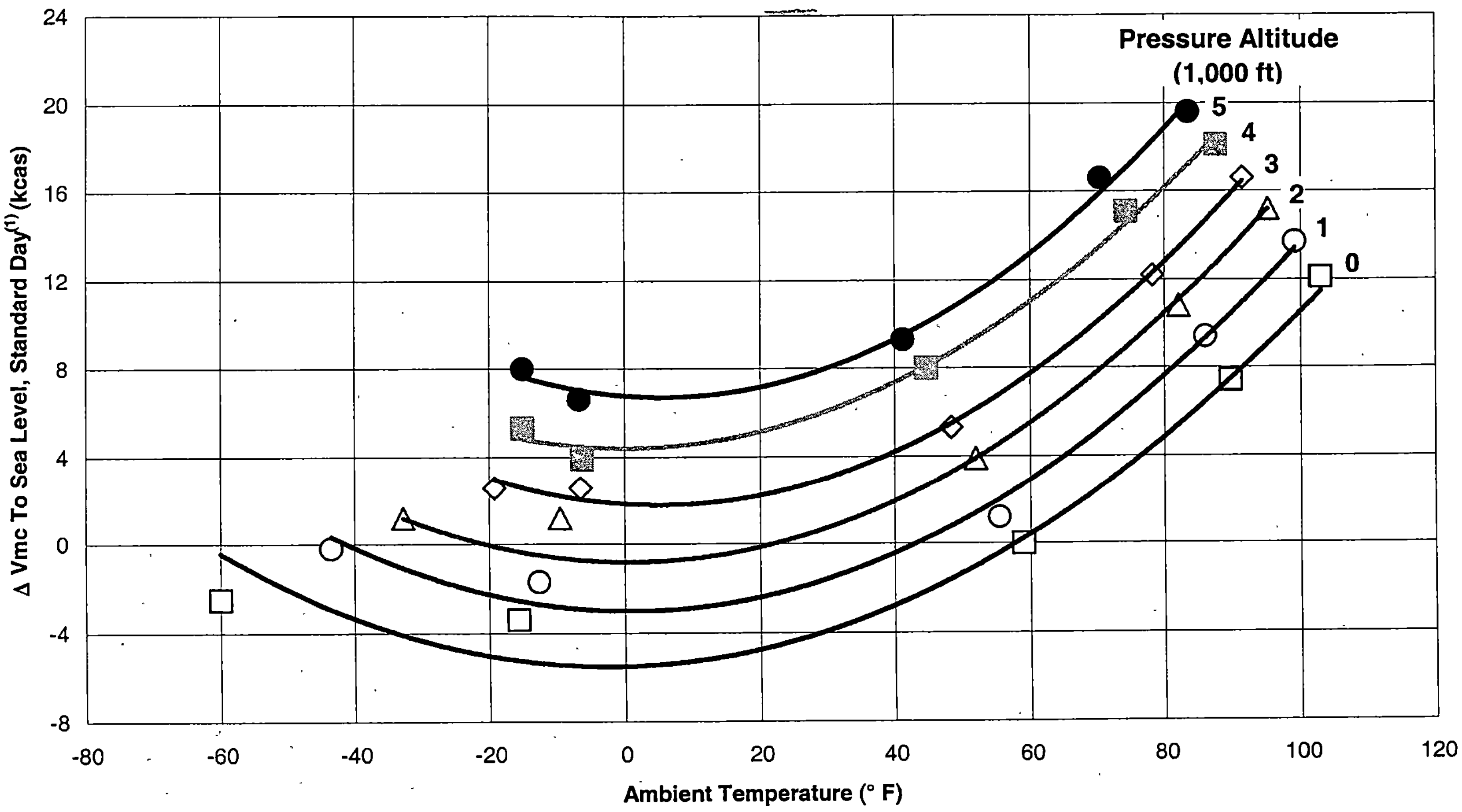


Figure 15. Dynamic V_{mcA} Variation With Atmospheric Conditions



(1) Correction Required To Normalize Demonstrated Point To Sea Level, Standard Day Conditions

Figure 16. Dynamic V_{mcA} Correction Curves

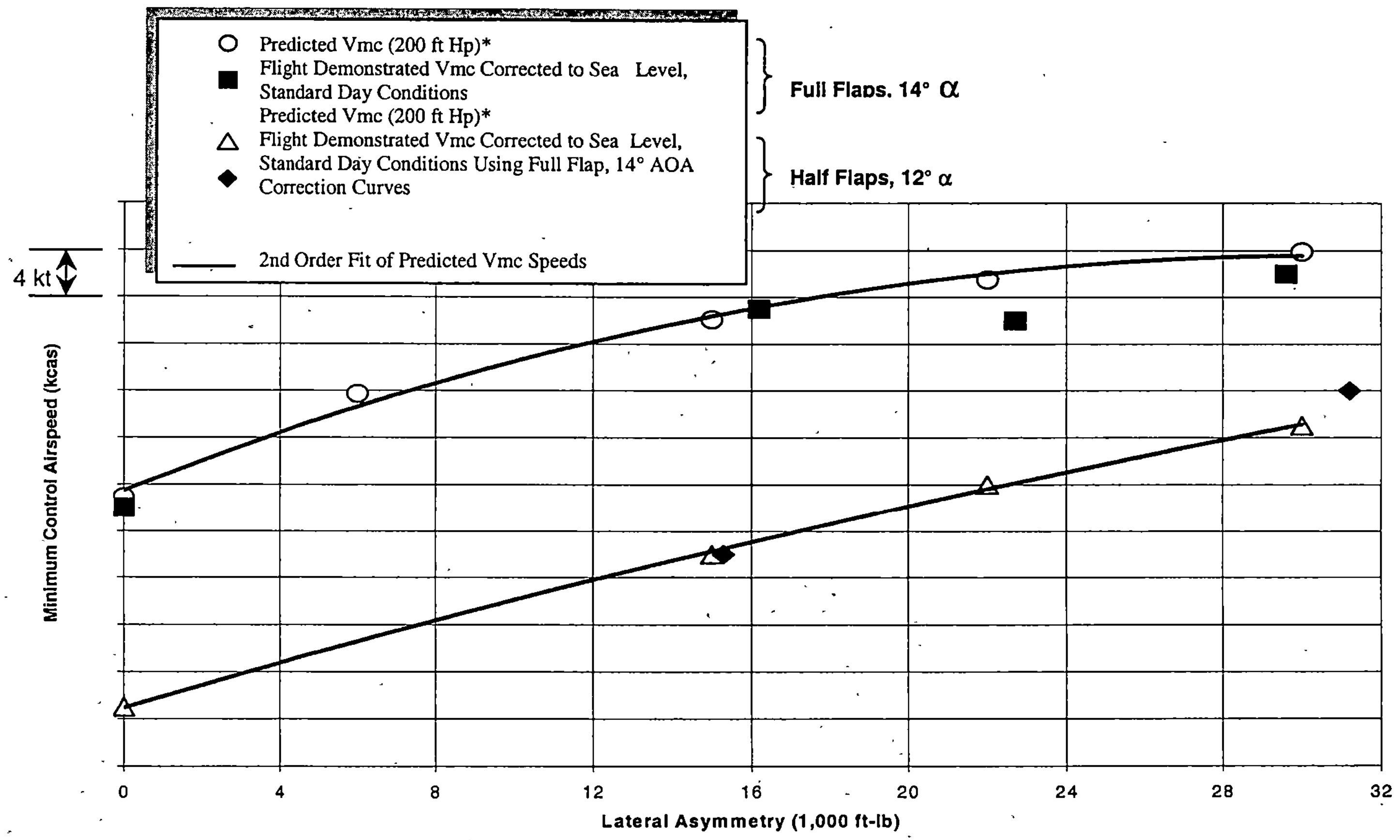
corrected to a reference sea level, standard day condition. Additional computer simulation and analysis were performed to determine the V_{mcA}, lateral weight asymmetry sensitivity to a particular store loading. This was performed since several loadings could be used to achieve a specific lateral weight asymmetry. Results from this analysis indicated that the sensitivity to store loading, for a fixed lateral weight asymmetry were negligible, and that one set of correction curves could be used to normalize the flight test data to a reference flight condition.

CHAPTER VII

PREDICTED VERSUS CORRECTED FLIGHT RESULTS

Following establishment of the correction curves the flight test data were adjusted to a SL, standard day reference condition. As illustrated in figure 17, the difference between the predicted and actual flight test results for V_{mcA} were less than 4 knots for both symmetric and asymmetric store loadings to 30,000 ft-lb. The V_{mcA} for 14 degrees AOA, full flaps, with MAX A/B power was presented since this was established to be the peak AOA during the catapult takeoff and flyaway trajectory. As illustrated, the V_{mcA} dependency upon lateral weight asymmetry was significant and varied non-linearly up to the airframe limit of 30,000 ft-lb. Similar results and accuracy were achieved for the 12 degree AOA, half flap, MAX A/B power configuration. This configuration was relevant to a dynamic engine failure in the approach and landing scenario. Further analysis of the flight test data determined that the flight test results were conservative due to the difference in lateral control input used during flight.

As discussed in the previous chapter, lateral control input was delayed for two seconds for the computer simulation to represent a worse case scenario. However, during the flight test program the pilots instinctively input small lateral control inputs to maintain wings level prior to two seconds and also rudder inputs just prior to two seconds. These differences in lateral-directional control input resulted in the difference



* Lateral Asymmetry Achieved By Artificially Moving BLCG To Desired Location

Figure 17. Predicted vs. Flight Demonstrated Dynamic V_{mcA}

in V_{mcA} between the computer analysis and corrected flight test results presented in this graph.

CHAPTER VIII

AIRCRAFT LAUNCH BULLETIN DEVELOPMENT

Following establishment of the symmetric and asymmetric V_{mcA} for the airplane, shipboard testing was performed to determine the SOB airspeeds and catapult takeoff envelope for the airplane. Once established the envelopes were used to generate a set of aircraft launching bulletins used by ships company to perform takeoffs for a range of tactical loadings, power settings and ambient conditions.

As illustrated in figure 18, the symmetric V_{mcA} limited the minimum takeoff airspeeds for light-to-medium gross weight loadings (horizontal line). Above this gross weight the minimum takeoff airspeeds were above the symmetric V_{mcA} and were restricted by the takeoff performance of the airplane (diagonal line). These points along the curves were established by performing catapult takeoffs at fixed gross weights, while decrementing the launch airspeed until an altitude loss of 10 feet at the airplane CG were achieved. Once the slopes of the curves were established, the minimum takeoff airspeed envelope of the airplane is complete. As presented in figure 19, the minimum launch airspeeds were incrementally adjusted to account for the asymmetric V_{mcA} store loading effects (horizontal lines).

Following establishment of the takeoff envelope, a 15 knot airspeed margin was applied to these minimum airspeeds and the aircraft launch bulletins was published based

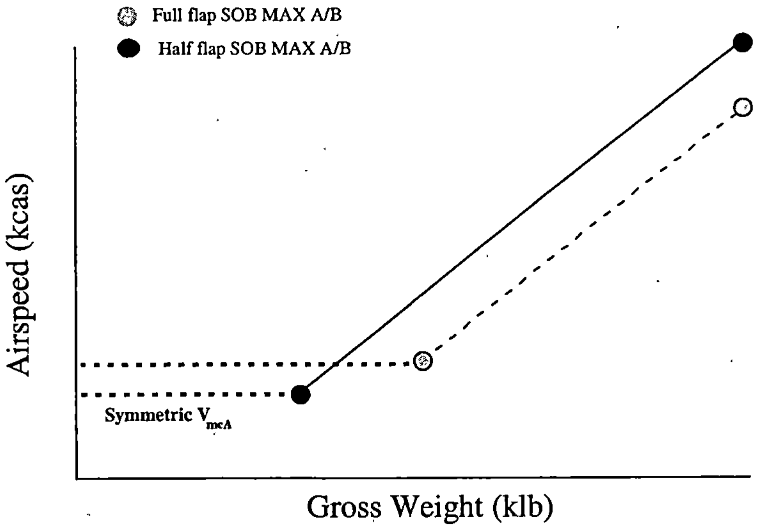


Figure 18. Symmetric Catapult Launch Envelope

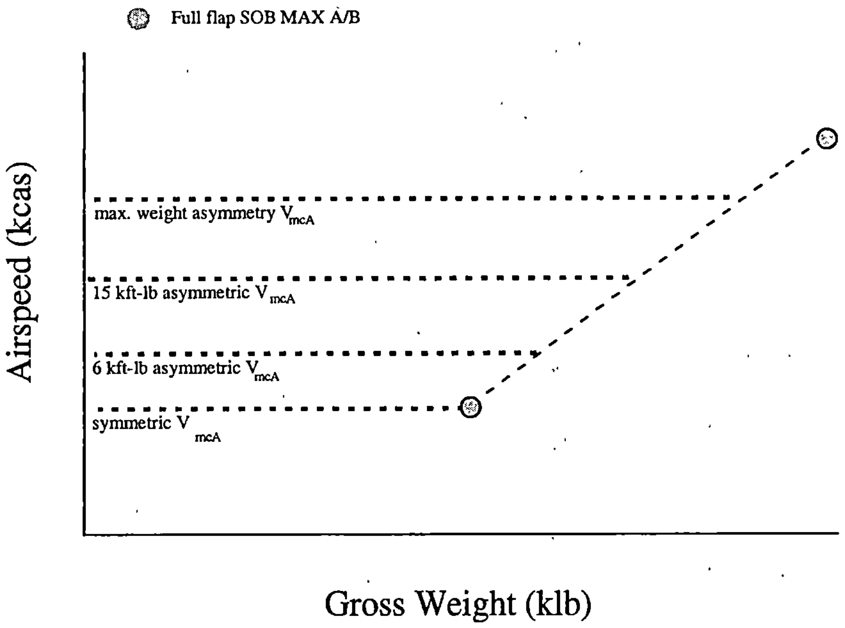


Figure 19. Asymmetric Catapult Launch Envelope

upon these results. This airspeed margin is used to account for variations in airplane and catapult performance, wind velocity measurement and several miscellaneous effects. Also, this margin is used to account for effects which were not tested during the V_{mcA} testing, such as the effect of an actual failed engine; windmilling as opposed to at flight idle as tested. As presented in figure 20, the effect of a failed, windmilling engine can be significant and the effect can be analytically determined and accounted for in the overall analysis of the takeoff performance of the airplane.

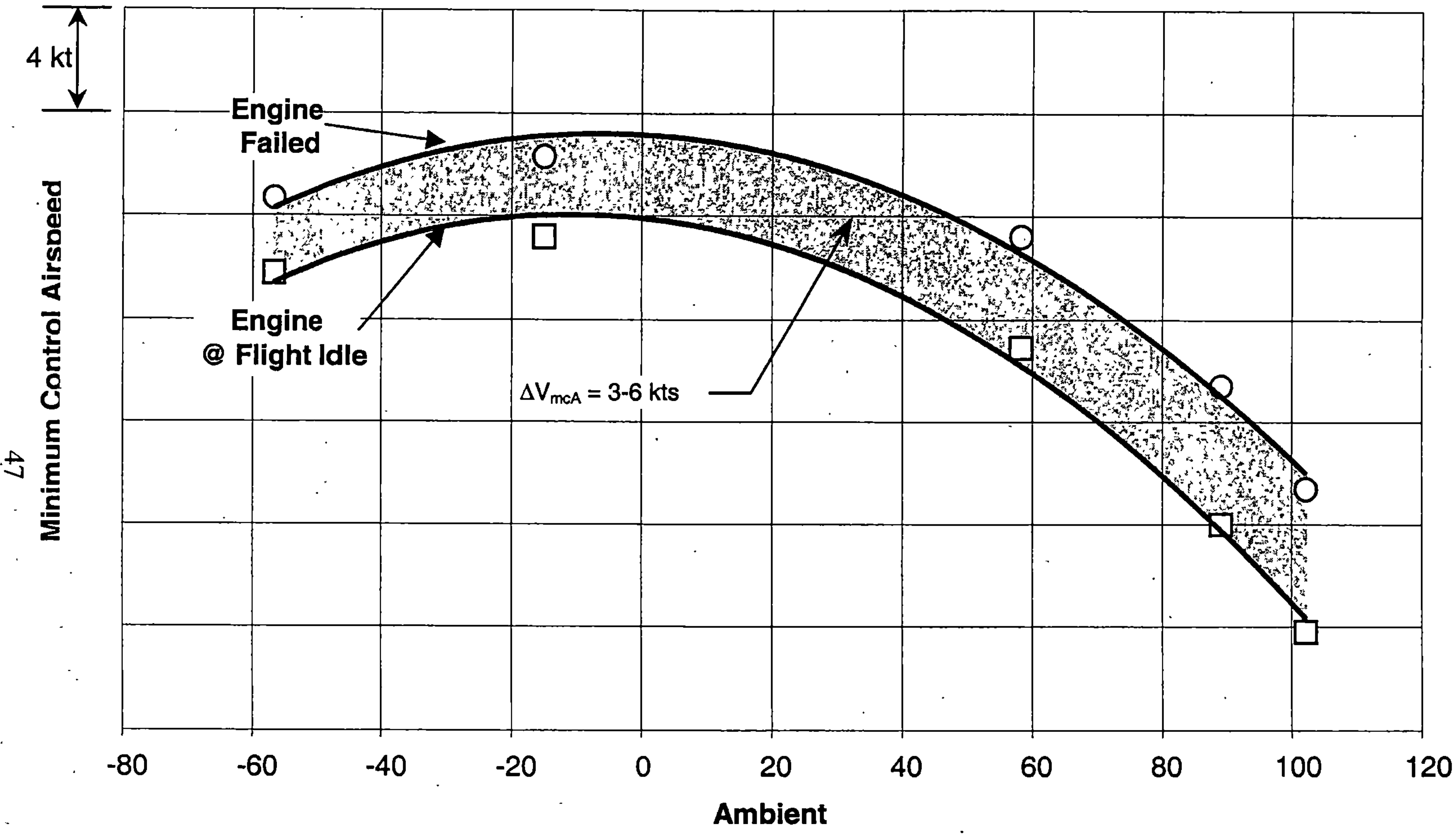


Figure 20. Flight Idle vs. Engine Failed (Windmilling Rotor) Dynamic V_{mcA}

CHAPTER IX

CONCLUSIONS

Over the course of the three and one-half years of the F/A-18 E/F EMD flight test program, approximately three hundred test points were performed in a variety of test loadings, power settings, flap configurations, and ambient conditions to establish the V_{mcA} for the airplane. The accurate determination of V_{mcA} was critical to the development of the aircraft launching bulletins, which were required for operational deployment of the F/A-18 E/F. Without accurate determination of V_{mcA}, engine failure during catapult takeoff could be catastrophic, since airplane controllability could not be ensured and escape with use of the ejection seat may not have been possible at the corresponding airplane attitudes and rates. This was significant for a carrier based airplane since safe single engine flyaway was not guaranteed in this scenario.

This thesis presented the dependency of atmospheric conditions, AOA and lateral weight asymmetry on V_{mcA} for a highly augmented, high thrust-to-weight fighter airplane. The methodology and test approach developed and utilized in this thesis were a practical, effective approach to quantifying these dependencies and resulted in the successful operational deployment of the F/A-18 E/F airplane. Also, this methodology resulted in a safe, efficient and accurate means to determine V_{mcA} that is applicable to other airplanes of this class and should be used to document these dependencies.

CHAPTER X

RECOMMENDATION

The methodology used in this thesis to determine V_{mcA}, and the dependency on AOA and lateral weight asymmetry are applicable to other airplanes of this class and should be used to document these dependencies.

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VITA

Henry Melton, III was born on 9 September 1961 in Sacramento, CA. He graduated from Potomac Senior High School, in Oxon Hill, MD in 1979. In the fall of 1979 he entered University of Maryland and in May 1986 received a Bachelor of Science Degree in Aerospace Engineering. In January of 1987 he began working for Northrop Corporation at the Naval Air Warfare Center, Patuxent River, MD. In the fall of the same year, he began working as a flight test engineer at the Strike Aircraft Test Directorate, Naval Air Warfare Center, Patuxent River, MD. In December of 1995, Mr. Melton graduated from the U.S. Naval Test Pilot School as a member of Class 108. During his tenure as a flight test engineer, Mr. Melton has been involved with flying qualities and performance, and Carrier Suitability testing of several Navy carrier based platforms, including the F/A-18 E/F, T-45A and F-14B airplanes. Mr. Melton is currently serving as the C-40A Assistant Program Manager for Systems and Engineering and is enrolled in the Navy's Senior Executive Management Development Program.