

**F/A-18 SIMULATION VALIDATION AND VERIFICATION -
MAKING A GOOD PRODUCT EVEN BETTER**

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Abstract

The Naval Air Warfare Center Aircraft Division (NAWCAD) F/A-18 flight simulator has numerous uses in the Test and Evaluation and fleet communities which include flight test risk reduction, pilot proficiency training, mishap investigation, and basic research. It is imperative that the simulation accurately model the F/A-18 airplane for valid training or efficient flight testing. To ensure that the F/A-18 simulation properly models the aircraft in flight, it was necessary to collect dynamic data across the entire flight envelope of the F/A-18 airplane in several weapon loadings. This paper discusses the results of a flight test program that will improve the fidelity of the F/A-18 simulation by providing the necessary flight data to update its aerodynamic data base throughout the flight envelope. Specific topics to be addressed include scope of the test conducted, test methodology used, and instrumentation systems developed specifically for this flight test program.

Nomenclature

AOA = Angle of Attack
b = Wing span
CAS = Control Augmentation System
C/C/C = Pitch CAS/Roll CAS/Yaw CAS
C/D/D = Pitch CAS/Roll DEL/Yaw DEL
 C_{l_r} = Rolling moment due to roll rate
 C_{l_y} = Rolling moment due to yaw rate
 C_{l_β} = Rolling moment due to sideslip
 $C_{l_\delta_a}$ = Rolling moment due to aileron deflection
 $C_{l_\delta_r}$ = Rolling moment due to rudder deflection
DEL = Direct Electrical Link
 F_x, F_y, F_z = Scalar components of external force vector

h_x, h_y, h_z = Scalar components of angular momentum vector
 I_x = Rolling moment of inertia
 I_{xz} = Product of inertia, $\int xz \, dm$
 L, M, N = scalar components of external moment vector, about the mass center
m = Airplane mass
P, Q, R = Scalar components of angular rate vector
PCM = Pulse Control Modulation
S = Wing area
t = Airplane natural frequency period
U, V, W = Scalar components of velocity vector
 β = Sideslip angle
 δ_a = Aileron deflection angle
 δ_r = Rudder deflection angle
 ρ = Density
 ω_n = Natural frequency
 Φ = Roll Euler angle
 Ψ = Yaw Euler angle
 ζ = Damping ratio

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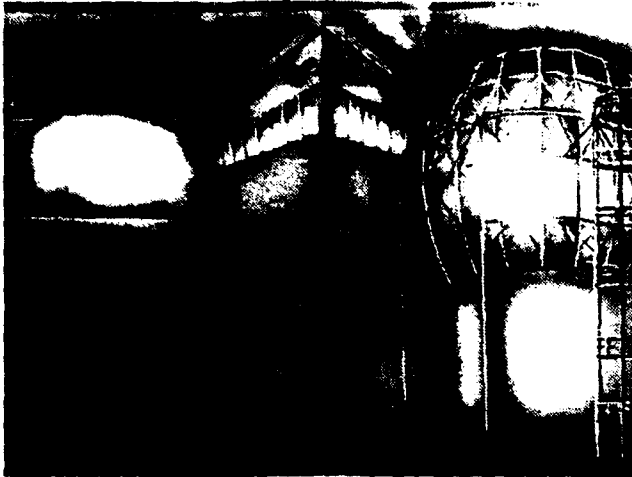
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I. Background



THE MANNED FLIGHT SIMULATOR

The NAWCAD Manned Flight Simulator (MFS) is the facility where the Navy conducts simulation development and testing. The MFS F/A-18 simulation has been operational since November 1984 and has been used to support many U.S. Navy and NASA flight test programs for the purpose of reducing flight test risk, facilitating test plan/test matrix development, refining flight test procedural development, as well as enhancing test pilot skills through test point practice. Additionally, the F/A-18 simulation is also used by the fleet for pilot proficiency training, mishap investigation and analysis, and basic research. Over the last decade, updates have been made to several regions of the MFS F/A-18 simulation's aerodynamic model, particularly in the supersonic and high angle of attack (AOA) portions of the flight envelope. Limited pilot evaluations of the simulation have been performed throughout the update cycle to qualitatively assess the changes made to the aerodynamic data base. The flight data gathered during this evaluation provided the first opportunity for a large-scale, systematic validation of the simulation across the entire flight envelope.

The MFS incorporates 360 degrees visual display on a 40 foot dome, an F/A-18 cockpit, and "hardware in the loop" technology using aircraft avionics equipment and computers. Actual F/A-18 flight control computers are used to close the loop between pilot stick and rudder pedal inputs and the bare airframe equations of

motion. The result is an accurate simulation of how the aircraft would respond dynamically to control inputs while maintaining a close approximation as to how the aircraft would feel to the pilot. The fundamental element for good simulation is accurate aerodynamic modeling of the aircraft's bare airframe response.

Aerodynamic modeling is accomplished numerically using the six equations of motion (equation 1) that describe three translational and three rotational motions of any aircraft in flight.

$$\begin{aligned} F_x &= m(\dot{U} + QW - RV) \\ F_y &= m(\dot{V} + RU - PW) \\ F_z &= m(\dot{W} + PV - QU) \\ L &= \dot{h}_x + Qh_z - Rh_y \\ M &= \dot{h}_y + Rh_x - Ph_z \\ N &= \dot{h}_z + Ph_y - Qh_x \end{aligned} \quad (1)$$

Figure 1 shows the axis system and sign conventions for the equations.

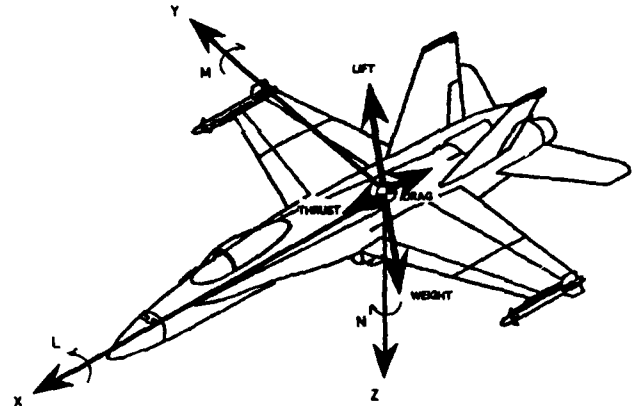


Figure 1
AXIS SYSTEM AND SIGN CONVENTIONS

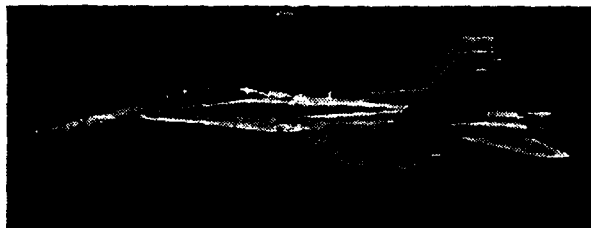
The moment about each axis is commanded by the flight control surfaces. Annoying second order airplane response is heavily damped by all flight control surfaces, as directed by the flight control computers. For example, along the X-axis, rolling moment (L) is governed by the ailerons; while the second order effect Dutch roll is damped by the rudders. Starting with equilibrium conditions and specifying that only asymmetric forcing functions, velocities, and

accelerations exist, the rolling moment equation of motion (equation 2) is derived.

$$\frac{2I_x}{\rho S b U_o^2} \ddot{\phi} - \frac{b}{2U_o} C_{l_p} \dot{\phi} + \frac{2I_{xz}}{\rho S b U_o^2} \ddot{\psi} - \frac{b}{2U_o} C_{l_r} \dot{\psi} - C_{l_\beta} \beta = C_{l_{\delta_r}} \delta_r + C_{l_{\delta_a}} \delta_a \quad (2)$$

The bare airframe stability derivatives and the control surface derivatives in equation (2) were calculated using the data gathered during this flight test program and represent how the F/A-18's bare airframe responded to simple control inputs, without the flight control computers in the loop. Similar equations can be found for the other two axes.

There are physical and aerodynamic differences between the single- and dual-seat F/A-18 airplanes. As a result, two test airplanes were required for this flight test program. Furthermore, the various weapon loadings produce differing aerodynamic effects and several were flown in this program. The MFS F/A-18 simulation is based on the single seat airplane and adds canopy and weapon loading effects to build the different models.



THE F/A-18 AIRPLANE

The F/A-18 is a twin-engine turbo jet fighter aircraft that incorporates fly-by-wire technology. This technology provides the pilot with superb handling qualities from slow speed near stalled flight to supersonic flight. Two flight control computers monitor stick and rudder commands from the pilot as well as the flight conditions from the air data computer (i.e., airspeed, altitude, AOA). This information is processed by the flight control computers which then command the flight control surfaces to provide the pilot with the desired aircraft response. It is important to note that, in addition to air data, the flight control computers also use feedback from linear accelerometers and angular rate gyros in all three axes. Consequently, in flight, there are numerous

flight control surface movements that occur which are transparent to the pilot. These flight control surface movements are optimized to enhance the flying qualities of the F/A-18 and, as a result, the real response of bare airframe dynamics becomes masked under the high order control system architecture.

To allow the pilot to make control inputs without feedbacks and observe the bare airframe response, it was necessary to install a switch in the cockpit to enable selection of the digital Direct Electrical Link (DEL) flight control system mode in the roll and yaw axes (Pitch CAS/Roll DEL/Yaw DEL (C/D/D)). The digital DEL mode removes the feedback loops of the respective axis and provides the pilot with direct control of the surfaces. Aircraft response in the pitch axis is well understood; therefore, Pitch CAS remained ON for all flights.

The airplane was equipped with a guarded, two-position switch in the cockpit to enable the pilot to arm/disarm the Roll/Yaw DEL mode. The C/D/D mode was armed by selection of "Roll/Yaw-DEL" with the guarded switch and engaged by depressing a button on the control stick. Disengagement of the C/D/D mode was accomplished by depressing a paddle switch located on the pilot's lower control stick, or by selecting "CAS" position on the guarded switch. A special analog card was installed in the flight control computers to degrade the airplane to the C/D/D mode when engaged via the button on the pilot's control stick.

A Quick Installation Data System (QIDS) instrumentation system was installed in the airplane for data recording and telemetry. QIDS is capable of recording onboard up to 256 PCM data parameters and telemetering up to 62 PCM data parameters from any of the 1553 Multiplex busses. Data were telemetered to the Real-time Telemetry Processing System ground station for real-time monitoring by engineers to verify satisfactory completion of test points and for flight safety. The onboard tape was the primary source for postflight data reduction. The data reduction was largely automated by MFS engineers to confirm data quality and to simplify the validation effort.

The bare airframe dynamic response data was used to validate the simulator's aerodynamic model. When a discrepancy was found, numerical techniques such as parameter identification were used to recalculate the stability and control derivatives used in the F/A-18 simulator's equations of motion. The flight test

data could then be used to revalidate the changes to the aerodynamic model before final acceptance into the simulator.

II. Test Methods

The flight tests were planned to provide the widest range of data for the validation and verification of the simulation. Validation refers to the comparison of simulation results to actual airplane responses, generally by driving the simulation with flight control surface movements from the flight test data. A good simulation is defined as one in which the simulation's response closely resembles the airplane's under the same flight conditions. Verification refers to the actual updating of the simulation by revising the coefficients in the equations that command the simulation to more closely represent true airplane response.

The majority of the test points were flown at three altitudes in three loadings and three configurations in order to cover a variety of possible flight conditions in the F/A-18 flight envelope. Testing was conducted at low, medium, and high altitudes from low speed to high speed. Test configurations were defined by the aircraft gear and flap position as Cruise (CR: gear UP, flaps AUTO), Power Approach (PA: gear DOWN, flaps FULL), and PA1/2 (gear DOWN, flaps HALF). Test loadings are shown in figure 2. The Fighter Escort (FE) loading has an AIM-9 missile on each wingtip station and an AIM-7 missile on the fuselage stations. The Fighter Centerline loading is the same as the FE loading with the addition of a centerline fuel tank. The Interdiction loading is the same as the FE loading with the addition of three fuel tanks and 4 MK-83 bombs on the wing stations.

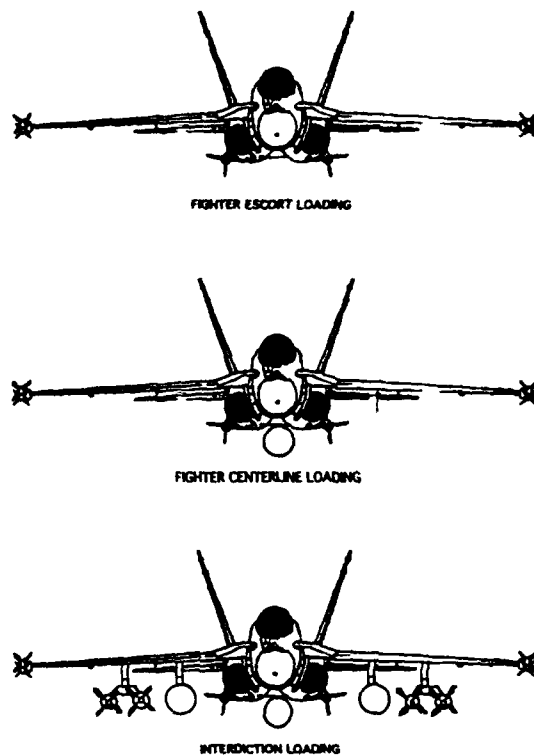


Figure 2
TEST LOADINGS

Maneuvers performed at the primary altitudes consisted of Integrated Test Blocks (ITB's) and windup turns (WUT's) flown in both the C/C/C and C/D/D flight control system modes. ITB's are a combination of maneuvers at a constant flight condition. WUT's are constant Mach number maneuvers, slowly increasing in n_z to the airframe n_z or AOA limit. Additional maneuvers were performed throughout the flight envelope to gather data for the validation and verification effort, including throttle transients, acceleration/decelerations, pushovers, winddown turns, and abrupt longitudinal stick pulls. The flight envelope and test conditions are shown in figure 3.

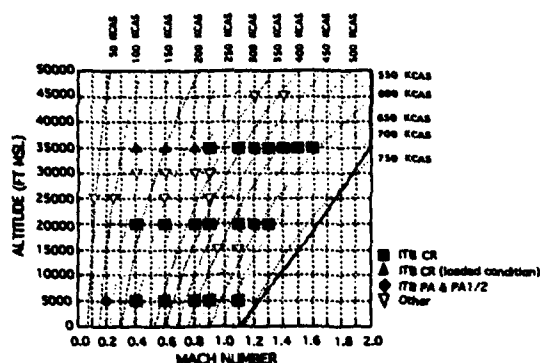


Figure 3
FLIGHT TEST ENVELOPE

Most of the data gathered will be used for time history matching of air data, control inputs, and control surface deflections. This information will be used to update the control surface derivatives (i.e., $C_{l_{\dot{\alpha}}}$ and $C_{l_{\dot{\beta}}}$) in equation 2.

Some data were gathered at different power settings (pushovers and throttle transients) and will be used to observe engine response characteristics, as well as the propulsion related effects on airframe aerodynamics (i.e., pitching moment due to thrust).

The ITB's were designed to provide aircraft dynamic response for parameter identification in all three axes. This information will be used to update the stability derivatives (i.e., $C_{l_{\dot{\alpha}}}$, $C_{l_{\dot{\beta}}}$, etc.) in equation 2. The ITB's included pitch, roll, and yaw axis 3-2-1-1 pilot input maneuvers (explained below), left and right rolling maneuvers, and left and right steady heading sideslips. The supersonic ITB's were followed by a WUT. ITB's were performed in both straight and level flight and at elevated AOA's.

The 3-2-1-1 pilot input maneuver was the driving function designed to provide a broad frequency range of excitation in the axis of interest. The basic 3-2-1-1 pilot input consisted of contiguous, equal amplitude, opposite sign square inputs of duration 3, 2, and 1 normalized time units (figure 4). A single time unit is equivalent to the airplane's natural frequency period (t). The amplitude for the 3-2-1-1 inputs was small enough so as not to significantly deviate from the test condition but large enough to adequately excite the mode of interest.

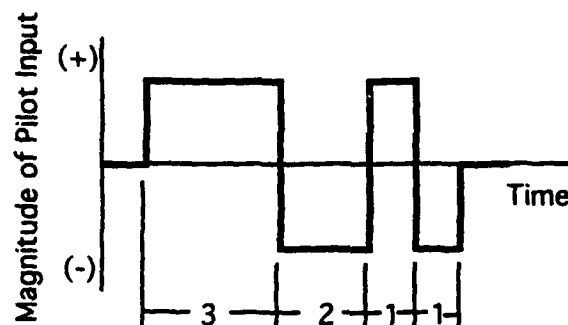


Figure 4
3-2-1-1 FREQUENCY PILOT INPUT

The second order natural frequency response of the F/A-18 airplane varies greatly with Mach number, altitude, and airplane loading. Using equation 3, the natural frequency period of the F/A-18 was determined for each of the test points. The longitudinal short period and lateral-directional second order Dominant Closed Loop Roots (natural frequency and damping ratio) were obtained from MDA. The natural frequency period (t) was then calculated as follows:

$$t = \frac{0.04\pi}{\omega_n / \sqrt{1 - \zeta^2}} \quad (3)$$

Solving for t and using the natural frequency period to govern the rate of the 3-2-1-1 input resulted in the greatest airplane response to control inputs.

Since over 1,000 test points were flown by several pilots, a method to provide for consistent inputs between pilots was required to maintain data quality. A set of tones was developed to give the pilot an aural cadence for each test point. The tones were transmitted to the pilot via a separate communication frequency, prior to conducting the maneuver. The pilot was then able to perform the maneuver at the desired frequency.

Over the course of the flight test program, it was determined that to produce the greatest response from the airplane, it would have been better if the pilot modified the forcing function slightly to make the inputs coincide with airplane motions. In other words, if the pilot inputs left rudder pedal and the airplane begins to yaw to the left, he should put in the right input as the airplane is settling back in the opposite direction. This modified forcing function resulted in more airplane response.

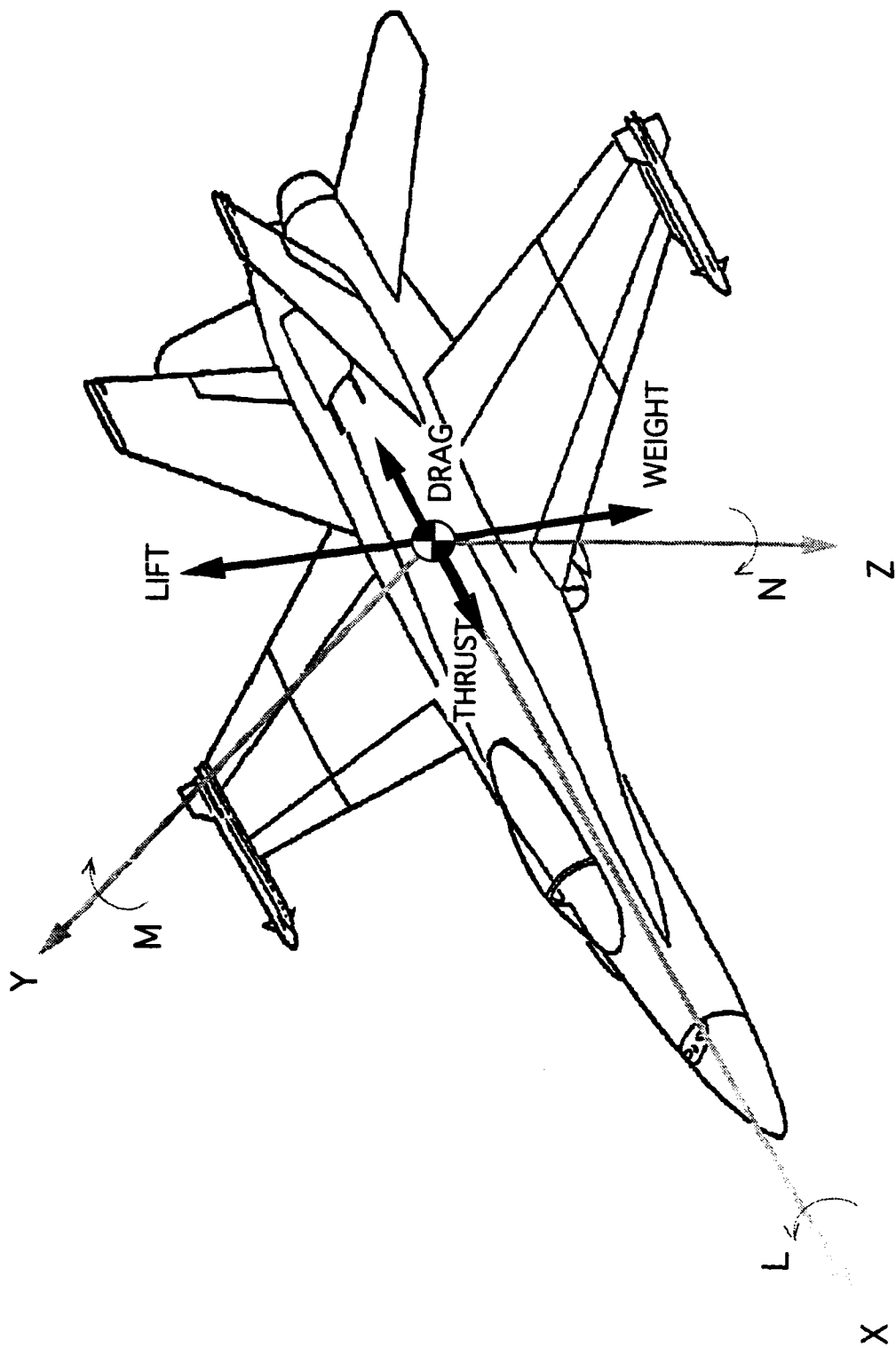
III. Results

Twenty-one flights were flown on the single-seat airplane, and six on the dual-seat airplane, with a total of over 68 hours of flight time. As a result, volumes of data were collected. To date, much of the data processing effort has been devoted to ensuring data quality (i.e., all maneuvers were completed satisfactorily and the data is free of dropouts). The validation effort is still ongoing. Verification of the F/A-18 simulation is planned to occur at a later date.

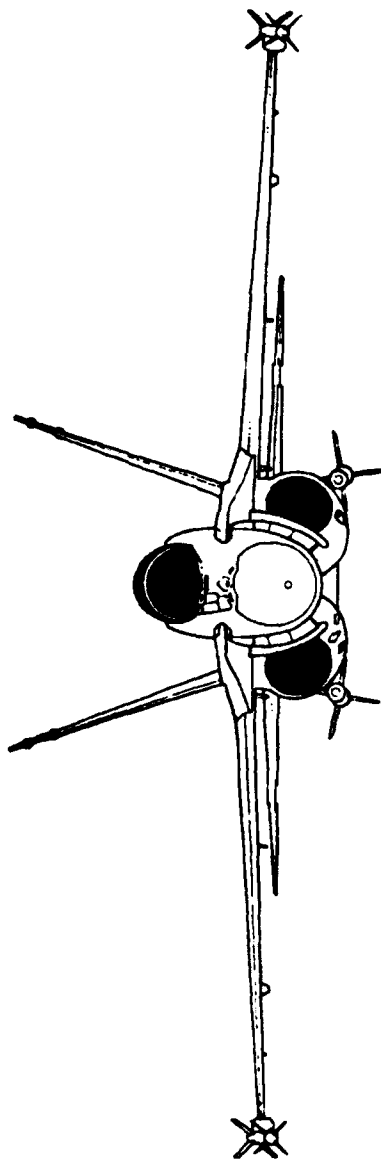
As a result of this flight test program, the F/A-18 simulation at NAWCAD will be the best F/A-18 simulation to date. This flight test program has expanded our ability to gather data for the specific purpose of improving simulations. In addition, previously unavailable data was obtained on the F/A-18 airplane in a degraded flight control system mode (C/D/D). New test methods for gathering frequency-dependent data were developed and improvements to those methods have been identified for future programs.

References

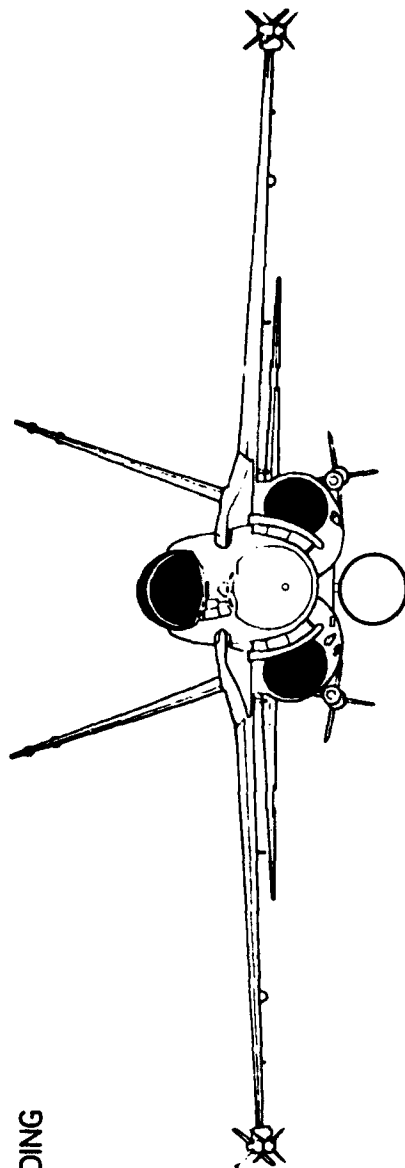
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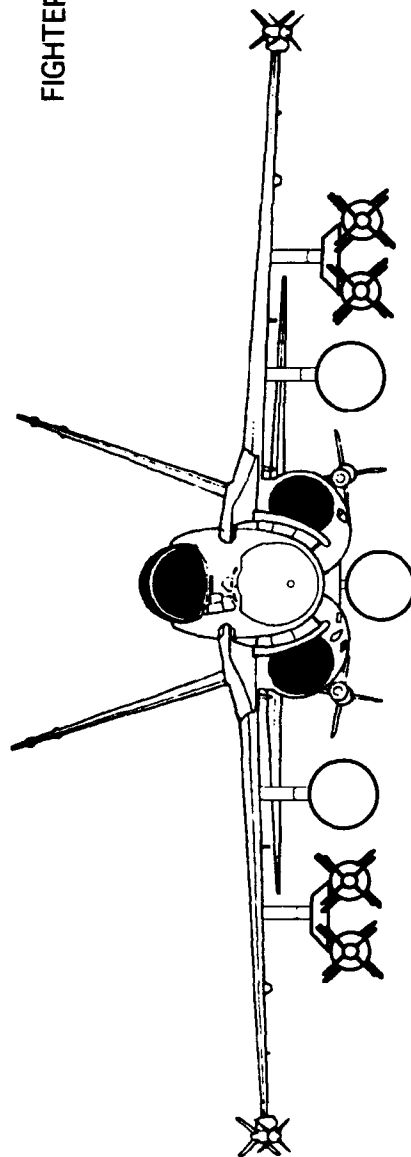
AXIS SYSTEM AND SIGN CONVENTION



FIGHTER ESCORT LOADING

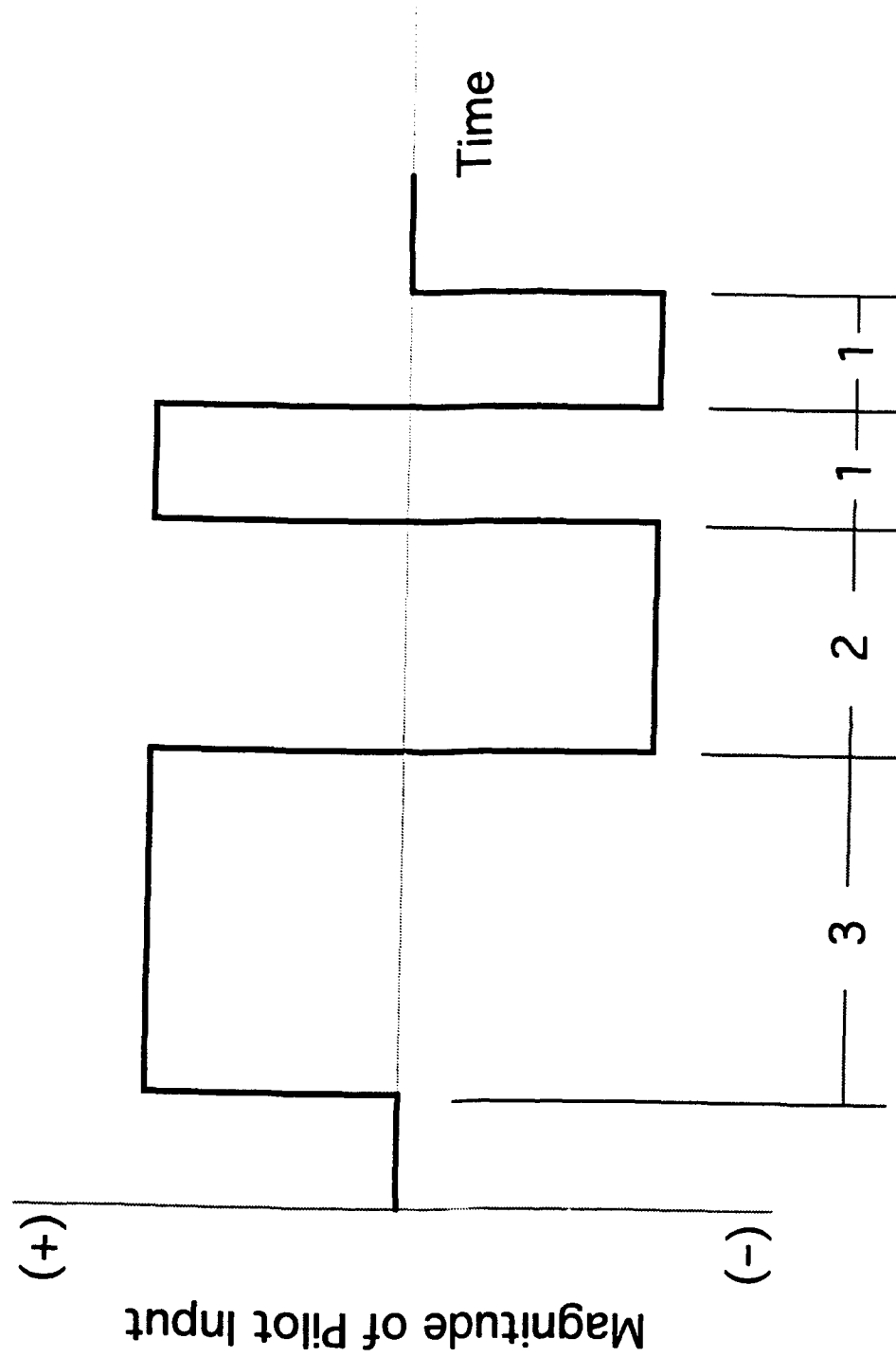


FIGHTER CENTERLINE LOADING

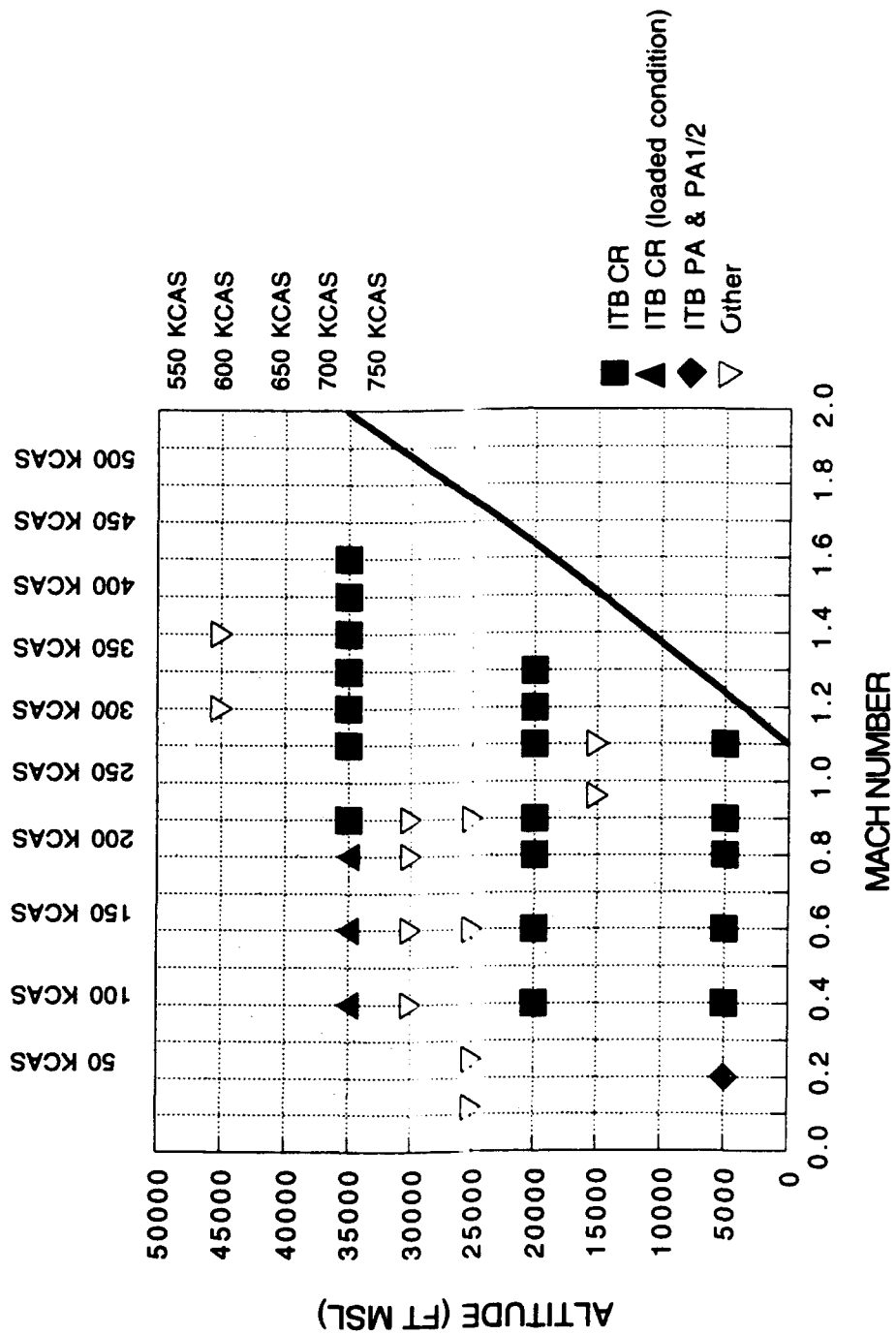


INTERDICTION LOADING

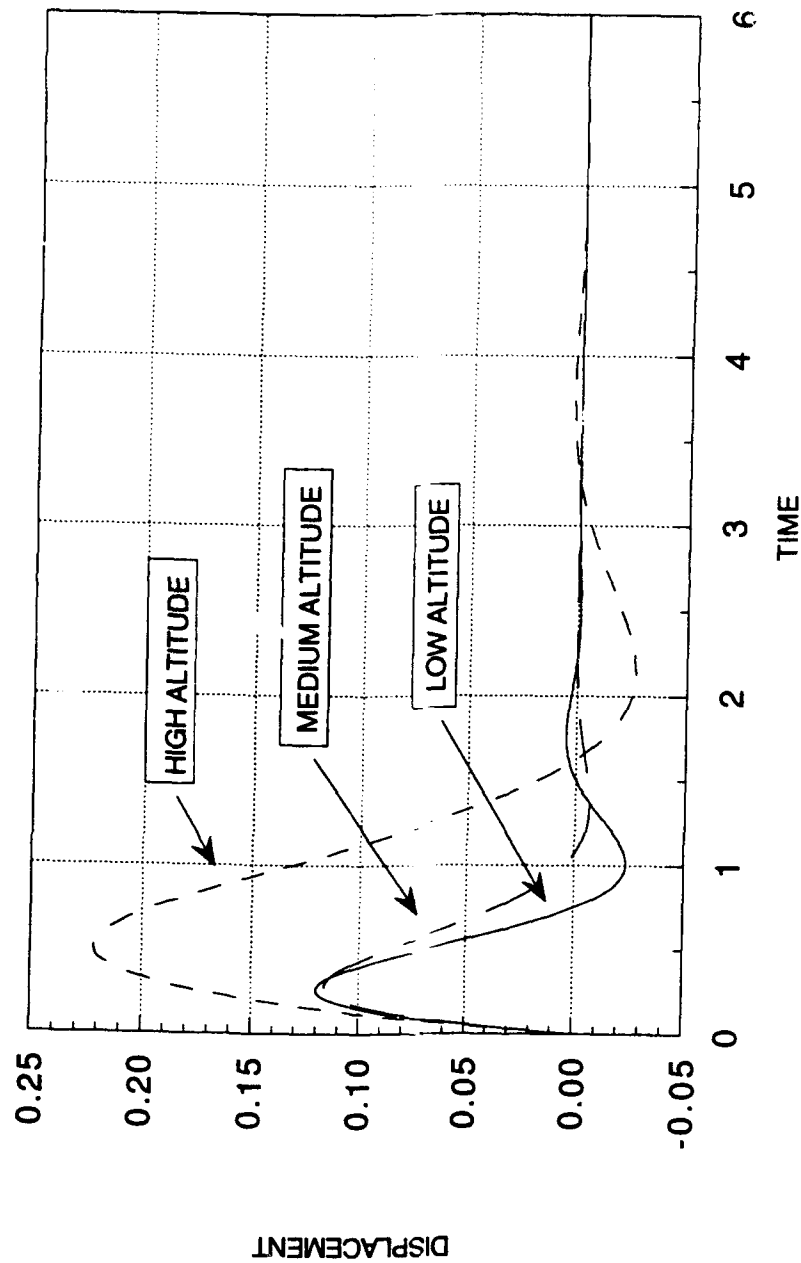
TEST LOADINGS



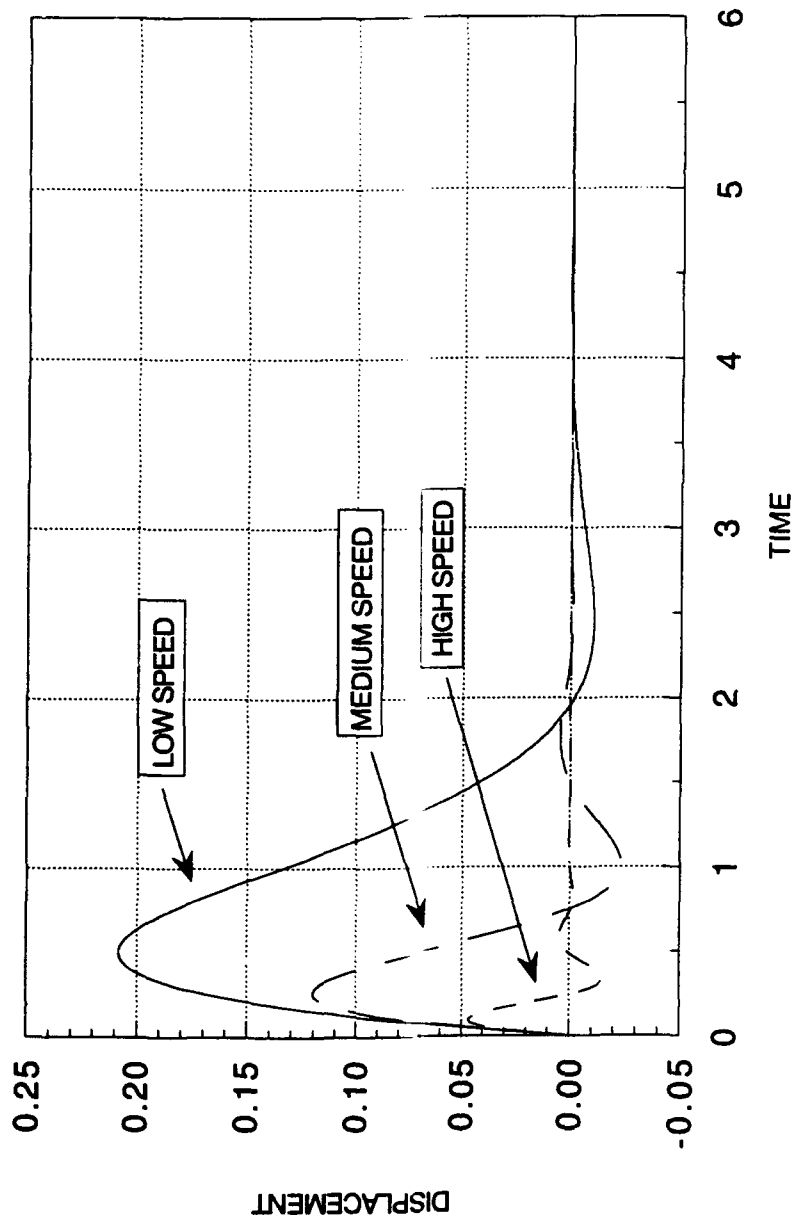
3-2-1-1-1 PILOT INPUT MANEUVER



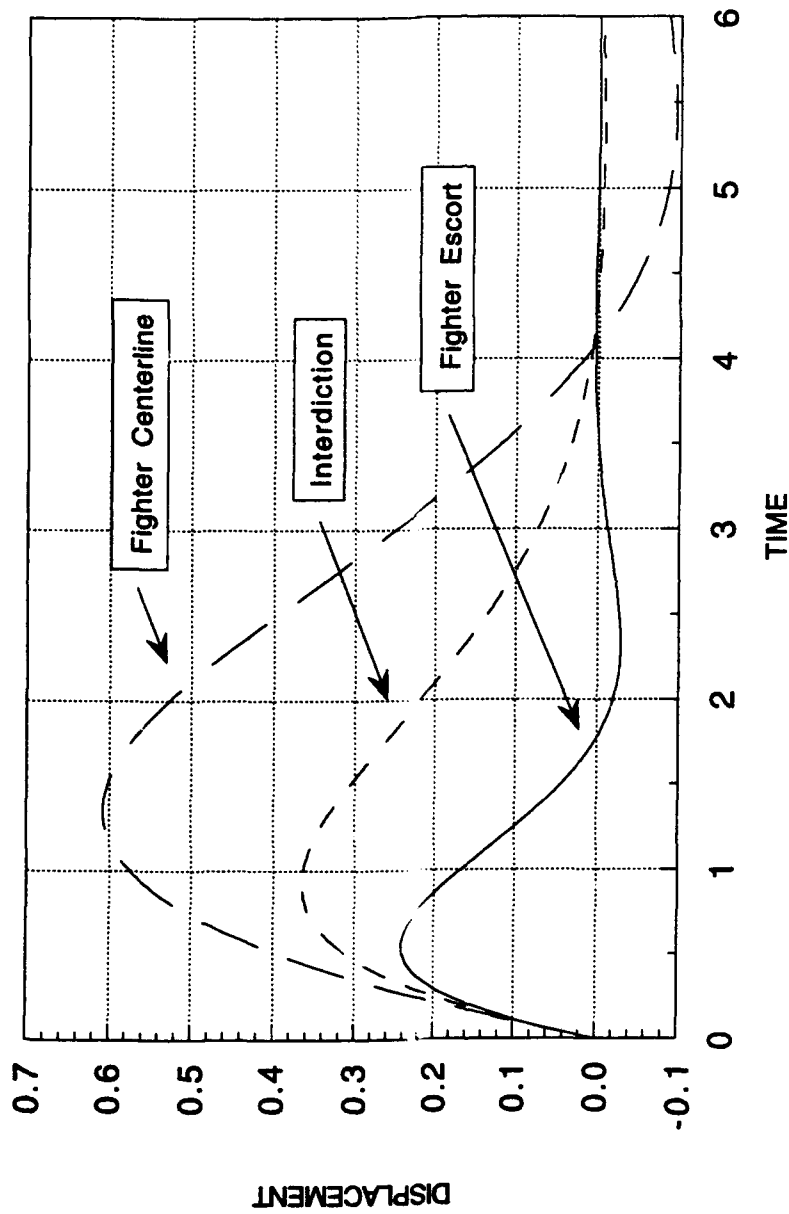
FLIGHT TEST ENVELOPE



F/A-18 NATURAL FREQUENCY VARIATION
AS A FUNCTION OF ALTITUDE



F/A-18 NATURAL FREQUENCY VARIATION
AS A FUNCTION OF AIRSPEED



**F/A-18 NATURAL FREQUENCY VARIATION
AS A FUNCTION OF LOADING**