DETERMINATION OF DEPARTURE SUSCEPTIBILITY AND CENTRE OF GRAVITY LIMITATIONS FOR CONTROL AUGMENTED AIRCRAFT

M. Medina
Project Engineer- Aircraft
Stability & Control & Performance
Israel Air Force

M. Shahaf
Aircraft Performance Analyst
Israel Air Force (Reserve)

Abstract

A six degree of freedom high fidelity digital computer simulation was developed by the Israeli Air Force for the General Dynamics F-16 Aircraft. The program is run using pilot inputs derived from operational high angle of attack maneuvers that proved to be departure susceptible. By simulating these maneuvers systematically for different configurations/center of gravity positions/flight envelope points and comparing the results with those for well documented and flight tested reference configurations, operational limits and relative departure susceptibilities were determined. The complexity of departure boundary evaluation is shown and the utility of digital simulation in the process is established.

I. Introduction

Full control augmentation as implemented in the General Dynamics F-16 Aircraft (and conceivably in most future combat aircraft) provides for exceptional flying qualities and, theoretically, departure proof flight. Extensive testing and operational experience have proven however, that the flight control system limiters which operate to keep the aircraft within the controlled flight envelope, can be broken. As a result, departures from controlled flight may occur. Engineering changes (Manual Pitch Override, Rudder Fade Out) and operating limits (airspeed and maneuver) have been used as a remedy to prevent departures, or at least permit automatic or manual recovery.

Unfortunately, pilots have been exceptionally successful in discovering new combinations of airspeed and maneuvers that will result in loss of control with sometimes irreversible consequences. At the same time, aircraft are operated in a bewildering array of configurations at varying center of gravity positions, each of which may exhibit radically different departure characteristics. This mounts a particular challenge for the Air Force that has to certify new operational configurations for which the aircraft's flight control system was not originally designed.

To date, aircraft departure susceptibilities and center of gravity limitations have been determined by flight test only. Configurations were grouped in categories and for each category, the apparent worst case configuration was flown to establish operational limits. As a result, some configurations are penalized (i.e. limited more than actually required) because they were never tested in flight to a less limited category. In addition, the maneuvers flown to establish the departure boundaries of aircraft configurations do not always reflect the requirements of modern air combat senarios.

This paper describes a systematic method for the determination of the departure susceptibilities and center of gravity limitations of a wide range of aircraft configurations using a six degree of freedom simulation of the F-16 aircraft. The maneuvers simulated are those employed in the ongoing flight test program and additional maneuvers which had proven to be highly departure susceptible in day to day operations.

The method was used to establish a ranking of relative departure susceptibility for the configurations investigated compared to flight tested reference loadings. Safe center of gravity and maneuver limitations are thus established for the required flight envelopes.

Since the method allowed for a maximum of differentiation between aircraft configurations, we were able to establish real limitations without penalizing individual loadings by assigning them to more limited maneuver categories. In addition, this method confirms the relative criticality of maneuvers that had not been flight tested until now. Maneuvers which were found to be critical in this work will be used in future Israeli F-16 flight test programs.

II. Flight Control Augmentation System

The F-16 Flight Control System was designed to provide the flexibility to achieve the goal of truly "eyes out of the cockpit" maneuvering in the combat arena. The performance goal established for the flight control system was to provide maximum performance in terms of usable lift and roll rate for maximum command, thereby achieving maximum combat effectiveness.

Several unique high-AOA enhancement features such as the AOA/g limiter, roll rate limiter, rudder authority limiter and the aileron to rudder interconnection (ARI) were incorporated into the flight control system. These features were designed to provide a high level of departure resistance throughout the air combat maneuvering envelope.

The AOA/g limiter is designed to prevent the pilot from maneuvering the A/C beyond its maximum allowable AOA to avoid longitudinal departures. The pilot command is reduced as the AOA increases (as a function of roll rate) as illustrated in Fig. 1.

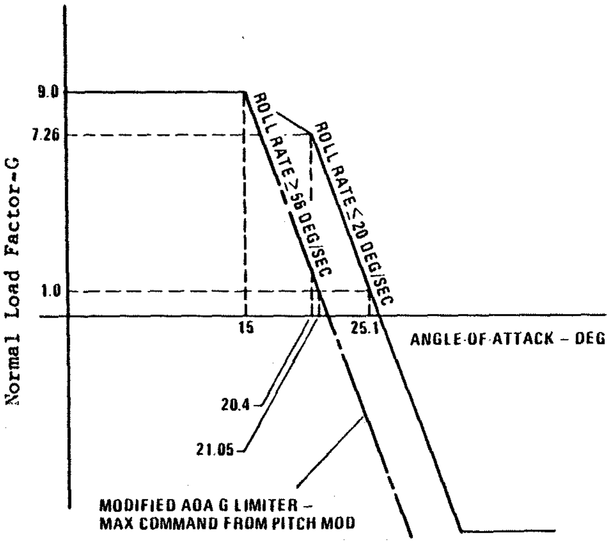


Figure 1. F-16 AOA/G Limiter

The roll rate limiter is designed to reduce the maximum roll rates during high-AOA maneuvering in order to prevent roll coupled departures. The maximum roll command is limited as a function of AOA, horizontal tail position and impact pressure as illustrated in Figure 2.

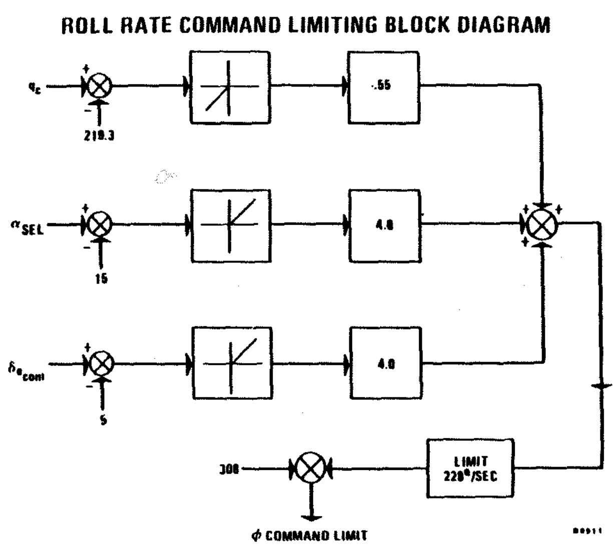


Figure 2. Roll Rate Command Limiter

The rudder command limiter is designed to prevent operation at large angle of sideslip (above 10°) at high AOA condition for which the A/C loses its lateral stability. The limiter cuts out the pilot rudder authority as a function of AOA and roll rate as shown in Figure 3.

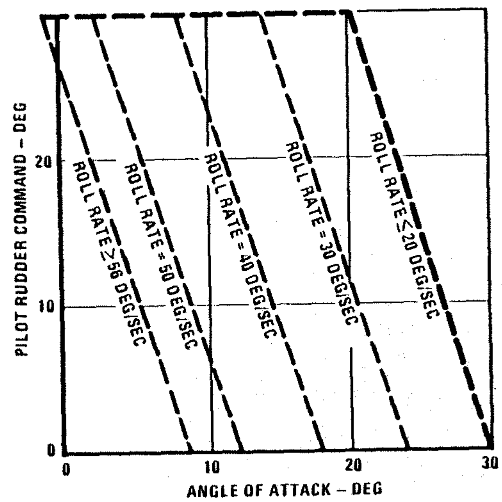


Figure 3. Rudder Authority Limiter

High-AOA roll coordination is automatically provided by the flight control system (i.e. no pilot coordination is required). This feature is achieved in terms of aileron to rudder interconnection and a roll rate to rudder crossfeed implemented in the flight control system.

Despite these sophisticated high-AOA features, operational experience has shown that the flight control system limiters can be broken and loss of control may occur. The requirement for a tremendous range of external store loadings led to the development of different control laws/limiters and corresponding F.C.S. settings, Cat I and Cat III, for air to air and air to ground configurations respectively.

Engineering changes that included yaw rate limiting (Anti Spin Mode) and Manual Pitch Override (MPO) were incorporated in the flight control system to increase departure resistance, prevent spins and permit automatic or at least manual recovery.

Nevertheless, non-recoverable departures from control flight may result during Air Combat maneuvers within the permitted flight envelope.

III. Basic Equations and Departure Mechanism

Aircraft behavior at high AOA air combat maneuvers is characterized by considerable Kinematic and Inertial coupling, which dominate the departure mechanism of the F-16.

The following equations describe the Kinematic coupling. Only the first order approximations are shown.

$$\dot{AOA} = Q - P \times \tan B \times \cos AOA + --- \quad (1)$$

$$\dot{B} = P \times \sin AOA - R \times \cos AOA + --- \quad (2)$$

The Inertial coupling is shown by the following equations. Only first coupled components are shown.

$$\dot{P} = (IYY - IZZ)/IXX \times Q \times R + --- \quad (3)$$

$$\dot{Q} = (IZZ - IXX)/IYY \times P \times R + --- \quad (4)$$

$$\dot{R} = (IXX - IYY)/IZZ \times P \times Q + --- \quad (5)$$

Complete equations can be found in reference (1).

An example of Inertial coupling is shown in a max g 360° roll maneuver as illustrated in Figure 4.

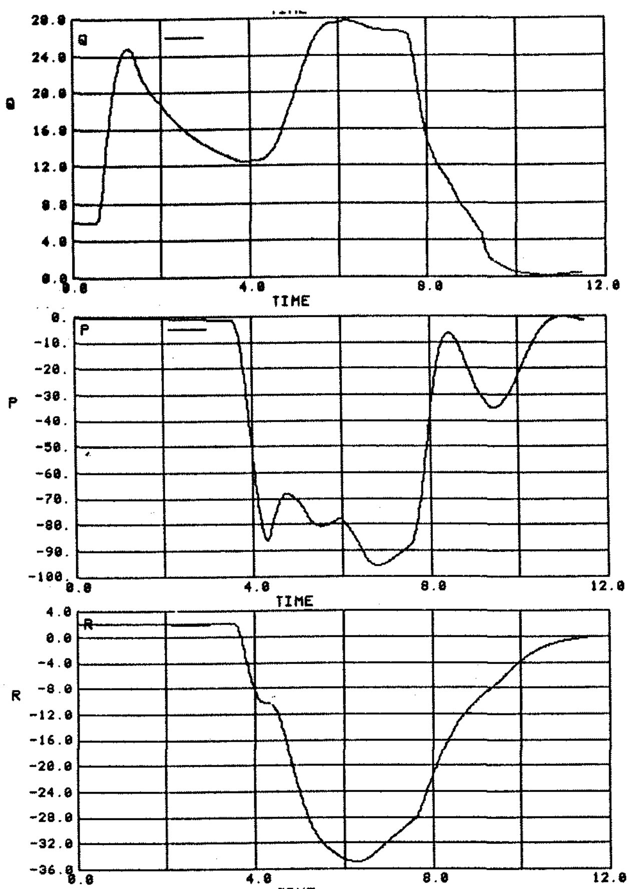


Figure 4. Inertial Coupling
A + 300G 40% 360° roll 30K/250kt.

Note the increase in pitch rate (Q) at simulation time of 4.5 sec. due to the positive P x R product of equation (4).

The kinematic coupling is also shown for the same maneuver. The AOA and angle of sideslip for that maneuver are illustrated in Figure 5. The angle of sideslip (Figure 5) follows the role rate (Figure 4) due to the P x AOA component of equation (2).

As previously discussed the F-16 flight control system measures and limits the angle of attack to remain within a maximum allowable value and prevents long. departures.

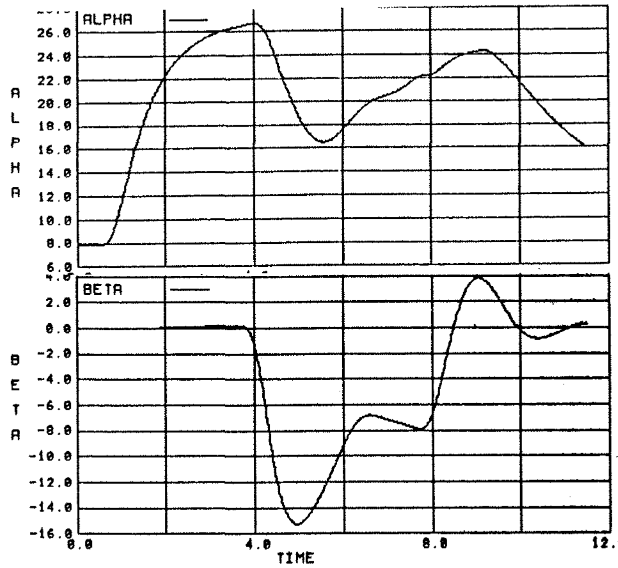


Figure 5. Kinematic Coupling
A + 300G 40% 360° roll 30K/250kt.

In the lat./dir. axis the F.C.S. provides roll coordination and lateral stability augmentation. However the angle of sideslip is neither measured nor limited from exceeding values beyond which stability can't be maintained.

Some high AOA coupled A.C.M. will therefore result in excursions of angle of sideslip which via kinematic coupling can cause AOA excursions beyond the AOA limiter and loss of control may occur.

IV. Configuration Certification Procedures

Certification procedures on the F-16 aircraft deal with two major issues:

1. Clearance of aircraft configurations:
This aspect relates to changes in mass, inertia and aerodynamic properties of the basic aircraft. Mass and inertia changes are the result of new engine and avionic system installations and/or structural reinforcements. Aerodynamic changes in this context include planform or shape changes of the external aircraft configuration such as large inlet and Increased Area Horizontal Tail (IAHT) or changes to the scheduling of control surfaces.

2. Clearance of external store configurations:
This aspect relates to changes in mass, inertia and aerodynamic properties of the aircraft configuration due to external store loadings. All aircraft external store configurations are divided into two major operational categories, Cat I and Cat III. Air to Air and Air to Ground configurations after weapon deployment are generally required to be certified to Cat I limits, for which the F.C.S. limiters provide maximum freedom for air combat maneuvers. All other configurations including a wide range of air to ground and highly asymetric configurations are usually certified to Cat III limits, for which the F.C.S. limiters restrict the maneuvering envelope significantly.

Contractor Approach

During the full scale development phase of the F-16 aircraft program a number of reference Air to Air and Air to Ground configurations were certified by flight test to Cat I and Cat III limits, respectively. When there is a requirement to clear a new configuration of aircraft or external stores to Cat I or Cat III limits, and it is not possible to do so by similarity to one already tested, flight testing is necessary to demonstrate Cat I/Cat III capability.

Due to economic realities and safety precautions, high AOA flight testing has been limited to several representative (worst case) configurations subjected to selected maneuvers within a restricted envelope (high altitude only).

As a result, two major deficiencies are observed:
1. Configurations (aircraft or external stores) may be required to operate under the more constraining Cat III limits solely because flight testing has not been conducted.
2. Operational experience has shown that vigorous ACM may result in departures from controlled flight with potentially catastrophic consequences even when operating a contractor certified Cat I configuration.

These deficiencies triggered a considerable effort by the IAF to develop a new, safer and more economical method to satisfy the ever increasing operational requirements.

IAF Approach

The IAF method is based on a high fidelity six degree of freedom simulation of the F-16 aircraft. The simulation uses contractor supplied 6DOF data bases which consist of:
- Full aerodynamic model of the basic aircraft obtained through wind tunnel testing and corrected by flight test.
- Aero increments for external store configurations and basic aircraft configuration changes obtained from wind tunnel and/or flight tests.
- Mass and inertia properties of aircraft and external stores.
- Engine data, including thrust and fuel consumption data, as well as engine dynamic characteristics.

The aircraft flight control system is fully integrated into the simulation for all FCS switch positions: LG up/down, CAT I/CAT III, MPO, Air Refueling and WOW.

The simulation is run from an initial user defined trim condition that includes configuration weight, inertia, c.g. position, velocity, altitude and type of maneuver. The user then "flies" the simulated aircraft by introducing pilot stick, throttle and pedal commands. The simulation solves the six degree of freedom equations of motion and as output provides time histories (numerical and graphical) of all aircraft and maneuver variables.

The 6DOF simulation is described schematically in Figure 4.

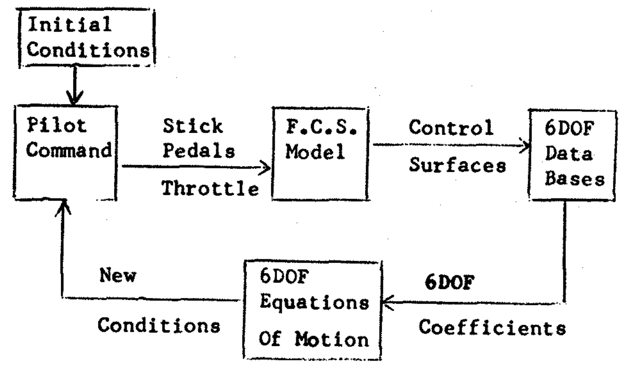


Figure 4. 6DOF Simulation Description

The 6DOF program was validated by simulating flight test maneuvers and comparing time histories to telemetry data from actual tests. This was done for several representative configurations for which flight test data was available. A comparison between flight test and simulation data is presented in Figure 5.

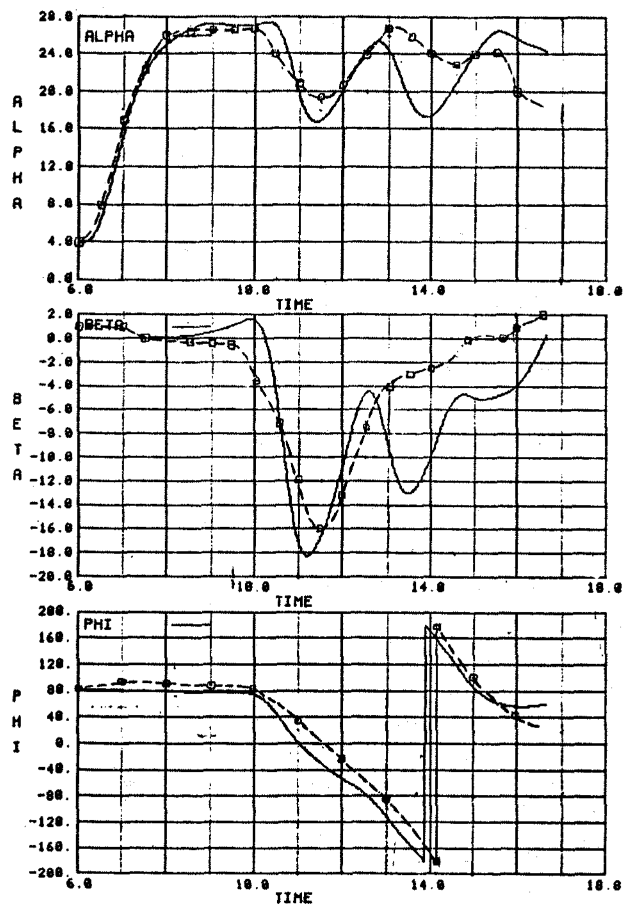


Figure 5. Flight Test Vs. Simulation Comparison
B + 300G Max G 360° roll 35K/250kt.
—— Simulation -□-□- Flight Test

This correlation (between simulation and flight test data) is considered to be excellent when compared to the fairly large bandwidth of flight test results encountered in repeated maneuvers, particularly in the High-AOA environment. This subject is further illustrated under "Timing Effect" in the technical discussion section (see Figure 11).

New configurations are certified by systematically simulating a set of maneuvers for a range of altitudes and velocities at representative mass and inertia conditions for different center of gravity locations. Output data is then compared to the worst case data of a similar reference configuration also provided by simulation. A total number of approximately ninety runs are required for a single configuration certification. The simulation is near real time, and the whole certification process can be completed within one day.

A reference configuration in the IAF method is a configuration for which the following conditions exist:

1. Flight test data is available and correlates well to the simulation.

2. Extensive operational experience has accumulated without any indication of departure sensitivity.

The term reference configuration refers to this definition throughout this paper.

For a Cat I certification effort: If it is possible to determine an operationally acceptable aft center of gravity location for which critical aircraft maneuver parameters (AOA, sideslip) reach values that are less or equal to those of the reference configuration over the whole simulation matrix, the configuration will be cleared to Cat I with that aft c.g. limitation. If such a c.g. does not exist, the configuration will be limited to Cat III.

For a Cat III certification effort: The same method as above is used except that in the absence of an acceptable aft c.g. location, conservative flight envelopes and maneuver restrictions will be determined.

The set of maneuvers used in the IAF method consists of those employed in the flight test program of the aircraft and additional maneuvers which had proven to be highly departure susceptible in day to day operations. While the IAF method employs several maneuvers, only two will be discussed in detail in the framework of this paper.

1. Maximum g - 360 degree roll maneuver, which was taken from flight tests.

2. Maximum g - bank to bank maneuver which was derived from operational experience.

For an illustration of the above two maneuvers, refer to Figure 8.

V. Technical Discussion

The major effects contributing to departure susceptibility encountered during the development of the IAF certification method, and its application to the determination of aft c.g. limits for investigated configurations, is discussed and illustrated in the following paragraphs.

Maneuver Criticality

Figure 8 shows a comparison between a 360° maximum g roll and a bank to bank maneuver initiated at the same conditions.

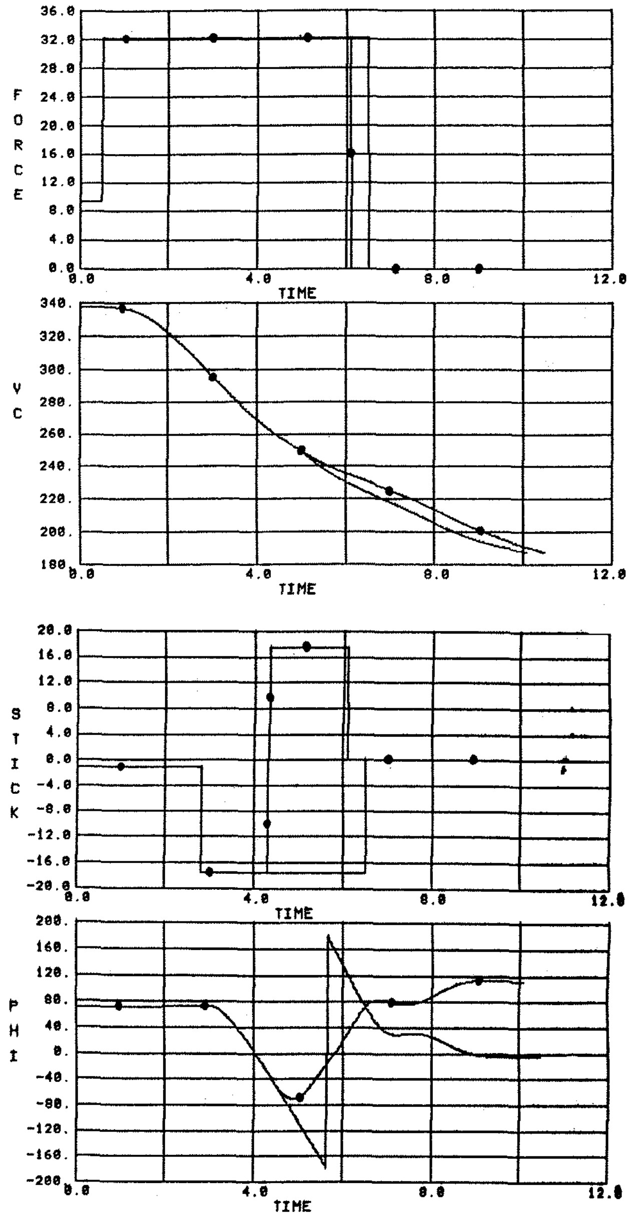


Figure 8. Continued on next page.

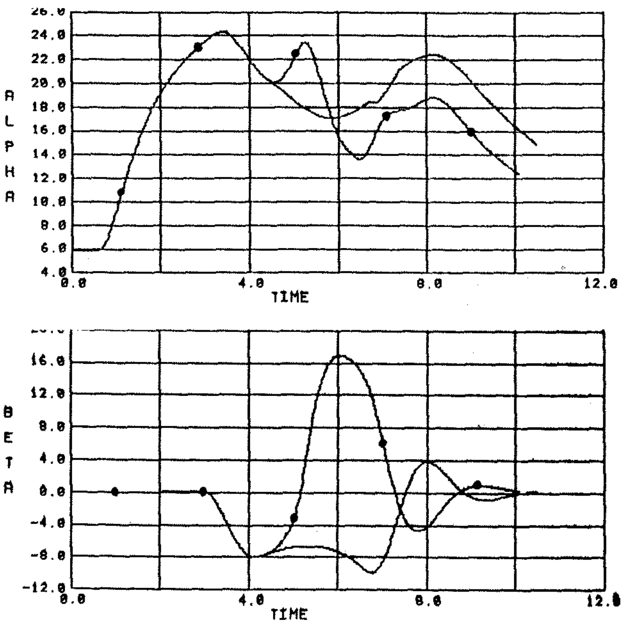


Figure 8. Maneuver Effect - B.T.B. vs. 360° roll
B + 300G-40% 30K/300kt.
——— 360° roll -•—•- B.T.B.

The comparison shows that although both maneuvers obtained a maximum AOA of 24 degrees, a maximum 17 degree angle of sideslip was reached by the bank to bank maneuver vs. only 10 degrees for the 360 degree roll. This indicates that the bank to bank maneuver is more critical than the 360 degree roll for this configuration and flight condition.

Velocity Effect

Figure 9 shows a comparison between a maximum g 360 degree roll conducted at 300 knots and at 250 knots, at the same altitude.

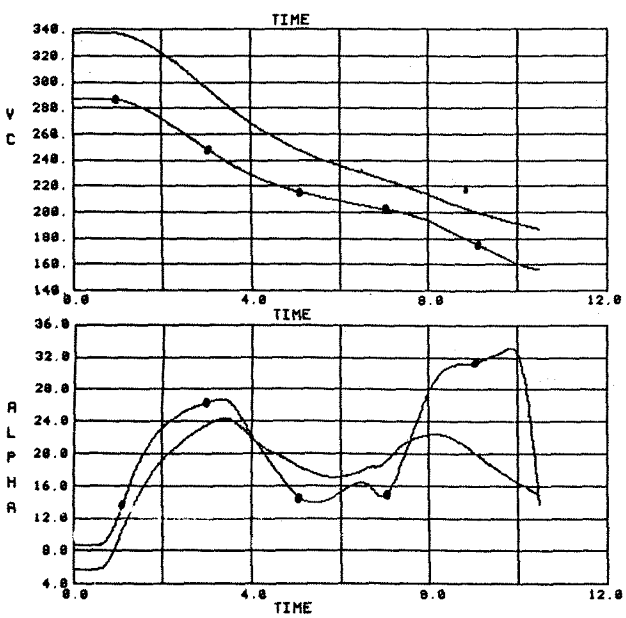


Figure 9. Continued on next column.

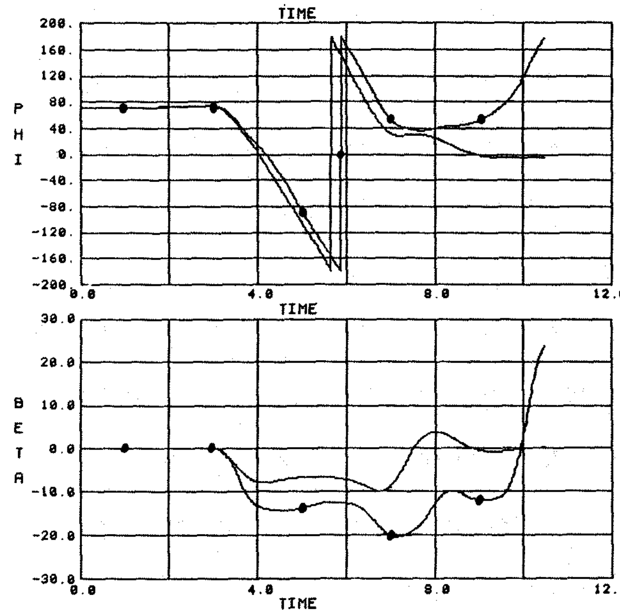


Figure 9. Velocity Effect-250kt. vs. 300kt.
B+300G - 40% 360°roll 30K
———300kt. -•—•-250 kt.

While the roll rates are very similar for both conditions, a maximum 20° angle of sideslip developed during the 250kt. maneuver, while only 10° were obtained during the 300 kt. maneuver. This demonstrates the sensitivity of the maneuvers to the velocity at which they are conducted.

Timing Effect

One of the most problematic issues simulating ACM at high AOA is the timing of the pilot control inputs. As shown in Figure 10, a ½ second difference in applying lateral stick command in a maximum g bank to bank maneuver may determine whether the aircraft departs or remains under controlled flight.

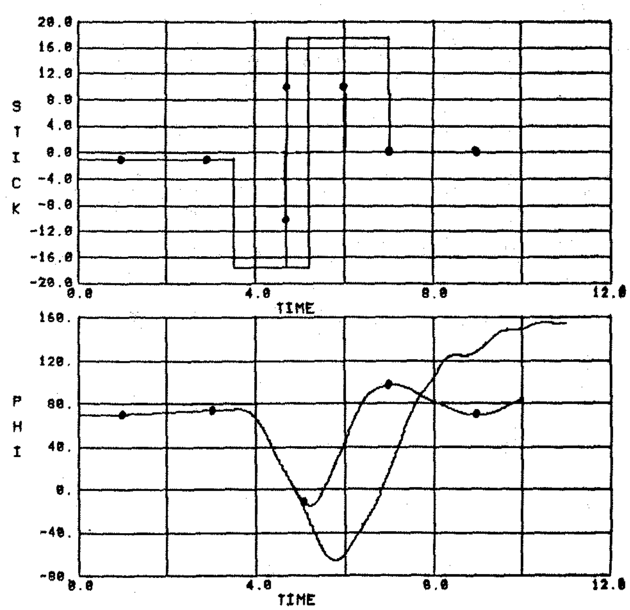


Figure 10. Continued on next page.

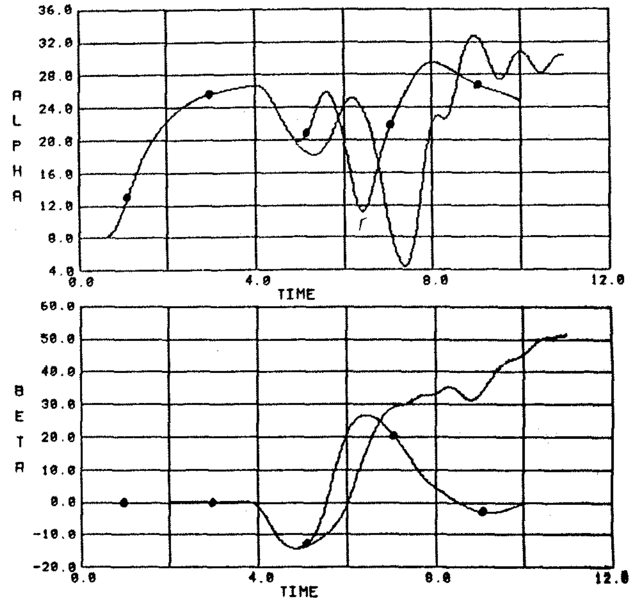
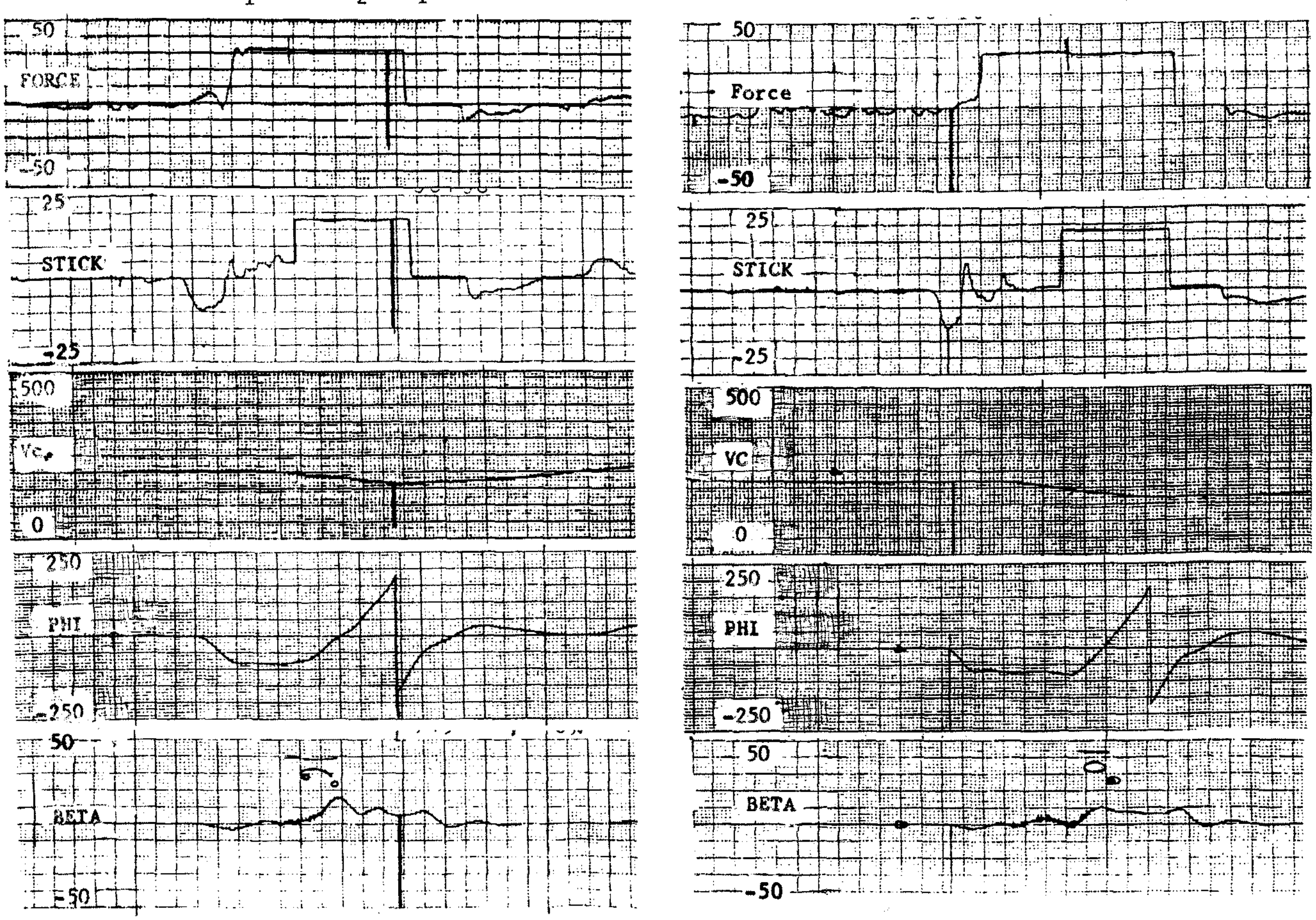


Figure 10. Timing Effect (Simulation)
A+300G-38% B.T.B. 30K/250kt.
—•—•— T_1 ——— T_2 ($>T_1$)

The timing effect is often encountered during flight tests. Figure 11 shows flight test data of two maximum g 360° roll maneuvers performed by the same pilot at the same aircraft/flight conditions.

For these type of maneuvers pilots are briefed to initiate the maximum g turn at a speed above the maneuver specified speed, wait for the speed to bleed down (to the maneuver speed) and then initiate the roll. Due to different initial entry velocities the pilot had to wait for one more second (between long. and lat. commands) resulting in 10° of sideslip in the second roll vs. 16° in the first one.

The critical timing for a given maneuver can easily be determined through a trial and error approach using the simulation. Statistically, pilots will encounter almost every combination of control inputs that engineers can simulate.



First Maneuver

Second Maneuver

Figure 11. Timing Effect (Flight Test)
Clean Aircraft 36% 35K/200kt.

Weight and Inertia Effect

Increased weight and inertia can influence departure characteristics dramatically. This effect is demonstrated in a maximum g 360° roll maneuver whose time histories are shown in Figure 12 for a given Cat I certified configuration.

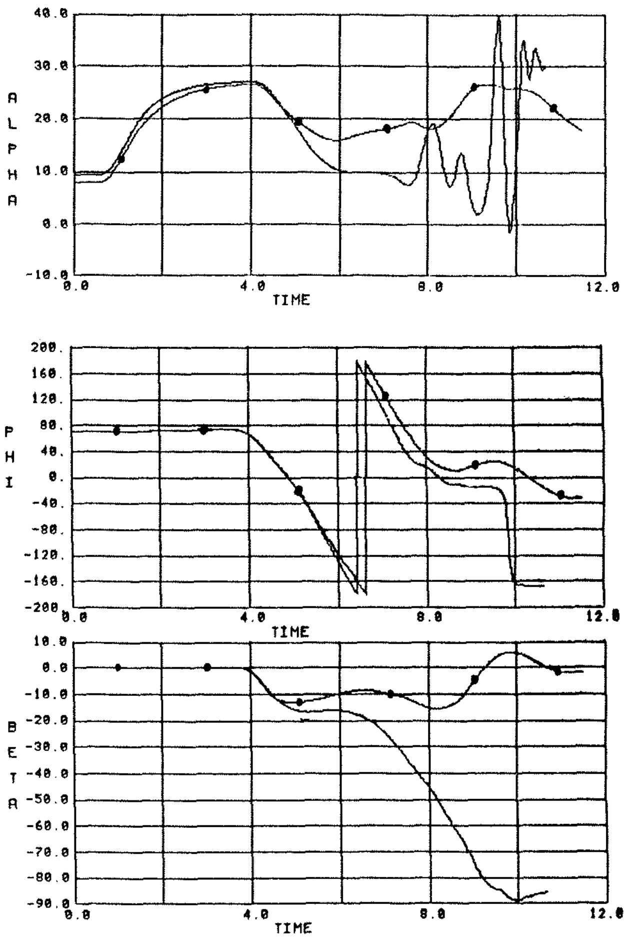


Figure 12. Weight and Inertia Effect
B+300G 38% 360° roll 30K/250kt.
—●—●—Basic ——— +15%

A 15% increase in weight and a commensurate increase in inertia caused departure of this particular configuration, a result which prevents certification at the Cat I level.

Aerodynamic Effect

The aerodynamic contribution of aircraft shape or external store differences is significant in determining departure characteristics. Figure 13 shows the difference between a single and a two seat aircraft in a maximum g 360° roll for a critical external store configuration (300 gal. centerline tank) at the aft c.g. limit.

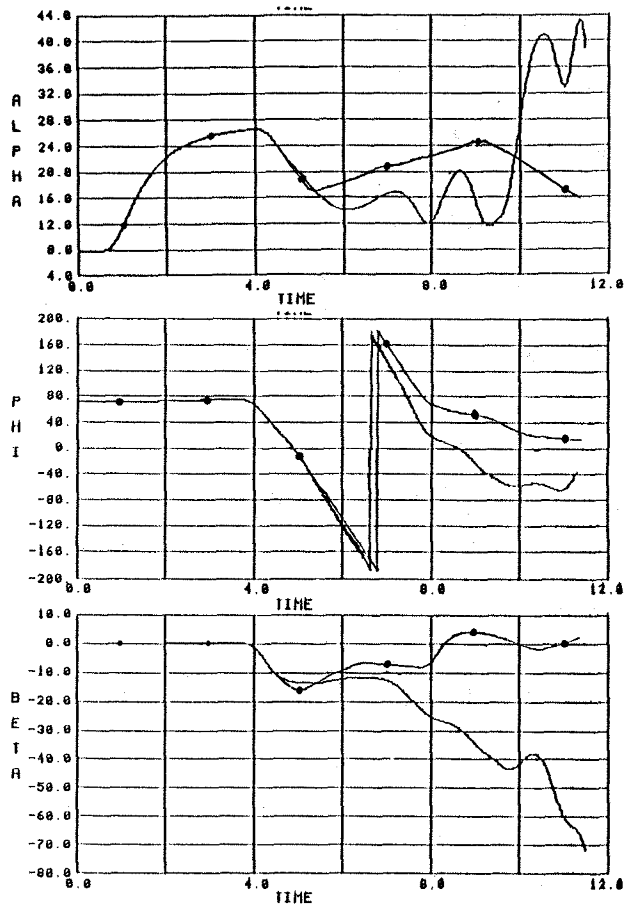


Figure 13. Aerodynamic Effect- A+300G vs. B+300G
40% 360° roll 30K/250kt.
—●—●— A+300G ——— B+300G

In this case the two seater departs from controlled flight while the single seater remains safely within the envelope.

Center of Gravity Effect and Aft C.G. Limit Determination

The two seater configuration with a center line tank is used as an example to demonstrate the center of gravity effect on the departure characteristics and to illustrate the IAF method of aft c.g. limit determination. Figure 14. shows a comparison of this configuration run at two different c.g. locations (one at the contractor recommended aft limit, and one at 2% Fwd.) in a maximum g 360° roll maneuver.

As shown, the 40% case departs from controlled flight whereas the 38% one remains well within the envelope. Note that the excursion in the AOA at the end of the maneuver is caused by the kinematic coupling from the large excursions in the angle of sideslip.

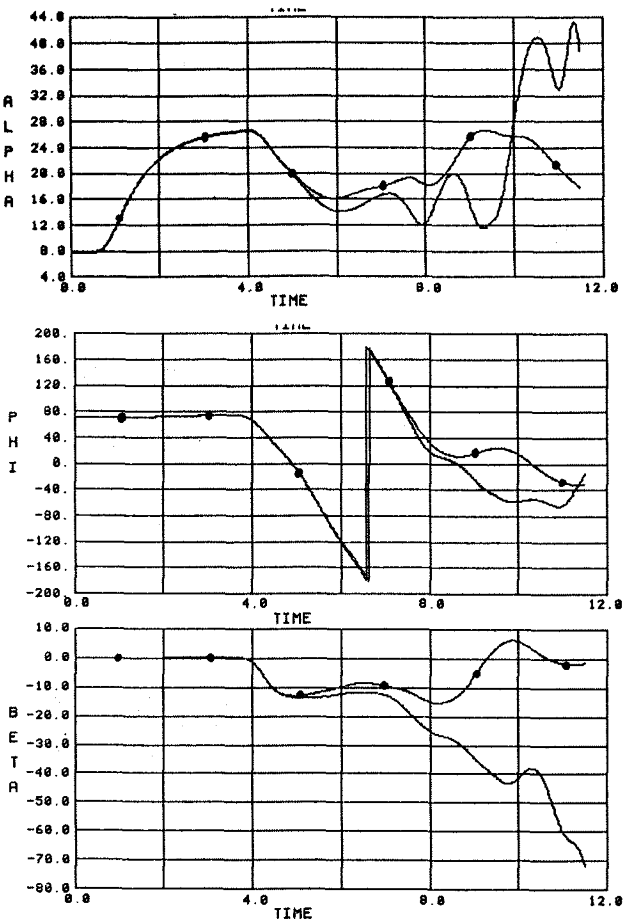


Figure 14. Center of Gravity Effect
B+300 gal. 360° roll 30K/250kt.
—— 40% —•—•— 38%

To establish the applicability of this new forward c.g. location as a valid c.g. aft limit for the above configuration, it is compared at the same conditions to the relevant reference configuration (single seat a/c with center line tank) at its aft c.g. limit. The comparison is shown in Figure 15.

Clearly, the maximum angles of attack and sideslip are similar, 27° and 15° respectively. This indicates similar departure characteristics for these two configurations at the specified conditions.

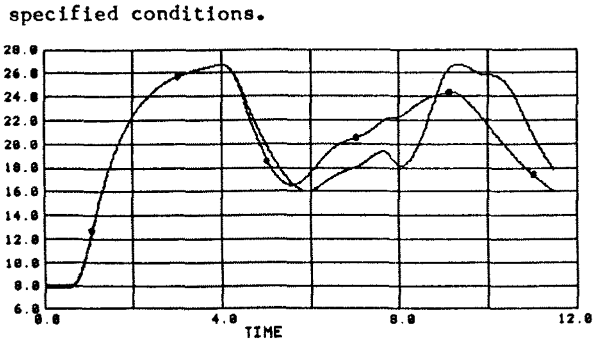


Figure 15. Continued on next column.

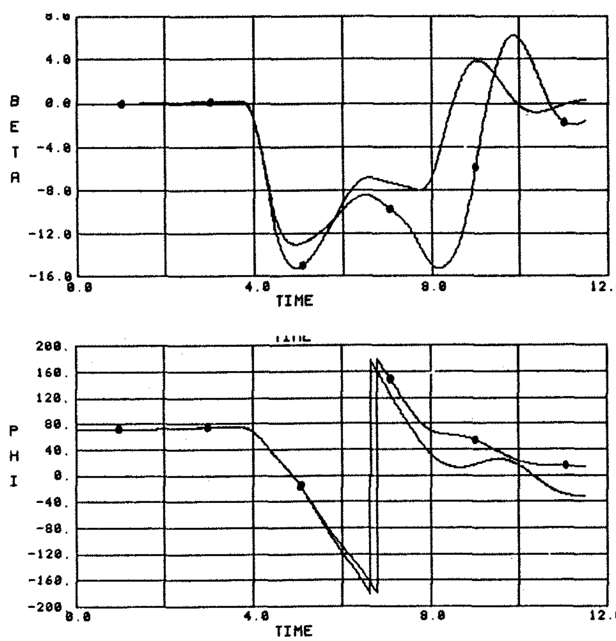


Figure 15. C.G. Limit Verification
300G 360° roll 30K/250kt.
—— B - 38% —•—•—A - 40%

As previously described in this paper the same comparisons are conducted throughout the whole test matrix for different altitudes, velocities, mass, inertias and maneuver conditions. Based on the results, the new aft c.g. limit is determined.

VI. Conclusions

The work conducted by the IAF to determine departure susceptibilities and center of gravity limitations using a high fidelity 6DOF computer simulation of the F-16 aircraft, has proven extremely valuable to -

1. Determine safe center of gravity limits for several Cat I configurations with centerline fuel tank. When operated under the original, more lenient limitations recommended by the contractor, these configurations had exhibited unacceptable departure characteristics under ACM conditions.

2. Reclassify configurations that had been cleared to Cat I limits in the original F-16A/B aircraft. When simulated with the newer F-16C/D aircraft with increased weight/inertia, several external store configurations had to be downgraded to Cat III to prevent potential ACM departures.

3. Clear new IAF external store configurations that incorporate small changes when compared to configurations certified by the contractor, to acceptable operating limits.

Due to the considerable agreement between the simulation and actual aircraft behavior, the 6DOF program and database are also used as a development tool in the effort to design flight control system modifications for the F-16 aircraft.

With the help of this program the IAF has developed a sophisticated departure warning system, which will be test flown this summer in Israel. The system picks out critical data from the flight control system and determines the criticality of a maneuver from the angle of attack, pitch rate and the roll rate. The simulation was particularly useful in determining the sensitivity of the alarm.

It is evident, that high fidelity 6DOF digital computer simulations in conjunction with baseline flight tests can reduce significantly the need for additional flight testing in configuration certification programs and as development tools for flight control modifications.

The work presented here indicates that this is true even for the boundaries of the flight envelope where simulation has traditionally been suspect.

While the economic and safety benefits of simulation methods are obvious, the exact criteria under which they can be used in configuration certification will continue to provide a challenge to the authors.

VII. References

1. Seckel, Edward, Stability and Control of Airplanes and Helicopters, Academic Press, N.Y-London, 1968.

2. Cochi, R.J., Detailed Test Information Sheet (TIS) For The 1/9-Scale F-16A Force Model Wind Tunnel Test March 1982 at GDLST, General Dynamics Report TIS GA101-14, Jan. 20, 1982.

3. King, C.L., and Medrano, J.S., F-16 Aerodynamic Data For The F-16C And The Revised Leading Edge Flap Schedule, General Dynamics Report 16PR11231, September 1983.

4. Anon, F-16 Block 15 Stability and Control Substantiation Report: General Dynamics Report 16PR11949, September 1981.

5. Ziehe, D.C., F-16 Block 25 Stability and Control Substantiation Report: General Dynamics Report 16PR3179; October 1983.

6. Walker, J.E., F-16 Simulation Data Package, General Dynamics Report 16PR3749, May 1984.

7. Shahaf, M. and Rivlin, T., A Modern Approach to Aerodynamic and Structural External Store Compatibility in Fighter Aircraft, 29th Israel Annual Conference on Aviation and Astronautics, 1987.

GLOSSARY

A-	F-16A
A/C-	Aircraft
ACM-	Air Combat Maneuvers
Alpha-	Angle of Attack
AOA-	Angle of Attack
B-	F-16B
B-	Angle of Sideslip
Beta-	Angle of Sideslip
B.T.B.-	Bank to Bank
Cat-	Category
C.G.-	Center of Gravity
DIR.-	Directional
F.C.S.	Flight Control System
Force-	Longitudnal Stick Force
g-	Normal Acceleration
IAHT-	Increased Area Horizontal Tail
IXY-	Moment of Inertia - X Axis
IYY-	Moment of Inertia - Y Axis
IZZ-	Moment of Inertia - Z Axis
K-	1,000 feet
kt.-	knots
Lat.-	Lateral
LG-	Landing Gear
MPO-	Manual Pitch Override
P-	Roll Rate
PHI-	Bank Angle
Q-	Pitch Rate
Qc-	Dynamic Pressure
R-	Yaw Rate
Stick-	Lateral Stick Force
Time-	Simulation Time
T_1, T_2-	Time Hacks
Vc-	Calibrated Airspeed
WOW-	Weight on Wheels
300 G-	300 gallon centerline tank
α sel-	Selected angle of attack
δ e com-	Horizontal tail position command
Ø-	Bank angle
$\dot{}$-	Time derivative