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INTEGRATED T&E APPROACH TO STORE SEPARATION - DIM PAST, EXCITING FUTURE

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ABSTRACT

Integrated Test and Evaluation (T&E) approach to store separation describes the present Navy concept, which utilizes a combination of Computational Aerodynamics, Wind Tunnel Testing and Flight Testing to ensure safe separation of stores in the most timely and cost effective manner possible. The Navy approach, which has been undergoing continuous development during the past decade, is unique among the three services in that it is performed by an Integrated Product Team (IPT), which belongs to one organization that is physically co-located. During the past several years, this approach has proven itself by providing considerable time and cost savings to the A-6E/TDU-34, F-14/GBU-24, F-18C/JSOW, F-18C/JDAM, and DC-130/BQM-74 programs. It is presently being applied to the F-18E/F aircraft/store integration program, with the potential of not only reducing the cost, but also ensuring the success of the program.

NOMENCLATURE

BL: Aircraft Buttline, positive outboard, in.
C_l: Rolling moment coefficient about C.G.
C_m: Pitching moment coefficient about C.G.
C_n: Yawing moment coefficient about C.G.
C_N: Normal force coefficient, positive up.
C_Y: Side force coefficient, positive to right
FS: Aircraft Fuselage Station, positive aft, in.
M: Mach number
P: Store roll rate positive rt wing down. deg./sec
PHI: Store roll angle positive rt wing down. deg.
PSI: Store yaw angle, positive nose right, deg.
Q: Store pitch rate, positive nose up, deg./sec
R: Store yaw rate, positive nose right, deg./sec
THE: Store pitch angle positive nose up, deg.
WL: Aircraft Waterline, positive up, in.
Z: Store C.G. location, positive down, ft.
α: Angle of attack, deg.
α_i : Upwash angle, positive up, deg.
δ_i: Sidewash angle, positive outboard, deg.

BACKGROUND

In the early days, store separation was conducted in a hit or miss fashion - the stores would be dropped from the aircraft at gradually increasing speeds as the store came closer to or, in some cases, actually hit the aircraft. This in some cases led to loss of aircraft, and made test pilots reluctant to participate in store separation flight test programs.

During the 1960's, the Captive Trajectory System (1) (CTS) method for store separation wind tunnel testing was developed. This provided a considerable improvement over the hit or miss method, and became widely used in aircraft/store integration programs prior to flight testing. However, it was not utilized in an integrated approach, since the group conducting the wind tunnel test was generally separated both in organization and location from those responsible for conducting the flight test program and determining the safe separation envelope. Furthermore, since fairly small models had to be used in the wind tunnel tests, in many cases the wind tunnel predictions did not match the flight test results, and no mechanism was in place to resolve the wind tunnel/flight test discrepancies.

During the late 1970's and early 1980's Computational Aerodynamics had finally matured to the point of providing a solution (2,3,4) for a store in an aircraft flowfield. However, instead of leading to a renaissance in store separation methodology, it mostly led to an ongoing argument among the three groups. The Computational Fluid Dynamicists (CFD) claimed that they could replace the wind tunnel, the Wind Tunnel (WT) engineers said (correctly, since one CFD calculation is useless in calculating a store's trajectory) that the CFD'rs were unaware of the complexity of the problem, and the Flight Test engineers (FT) said that neither group could provide them with the necessary data to conduct a successful flight test program.

During the same time period the Influence Function Method (IFM) was also developed(5). This method allowed for a straight forward estimate of store loads based on the aircraft induced flowfield that the store sees, and seemed to offer a bridge to the disagreement between the CFD and WT community, since it could provide store loads in the entire aircraft flowfield with just one CFD calculation. However, except for Grumman and the Air Force, this method did not readily gain acceptance in the store separation community. Furthermore, even then an integrated T&E approach was not truly implemented, since the FT community was still separated both physically and organizationally from the CFD and WT community.

INTRODUCTION

Originally, the Navy utilized either aircraft or weapon contractors to perform the testing and analysis necessary to clear a new aircraft/weapon configuration. This approach had several drawbacks, not the least of which was that the contractor's involvement usually ended with the start of the flight test program. This meant that the contractors had no mechanism for using the flight test results to improve their store separation methodology. Furthermore, no two contractors used the same approach to predict safe weapon separation prior to the flight test.

About ten years ago, the Navy decided to develop an in-house capability at the Naval Air Warfare Center, Aircraft Division (NAWCAD) to conduct the analyses necessary for a store separation flight test program. Not being burdened by any pre-existing capability in this area, the Navy was able to pick among the best attributes of the techniques used by contractors and the Air Force.

The NAWCAD has adopted a truly integrated approach to store separation. As may be seen in TABLE A, NAWCAD realized that the three legs, analysis, wind tunnel and flight test are not only intimately related to each other, but also provide essential information that can improve the product of each group. Not only is the entire program conducted by the same group, but ideally by one individual. The computational aerodynamics, wind tunnel test planning, trajectory simulation and flight clearance for each point in the flight test program are all done by the same person, who does not seek to be an expert in CFD methods or wind tunnel testing, but is competent in their use and knows their limitations. This individual not only has the authority, but also the responsibility for ensuring that the flight test program is conducted both safely and cost effectively.

Since the most critical feature that determines a store's trajectory is it's carriage load, the first step in the NAWCAD approach is to estimate the region of the flight envelope that might have the worst carriage loads. This is done by deriving an estimate of the aircraft flowfield. The primary analytic tool for this purpose is the PAN AIR program(6). With this code, complex aircraft configurations, with a variety of attached stores, can be modeled with ease. Furthermore, changes in configuration shape such as fuel tanks, pylons and other stores can be easily incorporated. PAN AIR models for most Navy aircraft have been generated and are readily available when aircraft or store configuration modifications are envisioned.

Although the PAN AIR program has demonstrated the ability to predict complex aircraft flowfields in the linear speed regime, yaw head probe flowfield test data, when available, are used to validate the PAN AIR aircraft models. At present, extensive yaw head probe test data are available at various Mach numbers and aircraft attitudes for both the F-18C and F-18E aircraft, and show good correlation with PAN AIR predictions up to $M = 0.95$.

The Influence Function Method is then used to determine the effect of the aircraft flowfield on the store loads. This first requires a determination of the store's influence coefficients. This is a relatively simple procedure(7,8) using the IDL/IFM code. The IDL/IFM code also provides an estimate of the store's aerodynamic freestream coefficients.

Using the aircraft flowfield and store influence coefficients, an estimate of store loads is made everywhere in the flowfield, including carriage. The estimated store loads are then checked by using the PAN AIR program to calculate the store loads at carriage. The store carriage loads, as well as freestream coefficients determined either from wind tunnel test data or IDL and PAN AIR predictions, are then input in a Six-Degree-Of-Freedom (6-DOF) program to simulate the store's trajectory prior to the wind tunnel test.

Store inertial and mass properties, as well as auto-pilot and ejection characteristics are the other needed inputs in the 6-DOF program, which is then used to examine the store launch/jettison characteristics throughout the aircraft operating flight envelope. The flight test program is then started for a benign condition, usually at M = 0.80, and the flight test results (generally both telemetry and photogrammetrics for the first flight) are reviewed to ensure that the pre-flight predictions match the flight test results.

EXAMPLES OF INTEGRATED T&E

F-18C/JSOW

Extensive wind tunnel flowfield and loads data were acquired at the DTRC 7'x10' transonic facility under the Joint Stand-Off Weapon (JSOW) program for the F-18C aircraft.

CTS loads for the JSOW, however, did not match the carriage loads that were measured on the opposite F-18 aircraft pylon at M = 0.95. Since the JSOW jettison simulations using these carriage loads indicated that the store might impact the fuel tank mounted on the inboard pylon while the CTS data indicated this to be a safe jettison condition, it was felt that the discrepancy between the CTS and carriage loads had to be resolved. A subsequent F-18C/JSOW wind tunnel test was conducted at the 8'X8' CALSPAN transonic facility at Buffalo. As may be seen in Figures 1 and 2, only the DTRC CTS data at M = 0.95 and the CALSPAN data at M = 0.90 show a sudden change in character near carriage, and have lower carriage measured load for C_n, which is critical for this case since the store's tail tends to yaw into the tank on the inboard pylon.

Previous analysis had shown$^{(9,10)}$ that the PAN AIR and TranAir programs could give a good prediction of the F-18 aircraft flowfield, up to M = 0.95. Initial calculations using the PAN AIR program to predict the JSOW CTS loads were inconclusive; although the predicted trends seemed to verify that the pylon measured carriage loads were correct, the PAN AIR predicted magnitudes were considerably lower than the test data. Since PAN AIR can not predict transonic effects, it was impossible to determine whether the CTS measured data were incorrect or if non-linear shock effects might be causing the inconsistencies between the CTS data and carriage loads.

The PAN AIR calculations were repeated for a selected number of store locations using the TranAir program. The TranAir results confirmed$^{(11,12)}$ that the sudden decrease seen in the CTS measured loads near carriage was not due to transonic effects, Figures 3 and 4. Therefore, during the flight test program, the M = 0.90 data was discarded and M = 0.95 CTS and carriage loads were used to predict the trajectory for M = 0.90.

As may be seen in Figure 5, this approach resulted in an excellent match with flight test telemetry data, which could not have been achieved if the test data at M = 0.90 had been used. A further indication that the CALSPAN measured aircraft induced carriage moments at M = 0.90 were incorrect may be seen in Figure 6, where pitch, yaw and roll rate telemetry test data for three separate flights (two at M = 0.95, one at M = 0.90) are compared. It is clear from this figure that the aircraft induced flowfield at M = 0.90 is as severe as that at M = 0.95.

F-18C/JDAM

A wind tunnel test for the Joint Direct Attack Munition (JDAM) MK-84 configuration was conducted at the 8'X8' CALSPAN facility at Buffalo. Both grid and trajectory test data were taken for eight different F-18C configurations. Carriage load test data, with the JDAM/MK-84 mounted directly on the aircraft pylon, were also taken for four aircraft configurations.

When the CTS data at M = 0.90 were examined, it seemed to be a case of dejavu all over again. As may be seen in Figures 7 and 8, the CTS measured moments suddenly change character and are smaller in magnitude near carriage than at M = 0.80. In this case the C_m (rather than C_n, as was the case for the JSOW) appeared to be unreasonably low. There appeared to be an anomaly for the F-18C aircraft at M = 0.90. Based on the results for the JSOW program, it was decided that M = 0.95 grid data would be used to predict the M = 0.90 trajectories.

As may also be seen from Figures 7 and 8, the pylon measured loads are also considerably higher than those measured by the CTS in the closest position to carriage (about 2 inches full scale). The effect of using the CTS grid data and ignoring the carriage loads may be seen in Figure 9, which compares the predictions with telemetry test data for the JDAM store jettisoned from the inboard F-18C/D pylon at M = 0.82. Clearly, wind tunnel test data that does not account for the loads increasing near carriage can cause the attitudes to be underpredicted, which is unacceptable for safety of flight.

Figure 10 compares the pre-test predictions with flight test telemetry data for the JDAM store at M = 0.90. The original predictions linearly interpolated the M = 0.80 and 0.95 wind tunnel data. It is clear from this figure that, unlike the M = 0.90 data for JSOW, the JDAM grid and carriage data at this Mach number were correct, and the flight test results confirm that the aerodynamic loads for this store decrease as the Mac number increases from 0.80 to 0.90. CFD computations and additional wind tunnel testing will be used in an attempt to determine the cause of the anomaly at M = 0.90.

F-18E/JSOW

A comparison of the clean (no pylons) F/A-18C and F/A-18E aircraft flowfields was previously undertaken$^{(13)}$ to determine if the F/A-18E flowfield might cause problems in safely separating stores relative to the F/A-18C. A PAN AIR model was developed and validated using wind tunnel pressure data. This preliminary analysis indicated the F/A-18E increased inlet area, coupled with the increased aircraft area ratio, had a significant impact on the aircraft flowfield, which might have a detrimental effect on store separation.

Prior to the January 1995 F/A-18E/F Series III wind tunnel test at AEDC$^{(14)}$, flowfield angularity predictions were made utilizing the PAN AIR model previously developed. Comparisons between these test data and analytical predictions correlated very well for both the F-18C and F-18E aircraft, Figures 11 and 12. This confirmed that the PAN AIR model of the F/A-18E aircraft is a good representation and should give good qualitative answers even at low transonic speeds.

Validation of the PAN AIR model of the F-18E provided an opportunity to evaluate the effects that the aircraft flowfield may have on the behavior of stores separating from the aircraft. Since the IFM technique had been used for the F-18C/JSOW program, this technique was used to predict JSOW trajectories from the F-18E aircraft. The IFM technique assumes that there is a direct relationship between the aircraft flowfield along a store and the forces and moments induced by the aircraft flowfield on the store. Conceptually, for a store broken into N segments, this is expressed by the relationship:

$C_N = \Sigma A_i*\alpha_i$, i=1,N

$C_m = \Sigma A_i*\alpha_i$, i=1,N

$C_Y = \Sigma B_i*\delta_i$, i=1,N

$C_n = \Sigma B_i*\delta_i$, i=1,N

The first step in the IFM process is calibration, i.e. determining the store's Influence Coefficients A_i and B_i which determine it's response to the aircraft flowfield. It must be emphasized that a stores Influence Coefficients are not an aerodynamic property, but rather a solution to a regression equation relating a series of store aerodynamic loads in a known flowfield, originally obtained from experimental data. Although the IDL/IFM code provides a quick estimate of these coefficients, they cannot be used blindly. In the first place, the IFM/IDL code only allows for an approximate representation of the store's geometry. Although the JSOW store, which had six fins, did not fit the IDL/IFM code restrictions, the influence coefficients that were generated for the store were previously validated by comparisons$^{(12)}$ with horizontal grid data.

Using the JSOW IFM coefficients that had been validated for the F-18C aircraft, and the F-18C and F-18E flowfields shown in Figures 11 and 12, trajectory predictions were made for the JSOW store from the F-18E aircraft, and compared to the equivalent trajectories from the F-18C aircraft. As may be seen in Figures 13 and 14, the IFM predictions for the JSOW trajectories from the F-18E were in excellent agreement with the test data for the three tank configuration, but considerably underpredicted the yawing moment for the clean configuration on the inboard pylon. However, considering the fact that the predictions were made three years prior to the wind tunnel test, it is clear that the IFM technique can give a good estimate of aircraft flowfield effects.

F-18C/ITALD

The Improved Tactical Air Launched Decoy (ITALD) was, so far, the only failure of the Navy's integrated T&E approach. When the wind tunnel grid data for the ITALD in the 6% F-18C/D aircraft flowfield were combined with the 50% freestream data and autopilot parameters, a large roll oscillation, followed by a recovery, was predicted. During the flight test the ITALD departed in roll in less than 0.5 seconds, Figure 15. The cause of the failure was determined to be erroneous 50% free stream data for the store. As may be seen in Figure 16, the original ITALD freestream data indicated that the store would be stable in yaw; freestream data that was taken during the 6% F-18/ITALD wind tunnel test indicated, at best, neutral stability. When the 50% ITALD model was retested, the new 50% free stream data matched the 6% data, Figure 16. Using this new 50% freestream data, the simulation not only matched the flight test failure, Figure 17, but also proved that the autopilot was properly functioning, Figure 18. The ITALD has been since redesigned to improve it's yaw stability, and the flight test program was successfully completed[15].

F-14/GBU-24

. The approach used for the GBU-24 store differed somewhat from that for all other aircraft/store programs. In this case the flight test results were used to determine how the wind tunnel data should be used.

The GBU-24 store has two characteristics that make predicting flight test trajectories challenging. In the first place, the wing of the store opens during the first 150 ms of the trajectory. It was not possible to model this wing opening sequence during the wind tunnel test trajectories. Furthermore, the GBU-24 canards are free floating during the initial part of the trajectory. Flight test data for the F-15 and F-18 aircraft have failed to match predictions based on wind tunnel data for either fixed canards (at zero deflection angle), or for the store with the canards removed. To predict flight test trajectories, particularly for the GBU-24 configuration released from the F-14 aft station, flight test results were used to interpret the wind tunnel data.

A wind tunnel test for the F-14/GBU-24 configuration was conducted at the 4'X4' AEDC facility at Arnold AFB. During this test, CTS grid and trajectory, as well as carriage loads and freestream test data were taken for both the canards on and off configurations, with the wings retracted and open. These test data were then used only to determine what, for any combination of canards on and off test data, would constitute a safe release point.

A flight test for the GBU-24 from the F-14 aircraft forward station was conducted on Jan. 23, 1996. Prior to this test, several predictions were made of the possible trajectories to be expected. The trajectory using the canards off freestream and grid data gave the best match to the flight test results for everything but the pitch rate, Figure 19. Analysis indicated that the reason for the disagreement in pitch results might be attributable to the aircraft flowfield effect on the undeflected canard, which might carry a positive lift, which would cause a nose-up pitch. When an increment of 2.2 in C_m was applied to the canards off grid data, an excellent match with the flight test results was obtained, Figure 20.

CONCLUSIONS

The Navy has developed an integrated T&E approach, combining computational aerodynamics, wind tunnel testing and flight testing, to determining the safe separation of stores from aircraft. This approach is anchored in the realization that flight test results are the truth, and the wind tunnel and computational data have to be used judiciously. The integrated T&E approach has proven it's utility in several recent Navy store separation flight test programs, and is presently being used in the F-18E/F aircraft/store integration program.

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NAWCAD APPROACH TO INTEGRATED T&E

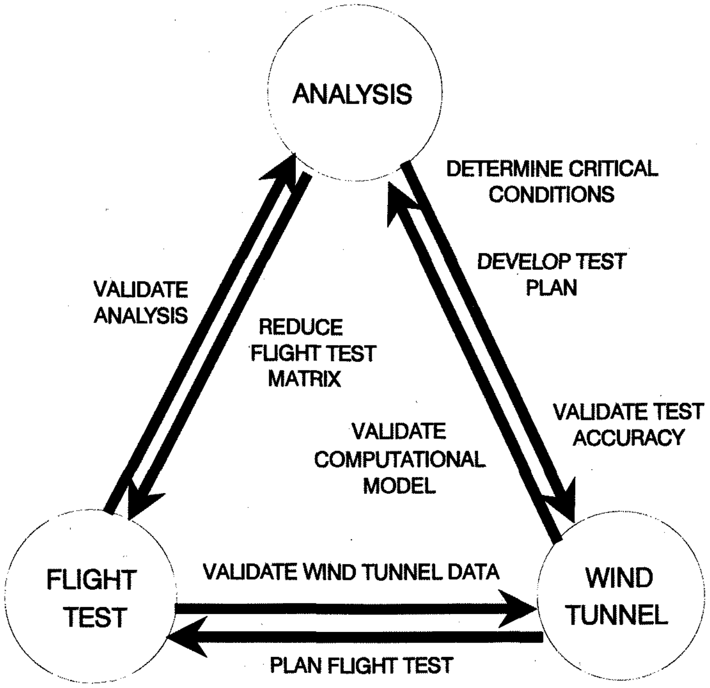

TABLE A

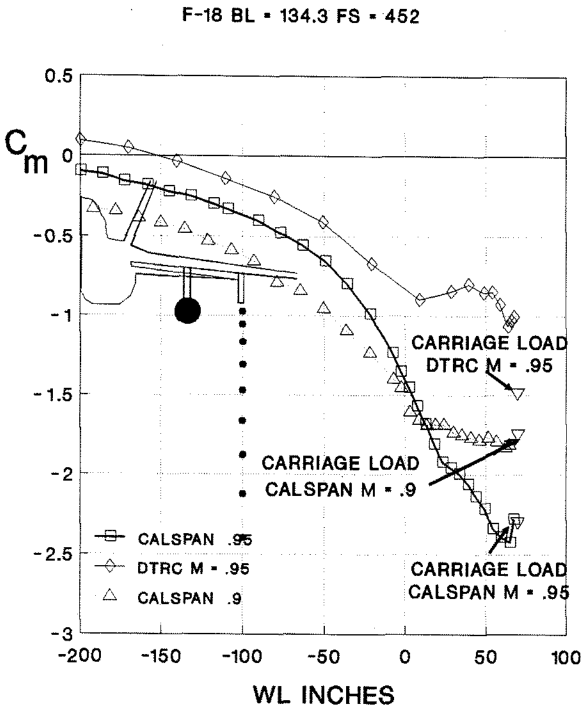

FIGURE 1 JSOW PITCHING MOMENT

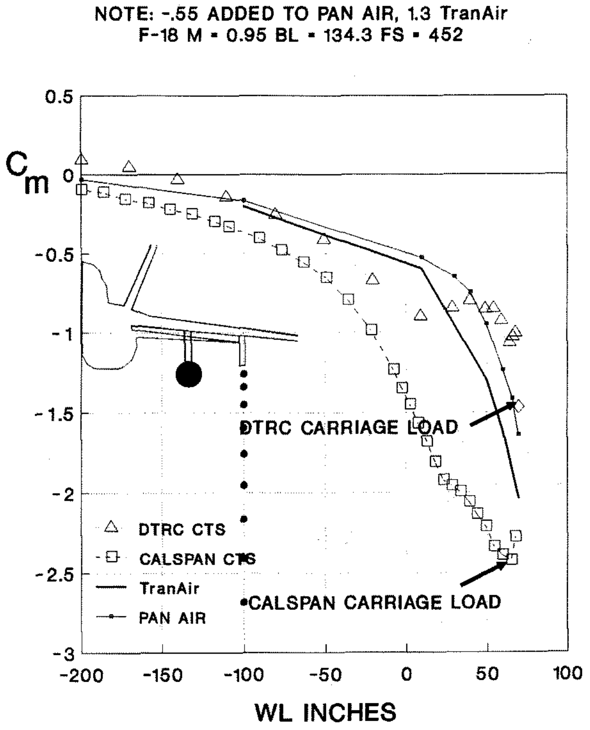

FIGURE 3 JSOW PITCHING MOMENT

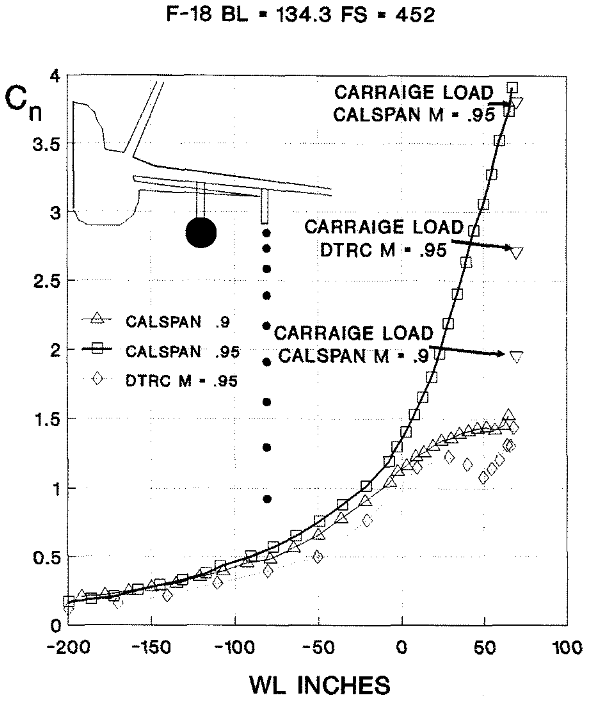

FIGURE 2 JSOW YAWING MOMENT

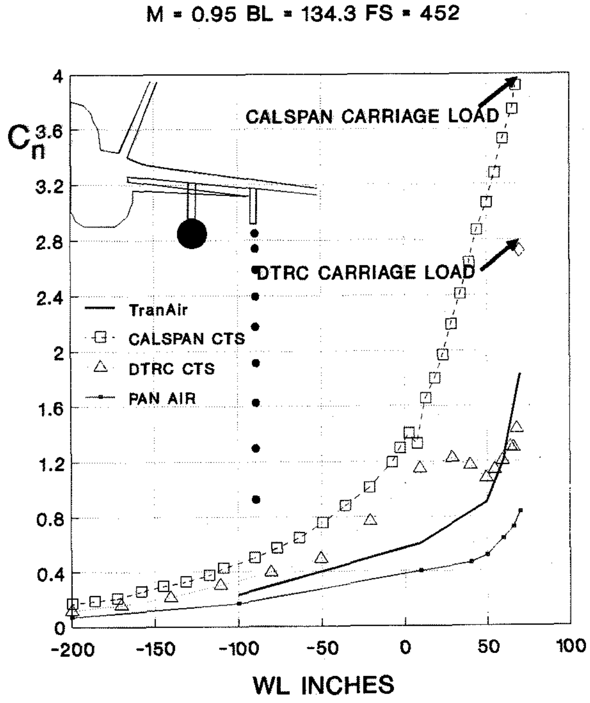

FIGURE 4 JSOW YAWING MOMENT

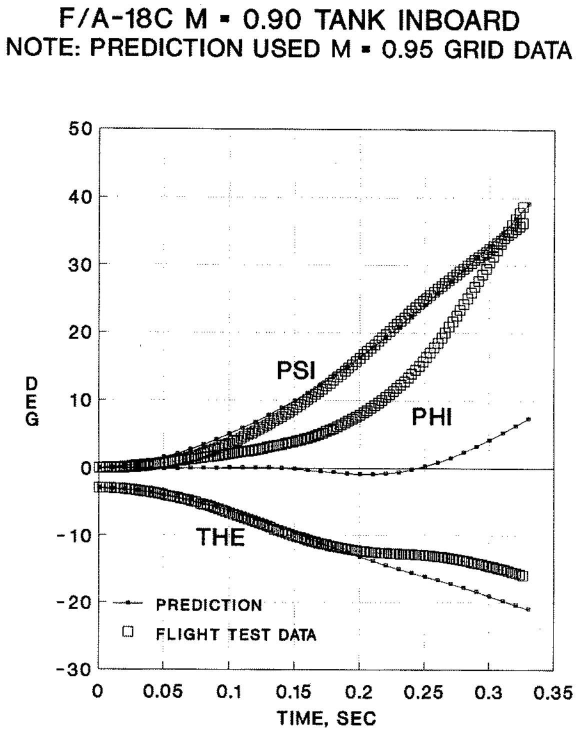
F/A-18C M = 0.90 TANK INBOARD
NOTE: PREDICTION USED M = 0.95 GRID DATA

FIGURE 5 JSOW JETTISON COMPARISON

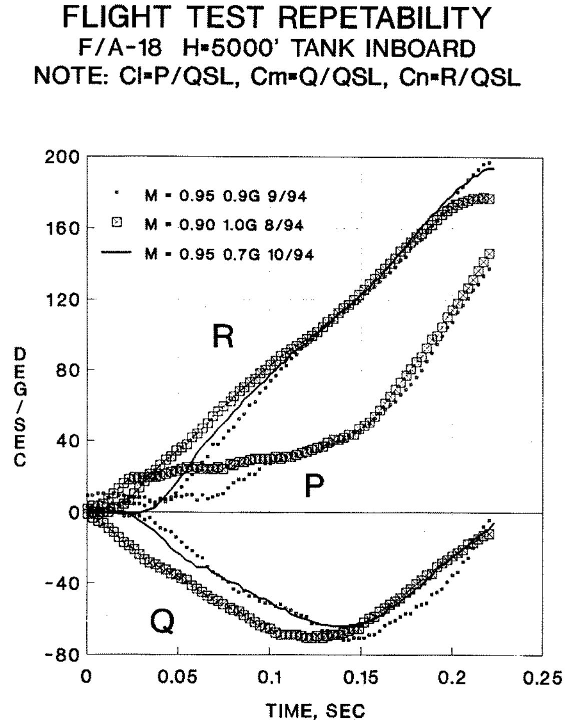
FLIGHT TEST REPETABILITY
F/A-18 H=5000' TANK INBOARD
NOTE: Cl=P/QSL, Cm=Q/QSL, Cn=R/QSL

FIGURE 6 JSOW FLIGHT TEST TELEMETRY DATA

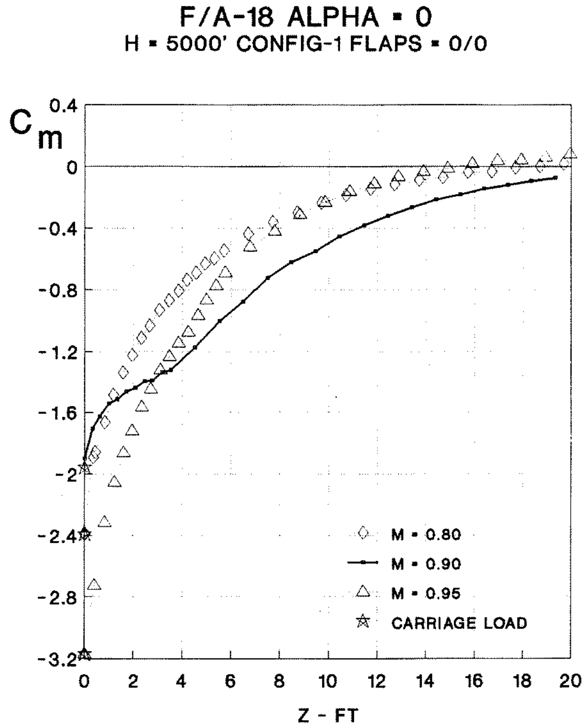
F/A-18 ALPHA = 0
H = 5000' CONFIG-1 FLAPS = 0/0

FIGURE 7 JDAM GRID COMPARISON

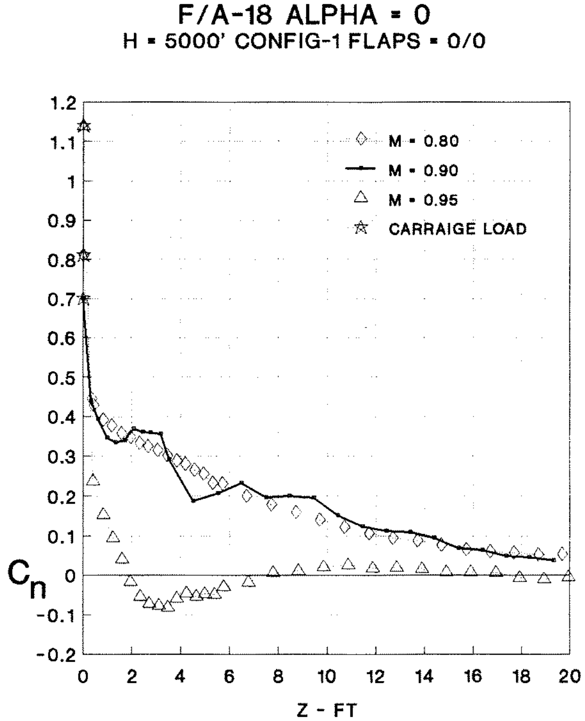
F/A-18 ALPHA = 0
H = 5000' CONFIG-1 FLAPS = 0/0

FIGURE 8 JDAM GRID COMPARISON

F/A-18 M = 0.82 H=5000' BL = 88

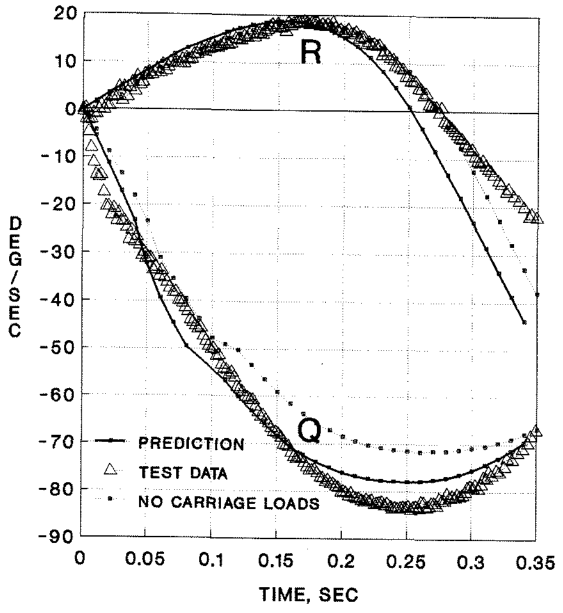

FIGURE 9 JDAM JETTISON PREDICTION

M = 0.90 ALPHA = 0.0 BL = 88 WL = 69

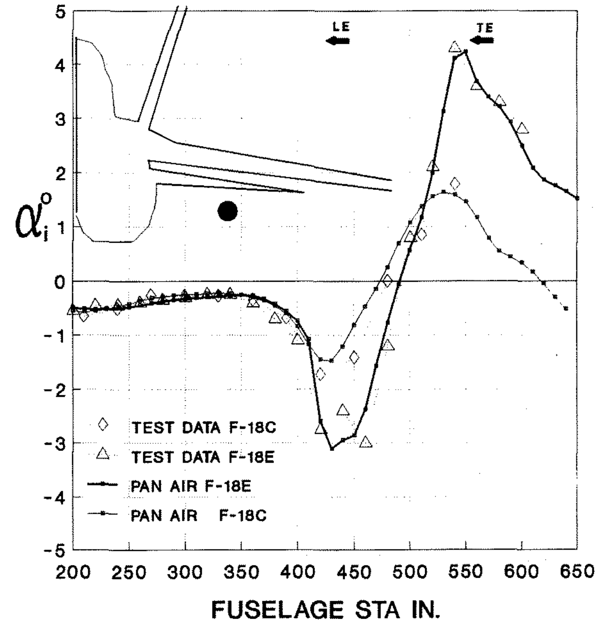

FIG 11 F-18 PAN AIR UPWASH PREDICTION

F/A-18 M = 0.90 H=5000' BL = 88

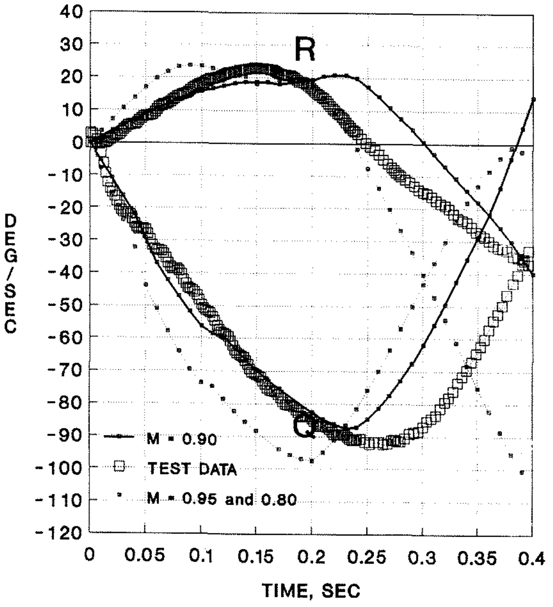

FIGURE 10 JDAM JETTISON PREDICTION

M= 0.9 ALPHA =0.0 BL 88 WL 69

NOTE: 1 DEG ADDED TO F-18C EXPERIMANTAL SIDEWASH TO ACCOUNT FOR FLOW ASSYMETRY

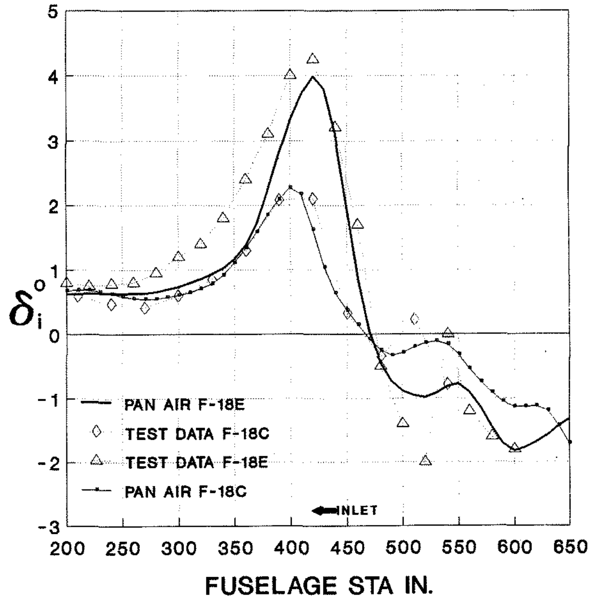

FIG 12 F-18 PAN AIR SIDEWASH PREDICTION

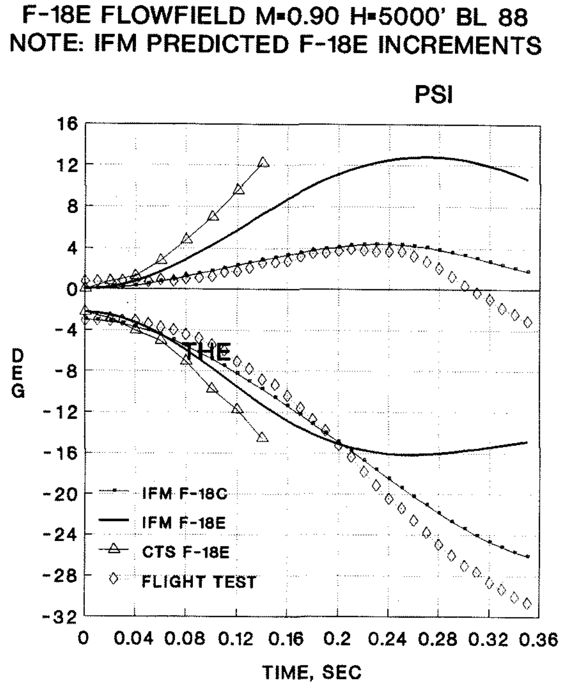
F-18E FLOWFIELD M=0.90 H=5000' BL 88
NOTE: IFM PREDICTED F-18E INCREMENTS

FIG 13 JSOW JETTISON PREDICTION

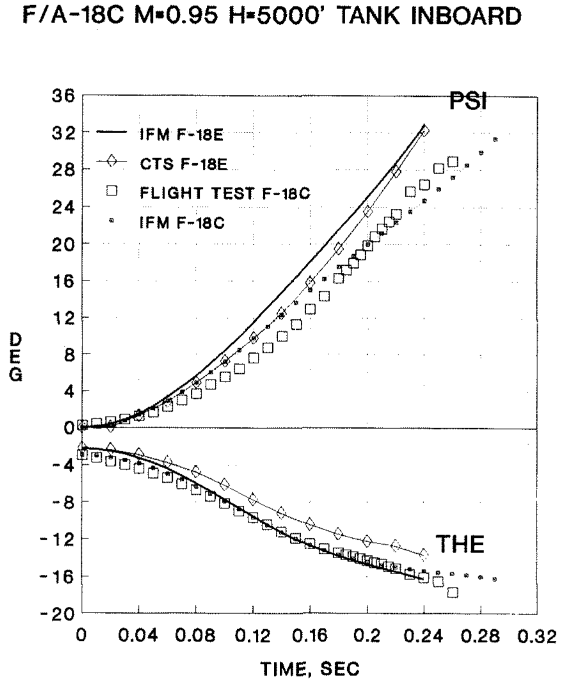
F/A-18C M=0.95 H=5000' TANK INBOARD

FIGURE 14 JSOW COMPARISON

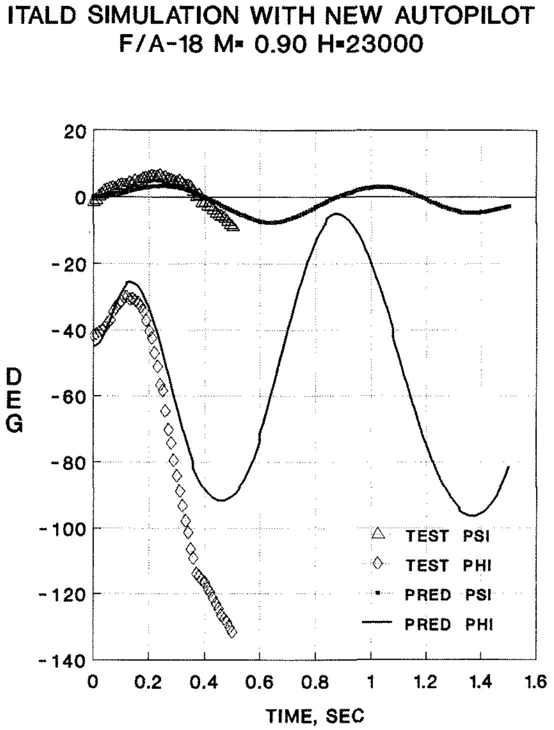
ITALD SIMULATION WITH NEW AUTOPILOT
F/A-18 M= 0.90 H=23000

FIGURE 15 FLIGHT TEST PREDICTION

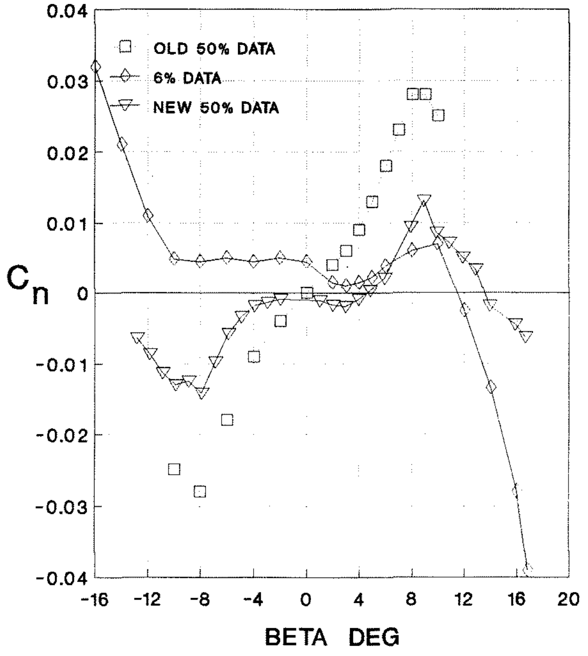

FIGURE 16 ITALD YAWING MOMENT

ITALD SIMULATION WITH NEW FREESTREAM
F/A-18 M= 0.80 H=17000 OUTBOARD PYLON

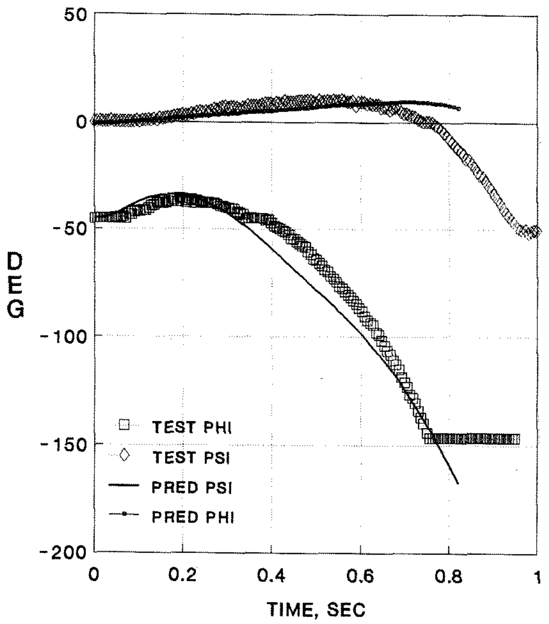

FIGURE 17 FIGHT TEST COMPARISONS

GBU-24 PRE FLIGHT TRAJECTORY
F-14 M = 0.80 H = 3600' STA 3
NOTE: RIGHT WING JUSTIFIED

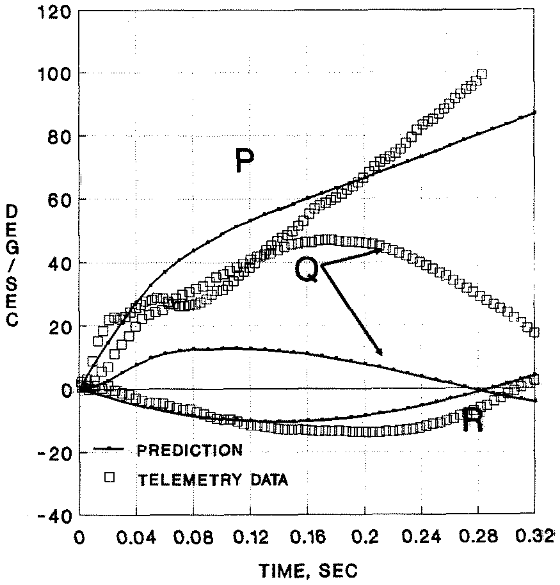

FIGURE 19 F-14/GBU-24 RATES

ITALD SIMULATION WITH INERTIAL ROLL
F/A-18 M = 0.80 H=17000 OUTBOARD PYLON
NEW ITALD FREESTREAM DATA

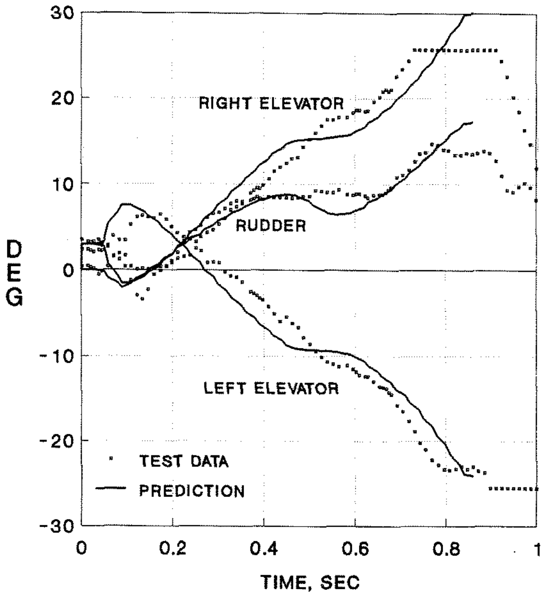

FIGURE 18 FLIGHT TEST COMPARISONS

GBU-24 POST FLIGHT TRAJECTORY
F-14 M = 0.80 H = 3600' STA 3
NOTE: RIGHT WING JUSTIFIED

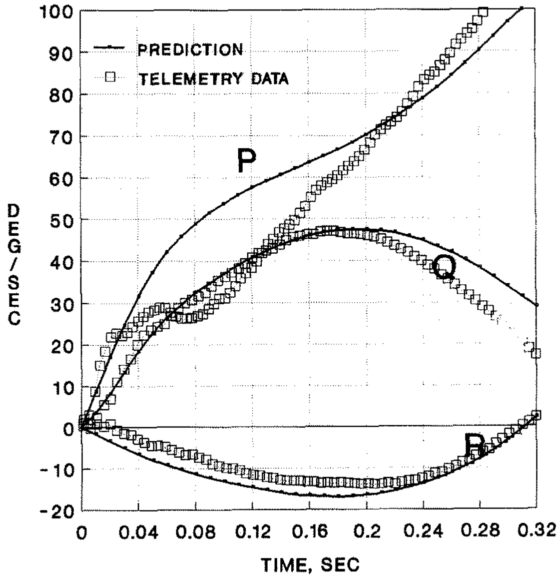

FIGURE 20 F-14/GBU-24 RATES