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In-Flight Captive Store Loads Compared with Wind-Tunnel and Mathematical Simulations

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A series of flight tests were made to acquire captive loads data on a store to compare with corresponding data from several wind-tunnel tests, as well as with the best mathematical models when conditions were matched as closely as possible. The store consisted of an Mk 83 bomb shape mounted on a triple-ejector rack (TER) on an F-4 aircraft which was instrumented complete with a standard research boom mounted on the nose. The flight conditions spanned Mach 0.6-0.9 in both maneuvering and steady flight. Corresponding wind-tunnel tests were made at 5% at both the Arnold Engineering Development Center (AEDC) and the David Taylor Naval Ship Research and Development Center (DTNSRDC), as well as tests at 10% at DTNSRDC. The data show good correlation between flight test and wind tunnel for moderate subsonic Mach numbers when good geometric similarity is maintained, but there is a pronounced divergence in this agreement as the Mach number is increased. Correlation between mathematical models of this problem and the flight test show the same magnitude in loads and moments, but the trends do not always agree. This is most pronounced in the pitch plane.

Introduction

A PERSISTENT and often heated technical debate in the area of store separation concerns the validity of wind-tunnel data when compared with flight test, not to mention the effectiveness of mathematical simulations. Investigators from the various disciplines have frequently cited favorite sets of data to establish credibility, but this has done little to settle the issue, since comparisons have been made despite improperly matched configurations and/or flight conditions. The result is that simulations, both wind-tunnel and mathematical, have been used most often in a qualitative sense and not in their most effective role to uncover the most hazardous separation conditions and to reduce the overall cost of qualifying a separation condition.

This document reports on a research program to obtain a set of measurements, both in the wind tunnel and in flight, on an instrumented aircraft with conditions matched as well as possible. This first phase consisted only of captive loading on an Mk 83 bomb shape on a standard triple-ejector rack (TER) mounted on an F-4 Phantom. Drop tests with this same configuration will be conducted in a later phase. The flight test, taken with an instrumented aircraft complete with a standard research boom mounted on the nose, is expected to supply a set of data for direct comparisons with wind-tunnel and mathematical simulations over a wide range of conditions. It should also supply a data base against which future improvements can be compared. The selection of the Mk 83 store for this series was the result of several compromises, but it appears representative of a wide variety of configurations and thus of general applicability.

These flight tests were conducted at the Naval Air Test Center (NATC), Patuxent River, through the joint efforts of the Naval Weapons Center (NWC), China Lake, Air Force Armament Laboratory (AFATL), Eglin AFB, and the Arnold Engineering Development Center (AEDC), Tullahoma. The basic wind-tunnel data base was the result of numerous wind-tunnel tests at 5% scale at AEDC with some testing at the David Taylor Naval Ship Research and Development Center (DTNSRDC) at both 5% and 10% scale. The existing flight-rated store and airborne balance combination was supplied by NWC and adapted and calibrated by AEDC. A special TER was supplied by AFATL. It should also be noted that on all flights, a similar balance for a similar program conducted by the United Kingdom was being flown on the right inboard pylon of the aircraft.

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Description of Test Apparatus

The flight tests were conducted with an F-4J aircraft, but a number of special precautions were taken to enhance both the validity of the data for the present comparisons and in the future as a data base for refinement of simulations. First, the aircraft was equipped with a typical research boom mounted on the nose and coupled to the aircraft recording system for measurement of flight parameters. Second, in order to match the large wind-tunnel data base that had been accumulated up to this time, an Air Force pylon was mounted on the left inboard station. The centerline and outer pylons were mounted but not used. An interesting feature, however, was that on the Navy pylon on the right inboard station a triple-ejector rack and adapter of the United Kingdom was mounted. As a result of joint cooperative efforts, a United Kingdom airborne balance in a Mk 10 store was flown simultaneously on the right wing, but the results of this separate correlation program are to be reported independently.

An Air Force TER was mounted on the left inboard pylon and the two shoulder positions were fitted with dummy Mk 83 bombs. The center position of the TER at the bottom was

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occupied by a conventional Mk 83 body modified internally to accept a flight-rated balance. Special precautions were taken to determine the attitude of the stores with respect to the aircraft by establishing the aircraft on jacks with the ordnance reference lines level. The store axes were then checked. The instrumented store, as a result of machining and special handling, was quite true, but the shoulder-mounted stores showed the effects of manufacturing tolerances. There was considerable camber in the axis of the inboard store, but both were leveled to within about ½ deg in the mean by means of lug and sway brace adjustment.

The airborne balance was of the Pastushin-type, described more completely in Ref. 1. The Mk 83 store shape was originally a standard Mk 83, but the center section had been hollowed out and machined internally to accept the balance. The center section had been further modified to provide isolation gaps around the inert elements with which the hooks and sway braces were in contact. All internal wiring was bundled together in an umbilical, fastened to the inert element, and brought out an extra hole in the top element. The umbilical was attached to the rack and then connected to the aircraft system. In additon to the normally detachable tail cone, the nose cone was also made removable for access to the balance. Since the tail cone was also made removable, an alternate tail cone was fabricated at AEDC, which duplicated the modification necessary to the store shape in order to mount it on a sting during wind-tunnel testing. The standard store shape, referred to as afterbody 1, and the modified shape, referred to as afterbody 2, are shown in Fig. 1. Both were flight tested.

Wind-tunnel data used in the comparisons consisted of several large blocks of data taken in different modes with limited differences in configuration during the several tunnel entries. The initial data were taken at AEDC at 5% scale with an F-4C model using a dual-sting technique as well as an internal balance model for the captive loading and is reported in Ref. 2. The dual-sting technique employs one sting for the aircraft model and a separate sting to hold the store model. In this manner, the store model is free to be moved independently of the aircraft model, and the captive loads are the result of an extrapolation of the data to the captive position. There is never a hard connection between the two models. As a result of this sting mounting, the store model is usually modified in the rear by increasing the diameter of the base in order to accommodate the sting. The internal balance model, on the other hand, is rigidly mounted to the aircraft model, and the installation is a direct simulation of the airborne balance flight-test configuration. Additional data for this configuration are reported in Ref. 2 in which the effect of the sting mounting was closely examined. Later this same aircraft/store model combination was used at DTNSRDC for additional tests using a dual sting to develop an extensive force grid. These data are reported in limited form in the publication cited in Ref. 3. Additional data were also taken at DTNSRDC with a dual sting and a 10% model of an F-4B modified to look like an F-4C. This 10% scale model also had the sway braces simulated.

After the DTNSRDC tests, the 5% scale model was again tested at AEDC with an internal balance. This constitutes the data referred to as the early model data used in the comparisons with the flight test results. After the flight tests had been concluded, the fins of the 5% scale model were reworked, and the TER was refabricated to include sway braces as well as cutouts on the rack to more nearly duplicate the real article. Again, additional data were taken with an internal balance. These data, referred to as the final model data, are documented in the reports noted in Refs. 4 and 5. Thus, three sets of data were obtained with two generations of models through this period but, except for the sway braces and cutouts, the differences were minor, both in the geometry as well as the resulting data.

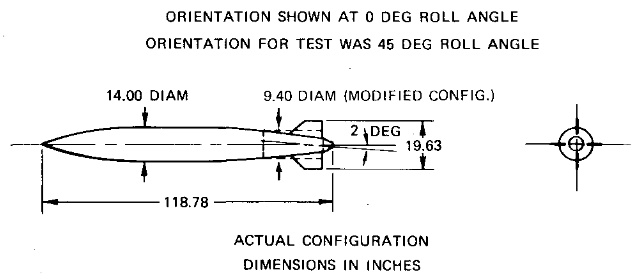

Fig. 1 Mk 83 test configuration.

Calibration

The balance calibration was done at AEDC by the Instrument Branch of the Propulsion Wind Tunnel Facility (PWT). Minor changes were made to update the electronics, but the largest change was to eliminate an internal recording system and mate the instrumentation to the aircraft recording system.

The balance calibration was accomplished by suspending the balance from the PWT large-balance calibration rig by means of conventional bomb lugs and four sway brace pads. During the calibration procedure, the balance was installed inside the bomb midsection, which served as a calibration body to which known loads were applied. Load points on the bomb midsection were at known positions so that the effect of incremental loads on the balance outputs could accurately be determined. The balance calibration followed normal wind-tunnel practice and consisted of three load cycles. All calibration data were recorded using the force and moment readout system (FAMROS), a multichannel, parallel, readout system for measuring and digitizing the output of strain-gage balances. The bilinear or two-slope method was used to reduce the balance calibration data. Slopes were determined by the method of least squares, which was applied to all digitized calibration data in determining the final balance calibration constants.

Although the laboratory FAMROS and the aircraft recording systems were electrically equivalent, differences in the length or gage of circuit wiring can affect the magnitude of these electrical outputs and hence the calibration. Therefore, a shunt ratio was used to relate in-flight strain-gage outputs to laboratory strain-gage outputs. During calibration, the box was attached so that the shunt resistors could be placed sequentially across the four elements of each strain gage. The absolute values from the four elements of each gage were averaged and recorded, and six shunt values were obtained. The same procedure was followed before each day's flights.

Accelerometer calibrations, both static and dynamic, were also accomplished at the AEDC. Four Statham accelerometers were installed—three inside the Mk83 bomb shape and one used as a backup. The static calibration was made by rolling the accelerometer from 0-180 deg, in increments of 10 deg, and the dynamic calibrations were made at 50 cycles/s. The average sensitivity for the static and dynamic calibrations were approximately equal. These accelerometers were used in conjunction with the Mk 83 bomb shape mass properties to determine the components of force and moment measurements attributable to inertial loading. Mass properties of the instrumented bomb shape were determined by means of a static tare calibration.

Numerous preflight and postflight procedures were utilized to insure the operational reliability of the Mk 83 instrumentation package. A shunt calibration using the same shunt box as used in the laboratory calibration was performed before and after each day's flights as a means of setting and checking the required reading at the gage amplifier outputs. This procedure provided the means of correlating balance and accelerometer outputs obtained during flight to outputs obtained during laboratory calibrations. The holes that had been drilled and tapped into the Mk 83 shell along the body-axis pitch and yaw planes to serve as load points during the laboratory balance calibration also served to hold a weight pan used for quick field checks of the calibration.

Data Acquisition and Results

Data acquisition, both straight and level and maneuvering, was concentrated around Mach numbers of 0.6, 0.7, 0.8, and 0.9 at angles of attack of -4 to 6 deg. The final selection of data to be reduced for comparison with wind-tunnel data at similar Mach numbers was made on the basis of Mach number by scanning the data with an IBM 370 interactive graphics system for data intervals, during which the Mach number fell on the desired values within a tolerance of ± 0.005. This data interval for which the Mach number was within the specified limits was further divided into subintervals, during which the angle of attack was within corresponding limits. Aerodynamic coefficient data were then averaged over the subintervals for correlation at the

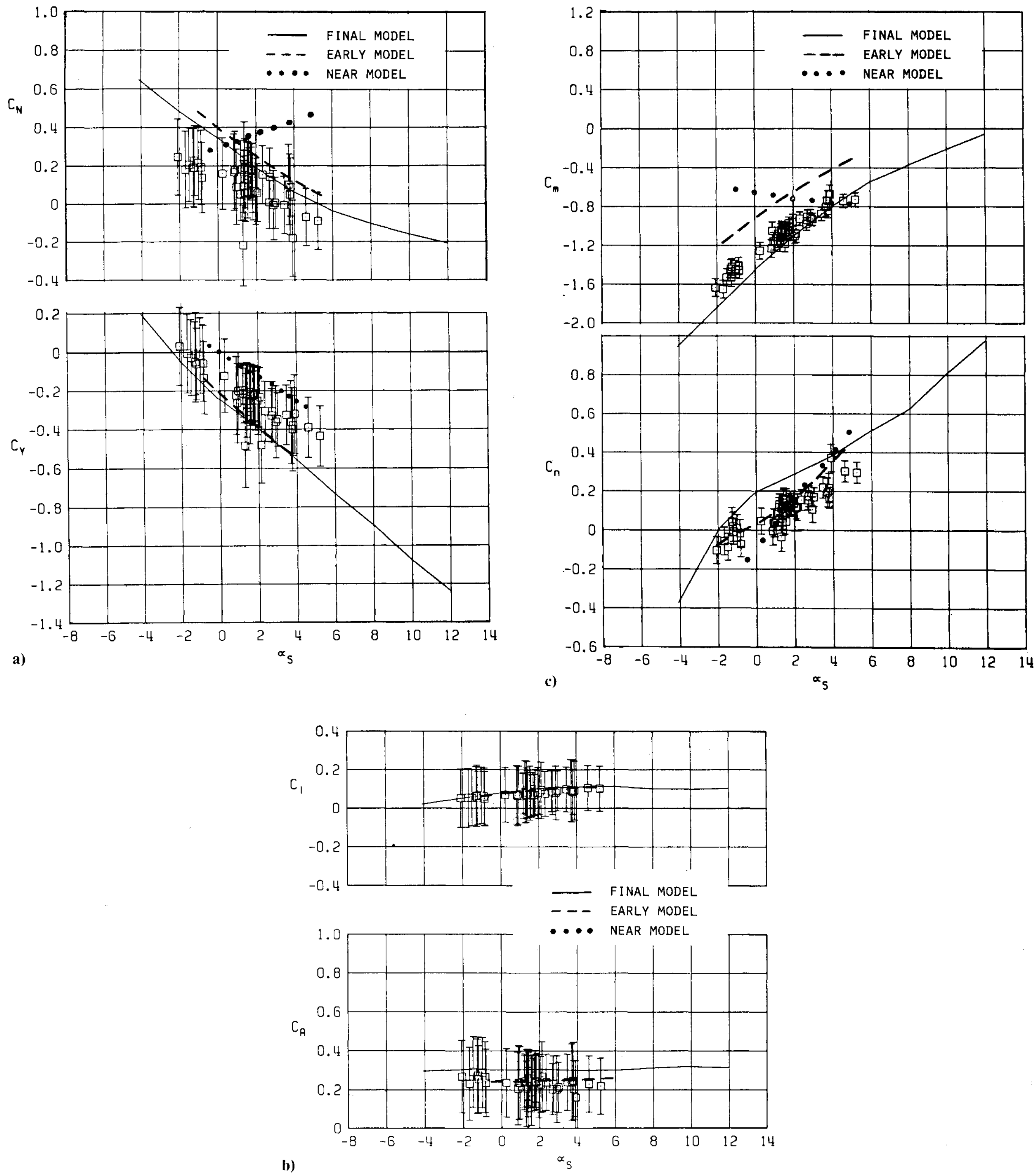

Fig. 2 Comparison of flight test results with wind tunnel, Mk 83/F-4, afterbody 1, LIP, TER-1, $M = 0.6$.

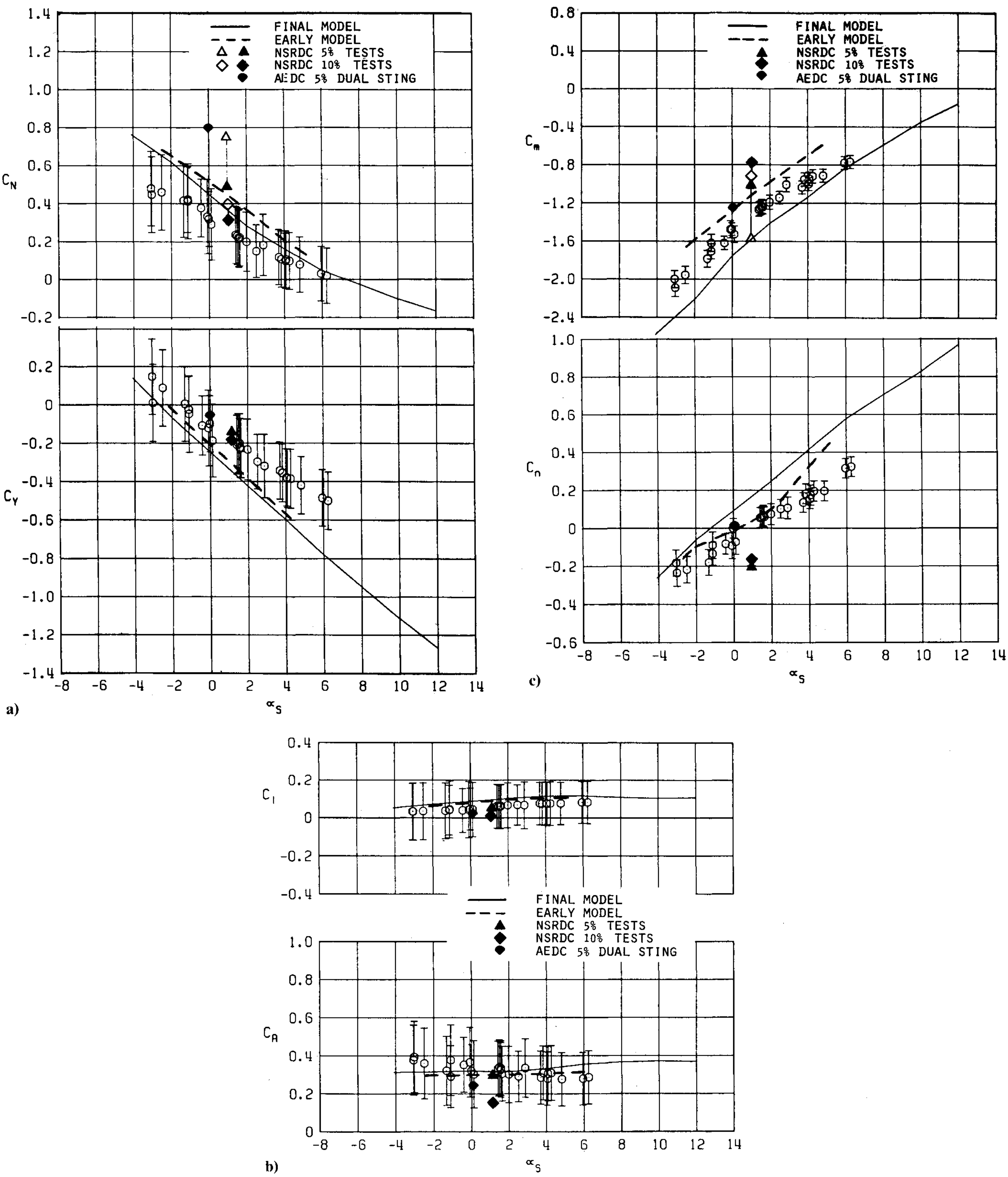

Fig. 3 Comparison of flight test results with wind tunnel, Mk 83/F-4, afterbody 2, LIP, TER-1, $M = 0.6$.

corresponding Mach number and angle of attack. Data anomalies, such as random spikes, were also eliminated during this process.

The number of data samples (recorded at the rate 10/s) within a given data interval or subinterval was a direct function of the flight maneuver. During straight and level flight, the Mach number remained within the ± 0.005 tolerance for several seconds, generally 5 to 10 and as long as 25. During the more transient flight maneuvers, the Mach number was within the tolerance for as little as 0.4 s. Each parameter of interest was then averaged arithmetically over the same time interval. Analysis indicated that first-order expressions would satisfactorily describe the data in any time interval. Data averaged over intervals of less than 1 s (less than 10 data samples) were considered statistically weak. Data at the same Mach number and aircraft angle of attack (plus or minus the uncertainty) were compared for steady and nonsteady flight maneuvers. These comparisons showed that the magnitudes of the calculated aerodynamic coefficients obtained at aircraft pitch rates of less than 0.6 deg/s were consistantly the same;

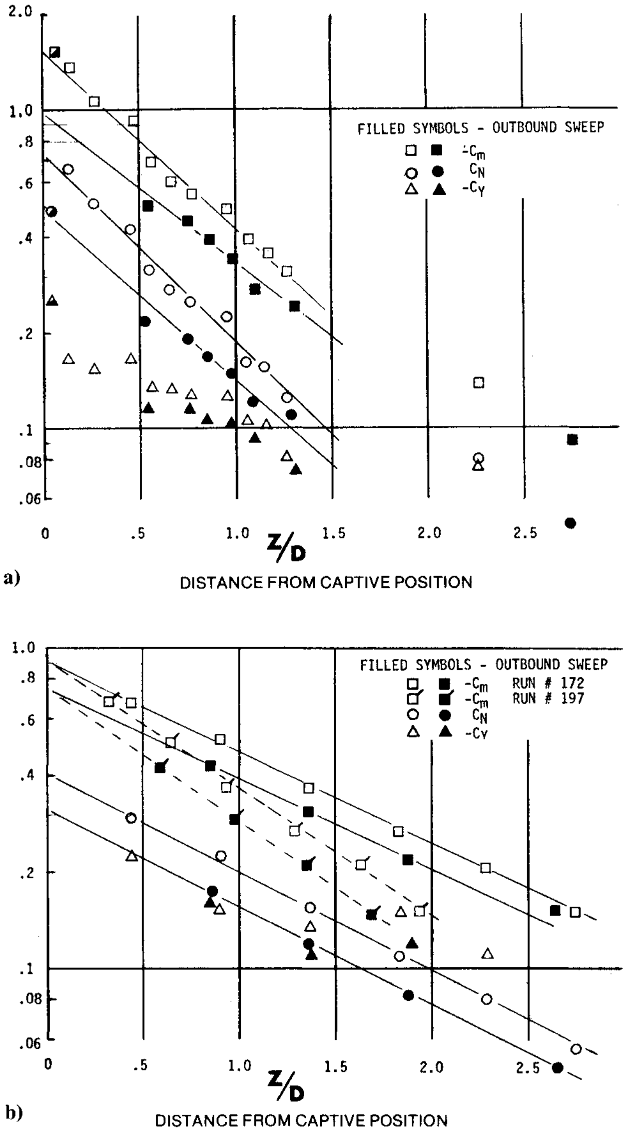

Fig. 4 Dual-sting wind-tunnel store loads, F-4/Mk 83, $M=0.6$. a) DTNSRDC 5% scale; b) DTNSRDC 10% scale.

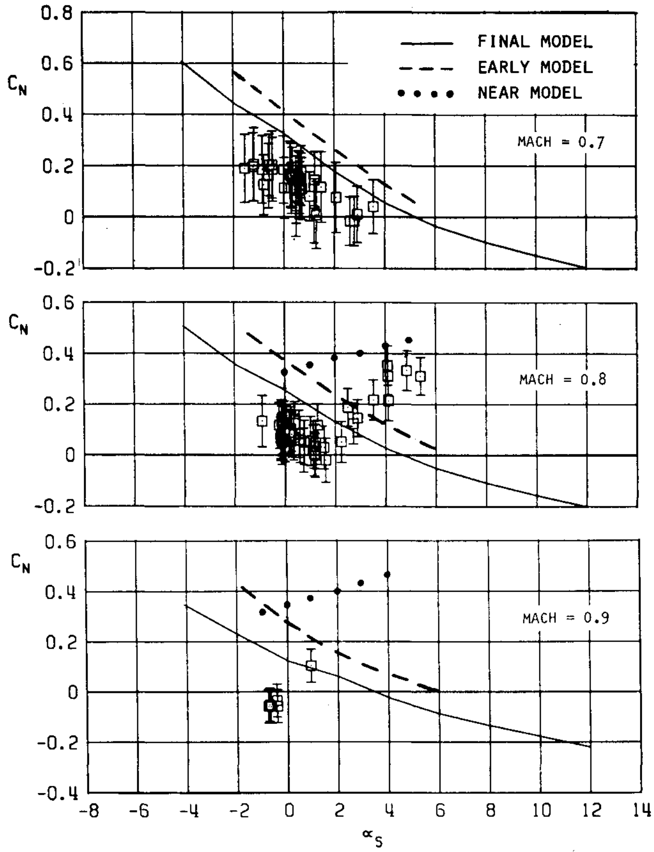

Fig. 5 Comparison of flight test results with wind tunnel, Mk 83/F-4, afterbody 1, LIP, TER-1, (normal force).

therefore, on the basis of repeatability, data obtained at aircraft pitch rates greater than 0.6 deg/s can be disregarded. They are included here, however, to illustrate the relatively few unreliable data samples that were obtained.

Results of the flight tests are shown in Figs. 2-6 along with the various wind-tunnel data for comparison. Aerodynamic coefficients for afterbody 1 at $M=0.6$, left-inboard pylon (LIP), are shown in Figs. 2a-c. On these figures, the final wind-tunnel results, corresponding to the best geometric simulation of the model made to date, appear to compare best with the flight test for the pitch plane coefficients. Axial and yawing moment coefficients appear to correlate better for the early model, while side force and rolling moment have an insignificant change. The changes, however, were not large and generally within or near the uncertainty. Also shown in these figures are the captive loads as obtained from the Nielsen Engineering & Research, Inc. (NEAR) mathematical model.[6] The NEAR mathematical model has been compared extensively against other approaches in the past. In Ref. 3, it was compared for this configuration against the approach of Fernandes and found to be superior. In Ref. 7, it was compared for a test configuration against a different approach due to Woodward and found to be comparable while being a more complete and versatile program. The NEAR model does an adequate job in some cases, but the trend with angle of attack is alarming. The slope of the normal force is counter to that indicated by both the flight test and the wind tunnel. In the case of the pitching moment, the slope differs considerably from the test data from both sources. In the case of the yawing moment, while the slope is in agreement, the magnitude is such that in the normal flight condition for straight and level flight, in the neighborhood of 0 deg, the yawing moment is opposite in sign from that indicated by experimental and flight data. The effect of the fin cant is not capable of affecting the rolling moment in the NEAR model, and the axial coefficient is not generated.

The corresponding comparisons for afterbody 2 at $M=0.6$ are shown in Figs. 3a-c, and they do not differ greatly from afterbody 1. The differences between early and final configurations appear slightly larger than afterbody 1, and the refinements move as much of the wind-tunnel data away from the flight test data as toward it. The differences, however, are again generally within the data uncertainty. The increase in scale to a 10% model appears to have a favorable effect on C_N, but the 5% scale data appear better for C_A and C_M. Scale has an insignificant effect on the other coefficients. However, the sting-mounted wind-tunnel models show some disturbing anomalies, particularly for the normal force and pitching moment. Generally, when taking this type of data with a dual sting, all conditions are fixed except for the store distance below the aircraft, and data are taken as the model is swept in toward the captive position and back out. This can generate two separate sets of data, one for the inbound sweep and one for the outbound sweep, if the data are not reproduced. This is the case for the DTNSRDC data as some samples show in Figs. 4a and 4b. The clear symbols indicate the inbound sweep and the filled symbols denote the outbound sweep. In some cases, the differences are substantial, as shown here. Similar problems are known to occur also at AEDC, but the differences have not been so large. Plotting the data on semilog paper as done here frequently shows the data close to the

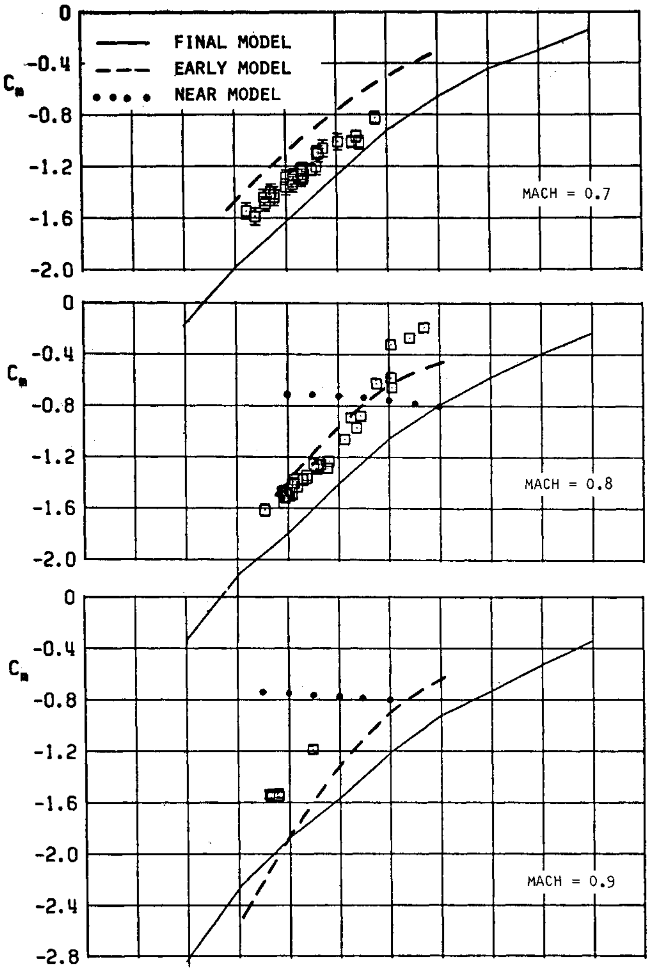

Fig. 6 Comparison of flight test results with wind tunnel, Mk 83/F-4, afterbody 1, LIP, TER-1, (pitching moment).

captive position to form a nearly straight line, which can easily be extrapolated into the captive position to yield an apparent captive load. However, this straight-line relationship frequently has a kink in it between 1½ and 2½ diam for the smaller scale data. This is not in evidence for the 10% data which is more uniform. These trends occur in all the data, but they are more pronounced in the normal force and pitching moment. When there was no difference between the inbound and outbound sweep, only the solid symbol is shown. This characteristic makes sting-mounted, wind-tunnel data difficult to interpret at times and even more so when one examines Ref. 2, where it is shown that sting data frequently do not merge smoothly into the internal balance data for the captive position. Caution must be exercised when applying such results.

While the $M=0.6$ data raise some questions concerning the simulations, particularly the mathematical simulations, it can be said in general that with enough care in the geometric simulation, the wind tunnel can be made to represent the full-scale article to a good degree. The small discrepancy left is undoubtedly due to the lack of Reynolds number simulation and remains as a problem in fine-tuning the simulation to even more realistically represent the full scale. There is some question concerning the adequacy of the mathematical model at this point. The adequacy of these simulations, including the wind tunnel, will be more fully quantified in the next phase of this program when actual drops will be made with this configuration and deviations between the simulated and actual trajectories will be examined. In fairness, it should be noted that the mathematical model represents, to a good degree, the level of the loads and moments in the most likely drop range (approximately 2-3 deg), and only the pitch plane aerodynamics disagree with the trend of the data into the transient or maneuvering range. Furthermore, the mathematical model has demonstrated some of the same sensitivity to gaps between the various components that has been demonstrated by the wind-tunnel model refinements. In a further examination of the calculated results, some deficiencies have been noted that might be responsible for the discrepancies shown and that may be easily correctable. The present calculations make an approximate correction for the mutual effect of the store in the flowfield of the aircraft, and the results of the flowfield itself and of one store alone on a pylon have, in other tests, shown different trends with angle of attack. It is quite likely that the mutual effects of the adjacent stores are improperly taken into account. This is particularly true of the fins. In the present calculations, the effectiveness of these fins as lifting surfaces is represented by a constant and input quantity in the form of a lift-curve slope corrected for wing-body interactions. The close proximity of the fins to one another in this configuration leads one to conclude that the fin effectiveness is most probably different in different planes and that the mutual interference of these lifting surfaces is most significant.

It is the development of the data with Mach number, however, that introduces the most uncertainty into the problem of simulation. Only the normal force and pitching moment are shown here, since they represent the most significant departures from the trends of the previous data. Figure 5 shows the development of the normal force with Mach number from 0.7-0.9. At Mach 0.7, there were limited simulations, and this condition is shown for completeness. It is at Mach 0.8 that a surprising divergence takes place. At approximately 2 deg angle of attack of the store (3 deg for the aircraft), the flight data appear to shift rather quickly to a different level and possibly resume the original trend with angle of attack, but there are inadequate data to definitely conclude the return to the original trend. In the particular region of the shift, the NEAR model seems to have the appropriate trend and more nearly represents the flight test than the wind tunnel. This may be fortuitous, however. At Mach 0.9, the same trend is still in evidence, but the data are quite limited. An interesting point to observe is that the shift occurs at about 0 deg at Mach 0.9 and about 2 deg at Mach 0.8. If one extrapolates this trend to the Mach 0.7 data, a shift would be expected at about 4 deg, and indeed there is an indication in the data that a shift could be imminent. Unfortunately, there are not enough data to confirm this as well as an inadequate data range at Mach 0.6. The results for the moment coefficient in Fig. 6 show a similar trend with Mach number, although the relative shift is less. Similar but smaller shifts occurred in the other aerodynamic coefficients.

The underlying cause of this divergence is unknown at this time, but it was quite consistent, occurring with both afterbodies. The flight data were taken over a wide range of attitude and g-loading combinations during maneuvering on several flights and with configurational changes, tending to rule out random anomalies. Critical post-test reviews of the apparatus and techniques tended to rule out problems arising from this source, even at the higher g levels of about 3 represented by these data where the resolution was poor. This lack of conflicting data further strengthened the assumption that the observed effect is real. This was even more reinforced by the discovery of a similar occurrence reported by Meyer and Sisson.[8] There could be a severe Reynolds number problem which causes some separation and/or shock pattern to be different between the wind tunnel and the full scale, or there could be a blocking effect in the tunnel obscuring the effects of angle of attack. More likely, however, the curvilinear flight path being flown by the full-scale aircraft produces a different flowfield with different attendant store loads than those produced by the static wind-tunnel model. At this time, no mathematical or experimental simulation has been devised to confirm this assertion, but it seems clear that the loads on a store released during a maneuvering condition are likely to be substantially different than those on a store in steady-state, but otherwise at the same flight conditions.

Conclusions

A flight test program utilizing an Mk 83 store shape on an airborne balance and mounted on an F-4J has been flown under well-instrumented and controlled conditions to produce a set of data for correlation purposes on captive loads. A comparison with a large block of wind-tunnel data run in support of this program shows general agreement between the flight test and wind-tunnel simulations at moderate subsonic Mach numbers, but there is a surprising sensitivity of the wind-tunnel data to apparently minor geometric similitude as well as the manner of taking the data. This sensitivity overshadows the remaining uncertainty due to a Reynolds number type of scale effect. The best mathematical simulations available generally agree in magnitude with the forces and moments, but occasionally differ in the trend of these coefficients with angle of attack.

As the Mach number is increased from 0.6, there is a surprising divergence between the flight-test and wind-tunnel results which occur at progressively lower angles of attack as the Mach number is increased. This sudden change is not reflected in the mathematical models either. The cause of this divergence is very much open to question at this time, but it must be resolved before the simulations, wind-tunnel or mathematical, can exert a significant effect on the mechanics of dealing with captive loading and store separation in general.

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