VOL. 17, NO. 11 J. AIRCRAFT NOVEMBER 1980

ARTICLE NO. 80-4113

Store Separation Trajectory Analysis

Arthur R. Maddox*
Naval Weapons Center, China Lake, Calif.

A series of store drops was made at moderate to high subsonic speeds with the same configuration on the center position of a triple-ejector rack (TER) on an F-4 inboard pylon. The data were compared with wind-tunnel and mathematical simulations. Both estimation techniques predicted the general nature of the motion, especially at low speeds, but failed to predict a minor collision observed at high speed.

Introduction

STORE separation test data are difficult to obtain under controlled conditions. The most recent publication dealing with this problem[1] provides valuable information on various wind tunnel-test techniques for a single-store configuration. Most earlier data are useful only in a qualitative sense.

In order to provide reliable quantitative data, a series of controlled drops using a multiple-store configuration with broad general implication has been conducted at speeds high enough for aerodynamic loads to be of the same order of magnitude as inertia loads and with trajectory data taken all the way to impact. Drops were made of a Mk 83 store shape over the Mach range 0.6 to 0.9 from the center station of a triple-ejector rack (TER) on the left inboard pylon of an F-4 aircraft. Various aircraft flight parameters, including ejector force-time information, were measured, so that certain results could be compared with those previously reported in Ref. 2.

Comparison of the flight data with wind-tunnel prediction methods shows generally good agreement. Occasionally, however, the wind-tunnel results differ significantly from the full-scale result, and the reasons are not apparent. The most complete analytical model of this problem exhibits similar limitations.

Descriptions of Tests

The drop tests were conducted at the Naval Air Test Center (NATC), Patuxent River, Md., with an F-4J aircraft having a number of special features. 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. The aircraft was the same and the recording system similar to that used for the captive-loading tests described in Ref. 2. Second, in order to match previous wind-tunnel and captive-load data, an Air Force pylon was mounted on the left inboard station. This Air Force pylon carries the stores approximately 6 in. forward and 3 in. higher than the Navy pylon and thus allows it to be released from the center rack position. This is not normally an operational configuration, but the Air Force has certified carriage and release of the Mk 83, pictured in Fig. 1, from this location over the speed range considered here. In addition, stores mounted in this location are known to have a significant level of mutual aerodynamic interference. Thus, this configuration represents a significant test condition.

The Air Force TER, mounted on the left inboard pylon, was that used in the captive-loads tests of Ref. 2. The two shoulder stations were fitted with dummy Mk 83 bombs, and special precautions were taken to determine the attitude of all the stores with respect to the aircraft. Even though the stores in some cases showed some camber, the axes were within 1/2 deg of the normal attitude on the ground. The drop stores were filled inert Mk 83 bomb shapes, but they were ballasted to have the center of gravity in a location consistent with the operational store. For all flights, the store weights were approximately 1000 lb with the center of gravity 7 in. behind the forward lug. The moments of inertia in pitch and roll were an average of 141 and 5.2 slug-ft^2, respectively. The standard Mk 83 weighs 985 lb with moments of inertia of 106 and 4.8 slug-ft^2.

During release, close-in information on the store motion was recorded photographically with a single camera. The reduction of this photographic data to position and attitude information was accomplished by the Photographic Position and Attitude Measuring System (PAMS) in operation at NATC and described in Ref. 3. Downrange tracking by ground-based radar and long-range camera coverage all the way to impact were also provided.

Previous Results

In establishing a data base for this configuration, a great deal of background work was done. Earlier comparative work on the effects of the sting mounting, by Arnold Engineering Development Center at 5% scale, is reported in Ref. 4. Grid data at 5 and 10% scale at Mach 0.6 and 0.8 were taken at the David Taylor Naval Ship Research and Development Center. Additional testing was done by AEDC at 5% scale to determine captive loading on a number of stores. Trajectories by the captive trajectory system (CTS) were also run at AEDC. Finally, full-scale captive loads were taken with an airborne balance. All these data are summarized and compared in Ref. 2.

Unfortunately, these data, although consistent within any tunnel entry, did not complement each other to give a clear picture of the loading field seen by the store. There were inconsistencies with the grid data and they did not smoothly merge into the captive-loading data. The CTS information was taken at an aircraft angle of attack of 3.3 deg, which nearly matches the angle appropriate to flight at Mach 0.6 but is considerably different from that at Mach 0.8 and 0.9. Insufficient data were taken to correct the CTS information as was done in Ref. 1.

Theoretical studies were carried out with a mathematical model developed by Nielsen Engineering and Research, Inc. (NEAR). The particular source-sink representation† for the F-4 aircraft was the same as that used in Ref. 1, but some

Submitted Feb. 13, 1979; revision received March 10, 1980.

Index categories: Aerodynamics; Structural Design (including Loads); Testing, Flight and Ground.

*Currently Navair Research Professor, U.S. Naval Academy. Associate Fellow AIAA.

†Harold R. Spahr of Sandia Laboratories in Albuquerque supplied a revised version of the source-sink model of the F-4 and Calvin L. Dyer supplied a preliminary version of the ejector model.

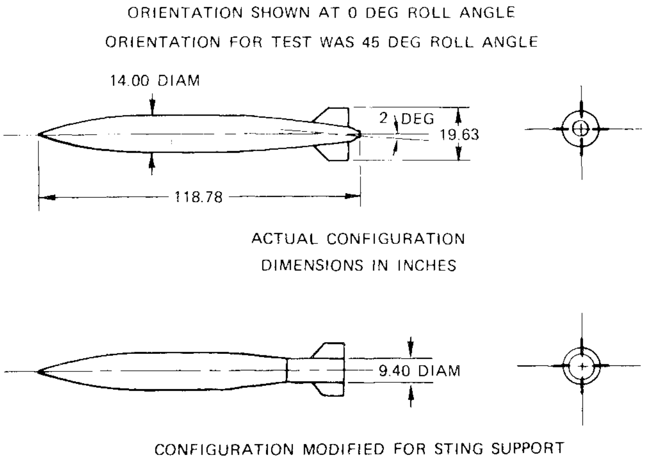

Fig. 1 Mk 83 test configurations.

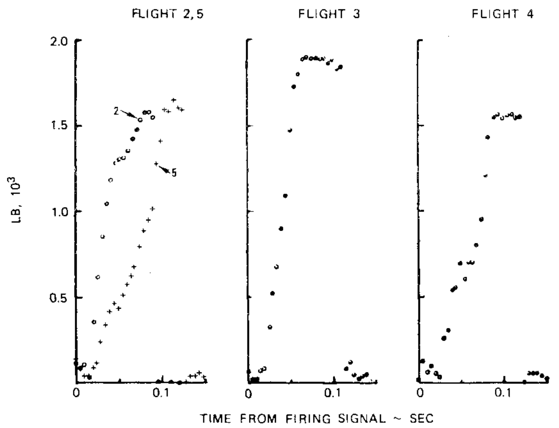

Fig. 2 Ejector force-time histories.

simplifications were made to shorten the run time. Earlier comparisons including this program have shown some shortcomings, but it still is the most effective engineering tool available at this time.

Specific shortcomings noted in Ref. 2 were a poor representation of the effects of angle of attack on the store and the lack of a fin-to-fin interaction for a closely mounted adjacent store. Earlier versions of this program also lacked a detailed description of the ejector force-time history, but a revision† is now available.

Description of Results of Store Motion near Aircraft

Release conditions are summarized in Table 1. The results of the ejector foot load cell output are given in Fig. 2. It seems highly likely that the hesitant force buildup combined with the lower force level for flight 4 contributed to an unexpected collision between the ejected store and a still-attached shoulder store.

Detailed close-in trajectory results for flights 2 and 5 are compared with various estimates in Fig. 3. Small differences in full-scale results due to slightly differing initial conditions are apparent. Similar differences appear in the estimates.

Pitch angle results from the CTS at AEDC agree quite well with the flight test as well as the grid tests, even though the captive loadings in all three cases were different. NEAR results, generated only for flight 2, were also a close representation of the full-scale results. Comparison of the yaw results, however, raises some question. Flight results, at first, follow the grid calculations but later approach the NEAR theoretical calculations which have the opposite sign. They deviate considerably from the CTS results. A part of this uncertainty comes from the fact that as the motion starts and

Table 1 Drop flight conditions

Flight No.	Mach	Velocity, knots	A/C angle, deg	Altitude, ft
2,5	0.6	405	2.7	5200 (avg.)
3	0.8	528	1.1	5455
4	0.9	601	0.33	5425

the roll builds up for this canted-fin configuration, the ejector forces show up in other places such as the yaw plane. Neither the CTS nor the NEAR model are capable at this time of accounting for this feature. This is partially confirmed by an unorthodox calculation with the NEAR model starting at conditions at the end of the ejector stroke with these conditions taken from the grid calculations for flight 5. This calculation, labeled "adjusted" NEAR, had a rate of roll imposed on the motion from the grid trajectory results, and the angular motions of the store are considerably improved. Other degrees of freedom, however, do not have commensurate improvement.

Further results are shown in Fig. 3b where all analyses of the translational motion in the z plane are shown to approach each other and differ only slightly from flight results. The z motion is a poor parameter with which to compare separation motion because of the effect of gravity. In fact, the point marked as special in Fig. 3b is the result of a point-mass trajectory with only the ejector and gravity considered. The interference effects must be large before this general trend changes appreciably. Sidewise motion results, shown in Fig. 3b, again have large differences, possibly due to the ejector interaction.

Roll results, shown in Fig. 3c, also indicate some conflicts. Flight results indicate an initial low rate of roll buildup followed by an acceleration. This is opposite to the analysis and captive-load data, both of which show the reverse. NEAR results, not accounting for the canted fins, showed the interference effects to be opposite to the direction of roll due to fin cant and hence similar to the flight results.

Results for Mach = 0.8, shown in Fig. 4, are not greatly different from those for Mach = 0.6. Unfortunately, CTS results which were made for an angle of attack of 3.3 deg were not applicable to this flight condition. In fact, the CTS results indicated some undefined contact almost immediately after launch terminating the trajectory. Flight results for the pitch and yaw angles, shown in Fig. 4a, are no longer bracketed by the wind-tunnel grid and NEAR theoretical calculations. Thus, the simulations, especially those by NEAR, are somewhat optimistic. Yaw results indicate more agreement in trend between wind-tunnel grid and NEAR results, but both differ from the flight results. Again the z translational results are not too informative for the reason mentioned before, and the sideways motion shows some disagreement. This disagreement, however, is probably within the accuracy of the data. Roll and drag results, shown in Fig. 4c, are similar to those for Mach = 0.6.

At this time, it seems appropriate to examine the trend exhibited by the results. There is a clear indication of an increasing divergence between the simulations and the flight test results. This is not likely to be a transonic effect, since neither the wind-tunnel nor the captive-loads tests showed anything peculiar to transonic flow until strong shocks began to form in the flowfield surrounding the store. The divergencies are much more likely to be the result of the relatively small descrepancies in the interference loading being magnified by the increasing q. Thus, the aerodynamic loading is beginning to dominate the inertia loading.

The simulations, at this point, are not accurate enough to give the exact set of conditions for an upper limit of the safe-separating store and thus become more qualitative than quantitative. The increasing pitch angle would lead one to

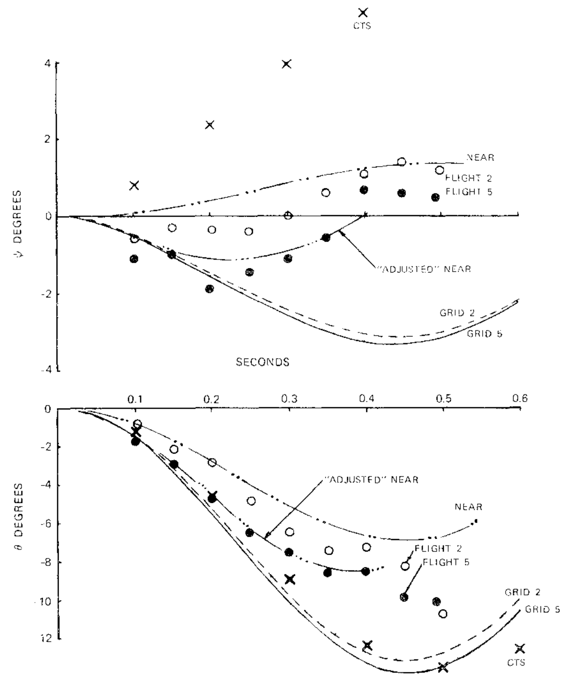

Fig. 3a Comparison of results for pitch and yaw motion, Mach = 0.6.

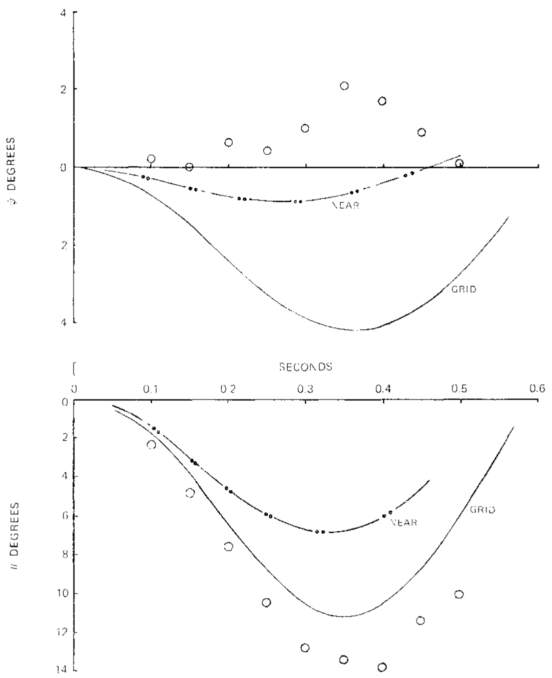

Fig. 4a Comparison of results for pitch and yaw motion, Mach = 0.8.

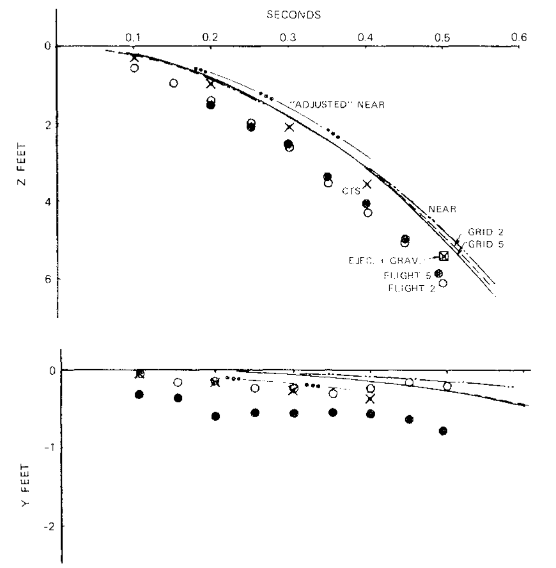

Fig. 3b Comparison of downward and sideways movement, Mach = 0.6.

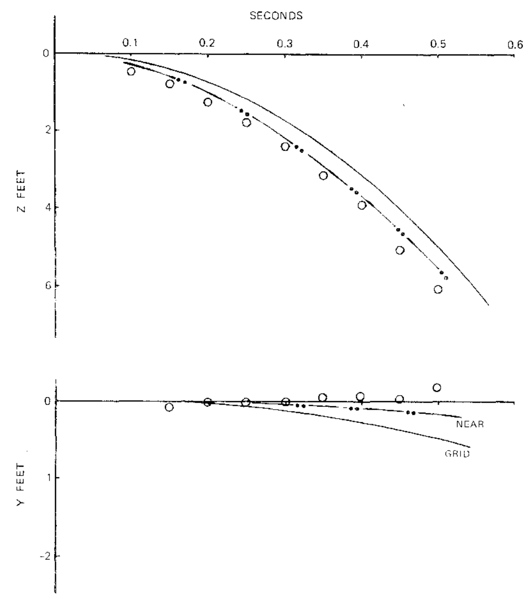

Fig. 4b Comparison of downward and sideways movement, Mach = 0.8.

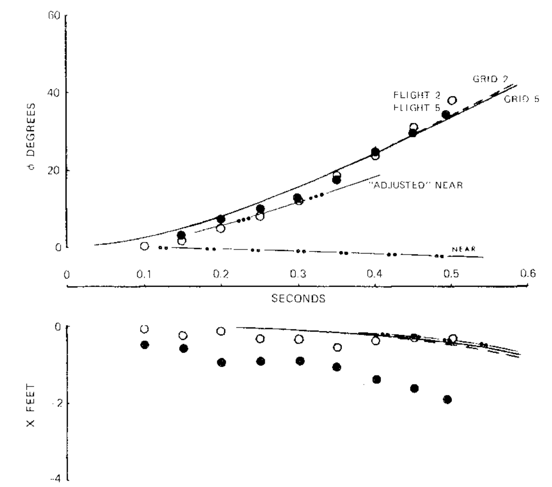

Fig. 3c Comparison of roll and axial movement, Mach = 0.6.

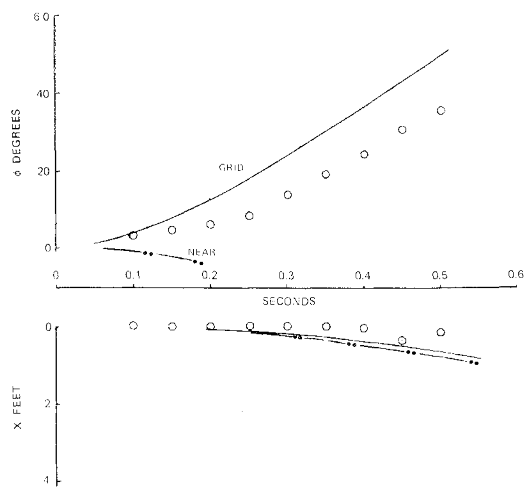

Fig. 4c Comparison of roll and axial movement, Mach = 0.8.

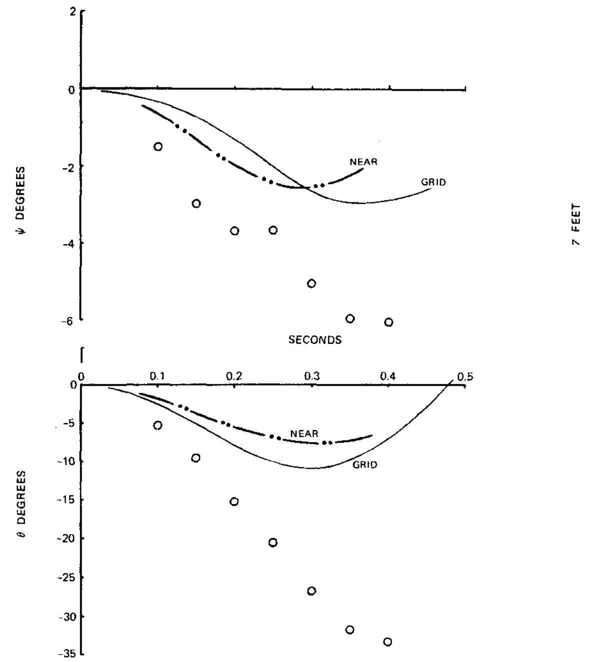

Fig. 5a Comparison of results for pitch and yaw motion, Mach = 0.9

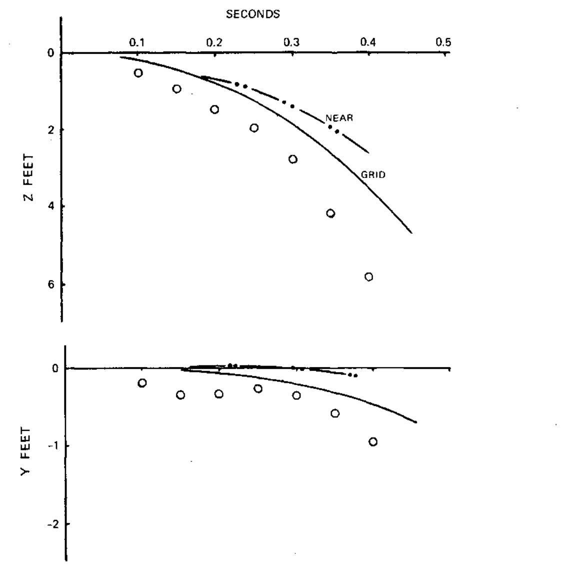

Fig. 5b Comparison of downward and sideways movement, Mach = 0.9.

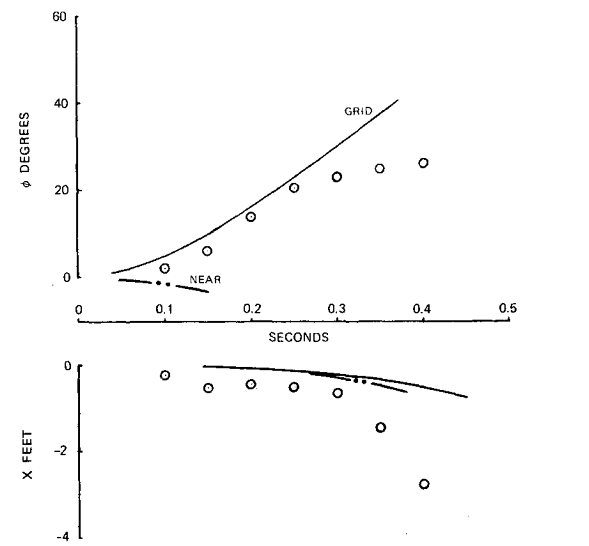

Fig. 5c Comparison of roll and axial movement, Mach = 0.9.

conclude that this store might at some higher dynamic pressure pitch too rapidly and strike the rack with the tail, but the z translational motion is sufficiently rapid that this is not a likely occurrence soon in the speed buildup. The yaw and side motions do not seem to be a problem at all. In fact, this configuration has been cleared operationally through most of the transonic speed range, and this is considered a safe launch condition. Nevertheless, at the next drop condition of $M=0.9$, a minor collision occurred. This collision is graphically illustrated in Fig. 5c in the roll history of the store. The roll virtually stops at about 0.25 s. The mode of collision was not in the pitch plane as might have been expected. Instead, the suddenly enhanced yawing motion allowed the store to roll into an adjacent shoulder-mounted store with the tail fins making contact. After some fin scraping and deflection of the whole system, the store continued on its way.

The overall comparison of $M=0.9$ flight test results with simulations is shown in Fig. 5. Here again, the captive-trajectory information was not beneficial.

The pitch and yaw angles seen in Fig. 5a indicate considerable disagreement between the flight results and both the NEAR and the grid calculations. Earlier work in Ref. 2 clearly established the shortcomings of the theoretical calculation in the pitch plane for captive loadings of this complex configuration. Apparently the entire flowfield representation is not adequate for this high q condition. Although the wind-tunnel captive loads included in the same reference indicated a better representation of the flight data, the wind-tunnel data used here in the grid information were an extrapolation of the data at Mach 0.6 and 0.8, and this is apparently quite inappropriate for the high q releases. Even though the flight data show a much higher amplitude of pitching motion than expected, the tail did not rise sufficiently quickly to contact the rack or other structure. The contact came in the yaw plane from the much larger than expected yawing motion. Again the theoretical as well as wind-tunnel simulations gave considerably less amplitude of motion. The same can be said, to a lesser extent, of the other modes of motion shown in Figs. 5b and 5c.

Impact Point Results

A calculation of the trajectory to the impact point brought out a sensitivity to aerodynamic data, including the drag, not illustrated in the previous work. Wind was also a factor, but since the aircraft was not tracked for heading, only the downrange components were considered. The large effect of the drag coefficient on the trajectory led to some investigation of that value in widespread use for this store. The wind-tunnel data base, assembled in support of these drops, gave a drag coefficient between 0.2 and 0.23 for the Mach range of these tests. Scale and mounting effects would have some correction on this value. Older wind-tunnel data, however, give a drag coefficient over this same range as low as 0.11, while the ballistic tables in the Joint Munitions Effectiveness Manual were generated using a value of 0.13. Captive-loads data, on the other hand, yielded a value in excess of 0.2, and if the wind-tunnel decay to freestream data are used, the final value for the drag coefficient over this range would be about 0.17. This latter value appears most likely for the representative drag coefficient for these tests, but the calculations were carried out for a range of values as summarized in Table 2.

In the ballistic calculation above, all the aerodynamics were taken out except for the drag giving the trajectory for a point mass with drag corresponding to the real store. After adding all the components due to aerodynamics, including the mutual store/aircraft interference, ejector, and average wind, the drag coefficient appears higher than 0.17 in two of the cases and lower in one. This would indicate the current trajectory tables used in aiming data need some re-examination for effects of a greater than expected variation in all aerodynamics.

Table 2 Impact point comparison, downrange distance traveled

Flight No.	C_D	Ballistic impact, no aero/eject/wind, ft	Full aero (interference + eject), ft	Wind component, ft	Calculated impact, ft	Flight results, ft
2	0.13	12,280	12,353	259	12,612	12,615
	0.17	12,158	12,267	260	12,527	
	0.20	12,068	12,217	261	12,478	
3	0.13	15,788	15,909		15,800	14,818
	0.17	15,602	15,794		15,685	
	0.20	15,467	15,714		15,604	
4	0.13	17,836				14,290
	0.17	17,609				
	0.20	17,443				
5	0.13	11,424	11,444	68	11,512	11,401
	0.17	11,317	11,383	68	11,451	
	0.20	11,239	11,342	69	11,411	

Flight 4 is included only for completeness. The impact was anomalous from the effects of the collision, and the calculations cannot take this into account.

Trajectories for these same drops were generated using representations for the interference to determine if some simple representation of interference could be used in aiming tables. To be specific, the loading indicated by the captive results of Ref. 2 was allowed to decay to the freestream in an exponential manner as was done earlier in the general computational study in Ref. 5. It was found that the impact point is not sensitive to the form in which the interference is expressed as long as the magnitude is generally correct. With such a representation, the above impact points were just as well represented with this approximate manner, although the close-in motion was not represented nearly as well. Thus, simple approximations to the interference could be used in generating nonballistic corrections to the aiming calculations.

Conclusions

In this complex case of close-coupled, multiple carriage of stores, the conventional wind-tunnel simulation is good for the general nature of the separation motion at moderate subsonic Mach numbers, but there are occasional large anomalies in some planes of motion (in this case, the yaw plane). Improvements in the wind-tunnel simulations could undoubtedly be made with greater attention to the geometric representation. The techniques in general use to simulate store separation, however, are not very flexible and do not lend themselves to a variation of parameters around a sensitive condition.

Quite surprisingly, after captive results indicated otherwise, the best engineering mathematical model of store separation showed a capability approaching that of the wind tunnel in simulating the low Mach number separation motion for this configuration. As the Mach number increased to the high subsonic range, however, neither the wind-tunnel nor the mathematical model was adequate to indicate a collision situation clearly.

It is clearly important to include the store/aircraft mutual interference as well as accurate basic aerodynamics in the downrange trajectory. The exact analytical representation of this interference is not critical in the calculation of the impact point; therefore, it would appear possible to include rough approximations of this effect in aiming data.

References

[1]Spahr, H. R., Everett, R. N., and Kryvoruka, J. K., "A Multifaceted Store Separation Analysis," *Proceedings of Ninth Aerodynamic Testing Conference,* Arlington, Tex., June 7-9, 1976.

[2]Maddox, A.R., Dix, R.E., and Matasits, G.R., "In-Flight Measurements of Captive Loads on a Store as Compared with Wind Tunnel and Mathematical Simulations," Naval Weapons Center, China Lake, Calif., NWC TP 6026, April 1978.

[3]Houck, M. and Nelson, R. "Photographic Position and Attitude Measuring System," Naval Air Test Center, Patuxent River, Md., NATC TM-1 TS/CS, 1978.

[4]Dix, R.E., "Comparison of Two Methods Used to Measure Aerodynamic Loads Acting on Captive Store Models in Wind Tunnel Tests," Arnold Engineering Development Center, Tullahoma, Tenn., AEDC-TR-76-122, Sept. 1976.

[5]Maddox, A.R., "A Parametric/Sensitivity Study of Store Separation," *Proceedings of Aircraft/Stores Compatibility Symposium,* Sacramento, Calif., Sept. 18-20, 1978.