Cavity Door Effects on Aerodynamic Loads of Stores Separating from Cavities

A. B. Blair Jr.* and R. L. Stallings Jr.†
NASA Langley Research Center, Hampton, Virginia

A wind-tunnel investigation was conducted to determine the effects of cavity doors on the aerodynamic characteristics of compressed-carriage store configurations during separation from a shallow box cavity. The tests were conducted in the NASA Langley Unitary Plan Wind Tunnel at freestream Mach numbers of 1.70, 2.00, and 2.65 for a constant Reynolds number/ft of 2.00×10^6. Results are summarized to show the effects of door opening angles and vertical height, folded and unfolded tail fins, and Mach number on the near-field aerodynamic separation characteristics of a single missile-type store with in-line cruciform wings and tail fins.

Nomenclature

A	= reference area; maximum cross-sectional area of store body, $\pi d^2/4$
C_A	= axial-force coefficient, axial force/$q_\infty A$
$C_{A,\max}$	= axial-force coefficient at $z/d = 10.0$
C_m	= pitching-moment coefficient, pitching moment/$q_\infty Ad$
C_N	= normal-force coefficient, normal force/$q_\infty A$
C_p	= pressure coefficient, $(p - p_\infty)/q_\infty$
$C_{P,b}$	= store base pressure coefficient
d	= reference store-body diameter, 1.20 in.
h	= cavity depth
M_∞	= freestream Mach number
p	= local measured static pressure
p_∞	= freestream static pressure
q_∞	= freestream dynamic pressure
w	= cavity door width
z	= perpendicular distance from splitter-plate surface to store axis of symmetry (store separation distance)
α	= store angle of attack relative to splitter-plate surface, deg
ι	= cavity length

Introduction

THE design of high-speed aircraft capable of sustained supersonic speeds must include weapons integration concepts that result in drag levels lower than conventional pylon or tangent carriage configurations. Internal carriage is currently receiving attention for more effective store carriage at supersonic speeds. Although considerable information is available in the literature about external store carriage and separation aerodynamics and acoustic measurements in cavities or weapons bays,[1,2] little information is available concerning the aerodynamic characteristics of stores during separation from internal carriage configurations at supersonic speeds. Internal carriage configurations can cause large perturbations in the aircraft flowfield through which the store must penetrate during launch. Several studies were initiated at NASA Langley to define the flowfields for given internal carriage concepts and the aerodynamic characteristics of stores separating from simple box cavities. Results from some of these studies are reported in Refs. 3–5.

This paper summarizes the significant findings of one of these studies, which consisted of an investigation to expand the data bases of Refs. 4 and 5 to include the effects of cavity doors on the aerodynamic characteristics of stores separating from cavities. Tests were conducted using compressed-carriage store configurations separating from a shallow box cavity (closed cavity flow) located in a splitter plate. Results presented and discussed are the effects of cavity door opening angles, vertical door height, folded and unfolded tail fins, and Mach numbers on the near-field aerodynamic separation characteristics of a single missile store with cruciform wings and tail fins. These tests will help identify internal carriage configurations that facilitate safe launch of stores from supersonic aircraft.

Test Facility, Models, and Instrumentation

The tests were conducted in the low-speed leg of the NASA Langley Unitary Plan Wind Tunnel, which is a variable-pressure, continuous-flow facility described in detail in Ref. 6. The present tests were conducted at freestream Mach numbers of 1.70, 2.00, and 2.65 for a constant Reynolds number Re/ft of 2.00×10^6.

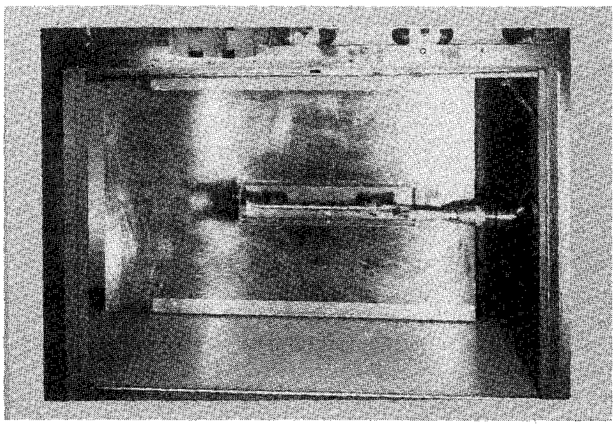
The parent body for the present tests was a vertical, two-dimensional splitter plate that extended from the floor to the ceiling of the tunnel test section, as shown in Fig. 1a. Splitter-plate details are presented in Fig. 1b. The splitter plate was 47.3 in. high and 72.8 in. long and contained a shallow rectangular-box cavity that simulated a store bay. The length and depth of the cavity were 34.0 and 2.43 in., respectively. The leading edge of the cavity was located 27.5 in. downstream of the plate leading edge. Since the boundary layer approaching the weapons bay on most full-scale aircraft is turbulent, a band of no. 35 sand grains was located 0.40 in. downstream from the leading edge of the splitter plate to insure a fully developed turbulent boundary layer approaching the cavity. The measured boundary-layer thickness on the splitter plate at the cavity leading edge was 0.4 in. In addition, all tests were performed with a boundary-layer transition strip located 1.20 in. aft of the store nose. The cavity has a length-to-depth ratio of 14.0 and can accommodate up to four folded tail-fin stores in a side-by-side arrangement. However, for the present tests only one store was utilized.

In order to establish supersonic flow on the back side of the splitter plate, which was required to eliminate contamination of the front surface due to spillage, the back side discharge area was increased by inclining the plate 1 deg relative to the freestream flow, as shown in Fig. 1b. Because the flow over

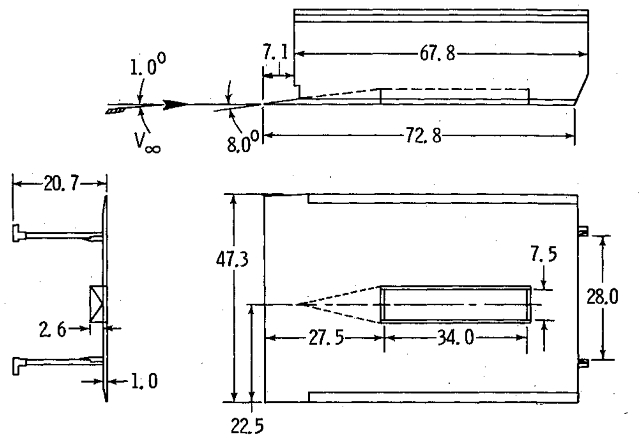
Presented as Paper 88-0333 at the AIAA 26th Aerospace Sciences Meeting, Reno, NV, Jan. 11–14, 1988; received Feb. 5, 1988; revision received Oct. 20, 1988.

*Aero-Space Technologist, Supersonic/Hypersonic Aerodynamics Branch, Applied Aerodynamics Division. Senior Member AIAA.

†Aero-Space Technologist, Supersonic/Hypersonic Aerodynamics Branch, Applied Aerodynamics Division. Associate Fellow AIAA.



a) Photograph of splitter plate and store model installation



b) Splitter-plate details

Fig. 1 Photograph and details of splitter plate.

Fig. 2 Store model details.

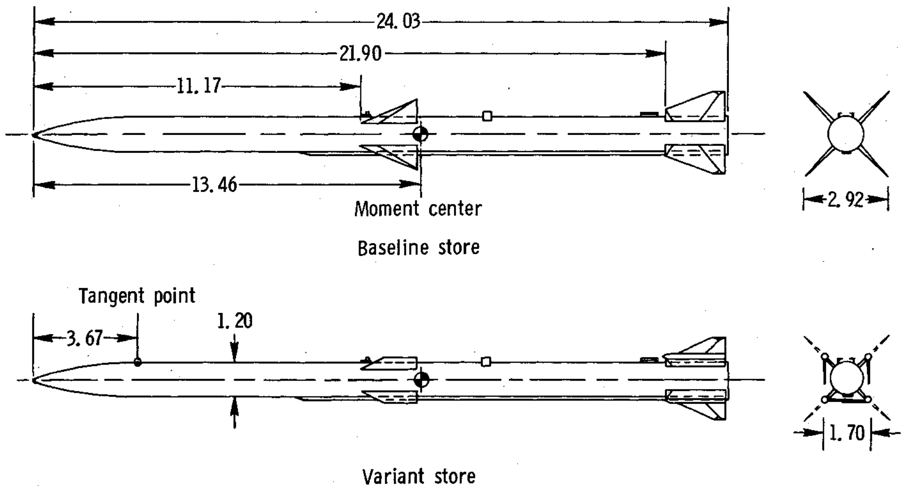
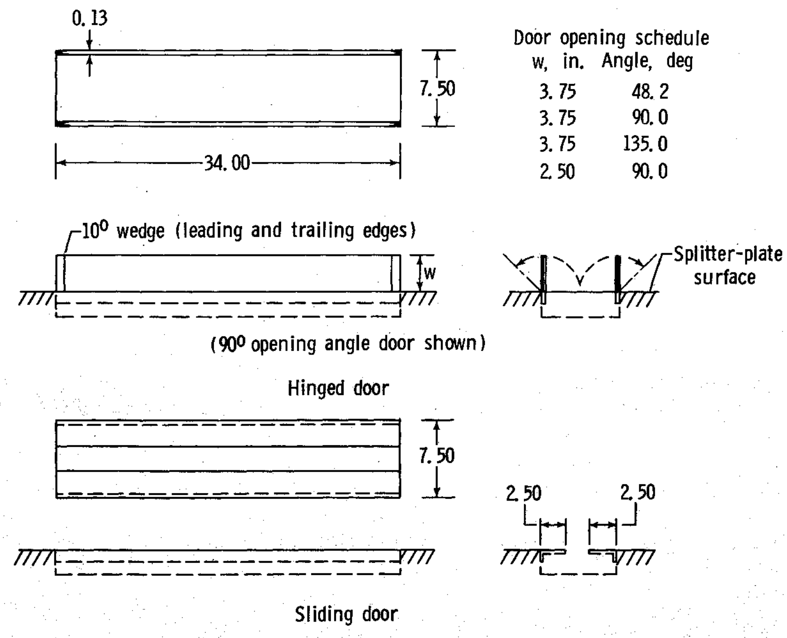


Fig. 3 Cavity-door details.



the plate is two-dimensional and the centerline of the store model is always parallel to the splitter-plate surface, the major effect of this 1 deg angle is a small change in the local flow conditions on the plate. For example, at a freestream Mach number of 2.65, the local Mach number of the splitter-plate flowfield is 2.60, and the local nominal Re/ft is 2.06×10^6 rather than 2.00×10^6. Force and moment data reduction was based on freestream conditions rather than the local plate conditions.

Shown in Fig. 2 are drawings of the two test store configurations, which are identified in this paper as the baseline and variant stores. The baseline store was a 1/6-scale model of an

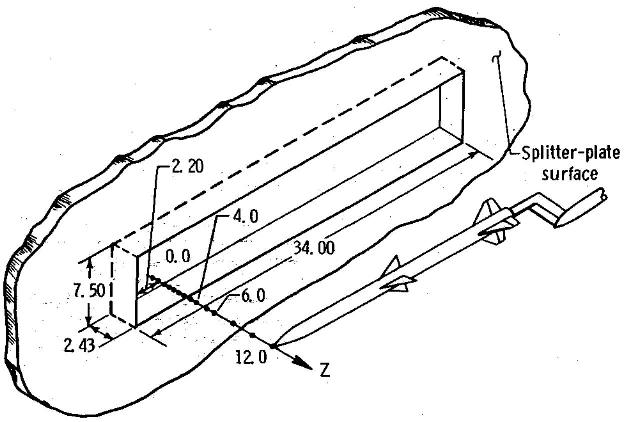


Fig. 4 Cavity and store separation details.

advanced cruciform tail-controlled missile with fixed in-line delta wings and a high-fineness-ratio (20.0) ogive-cylinder body. The variant store was a minimum-volume carriage configuration and differed from the baseline store in that it had clipped-delta cruciform wings in line with fixed folded and/or unfolded tail fins. Each variant tail fin had a simulated pod fairing to enclose a fin-folding hinge mechanism.

Several pairs of conventional rectangular doors with sharp leading and trailing edges could be attached to the cavity, as illustrated in Fig. 3. These doors were used to simulate hinged doors having opening angles of 48, 90, and 135 deg, and a sliding-door arrangement that had an opening angle of 0 deg. In addition, for the 90-deg opening case, one pair of shorter-width doors was also tested. For selecting door opening angles, including a reference no-door cavity configuration, the aerodynamic store loads were measure during separation from the cavity for store configurations with folded and/or unfolded tail fins in the x orientation. The cavity door opening was wide enough for a single folded tail-fin store to pass through for all test door opening angles.

The store models were instrumented with a six-component strain-gage balance to measure aerodynamic forces and moments. However, in the present paper, only normal-force, axial-force, and pitching-moment coefficients are presented. Store base pressure was measured by means of a single static-pressure orifice located in the vicinity of the balance. The balance was attached to an offset sting assembly that was rigidly fastened to the tunnel model support system, which could be remotely varied in either the lateral or longitudinal direction. This offset sting arrangement allowed the store model to be actually positioned inside and outside the cavity. In order to minimize sting interference effects, the leading-edge wedge angle of the offset blade of the sting was made sufficiently small to insure attached supersonic flow on the wedge for the test Mach number range.

Cavity and store separation details are presented in Fig. 4. For the present tests, measurements were obtained at 15 discrete store separation distances (z) in a plane perpendicular to the plate surface that passed through the longitudinal centerline of the cavity. All measurements were obtained with the store model nose located 2.20 in. downstream of the front face of the cavity. Store model angles of attack and slideslip relative to the splitter-plate surface were approximately 0 deg. The moment reference center was located at 56.0% store-body length measured from the nose. The store tail fins were tested only in the x orientation and not deflected.

Results and Discussion

Previous investigations have shown that for simple box cavities without doors, there are two fundamentally different types of cavity flowfields at supersonic speeds,[3] and that the type of flowfield can have large effects on the aerodynamic characteristics of stores that are launched from the cavities.[4,5]

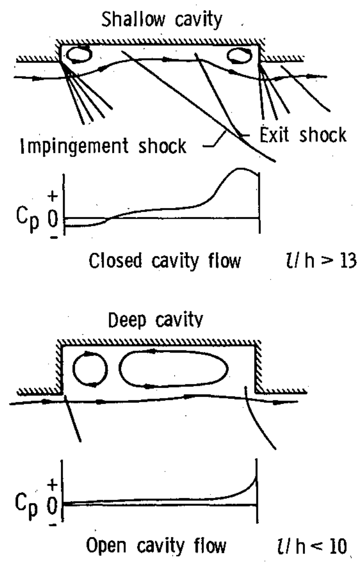


Fig. 5 Typical sketches of cavity flowfield and pressure distribution for cavities with closed and open cavity flow at supersonic Mach numbers.

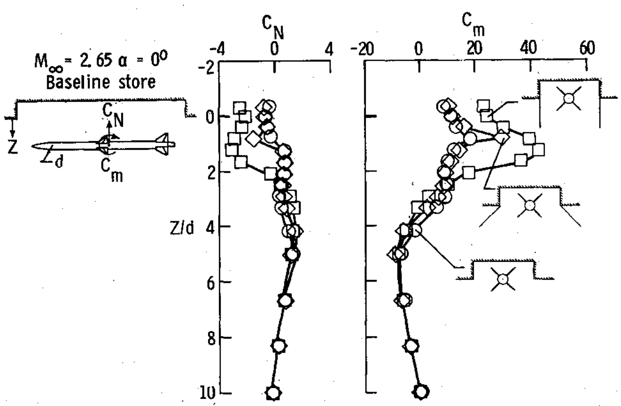


Fig. 6 Effect of cavity-door opening angle on longitudinal characteristics of baseline store during separation.

The two types of cavity flowfields are strongly dependent upon cavity to length-to-depth ratio (l/h). Flowfield sketches based on schlieren photographs and pressure distributions from Ref. 3 and 4 that are representative of the two types of flowfields are presented in Fig. 5. For the case of the shallow cavity ($l/h > 13$), the flowfield is the type that is often referred to as a closed or attached cavity flow. For this type of flowfield, the flow expands over the cavity front face, impinges on the cavity ceiling, and exits ahead of the rear face. The local flow turns through large angles, which results in large pressure gradients as shown by corresponding pressure data. A store being launched through this type flowfield has its nose exposed to an upwash region and its tail exposed to a downwash region, which results in large positive pitching moments. These large pitching moments result in undesirable separation characteristics, as discussed in Ref. 4. For the case of the deep cavity ($l/h < 10$), the flowfield is of the type that is generally referred to an an open or detached cavity flow. For this type flowfield, the flow simply passes over or bridges the cavity and impinges on the outer edge of the rear face, resulting in relatively small turning angles and, consequently, a much more uniform pressure distribution over the cavity ceiling. This type flowfield, as discussed in Ref. 4, generally resulted in relatively benign store separation characteristics.

For the present tests, the cavity has a length-to-depth ratio of 14. This cavity is, therefore, considered a shallow cavity and should produce a closed-cavity flowfield, at least for a cavity without doors. The effects of cavity doors on the closed-cavity flowfield and on the store separation characteristics are the primary objectives of this study.

The effects of cavity-door opening angle on the longitudinal aerodynamic characteristics of the baseline store during separation are presented in Fig. 6. It should be noted that the longitudinal characteristics measured for the baseline store were essentially the same as those measured for the variant store with the fins unfolded. The results presented in Fig. 6 and all succeeding figures for the baseline store should, therefore, also be representative of the variant store as it separates from a shallow cavity after the fins have been unfolded. In the carriage mode, of course, the variant store would be fully contained in the cavity with all four fins folded and the cavity doors closed. Data are presented in Fig. 6 for hinged-door opening angles of 90 and 135 deg and also for a reference case of no doors. The results show that door opening angles can have a large effect on the store separation characteristics. For the case of the doors at 135 deg, as shown by the diamond symbols, the store separation characteristics are approximately the same as were measured for the no-door case as shown by the circular symbols. For both of these cases, the store pitching moments are very similar to previously published data for shallow cavities having closed-cavity flowfields, and consist of large positive values as the store exits from the cavity. At a door opening angle of 90 deg, the maximum store pitching moments that occur are approximately double the maximum measure values for the store separating from the cavity with no doors. These elevated pitching-moment coefficients for the 90 deg doors extend into the cavity flowfield to $z/d \approx 2$. For this range of z/d, the store separating from the 90-deg door cavity also experience normal-force coefficients that were considerably more negative than measured for the cavity without doors. A possible explanation for the observed elevated magnitudes in C_m and C_N for the 90-deg doors is that the doors act as side plates, which tend to contain the high pressures in the flowfields ahead of the cavity rear face to greater values of z/d than occur for the cavity without doors. This hypothesis is substantiated to some extent by store base pressure measurements to be discussed subsequently. The increase in flowfield pressures in the region ahead of the cavity rear face would result in a more negative normal force on the store because of the increase in the local pressures in the downwash region of the tail assembly, and an increase in pitching moment because this increment in negative normal force occurs aft of the moment reference center. Of course, a negative normal-force increment could be beneficial (zero pitching moment) if it acted at the store moment center for z/d values near 0.

Shown in Fig. 7 is the effect of decreasing the height of the 90-deg doors from 3.75 to 2.50 in. on the separation characteristics of the baseline store. The 2.50-in. door simulates a door assembly that is partially retracted into the cavity as it opens. Decreasing door height results in a reduction in the peak values of C_m and C_N and a reduction in the range of z/d over which these elevated coefficients occur. This trend is consistent with the "side-plate effect" discussed previously.

The effect of Mach number on the normal-force and pitching-moment coefficients of the baseline store as it separates from the cavity with 90-deg doors is shown in Fig. 8. Decreasing the Mach number from 2.65 to 2.00 had no noticeable effect on the peak pitching-moment coefficient; however, a further reduction in Mach number from 2.00 to 1.70 resulted in a reduction in the peak values. Decreasing the Mach number for the test range from 2.65 to 1.70 resulted in an increase in the range of z/d over which the elevated values of C_N and C_m occurred. This increase in the range of z/d may be due to an increase in the standoff distance and angle of the shock wave ahead of the cavity rear face that would be expected to occur with decreasing Mach number.

The results discussed to this point have been for the baseline store, which, as discussed previously, are also representative of the variant store with unfolded tail fins. Figure 9 shows the separation characteristics of the variant store for several folded tail-fin configurations as it separates from the cavity with 90-deg doors. Also shown as solid circular symbols in Fig. 9 are baseline store 90-deg door data presented in Fig. 6 (square symbols). The variant store results are shown for all four fins unfolded, all four fins folded, the two upper fins folded, and the two lower fins unfolded. The latter configuration simulates a case where the deployment of the upper fins is delayed because of their close proximity to the cavity ceiling. The data for these variant store configurations show that the reduction in tail-fin area that occurs as the fins are folded results in a decrease in the peak values of C_m and C_N at

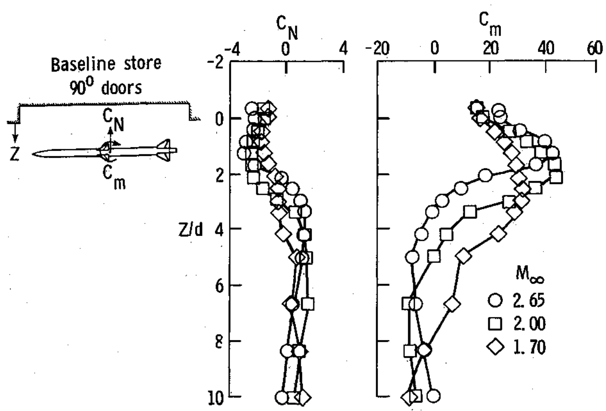


Fig. 8 Effect of Mach number on longitudinal characteristics of baseline store during separation from cavity with 90-deg door opening angle.

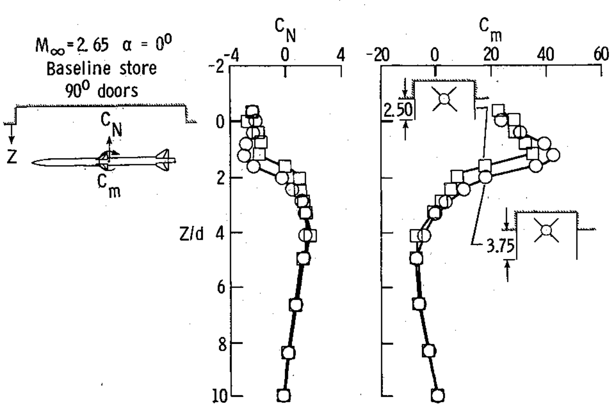


Fig. 7 Effect of door height on longitudinal characteristics of baseline store during separation from cavity with 90-deg door opening angle.

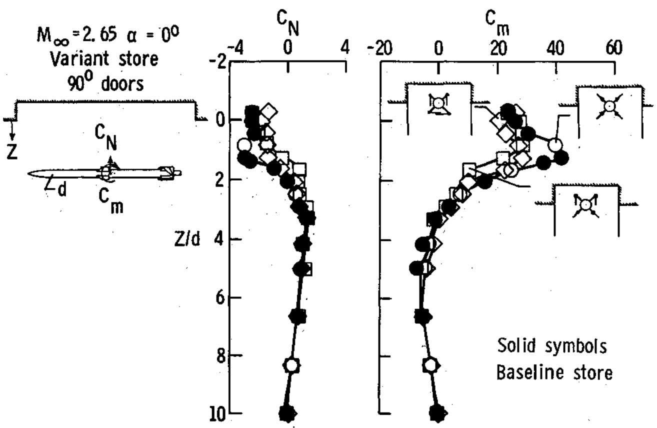


Fig. 9 Effect of folding tail fins on longitudinal characteristics of variant store during separation from cavity with 90-deg door opening angle.

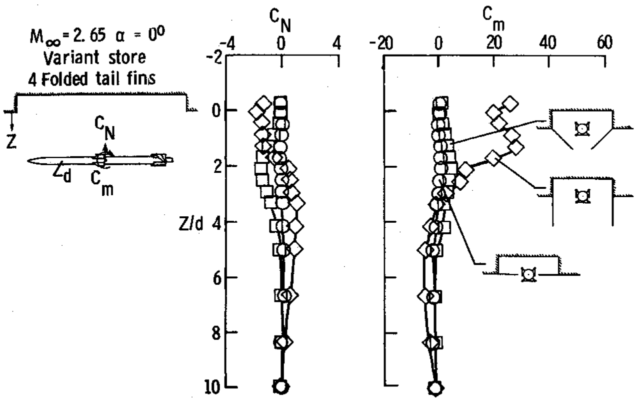


Fig. 10 Effect of cavity-door opening angle on longitudinal characteristics of variant store with folded tail fins during separation.

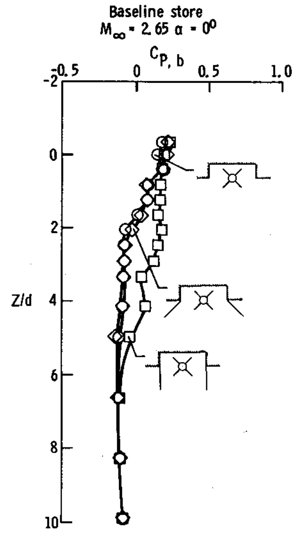


Fig. 11 Effect of cavity-door opening angle on baseline store base pressure coefficients during separation.

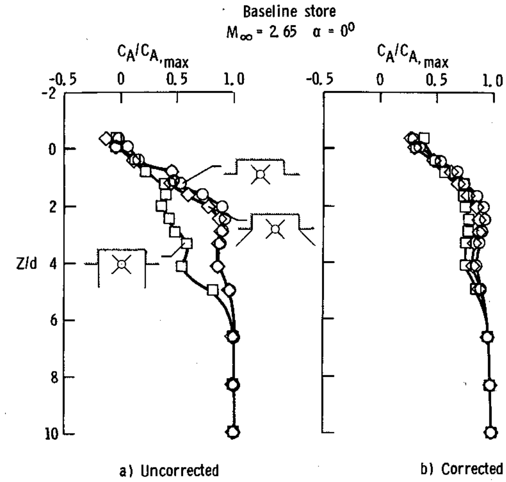


Fig. 12 Effect of cavity-door opening angle on baseline store axial-force coefficients during separation.

$z/d \approx 1$. The data also show that these peak coefficients for the configuration with four folded tail fins are approximately the same as obtained for the configuration having the upper fins folded and the lower fins unfolded. This increased sensitivity of the coefficients to the upper fins is probably due to the fact that, relative to the downwash at the rear of the cavity, the upper fins are windward and are therefore exposed to higher local dynamic pressures than the lower or leeward fins. Even though the peak values of C_m for the configurations with four folded tail fins are less than for the unfolded fin configuration, the peak values are still very large and most likely would results in undesirable store separation conditions. A comparison of the data presented in Fig. 9 for the unfolded tail-fin variant store (open circular symbols) with the baseline store data (solid circular symbols) clearly shows the similarity of the characteristics of these two store configurations. Similar comparisons were obtained for the range of duplicated test conditions.

Figure 10 shows the separation characteristics of the variant store with four folded tail fins for several door opening angles. The data shown with the cavity doors at 90 deg are the same data that were shown for this store configuration in Fig. 9. The other two cavity door configurations, one simulating a hinged door and the other simulating a sliding door, are different from the door configurations that have been presented previously in that the opening formed by the doors at the open position are just wide enough for the store configuration with four folded tail fins to pass through. This reduced opening area created by both the hinged and sliding door configurations resulted in a very large reduction in the values of C_m as the store separated from the cavity. The reduced values of C_m are indicative of a cavity that has an open-cavity flowfield, as shown in Ref. 4. Similar reductions in peak pitching-moment coefficients have been reported previously in Ref. 5 for a wing control missile model separating from a shallow silhouette cavity relative to a box cavity of the same depth. The cutout for the silhouette cavity matched the silhouette of the store.

In the discussion of data presented in Fig. 6, it was stated that the 90-deg doors could be acting as side plates to the cavity, which tend to contain the high pressure in the flowfield ahead of the cavity rear face to greater values of z/d than occur for the cavity without doors. This reasoning is substantiated to some extent by the store base pressure coefficients presented in Fig. 11. The store base pressure coefficients are presented for the baseline store separating from the cavity with the same door configurations for which the force and moment data were presented in Fig. 6. The store base pressure measurements for the cavity without doors and with 135-deg doors are approximately the same for the range of separation distances. For these two door configurations, positive base pressure coefficients are measured for $z/d < 1.75$. At $z/d \approx 5$, the pressures reach a minimum value and remain approximately constant to $z/d = 10$. For the 90-deg doors, the store base pressure coefficients remain positive as shown by the square symbols to $z/d \approx 4.5$, which may be due to the doors acting as side plates and containing the high pressures ahead of the rear face to greater values of z/d than for the cavity without doors.

Presented in Fig. 12 are axial-force coefficients for the baseline store for the same three cavity-door configurations, as shown in Fig. 11. The axial-force coefficients are ratioed to $C_{A,\max}$, which is the value measured at $z/d = 10$ and are presented both without base pressure corrections (Fig. 12a) and with base pressure corrections where the base pressure are adjusted to freestream static pressure (Fig. 12b). The uncorrected values presented in Fig. 12a show that inside the cavity $Z/d < 0$, the slightly negative axial-force coefficients are measured for all three door configurations, which is partially due to the positive base pressure coefficients shown in Fig. 11. As the store separates from the cavity without doors and with the 135 deg doors, the axial force rapidly increases and reaches an approximately constant value at $z/d \approx 2$. For the store separating from the cavity with 90-deg doors, the axial force increases more gradually with increasing z/d and reaches a value of $C_A/C_{A,\max} \approx 1$ at $z/d \approx 6$. Much better correlation of the axial-force coefficients were obtained for all three door configurations when corrections for base pressures were made, as shown in Fig. 12b.

Conclusions

An experimental wind-tunnel investigation has been conducted at supersonic Mach numbers to determine the effects of cavity doors on the aerodynamic characteristics of compressed-carriage store configurations during separation from a shallow box cavity. The tests were conducted in the NASA Langley Unitary Plan Wind Tunnel at freestream Mach numbers of 1.70, 2.00, and 2.65 for a constant *Re*/ft of 2.00×10^6. Results are summarized to show the effect of cavity-door opening angles, vertical door height, folded and unfolded tail fins, and Mach number on the near-field aerodynamic separation characteristics of a single missile store with in-line cruciform wings and tail fins. The results of the investigation are as follows:

1) Cavity-door opening angle had large effects on store aerodynamic loadings for both unfolded and folded tail-fin configurations.

2) Reducing cavity vertical door height decreased the aerodynamic loadings of the baseline store in the vicinity of the cavity.

3) Decreasing freestream Mach number of 2.00 to 1.70 reduced peak pitching-moment coefficients, however, at the lower Mach number, the effects of the cavity flowfield on the store loadings occured at greater separation distances.

4) Peak pitching-moment coefficients in the cavity flowfield for a cavity door opening angle of 90 deg were lower for the folded tail-fin store configurations.

5) Longitudinal pressure gradients in the cavity flowfield had large effects on measured store base pressure coefficients.

References

[1]Arnold, R. J. and Epstein, C. S., "Store Separation Flight Testing," AGARD-AG-300, Vol. 5, April 1986.

[2]Shaw, L., Clark, R., and Talmadge, D., "F-111 Generic Weapons Bay Acoustic Environment," AIAA Paper 87-0168, Jan. 1987.

[3]Stallings, R. L., Jr., and Wilcox, F. J., Jr., "Experimental Cavity Pressure Distributions at Supersonic Speeds," NASA TP-2683, 1987.

[4]Stallings, R. L., Jr., "Store Separation From Cavities at Supersonic Flight Speeds," *Journal of Spacecraft and Rockets*, Vol. 20, March–April 1983, pp. 129–132.

[5]Stallings, R. L., Jr., Wilcox, F. J., Jr., Blair, A. B., Jr., and Monta, W. J., "Store Carriage Drag and Separation at Supersonic Speeds," *Langley Symposium on Aerodynamics*, Vol. II, compiled by Sharon H. Stack, NASA CP-2398, 1986, pp. 251–268.

[6]Jackson, C. M., Jr., Corlett, W. A., and Monta, W. J., "Description and Calibration of the Langley Unitary Plan Wind Tunnel," NASA TP-1905, 1981.