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Aerodynamic Effects of Body Slots on a Guided Projectile with Cruciform Surfaces

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Aerodynamic characteristics are examined for a cannon-launched guided projectile with internally stored cruciform wings and tails. Effects of longitudinal body slots required for wings and tail deployment are emphasized. The control section design permits internal air flow longitudinally and transversely between slots during flight; however, no flow exists through the sealed projectile base. Wind tunnel test data for a full-scale model are presented for Mach numbers of 0.5 and 1.5. Body-alone, body-tail, body-wing, and body-wing-tail configurations were tested with open and closed body slots. Compared to a closed body, open slots change normal force and aerodynamic center of pressure in complex ways, depending upon configuration, Mach number, roll angle, and angle of attack. Open slots also reduce untrimmed lift/drag ratio as much as 33% at low angles of attack, due primarily to severe increases in "effective" forebody drag.

Nomenclature

B	= body
C_A	= axial force coefficient
C_{AF}	= forebody axial force coefficient
C_D	= drag coefficient
C_m	= pitching moment coefficient
C_N	= normal force coefficient
L/D	= lift-to-drag ratio
M	= Mach number
T	= tail
W	= wing
$\bar{X}$	= static margin = $-C_m/C_N$
α	= angle of attack, deg
ϕ	= aerodynamic roll angle, deg

Subscripts

ADJ	= adjusted for internal pressure drag
F	= forebody
NR	= nonrolling (missile) axes
TOT	= total or combined

Introduction

COPPERHEAD, a cannon-launched guided projectile, is in initial production to provide a major improvement in artillery accuracy against tanks and other mobile point-type targets. The projectile is 54 in. long, weighs 138 lb, and is fired from a conventional 155 mm (6.1 in.) howitzer. It has cruciform wings and tails housed within the afterbody during launch. Immediately after launch, the tails are deployed through open slots in the control section (Fig. 1) to give roll rate stabilization and static longitudinal stability. The projectile flies ballistically to a timed point beyond apogee while in the body-tail configuration which, for convenience, is referred to as the launch configuration. When its velocity decays to high subsonic speed, the tails are commanded to stop the roll rate and the wings are extended through open slots, also located in the control section. After wing extension, the projectile is in its maneuver configuration. A semiactive laser seeker is energized, and the projectile maintains a trimmed glide path at an arbitrary roll attitude until the terminal flight phase. The laser guidance system is used during terminal flight to initiate maneuver commands resulting from target location and motion errors, as well as flight dispersions.

Two failures early in the Engineering Development flight test program were attributed wholly, or predominantly, to an unexplained loss of more than 20% in trimmed normal force coefficient.[1] This, coupled with equally large increases in drag values derived from flight test measurements compared to those of previous wind tunnel data, led to additional wind tunnel tests. Results of these tests, using a full-scale model, demonstrated that body slots exert a stronger influence on aerodynamic performance than previous tests had shown.[2] The effects of projectile body slots on static longitudinal stability, axial force characteristics, and lift-to-drag ratios are discussed herein.

Experimental Program

Test Background

The literature on slotted bodies and cavity flows deals largely with experimental investigations due to the flow complexity.[3] These investigations are generally limited to one or more of the following conditions: 1) flow at $\alpha=0$ deg, 2) isolated cavities, 3) acoustic or drag effects, and 4) flows not in proximity to lifting surfaces. The Copperhead design, however, allows air to flow within the control section longitudinally and transversely as a function of roll attitude and angle of attack. Flow entering or exiting the slots passes close to the wing and tail roots, but does not exit through the projectile base because it it sealed to prevent internal damage and blow-by during launch.

Accordingly, a comprehensive wind tunnel test program was conducted. One hundred and ten hours of testing were performed in the Rockwell International Trisonic and the Calspan Transonic wind tunnels.[4,5] Approximately 85% of the test program was devoted to the launch and maneuver configurations; however, body-alone and body-wing combinations were also tested to determine tail and wing effectiveness. In addition to the open slot configurations, tests were conducted with wing and tail slots closed to derive internal drag and other incremental effects.

Operational and Test Conditions

Flight Mach numbers vary from 0.5 to 1.8 and from 0.5 to 0.95 for the launch and maneuver configurations, respec-

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tively. Wind tunnel testing was conducted throughout these Mach number ranges, and the results presented for Mach 0.5 and 1.5 are considered representative. Test Reynolds' numbers, ranging from 9 to 45×10^6 based on model length, match typical flight conditions. Aerodynamic roll angles from 0 to 90 deg were tested for selected configurations to evaluate pitch-yaw symmetry. Illustrated in Fig. 1, the pitch and yaw plane fins are staggered 0.65 in. to prevent interference of the actuator shafts. This difference is only 3.6% of the distance from the moment reference center to the body station of the pitch fin shafts. Its effect on longitudinal stability characteristics is negligible except at attack angles greater than 15 deg. The moment reference center (c.g.) for all test data is station 31.360. Aerodynamic coefficients are based on a reference length and area of 6.00 in. and 28.27 in.^{2}, respectively.

Model Characteristics

Insofar as possible, actual production components, e.g., wings, tails, and the forebody external structure, were used in the full-scale model. This technique minimized potential experimental errors due to aeroelasticity of lifting surfaces and inaccuracies in modeling forebody geometrical details. To reduce model tare weight and facilitate sting and balance installation, the warhead and control sections were fabricated from aluminum alloy. Bourrelets and other protuberances, as well as the nonslip surface finish used to improve projectile handling, were duplicated on the model. An obturator from a fired projectile was used to ensure representative boundary layer conditions at the model base (Fig. 2). The obturator is a flared plastic band that serves to minimize blow-by in the gun barrel and to reduce the projectile's initial spin rate by partially decoupling it from the rifling. Unlike the actual projectile, the model base is penetrated by a sting assembly. Therefore, a sting sleeve extending from the model balance adapter to the tail hub is used to seal the base. The annular area between the sleeve and the model skin permits longitudinal and circumferential flow between slots, thereby retaining the internal flow characteristics of the projectile to the maximum feasible extent.

Basic Data and Adjustments

Six-component main balance, three-component tail balance, and pressure data were obtained. The longitudinal stability data are untrimmed; i.e., tail surfaces were set at a deflection angle of 0 deg. Main balance axial force measurements were corrected to freestream balance cavity and base pressures to obtain forebody coefficients (C_{AF}). Forebody data were chosen for presentation to make slot effects more explicit. The projected area of each wing and tail slot is 3.45 and 3.94 in.^{2}, respectively. These open areas are reduced by the corresponding hub areas, 0.54 in. (wing) and 0.40 in. (tail), as illustrated in a related study of wing-body and wing-tail interference.[6] Pressures were measured in the main balance cavity, on the model base, and in the control section annulus. Control section pressure data are discussed in a subsequent analysis that compares wind tunnel and flight test drag results.[7]

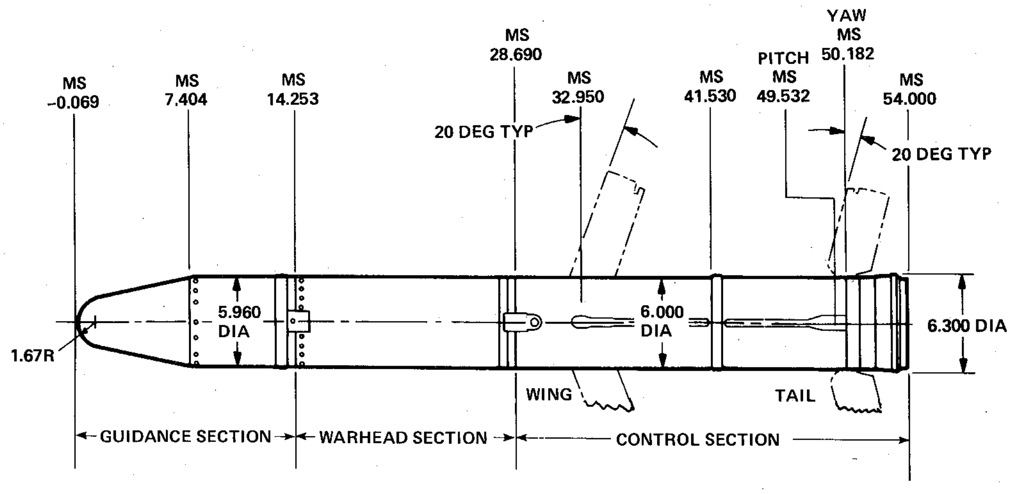

Fig. 1 Full-scale Copperhead model configuration.

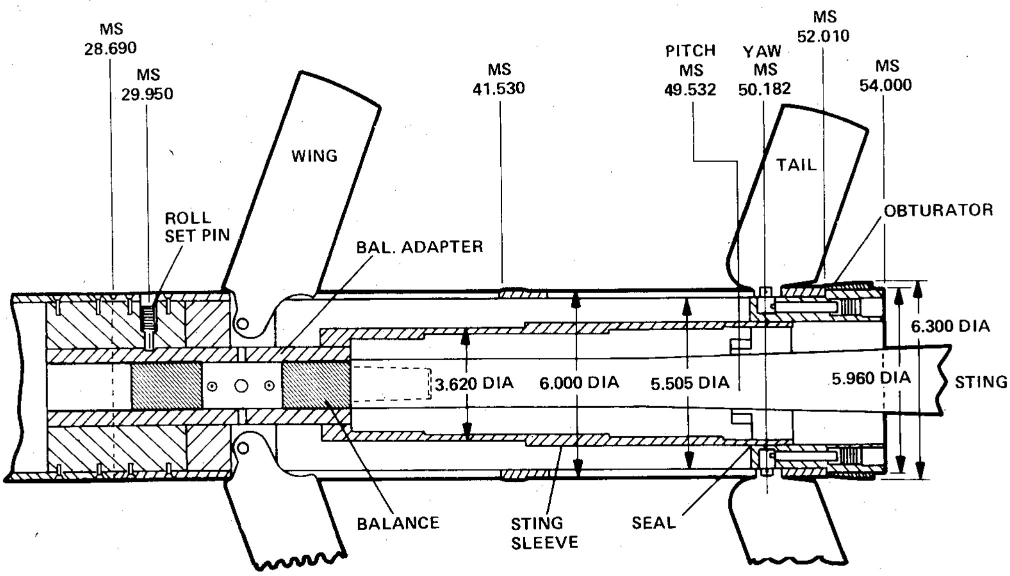

Fig. 2 Model control section details.

Axial force coefficients for configurations with open slots were adjusted to account for differences in control section internal area between the wind tunnel model and actual projectiles. Each configuration was tested with slots closed to obtain incremental axial force data (ΔC_{AF}). The ratio of projectile internal cross-sectional area to the model annular area was 1.72. A data adjustment was developed by assuming that the axial force due to the slots is proportional to the internal area exposed to slot flow. Thus, the incremental adjustment ($\Delta C_{AF_{\mathrm{ADJ}}}$) was 72% of the axial force due to the slots which, in turn, was obtained by differencing C_A measurements for open and closed slot configurations. For a given configuration and test condition, $\Delta C_{AF_{\mathrm{ADJ}}}$ was calculated as follows:

$$\Delta C_{AF_{\mathrm{ADJ}}} = 0.72 \left\{ C_A \,]_{\text{open slots}} - C_A \,]_{\text{closed slots}} \right\} \tag{1}$$

Adding this to the measured data gives the "effective" forebody coefficient:

$$C_{AF_{\mathrm{ADJ}}} = \left\{ C_A \,]_{\text{open slots}} + \Delta C_{AF_{\mathrm{ADJ}}} \right\} \tag{2}$$

This method was used to adjust all axial force data, after which standard axis transformation methods yielded drag coefficients used in analysis of projectile glide path (lift/drag) performance.

Results and Analysis

Test results are presented for various configurations with body slots open and closed at Mach numbers 1.50 and 0.50. The supersonic data are representative of the projectile's ballistic flight, during which it operates in the body-tail configuration. At subsonic speeds, the projectile glides and maneuvers with wings deployed after terminating its ballistic flight phase; therefore, both the maneuver and launch configurations are represented in the data.

Supersonic Data

Effects of slot closure on longitudinal stability characteristics at Mach 1.5 are presented for the body-alone and launch configurations in Figs. 3-5. Axial force and lift/drag comparisons are given in Figs. 6 and 7, respectively.

Longitudinal Stability

In Fig. 3, normal force and pitching moment coefficient data are shown at $\phi = 0$ deg. At this roll angle, one set of slots is coincident with the windward ray of the body, thus providing the most direct opening for crossflow. The body-alone is unstable, based on the reference c.g. at station 31.360. Closing the slots tends to reduce body-alone C_N and increase the unstable C_m at a given angle of attack, indicating a forward shift of the aerodynamic center of pressure (c.p.). Exactly opposite effects were expected with slot closure because of the resultant increase in afterbody surface area, but the data show that more crossflow momentum is dissipated inside the control section (slots open) than on the slot surface areas. The control section blockage produced by the sting sleeve in the model was designed to be no greater than that of the control actuation components in the projectile; thus, model force measurements are considered valid.

Closing the slots does not affect the launch configuration C_N at $\phi = 0$ deg, indicating that an increase in tail effectiveness compensates for the loss of body-alone C_N discussed previously. At this roll angle, slot closure increases negative C_m for the launch configuration. The increase in negative C_m corresponds to a rearward c.p. shift, again demonstrating the greater tail lift obtained with slots closed.

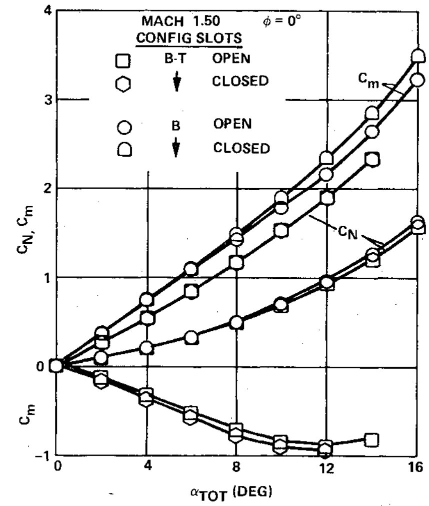

Fig. 3 Effect of slots on supersonic longitudinal stability.

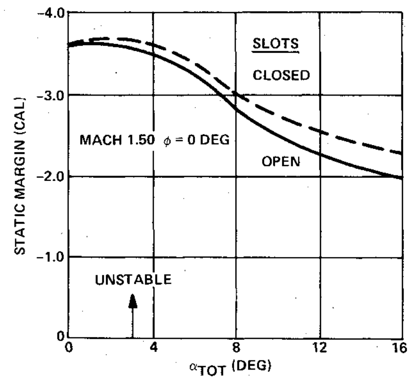

Fig. 4 Effect of slot closure on body-alone supersonic static margin.

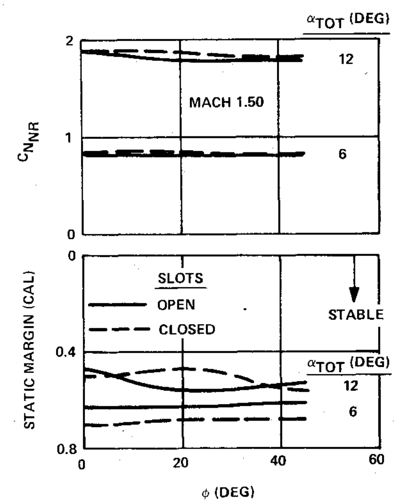

Fig. 5 Summary of launch configuration supersonic longitudinal stability.

Comparisons of c.p. variations expressed as static margin are presented in Figs. 4 and 5 for the body-alone and launch configurations, respectively. The forward c.p. shift with slot closure for the body-alone increases with angle of attack, reaching 0.25 caliber at $\alpha = 10$ deg, as shown in Fig. 4. In addition to static margin, launch configuration $C_{N_{\mathrm{NR}}}$ is plotted as a function of roll angle in Fig. 5 for total angles of attack of 6 and 12 deg. The subscript NR is used to denote coefficients obtained at combined angles of attack and yaw (α_{TOT}). These missile axes coefficients do not imply data transformations from a rotating model. Generally, the launch configuration experiences angles of attack no greater than 6 deg during its ballistic flight. With either slot condition, C_N varies no more than 5% with roll angle, but the c.p. is affected more significantly Closing the slots shifts the c.p. aft nearly 0.1 caliber at $\alpha = 6$ deg. At $\alpha_{TOT} = 12$ deg, slot closure has little effect on c.p. at roll angles of 0 and 45 deg, but produces a forward c.p. shift of 0.1 caliber at $\phi = 22.5$ deg. This forward c.p. shift is due partially to an increase in body normal force because the C_N increases also at $\phi = 22.5$ deg.

Axial Force

Launch configuration forebody axial force data for Mach 1.5 are presented in Fig. 6 as functions of total angle of attack. Closing the slots reduces the axial force coefficient at $\alpha = 0$ deg, i.e., the zero-lift drag coefficient C_{D_0}, by 5%. Changes in angle of attack and roll angle for the closed slot configuration produce variations of less than 3% in C_{AF}. With slots open, adjusted C_{AF} is also virtually independent of roll angle at angles of attack below 4 deg; however, the variation with ϕ is as much as 10% at higher α_{TOT}. The maximum $C_{AF_{ADJ}}$ occurs when the open slots are aligned with the windward ray of the body ($\phi = 0$ deg). At $\phi = 45$ deg, the axial force curve for the open slots converges with the closed slots data as α_{TOT} increases.

Lift-to-Drag-Ratio (L/D)

Normal and axial force data from Figs. 5 and 6 have been resolved into the wind axis coefficients, lift and drag, to evaluate the effects of slots on L/D ratio, the aerodynamic glide performance parameter. In Fig. 7, $(L/D)_F$ values for total angles of attack of 6 and 12 deg are shown as functions of roll angle. Closing the slots at $\phi = 0$ deg, increases the untrimmed $(L/D)_F$ as much as 9% at angles of attack up to 12 deg. This increase is due primarily to the reduced axial force with closed slots exhibited in Fig. 6. Variations in L/D ratio with ϕ are relatively small; however, as the open slots are rolled away from the windward ray of the body, $(L/D)_F$ approaches the closed slot values.

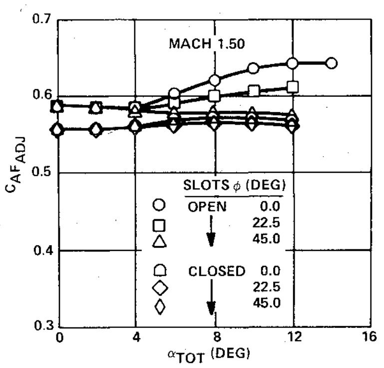

Fig. 6 Effects of slots and roll angle on forebody supersonic axial force coefficient.

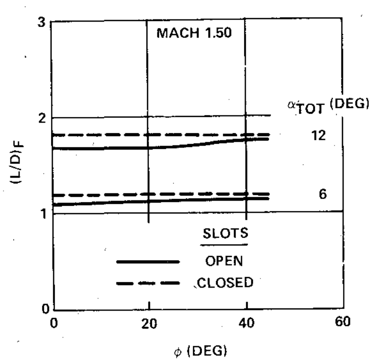

Fig. 7 Summary of launch configuration supersonic lift/drag.

Subsonic Data

Longitudinal stability characteristics for the configurational buildup from body-alone to body-wing-tail at Mach 0.50 are shown in Figs. 8-13. Axial force results are limited to the launch and maneuver configurations and are presented in Fig. 14 and 15, respectively. Similarly, L/D performance for the two configurations is summarized in Figs. 16-18.

Longitudinal Stability

Normal force and pitching moment coefficients are presented as functions of angle of attack in Figs. 8 and 9 for a roll angle of 0 deg. Subsonic body-alone and launch configuration longitudinal characteristics in Fig. 8 are affected by slot closure in ways similar to the supersonic data in Fig. 3. Closing the slots tends to decrease the body-alone C_N and shift the c.p. forward (increasing the unstable C_m). In contrast, the C_N and C_m of the launch configuration are virtually unaffected by slot closure except at angles of attack greater than 14 deg, well above the stall angle of the tails.

The body-wing combination is affected somewhat differently by closing the slots than is the launch configuration. Figure 9 shows the body-wing C_N increases as much as 20% at low angles of attack when the slots are closed; however, C_m is affected only slightly. The wing stalls as α approaches 10 deg

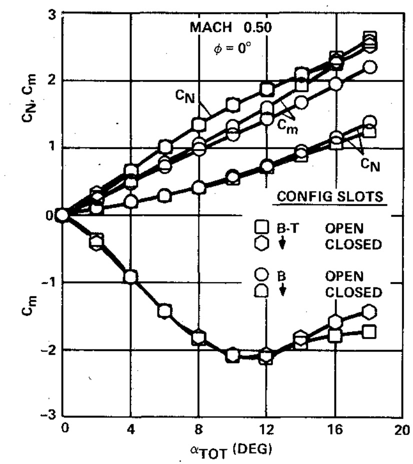

Fig. 8 Effects of slots on body-alone and launch configuration subsonic longitudinal stability.

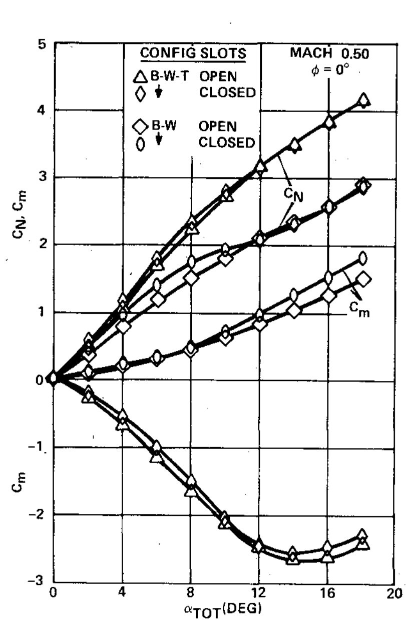

Fig. 9 Effects of slots on body-wing and maneuver configuration subsonic longitudinal stability.

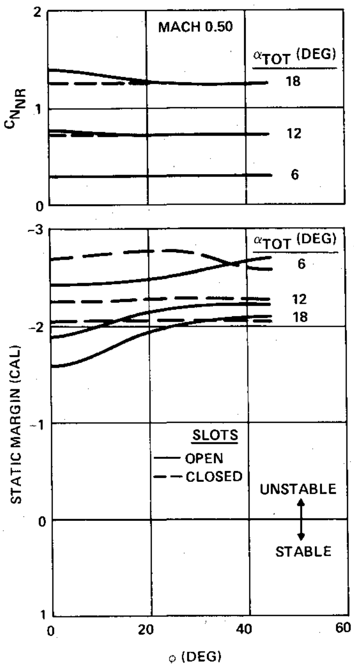

Fig. 10 Summary of body-alone subsonic longitudinal stability.

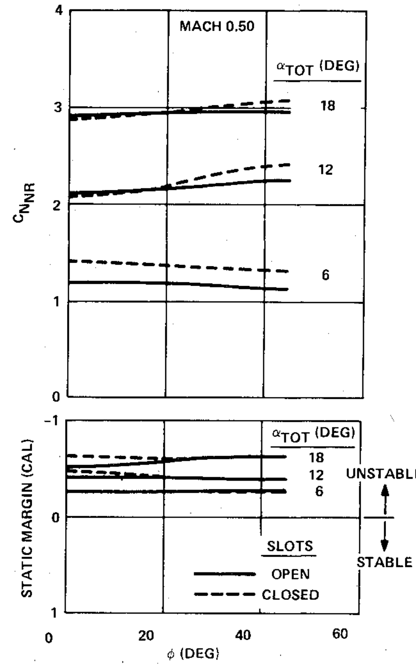

Fig. 12 Summary of body-wing subsonic longitudinal stability.

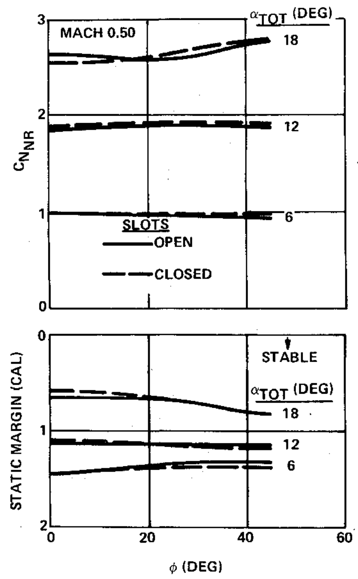

Fig. 11 Summary of launch configuration subsonic longitudinal stability.

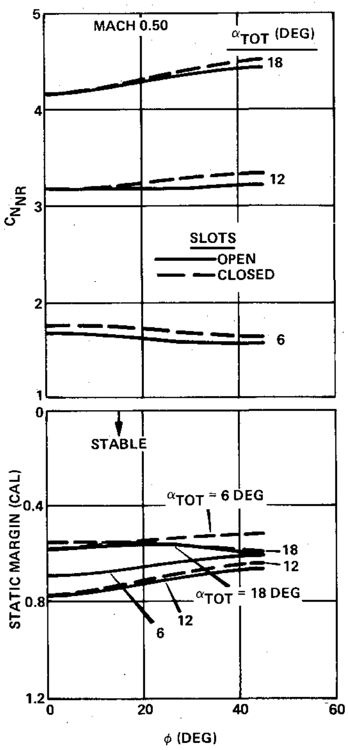

Fig. 13 Summary of maneuver configuration subsonic longitudinal stability.

and, at higher angles, the closed slots produce virtually no effect on C_N while shifting the c.p. forward. With slots open, an internal bulkhead immediately forward of the wings creates an effective base pressure region adjacent to the wing roots. This tends to reduce the local wing surface pressure differential due to flow through the body, thus causing a loss of lift. Conversely, an aft bulkhead just behind the tail slots stagnates the internal flow at this position. The resultant high-pressure region could also adversely affect lift at the tail roots; however, these surfaces are not as effectively surrounded by the slots as are the wings (see Fig. 1). At angles of attack below the stall, very small changes in C_m result from slot closure for either the body-wing or the launch configuration. The short moment arm of the wings tends to minimize stability changes for the former configuration, whereas the small C_m variation of the launch configuration with slot closure is attributed to its nearly constant C_N slope and isolation of the tails from the slots.

Figure 9 also shows the untrimmed longitudinal stability characteristics of the maneuver configuration at $\phi = 0$ deg. The increase in the wing C_N at low α provided by closing the slots is partially offset by increased downwash on the fins; thus, the net increase in C_N is less than 7%. At angles of attack above the stall, the maneuver configuration C_N is unaffected by slot closure. Pitching moment coefficient is reduced slightly at all test angles of attack when the slots are closed. This forward c.p. shift is consistent with the increase in wing loading and downwash on the tails, which reduces the tail C_N contribution.

Operationally, these effects are reversed in the Copperhead projectile which flies with slots open. Under those conditions, the loss in wing lift and the gain in tail effectiveness shift the c.p. aft, making the maneuver configuration more stable. With greater stability, a given tail deflection produces a smaller trim angle of attack, thus explaining the loss of trimmed normal force observed in the early flight test failures.

Figures 10-13 illustrate the effects of roll angle on nonrolling normal force and static margin at selected angles of attack for the several configurations. For the body-alone, as the slots are rotated away from the windward ray of the body, their effects on C_N and static margin diminish (Fig. 10). Both C_N and static margin become essentially equal to the closed slot values at $\phi = 45$ deg. As previously discussed, longitudinal stability characteristics of the launch configuration are only slightly affected by slot closure at $\phi = 0$ deg. Similar results are obtained at other roll angles (Fig. 11). The launch configuration was tested at roll angles up to 90 deg at Mach 0.50. Although not presented, the 90 deg data are in excellent agreement with the data at $\phi = 0$ deg, indicating pitch-yaw symmetry.

Figure 12 presents roll angle effects for the body-wing combination. At a given angle of attack, C_N varies significantly due to the combined effects of changes in wing lift and body pressure distribution which in turn result from slot closure and changes in roll angle. However, variations in static margin are minimized because the wings are located close to the moment reference center. At subsonic Mach numbers, the maneuver configuration is of primary importance and its longitudinal stability data are summarized in Fig. 13. Synthesizing the characteristics of the body, wings, and tails, the maneuver configuration C_N varies primarily with slot closure at low angles of attack and with the combined effects of roll angle and slots at intermediate and high α. For clarity, the static margin scale has been expanded in this figure. Closing the slots reduces static margin approximately 0.1 caliber at low α_{TOT} for all roll angles. This reflects the increases in wing lift and downwash on the tails, as well as redistribution of the body lift. At higher angles of attack, wing stall and decreased downwash reduce the effects of slot closure on stability.

Axial Force

Adjusted forebody axial force data are illustrated in Figs. 14 and 15 for the launch and maneuver configurations, respectively. Closing the slots eliminates the internal pressure drag and reduces the launch configuration C_{D_0} by 30%.[7] Axial force coefficient is relatively constant with angle of attack and roll angle when the slots are closed. With slots open, roll angle affects the $C_{AF_{ADJ}}$ of the launch configuration at angles of attack greater than 2 deg, the maximum values occurring at $\phi = 0$ deg. Slot effects are minimized at $\phi = 45$ deg and high α.

Figure 15 shows maneuver configuration C_{D_0} is decreased 22% by slot closure. At a typical angle of attack during glide, e.g., 8 deg, closed slots reduce the untrimmed $C_{AF_{ADJ}}$ twice as much as at $\alpha = 0$ deg. Maximum values of $C_{AF_{ADJ}}$ occur at $\phi = 0$ deg with moderate to high α for either slot condition, as was the case with the launch configuration.

Limitations of Copperhead flight test and range instrumentation at the White Sands Missile Range restrict direct comparisons of wind tunnel and flight test drag data to the launch configuration at Mach numbers between 0.7 and 1.2. The differences between adjusted wind tunnel drag and flight test results are less than 5% at Mach 0.9 or greater, with increasing discrepancies at lower Mach numbers. This represents an improvement of at least 4:1 compared with the earilier wind tunnel data. Lack of knowledge of the higher drag, as well as the loss of lift, were key factors in the early flight failures described in the Introduction.

Lift-to-Drag Ratio (L/D)

This parameter is of primary importance for the maneuver configuration because it flies on a glide-path trajectory toward the target. For a constant velocity, glide-path angle is inversely proportional to L/D; conversely, range varies directly with L/D. In Figs. 16 and 17, untrimmed $(L/D)_F$ curves are presented for the launch and maneuver configurations, respectively. Slot closure increases the ratio of lift to drag for both configurations, with improvements of 33% or more at angles of attack below 8 deg. At higher angles, $(L/D)_F$ increases significantly when the open slots are rolled away from the windward ray of the body. These roll angle effects are summarized in Fig. 18. Equally important, launch configuration lift/drag values approach the corresponding

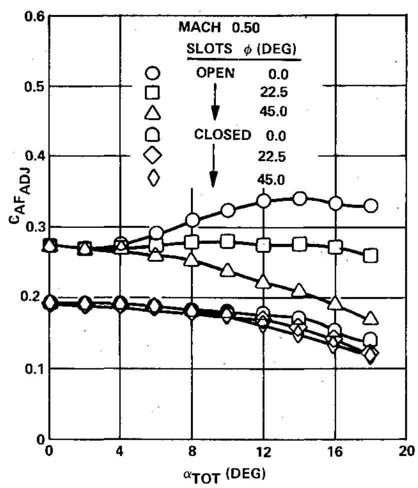

Fig. 14 Effects of slots on launch configuration forebody subsonic axial force coefficient.

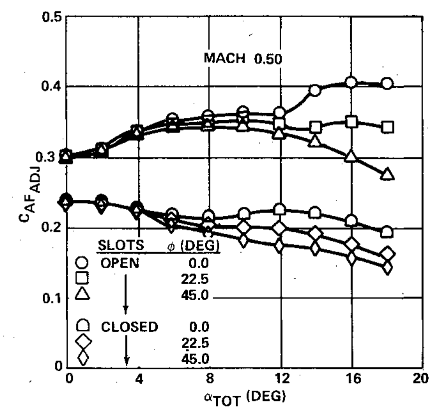

Fig. 15 Effects of slots on maneuver configuration forebody subsonic axial force coefficient.

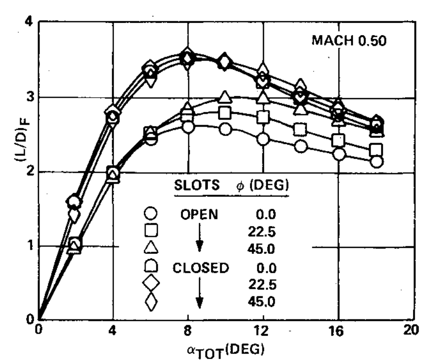

Fig. 16 Effects of slots on launch configuration subsonic lift/drag.

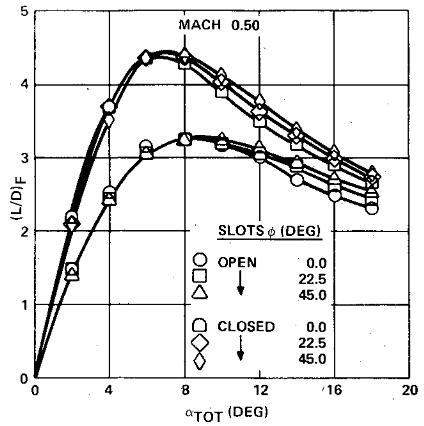

Fig. 17 Effects of slots on maneuver configuration subsonic lift/drag.

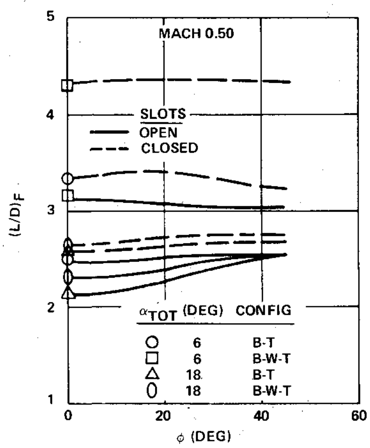

Fig. 18 Summary of subsonic lift/drag comparisons.

maneuver configuration ratios at $\alpha_{TOT} = 18$ deg, indicating that the wings offer very little improvement in glide performance at high angles of attack.

Conclusions and Remarks

Body slots, through which the wings and tails are deployed, tend to decrease the projectile's normal force coefficient through losses in lift on these surfaces. For a given configuration, static margin is affected significantly and unpredictably with open slots and varying roll angle at a given angle of attack. Conversely, slot closure could increase lift/drag ratios as much as one-third, due largely to reductions in forebody drag coefficient. To date, however, no satisfactory methods have been developed for closing the projectile slots before and after deployment of the wings and tails because of the extremely severe gun launch environment and other operational requirements.

Specific conclusions are as follows:

1) For the body-alone configuration, closing the slots decreases normal force coefficient as much as 10% and shifts the aerodynamic center of pressure forward up to 0.40 caliber. Slot flow is minimized at $\phi = 45$ deg; consequently, the body-alone longitudinal stability data agree closely for the open and closed slot conditions at this roll angle.

2) For the launch configuration, closing the slots increases normal force coefficient slightly at angles of attack below the stall because increased tail effectiveness counterbalances the decreased body normal force. Static margin varies up to 0.1 caliber with slot closure.

3) With slot closure, the normal force coefficient of the body-wing combination increases up to 20% at angles of attack below the stall; however, changes in longitudinal stability are negligible because of the short moment arm of the wings.

4) For the maneuver configuration, closing the slots increases normal force coefficient no more than 7% at Mach 0.50, because the gain in wing effectiveness is partially offset by greater downwash on the tails. Slot closure decreases static margin approximately 0.1 caliber at low angles of attack, consistent with the changes in effectiveness of the lifting surfaces.

5) Reductions of 5% and 30% in zero-lift drag coefficient result from slot closure in the launch configuration at Mach 1.50 and 0.50, respectively. The closed slots also minimize the combined effects of roll angle and angle of attack on axial force.

6) Zero-lift drag coefficient for the maneuver configuration is reduced 22% at Mach 0.50 by slot closure. At a roll angle of $\phi = 0$ deg, maximum values of axial force coefficient occur for either slot condition at moderate to high angles of attack.

7) At Mach 0.50, lift/drag ratio increases 33% or more at angles of attack below 8 deg when the slots are closed. At higher angles, lift/drag ratio increases significantly when the open slots are rolled away from the windward ray of the body. Launch configuration lift/drag ratios approach those of the maneuver configuration at $\alpha = 18$ deg, indicating that the wings offer very little improvement in glide performance at high angles.

Acknowledgments

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