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A Lesson Learned about Cannon-Launched Guided Projectiles

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During early flight testing of the 155 mm Copperhead guided projectile, two rounds impacted short of the target. This paper addresses how the problem was identified and corrected. Post-flight analysis indicated that aerodynamic maneuverability was less than that predicted by wind tunnel tests. The cause was traced to the presence of full slots at the base of the fins and wings, which permitted more air flow to enter the aft section of the projectile than the slot configuration used on the wind tunnel model. Fins and wings are deployed through these slots after the projectile clears the gun tube. The actual slot configuration was found to reduce the pressure distribution on the wings located forward of the control fins and to alter downwash characteristics on the fins. The net result was reduced normal force and increased stability characteristics. After learning about the slot effects, the autopilot gains were adjusted and Copperhead now consistently hits the target.

Introduction

THE 1970's have witnessed the evolution and development of a revolutionary new tactical weapons concept called cannon-launched guided projectiles (CLGP's). Development of CLGP's is being actively pursued to give conventional artillery a quantum improvement against moving, point type targets. CLGP's utilize terminal guidance to null flight dispersion, target location, and motion errors which degrade the effectiveness of conventional unguided projectiles. Dispersion and target errors degrade accuracy of conventional shells to make them relatively ineffective against moving, armored targets where a direct hit is required to neutralize the target. One current CLGP concept called Copperhead is in engineering development (ED) and utilizes semiactive laser guidance to provide artillery an unprecedented effectiveness against moving, armored type targets.

Copperhead is a 155 mm projectile which is 4.5 ft long and weighs 138 lb. It relies on a ground or airborne laser to illuminate the intended target. Laser energy reflected by the target is sensed by the Copperhead seeker and a biased proportional navigation scheme is utilized to develop steering commands for tail control fins. The bias term is used to compensate for gravity droop of the trajectory. Line-of-sight (LOS) rate is measured by a steerable, two-axis gimballed gyro. The autopilot (Fig. 1) uses the LOS rate signal to command a fin deflection for the tail fin control subsystem. Because of the emphasis on cost, the guidance system does not contain an acceleration-type feedback loop, which eliminates the need for pitch and yaw accelerometers to close the control loop.

Proportional navigation works on the basis of commanding a velocity turn rate (or maneuver) for the airframe which is proportionally larger than the LOS rate between the projectile and target. Copperhead achieves the velocity turn rate by commanding a control fin deflection. Thus, the velocity turn rate per unit fin deflection ($\dot{\gamma}/\delta$) must be accurately established a priori to ensure that the required navigation gain is achieved.

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Maneuver augmentation is provided by four fixed wings which are located forward of the tail control fins. Contrary to most tactical missiles, guided projectiles require that fins and wings be contained inside the projectile or folded down outside to enable the projectile to be shot from guns. Fins and wings for Copperhead are folded inside the control housing structure prior to launch and deployment is through open slots in the skin, after the projectile has cleared the gun tube.

This paper addresses the critical influence these open slots can have on aerodynamic characteristics and subsequent guidance loop design of a guided projectile or similar missile.

Early Flight Test Results

During initial flight tests of the Copperhead, a projectile impacted approximately 10 m in front of the intended tank target. After an analysis of the flight data, it appeared the failure was due to a miscalculation in the gravity bias command by on-board sensors which resulted in the trajectory being "under-biased." The low bias resulted in the trajectory sagging below the intended flight profile and impacting short of the target. A subsequent round also impacted 28 m short and 18 m to the right of the target; however, flight data did not indicate any hardware problems similar to those of the previous flight. The proportional navigation LOS rates measured by the laser seeker and the resulting vane commands shown by the first two traces of Fig. 2 indicated a steady divergence from zero error and command in the endgame of the trajectory. Consequently, the guidance loop was sensing the impending target miss, but for some reason was unable to recover. In an attempt to match the observed behavior, the Copperhead six-degree-of-freedom (6-DOF) computer simulation was flown using reduced aerodynamic normal force characteristics. A good match of the failure was obtained using a multiplying factor to reduce the normal force characteristics by 30% (Fig. 2). The reduced normal force acted to reduce the velocity turn rate per unit fin deflection.

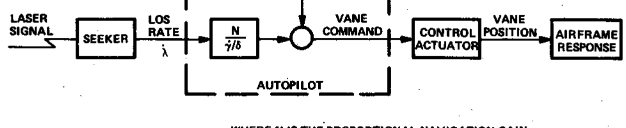

Fig. 1 Copperhead guidance and control loop.

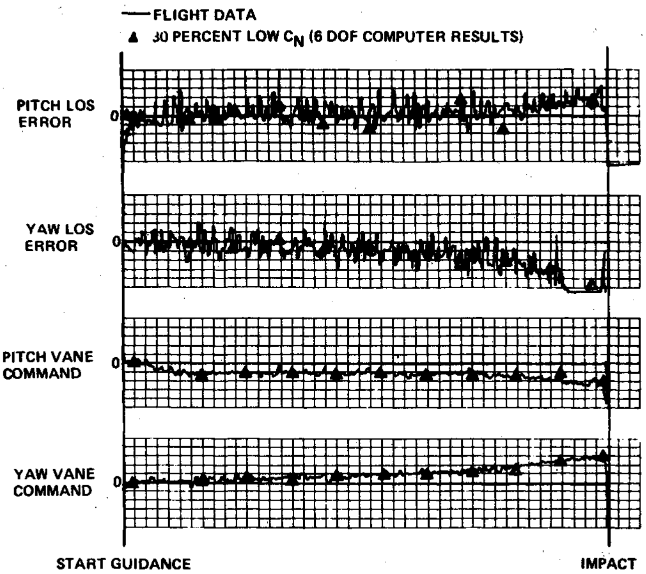

Fig. 2 Comparison of simulation and actual flight results.

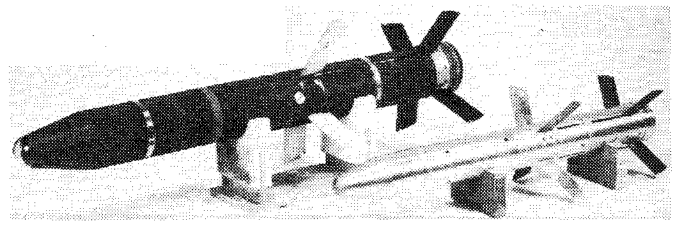

Fig. 3 Comparison of full-scale (top) and ¾-full-scale (bottom) wind tunnel models.

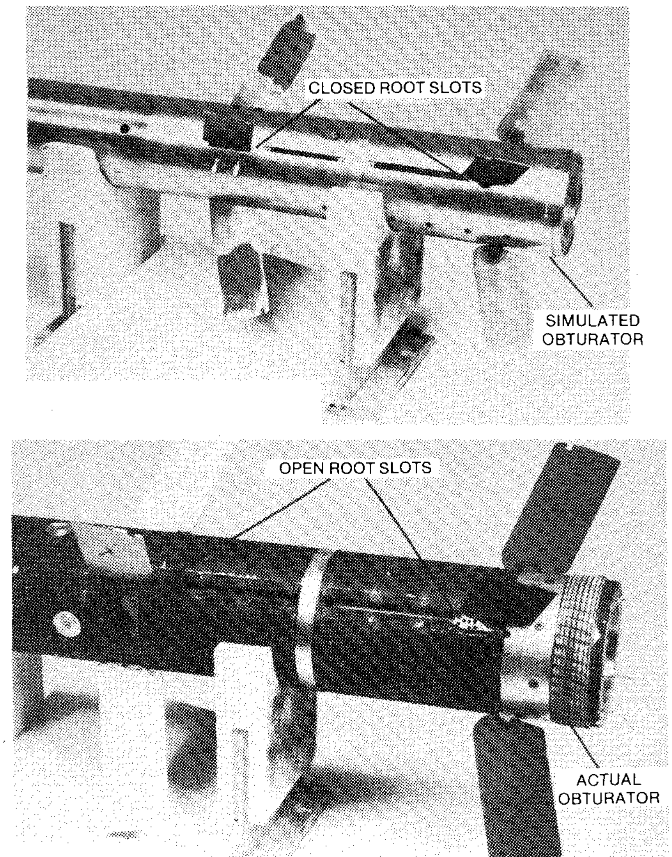

Fig. 4 Comparison of full-scale (top) and ¾-scale (bottom) slot configurations.

The second observation was that the subsonic drag had to be increased by roughly 30% to match the ballistic portion of flight. This drag discrepancy had been observed on earlier flights but the cause had not been isolated.

Simulation inputs were next verified and independent checks of the 6-DOF computer results, using other computer simulations, were successfully performed. Analysis subsequently focused on comparisons of the flight hardware configuration with respect to the ¾-scale wind tunnel model (Fig. 3) used to obtain the aerodynamic characteristics used for design. Four significant differences were identified. Most obvious was the difference in the sweep angle of the wings. The wind tunnel model had a sweep angle of 20 deg while the wing sweep on the flight hardware was about 30 deg because of out-of-tolerance hardware in the mechanism which deploys and establishes the sweep angle of the wings. Corrected hardware was forthcoming on future flights, but preflight analysis of the sweep angle difference indicated the maximum degradation in normal force capability was 6-11% maximum. A more detailed analysis following the failure predicted the sweep effect could have been closer to 10-17%, a significant loss.

Another major difference was the method in which the wing and fin slots were represented on the wind-tunnel model (Fig. 4). The same method of fin attachment used in the wind-tunnel testing of the highly successful Advanced Development Copperhead[1] was used to limit model cost and complexity. With this technique the slot is extended up near the leading edge of the fin (or trailing edge of the wing) and the base of the fin (or wing) is not open. This solid area at the base of the fin and wing provides a simple and strong structural attachment capability. The solid root area had the effect of preventing flow from bleeding inside the body at these fin attachment points, but the remaining open slots were felt adequate to fully represent the slot effect. As part of the failure analysis this assumption was readdressed and it was felt that the presence of a full slot at the wing could possibly produce significant flow inside the structure which would reduce the body carryover force and net wing lift.

Due to the relative uniqueness of the popout aerodynamic surfaces and open slots to CLGP's and the relative short existence of CLGP's, applicable literature data were limited. One source[2] which was not entirely analogous to the Copperhead wing slot configuration was used to estimate order-of- magnitude effects for equivalent air gaps at the base of the wing. Using gaps of 0.1 and 0.25 in., it was estimated the wing losses could range from 2 to 8%.

The wings used on the wind tunnel model were steel as opposed to aluminum wings on the flight configuration. Thus, a potential loss of wing lift due to increases in wing aeroelastic effects was possible. It was estimated that the loss could amount to as much as 5-13%.

When the combined effects of wing sweep, full slots, and aeroelastic effects were considered, it was felt that the trim normal force capability could potentially be low by 17-38%. Thus, the ability to explain the flight failure based upon wind tunnel model differences was possible. No apparent reason for the 30% drag increase was evident except for the projectile's obturator configuration. The obturator is a nylon band at the base of the projectile which provides a gas seal between the gun tube and projectile base. The model's obturator was smooth and machined on the profile of the model while the actual obturator is rough with gaps between the leading and trailing edge of the obturator and projectile (Fig. 4), but none of these effects was considered an adequate explanation of the magnitude of the higher observed drag.

Additional Wind Tunnel Testing

Because of high probability that the wind tunnel test results were in error, additional tunnel tests were conducted in an

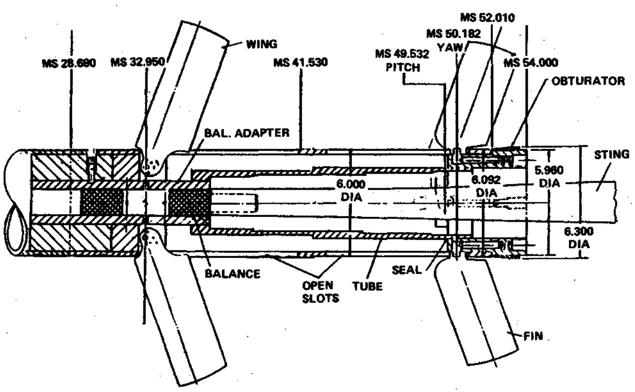

Fig. 5 Full-scale wind tunnel geometry-control section.

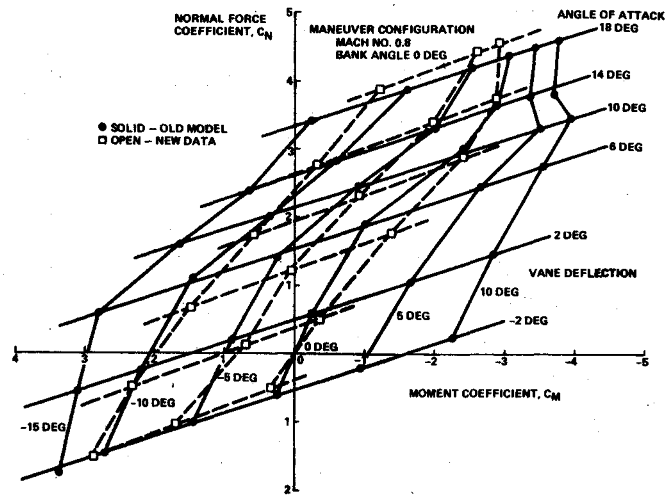

Fig. 6 Force and moment data comparison.

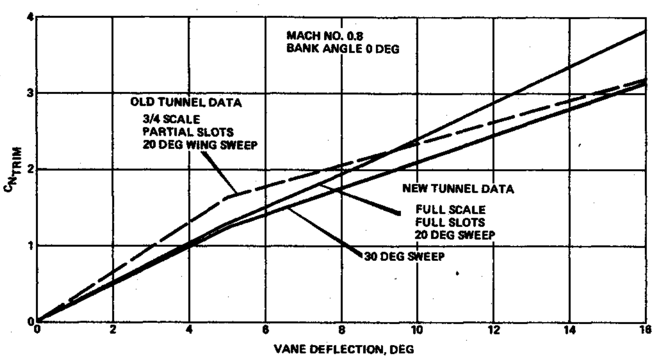

Fig. 7 Trim normal force coefficient vs fin deflection.

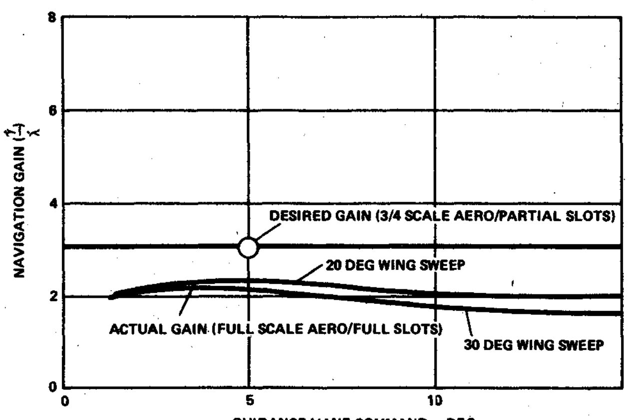

Fig. 8 Navigation gain vs vane command (flight failure).

attempt to quantify the effects of wing sweep, wing and fin gaps, and aeroelastic effects. To ensure the maximum fidelity possible with respect to flight hardware, a full-scale wind tunnel model was constructed using actual production hardware wherever possible. The nose dome, guidance electronics housing, wings, fins, and obturator were all production hardware. For further realism the obturator had been previously fired from a cannon on an earlier test round and recovered. Because of the degree of modification and cost required to make the warhead housing, control housing, and aft closure compatible with the wind tunnel force and moment balance and sting hardware, an aluminum aft structure was built using production drawings to establish external profiles and the geometry of the wing and fin slots. The resulting model pictured in Fig. 3 was painted with the same antislip paint used to improve handling qualities, and which was estimated to produce less than a 1% increase in total drag. The model was felt to be the closest possible match to the actual hardware that could be realistically achieved.

The sting/balance mechanism was sealed internally (Fig. 5) to prevent flow from entering through the slots from being vented out through the base where the sting was attached. The free volume of the open annular area was estimated to be about two-thirds the volume present in the tactical round, which contains a gas bottle, battery, actuator, electronics package, wing mount, etc.

The full-scale test was conducted at the Rockwell Trisonic Wind Tunnel in Los Angeles, California. Since the aerodynamic analyses had indicated that the problem was primarily due to loss of lift, the test was largely limited to the maneuver configuration (body-wing-tail). A total of 63 runs was made during the 40 h test and most of the data were obtained at $M=0.8$, although several runs were made at $M=0.73$ and $M=0.50$. This bracketed the flight range region encountered during the two test failures. Effects investigated[3] included changes in the wing sweep angle from 20 to 30 deg and variations in slot closure in the body around the wings and fins. In comparison with previous test data, the full-open slots (not wing sweep) of the full-scale model configuration produced greater effects on aerodynamic characteristics than any other variable tested. Trimmed normal force coefficient of the maneuver configuration was reduced as much as 20% by the fully opened slots. At low angles of attack, the slots increased static margin of the maneuver configuration and decreased it for the launch configuration. With full slots, the total axial force coefficient was increased 25% at an angle of attack of 0 deg, with even larger increases at trim conditions.

The full-scale wind tunnel test results are compared against the ¾-scale model results at $M=0.8$ and 0-deg bank angle in Figs. 6 and 7. These data reflect the effects of fully opened wing and fin slots for a wing sweep angle of 20 deg. Figure 7 also shows the effect on trim normal force capability when the effect of the 30-deg wing sweep is included. Because the autopilot gains were based upon the linear transfer function for small vane deflections, the impact of the full slots was to reduce the velocity turn rate per unit fin deflection ($\dot{\gamma}/\delta$) transfer function by 20% while the presence of the 30-deg wing sweep added another 4% degradation. Referring back to Fig. 1, it is observed that the net effect of these reductions was to reduce the overall navigation gain by 24%. The navigation gain in Fig. 8 (i.e., the ratio of the velocity turn rate $\dot{\gamma}$ to the measured LOS rate $\dot{\lambda}$) was calculated for the flight failure conditions and it shows graphically why the projectile failed to hit the target. The aerodynamic degradation of the full slots had resulted in a navigation gain of roughly 2.0, which is the theoretical minimum gain for proportional navigational schemes that will enable target impact. Consequently, any further errors would prevent the navigation loop from converging to produce a hit. Once the failure mode was

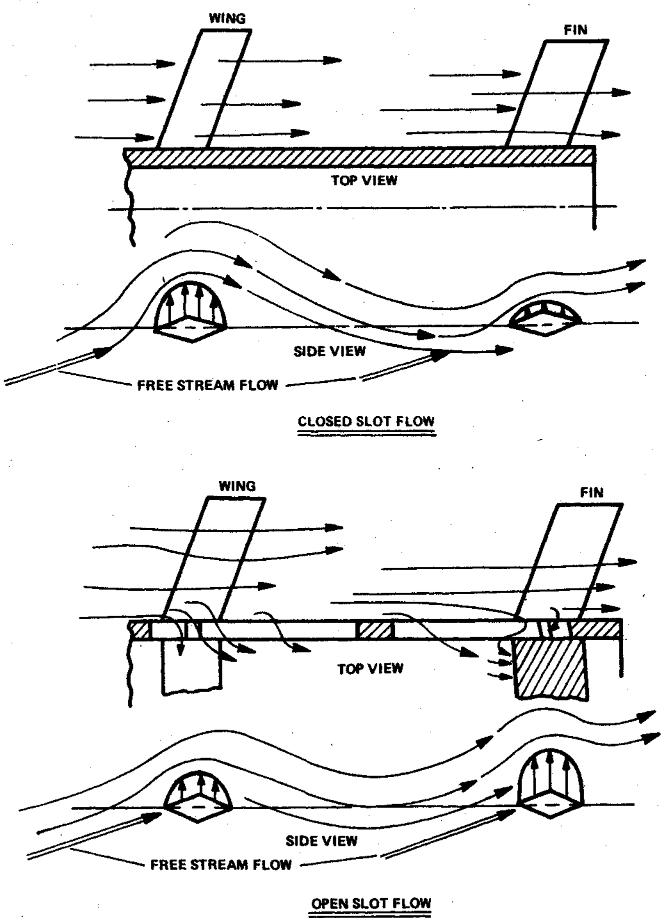

Fig. 9 Effect of slots on wing downwash and fin effectiveness.

known, the corrective action was simple. The autopilot gains were scaled upward to produce more vane command for a given LOS rate, which would then produce the desired velocity turn rate to LOS rate ratio. The hardware tolerance problem was also corrected so that the gain increase did not reflect the sweep angle degradation.

The mechanism which produced the significant loss of lift can be understood best by considering three factors: wing lift, wing downwash on the fin, and stability. The presence of the open slots at the root of the wing (Fig. 9) allows flow to bleed inside the housing, thus reducing the net pressure distribution on the wing (over the sealed root slot case). The reduction in the pressure distribution means loss of wing lift amounting roughly to one-third the total degradation. In turn, the loss of wing lift also tends to reduce the downwash on the tail control fin, which places the fin in a more effective flowfield since the incident angle of the flow on the fin is increased. With increased effectiveness, the tail now makes the airframe more stable, and thus for a given fin deflection the airframe achieves a smaller angle of attack.

Contrary to the initial wind tunnel test, the forebody axial force coefficient on the full-scale model was also observed to shift, depending upon whether the slots were opened or closed. At $M=0.8$ the coefficient was found to be roughly 15% larger with the slots open than with them fully closed. Since all other things were equal, it implied that the flow entering the slots was pressurizing the interior of the housing. Based upon the observed changes in the coefficient, the pressure was estimated to be between 0.5 and 1.0 psi. The only reason why the effect was not previously observed was the size of the annular area inside the control housing upon which the pressure acted and the presence of added slot area. With the ¾-scale model the annular area was 12% of the reference area, while on the full-scale model the annular area was 48% of the reference area. Hence, the effect for the smaller model was less pronounced and the slots appeared to have an insignificant effect on the axial force coefficient.

Recognizing the presence of a pressure differential inside the housing (relative to the freestream pressure), the net force produced by the pressure acting over the "entire 23 square inch internal base area" was factored into the total axial force coefficient calculation. The adjusted full-scale model results then showed a 23% increase in total axial force coefficient over the values predicted by the ¾-scale wind tunnel tests. The full-scale data agreed closely with observed flight results and the last of the discrepancies on the flight failure was resolved. Incidentally, these findings also explain the source of the higher than predicted drag observed in the advanced development program. Similar model slot effect errors were present, but to a lesser degree because of lack of wings and wing slots in the advanced development configuration.

The degraded aerodynamic characteristics were incorporated into 6-DOF flight simulations and two autopilot gains were increased. With these minor changes, Copperhead achieved a direct impact on a laser-designated tank target on its next flight test. Since then, Copperhead has consistently hit moving and stationary targets with accuracy surpassing the desired requirement. Thus, a lesson was indeed learned about the cannon-launched guided projectile.

Conclusions

1) Tactical low-cost missile and projectile systems with their less sophisticated guidance and control loops still require accurately defined aerodynamic characteristics. Usage of full-scale wind tunnel models and maximum duplication of actual hardware is always desired but may, as in the case of Copperhead, be required.

2) With the advent of the cannon-launched guided projectile, open slots are usually required for deployment of aerodynamic control surfaces after launch. The presence of these slots, especially at the base of the wings and fins, can degrade both maneuverability and drag.

3) Slotted configuration wind tunnel models should be constructed with the full knowledge of potential flow effects. Consequently, sealing of the cavity and recognition of annular area effects is required. Also, future wind tunnel tests of Copperhead will utilize pressure sensors inside the housing to further define the extent of flow and pressurization.

References

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