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Design Approach for Estimating Body Slot Effects on Wing-Body-Tail Lift

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Abstract

PREVIOUS experimentally based studies have described the aerodynamic effects of body slots on a guided projectile with cruciform lifting surfaces.[1,2] For the configuration investigated (Fig. 1), the body slots through which the wings and tails deploy after cannon launch were shown to affect lift, drag, and longitudinal stability in complex ways. Theoretical modeling of such flow problems is, at best, an approximation. However, meaningful information can often be obtained by modifying an existing theory to predict overall trends, even though smaller details of the flow are not modeled. Following this approach, the Slender Body Theory of Pitts et al.[3] was modified to account for the loss of carryover lift from the wing to the body and for changes in wing-tail downwash due to flow through the slots. The results are presented as a design approach for estimating the effects of open body slots on wing-tail interference lift.

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Complete model and individual tail balance force and moment data were measured with body slots open (Fig. 2) and closed to gain an understanding of how the slots affect aerodynamic characteristics. Evaluation of these results led to the hypothesis that theoretical expressions for wing-body lift could be modified to account for slot effects. According to the Slender Body Theory,[3] the lift of wing-body combinations can be treated in two parts: 1) basic wing lift plus upwash from body to wing ($K_{W(B)}$) and 2) carryover lift from wing to body ($K_{B(W)}$). The assumption is made that open body slots do not significantly affect basic wing and upwash lift, but simply reduce carryover by bleeding off the "spill-over" pressure from wing to body. A multiplier term (G) is inserted in the equations as a coefficient for the wing-body carryover ($K_{B(W)}$). Thus, the equation for wing-body interference lift ($C_{N_{WI}}$) becomes

$$C_{N_{WI}} = (K_{W(B)} + GK_{B(W)})(C_{N_\alpha})_W(\alpha) \qquad (1)$$

The term G is set equal to 1 for the standard case (slots closed) and to 0 for slots open. Actually, G could have any value from 0 to 1, depending on slot size and shape, but additional correlation data would be needed for that result. Taking G equal to 0 (100% loss of carryover lift) is supported by comparisons with experiment as shown in Fig. 3. Although the normal force slopes are underpredicted by the theory, the increment between open and closed slots is accurately

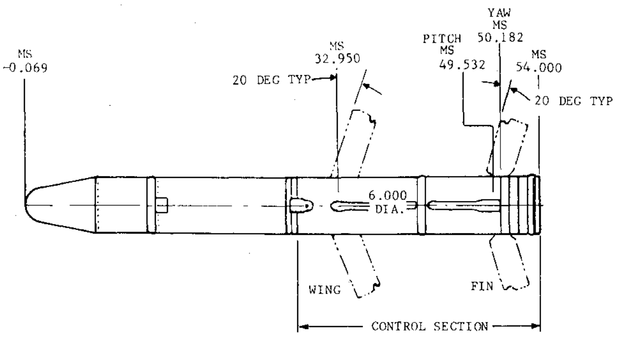

Fig. 1 Full-scale copperhead model configuration.

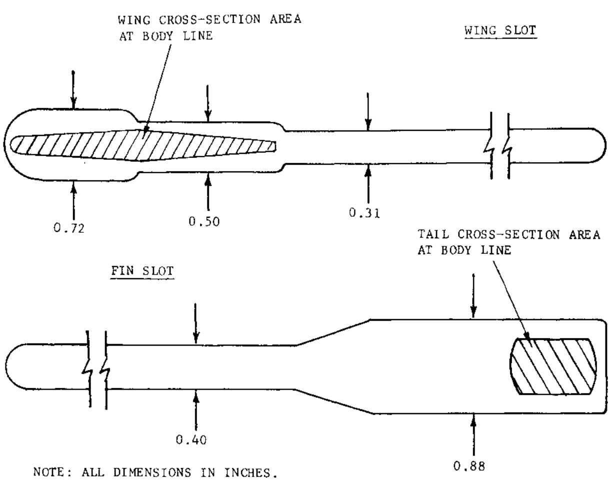

Fig. 2 Open slot geometry with surfaces deployed.

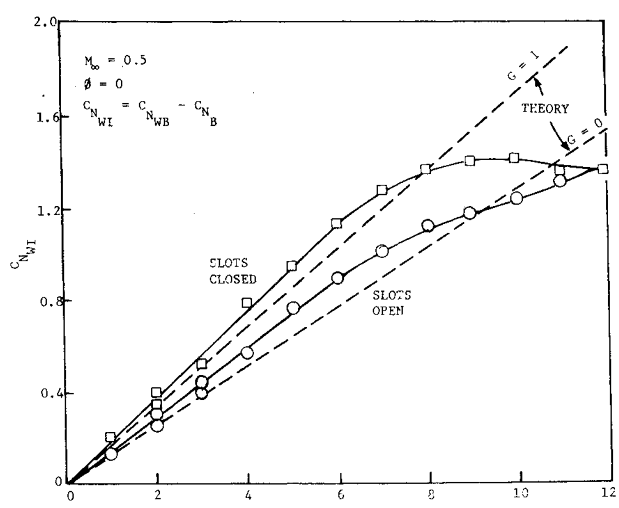

Fig. 3 Normal force coefficient of wing plus interference.

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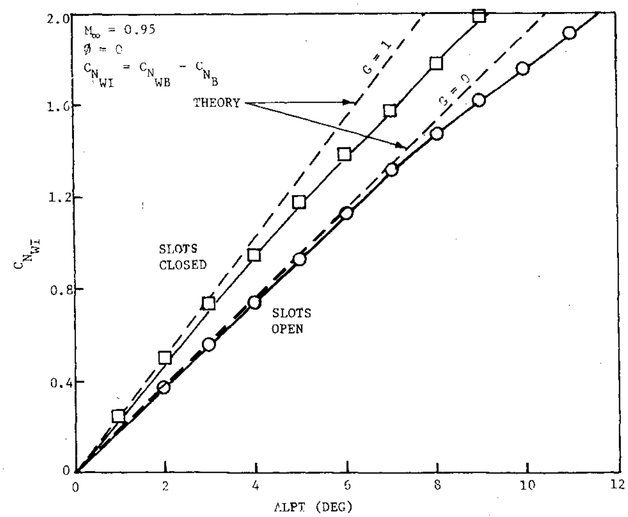

Fig. 4 Normal force coefficient of wing plus interference.

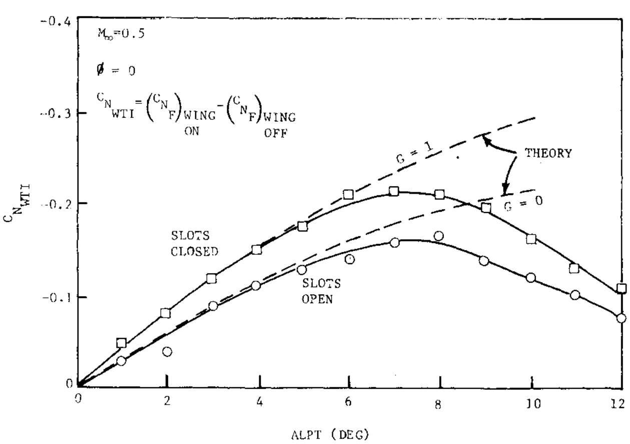

Fig. 5 Downwash normal force coefficient.

predicted for angles of attack up to 6 deg. At higher angles, the theory is not applicable because it is limited to the range of linear aerodynamics. Accurate incremental effects due to slots are obtained with the modified theory for Mach numbers up to 0.8. At higher Mach numbers, the theory overpredicts the effect of slots, as illustrated in Fig. 4.

The loss of wing carryover lift also affects the tail effectiveness. Downwash from the wings on the tails is directly proportional to the lift being generated by the wing-body combination. If the lift of the wing-body combination is reduced, then the strength of the wing trailing edge vortices will decrease, hence reducing the negative lift (or downwash) on the tails. Modifying the equations for wing-tail downwash is somewhat less straightforward than the use of the simple multiplier in the body-wing lift equation. Theoretically, the lift on the tails due to wing downwash in proportional to the circulation strength (Γ_m) of the wing-body combination. The circulation strength can be expressed in terms of the two components of wing-body lift, ($K_{W(B)}$) and ($K_{B(W)}$). The same multiplier term (G) is used as before. A development of the equations is presented in the backup paper. The equation for calculating tail lift due to wing downwash is multiplied by the ratio (Γ_{mG}/Γ_m), which effectively incorporates slot effects. In basic form,

$$C_{N_{WTI}} = (C_{L_\alpha})_T i \left(\frac{\Gamma_m}{2\pi v_\infty (s_T - r_T)}\right)\left(\frac{\Gamma_{mG}}{\Gamma_m}\right) \tag{2}$$

where

$$\frac{\Gamma_{mG}}{\Gamma_m} = \left(1 + \frac{GK_{B(W)}}{K_{W(B)}}\right)\left(\frac{1 + \frac{\pi}{4}\frac{b_{0W(\mathrm{TE})}}{\gamma_W}}{2 + \frac{\pi}{4}\frac{b_{0W(\mathrm{TE})}}{\gamma_W}}\right) \tag{3}$$

The term ($b_{0W(\mathrm{TE})}$) is the exposed semispan of wing (at trailing edge) and (r_W) is the body radius at wing root. Incorporating the multiplier G and Eq. (3) into the equation set 50 through 56 of Ref. 3, results in a modified theory that includes the effect of slots. These equations are subject to the same restrictions as the basic set and are equivalent to the original set when G is equal to 1. The advantage of using a multiplier is to allow the use of existing computer programs based on the Slender Body Theory with only a relatively simple change in computer coding.

A comparison of theory and experiment is shown in Fig. 5. The absolute level of downwash lift, and the difference between open and closed slots, is accurately predicted by the modified theory at Mach 0.5. At higher Mach numbers, the level of downwash is overpredicted by theory, but the incremental slot effect is accurately predicted for all Mach numbers tested. Again, the theory is only valid in the small angle of attack range where viscous separation effects are negligible.

In summary, the hypothesis that open body slots adjacent to the wing root chord practically eliminate wing-body carryover lift appears to be a valid approach for analytically modeling slot effects. Incorporating this modification into existing computer programs is a relatively easy task. This approach can be used as a design tool for estimating the effect of slots on wing-body-tail stability.

References

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