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ASSESSMENT OF TWO FAST CODES USED FOR PRELIMINARY AERODYNAMIC DESIGN OF GUIDED PROJECTILES

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Two missile aerodynamic prediction fast codes, namely the NSWCAP and Missile-DATCOM, have been applied to the geometry of the guided, gun-launched Copperhead projectile. Assessment of the two codes was made in comparison with wind tunnel and free-flight range test data. Two configurations were considered for computation: the launch configuration (body-tail) in the Mach range of 0.5 to 1.8 and the maneuvering configuration (body-wing-tail) in the Mach range of 0.3 to 0.95. Results show reasonable agreement for the drag coefficient, C_D, and show very large disagreements for both C_{N_α} and C_{M_α}. The incapability of both codes to include body slots and fin gap effects seems to have contributed largely to these differences. The dynamic derivatives C_{ℓ_p} and $(C_{M_q} + C_{M_{\dot\alpha}})$ are not adequately estimated

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19. Abstract (Continued)

by the NSWCAP code, and are not calculated in the DATCOM code. For the coefficients actually computed, the DATCOM code results were slightly more accurate than those of the NSWCAP code. Both codes lack the determination of the explicit effects of control surface deflection angles on the aerodynamic coefficients. Development is needed for the determination if both codes are to be used for predictions for guided projectiles. Several areas of improvements in both codes are identified.

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I. INTRODUCTION

Several fast aerodynamic prediction codes for missiles were written in the last decade. These codes were intended for aiding missile designers in obtaining quick engineering estimates for the aerodynamic coefficients and the dynamic stability of their particular configurations.

These fast codes are based on 1) basic and simplified theorems, 2) experimental data which are algebraically or numerically fitted, and 3) some empirical formulae based on observations and some personal experience. Methodology of these codes is based on missile component build-up with adjustments for component interference (interaction) effects. These codes were required to be fast, usually using less than 60 CPU seconds on a typical mini-computer (such as a VAX-11/780) for each flight condition. They originally were meant to give estimates for the basic aerodynamic coefficients, in particular: C_D, C_N, C_M, C_{M_α}, C_{N_α} over a range of Mach numbers and angles of attack.

Now it is required that these codes yield more accurate predictions, to provide all the aerodynamic coefficients, and to cover a larger variety of missile configurations. It is also necessary to examine the application of such missile codes to gun-launched projectiles, both for spin- and fin-stabilized configurations. For this application the L/D ratio is usually smaller than those of missiles.

At present, due to more sophisticated projectile and missile applications, there is a desire to develop such codes to provide more accurate predictions, rather than merely a rough tool to yield engineering estimates. To be useful in that sense, the following accuracy guidelines for the basic five coefficients, should be targeted.

C_D within $\pm$ 5%

C_{N_α}, C_{M_α} within $\pm$ 15%

C_{ℓ_p} and $(C_{M_q} + C_{M_{\dot\alpha}})$ within $\pm$ 25%

These demands of accuracy are more relaxed than the accuracy achieved in actual firing tests in the ranges as provided by Rogers.[1] This relaxation is intentionally allowed because codes cover a wide variety of body configurations and different speed regimes where different methods may be used and extrapolation of experimental data may be allowed. Rogers[1] estimates the accuracy of the free-flight measurements to be as follows:

C_D within $\pm$ 1%

C_{N_α} within $\pm$ 5%

C_{M_α} within $\pm$ 2%

$(C_{m_q} + C_{m_{\dot\alpha}})$ within $\pm$ 15%

This required accuracy of the codes has not been achieved for the present application as will be discussed in section IV for the results. However, for more traditional configurations in the low supersonic speed regime (Mach number 1.5 to 2.5), the results are usually more accurate and can fall within these targeted accuracy guide lines.

It is the purpose of this work to gauge the results of the two fast codes based on the results obtained through an application to the hybrid missile-projectile configuration of the Copperhead. The Copperhead projectile is a laser guided, gun-launched projectile with two sets of spring-out fins. The geometry will be discussed in detail in the next section.

The two codes examined are the Naval Surface Weapons Center Aerodynamic Prediction (NSWCAP) Code[2] and the Air Force Missile DATCOM Code.[3] The former code was developed during the 70's and provided a good tool for design configuration studies. The latter code is a more recent code which is built to make use of all the methodologies of the former code, with modifications and improvements. The code was built to reflect updated theories, include more recent and accurate experimental data, add more options for practical missile applications (such as non-axisymmetric bodies, effects of inlets and rocket motor thrust), and reconstruct the code into a more modular form.

Several studies were made by different researchers with regard to the capabilities of several existing fast prediction codes. Some of these codes have narrow capabilities in terms of applicable configurations, flight speed, estimating specific coefficients only, among other restrictions. Reference 4 compares the capabilities and results obtained using MISSILE-2 and DEMON-Series codes. Reference 5 lists and compares some of the methods in ten different codes, among them are the NSWCAP and Missile DATCOM codes. Reference 6 evaluates the NSWCAP and MISSILE-2 codes and refers to several other codes. Reference 7 evaluates methods used for component build-up that were later used in the Missile DATCOM code. Reference 8 is a description of the NSWCAP code, its capabilities, and its analytical techniques as viewed by its authors. Reference 9 is a description of Missile DATCOM code with regard to its different methods, as viewed by its principal authors.

It is not the purpose of this work to survey or compare such variety of codes but rather to apply two particular codes, which are of more general nature and which are of interest to the Army, to a particular hybrid projectile-missile configuration. The objective is to assess the accuracy of these two codes as applied to this configuration. A second objective is to identify areas of needed development in both codes for possible future improvements.

II. GEOMETRY OF THE COPPERHEAD PROJECTILE

The Copperhead projectile, Figure 1, has a total length of 54 inches (1371.6 mm) and a diameter of 6.09 inches (155 mm). It has a spherical nose cap and a conical section of semi-vertex angle of 12.5° connecting the nose and the body sections. There is an obturator ring at the end of the body. The base of the projectile is solid with no holes in it.

The projectile is laser guided with two sets of spring-out fins. The rear fins (tail) spring out shortly after the projectile leaves the gun tube. The projectile travels in this configuration, usually called the launch configuration, unguided and with a speed decreasing from Mach number of 1.8 to about 0.95.

The front set of fins (wings) springs out in the subsonic Mach range from 0.95 - 0.80, and the rear control fins (tail) are then activated to guide the projectile to its target. The projectile is said to be in its maneuvering configuration at this Mach range with both wing and tail fin sets deployed.

The rear fin geometry is shown in Figure 2. The fin is swept back 20° and is tapered in thickness from the root to the tip section. The cross-section near the root is of diamond shape with leading and trailing edge rounding. The fins are controlled through stems, with 0.2 inches (5.08 mm) clearance between the body and the fin root. The pitching panels, fins number 2 and 4 of Figure 3, are located .75 inches (19.05 mm) ahead of the yaw fins, fins number 1 and 3 .

The front fins (wings) are similar to the tail fins except for two differences. First, the semi-span length is 7.149 inches (181.6 mm), compared to 5.974 inches (147.2 mm) for the tail fins. Second, there is no noticeable clearance between the fin root section and the projectile body surface, since these fins are fixed and are not used to guide the projectile.

Both sets of fins have slightly different shapes of slots in the projectile body where they are housed before deployment. Both sets of fins have tip notches for the releasing mechanisms to hold the fins before they are sprung out from their housing locations. Geometry of both sets of fins is listed in Table (1).

III. APPLICATION OF THE TWO CODES

Both codes were applied for sea level conditions with a Reynolds number of 6.18×10^6 per Mach number per foot. For $M = 1.8$, the Reynolds number is 11×10^6 per foot.

Both codes were applied for both launch and maneuvering configurations in the range of Mach number $0.3 < M < 1.8$. Some modifications in the fin geometry had to be made to suit the input capability of each code. For example, the fin swept tip chord had to be made horizontal and the semi-span was adjusted to account for that. Also, the tail fin body gaps were not considered, and the tail fins were assumed to extend continuously to the root section. Also, the details of the obturator were ignored and the obturator was modeled as if it was a small "bump" on the body, with a certain height as is usually the case for simulating a "rotating band".

The zero lift case was always computed in addition to the small angle of attack case ($\alpha = 2°$).

IV. RESULTS AND COMPARISONS

Free-flight data are available in Reference 10, while wind tunnel results are obtained from Reference 11.

1. LAUNCH CONFIGURATION

First, four flight conditions were chosen from Reference 10 and both codes were run at Mach number and angle of attack of (1.77, 2.9°), (1.47, 1.8°), (1.20, 1.1°) and (0.81, 0.9°). The results for C_D, C_{M_α}, C_{N_α} and X_{C_P} are considered reasonable. The results of $(C_{M_q} + C_{M_{\dot\alpha}})$ as obtained by NSWCAP is largely inaccurate especially for $M = 0.8$. For subsonic speeds, the NSWCAP code does not include $C_{M_{\dot\alpha}}$, therefore the value of $(C_{M_q} + C_{M_{\dot\alpha}})$ is not properly calculated in that speed regime. In fact, for the case of ($M = 0.81$, $\alpha = 0.9°$) the range result showed an unstable flight condition based on pitch damping, while the code predicts a stable condition. Range data are compared to the computed results in Table (2).

Second, the two codes were applied in the Mach range of 0.3 to 1.8 and at zero angle of attack. The results for C_D is shown in Figure 4. Both codes underpredict the wind tunnel and range data. This may be expected due to lack of consideration of the effects of the fin slots of the projectile body, in both codes. Also body-fin clearance (gap) effects which should be applied to the tail fins are not considered by either code. In addition, the DATCOM code does not include the obturator effect, which is usually modeled as a rotating band. The computed results of both codes agree better with the experimental data in the supersonic regime ($M > 1.2$), they worsen in the transonic regime ($M = 0.8$ to 1.2) and they deteriorate further at subsonic speeds ($M < .8$).

Reference 12 was first to report the effects of fin slots on the normal and axial forces of the Copperhead. Wind Tunnel tests were made on a full-scale projectile at both subsonic ($M = 0.5$) and supersonic ($M = 1.5$) speeds.

References 13-16 have also reported the effects of body slots. Such information should be used in the future for modeling in both codes. Also, Reference 15 suggests a modification to account for the fin-body gap (clearance) effects.

Figure 5 shows the slope of the normal force, C_{N_α}, as it varies with the Mach number. The two codes gave close values to each other but they both considerably overpredicted the range results in the transonic regime between Mach number 0.8 and 1.2. It is surprising that the wind tunnel results are also significantly higher than those of the free flight range tests. The normal force predictions of the codes can be improved if the fin gap effect has been accounted for and if an average roll orientation angle is considered.

Figure 6 shows the slope of the pitching moment about the C.G. Consistent with the overprediction of C_{N_α}, both codes overpredict the pitching moment slope. The predictions are twice or three times larger than free-flight data. The DATCOM code is closer to the experimental data than the NSWCAP, due to better prediction of the location of the center of pressure. The same dilemma of the wind tunnel data being considerably higher than the range data is also observed.

Figure 7 shows the DATCOM results for the X_{C_P} location to be more accurate then those of NSWCAP. Compared to free-flight data of Reference 10, the DATCOM results are more accurate, but still overpredict X_{C_P} by about 0.4 calibers.

Figure 8 shows the NSWCAP predictions for the pitch damping coefficient. The DATCOM code, on the other hand, does not compute this derivative. The trend shown agrees with the range results only in the supersonic Mach range down to $M \approx 1.2$. The numerical values are about 67% larger than those measured in the free-flight range. It is suggested that the unsteady pitch damping coefficient, $C_{M_{\dot\alpha}}$, is largely in error possibly due to fin flutter or to unsteady flow effects in and out of the body slots and around fin-body gaps which are not considered in the code. However, for transonic and subsonic speeds, the code fails to predict the trend as well as the values. The lack of including $C_{M_{\dot\alpha}}$ for those speed regimes is a possible reason for such failure.

2. MANEUVERING CONFIGURATION

With the wing fins deployed, the projectile decelerates from Mach 0.95 down to Mach 0.3. Computations were made, however, for this B-W-T configuration for the Mach range of 1.8 to 0.3.

Figure 9 shows the total drag coefficient for this configuration in comparison to the launch configuration (B-T). The increase in drag is due to wing fin drag less the reduction in drag due to the interference of the wing fins on the tail fins. The DATCOM code shows smaller increase than that of the NSWCAP code, due to vortex tracking corrections included in DATCOM, while the larger effect as computed by the NSWCAP, is due to the lack of consideration of wing-tail interference effects. It should be pointed out that a recent nonlinear vortex tracking procedure has been developed[17] and proved to give more accurate predictions.

Figure (10a) shows the normal force slope, where the increase caused by the wing fin lift is smaller for the DATCOM code than the increase predicted by the NSWCAP code. The cause for this is the reduction in lift of the tail fin due to the trailing vortex of the wing, as accounted for in the DATCOM code. Figure (10b) shows the change in normal force slope as predicted by DATCOM Code, due to the deployment of the wing fins. Three Mach numbers .95, .9 and .8 were chosen for the projectile speed at deployment.

Figure (11a) shows the pitching moment slope for a range of Mach numbers. For the B-W-T configuration, the wing normal force pushes the center of pressure forward towards the nose, thus causing the pitching moment about the C.G. to be smaller. Thus the projectile is less stable. Figure (11b) displays a decrease in the dynamic stability of the projectile due to the reduction in pitching moment slope from -25. to -5. The location of the center of pressure, X_{C_p}, is shown in Figure (12a) to shift towards the C.G. and away from the projectile base. Figure (12b) shows the sudden shift in the location of the X_{C_p} due to wing deployment.

The dynamic stability for pitch disturbance remains almost unchanged for the B-W-T configuration (compared to the B-T) in the supersonic regime as predicted by the NSWCAP code and shown in Figure 13. The DATCOM code, on the other hand, does not compute this derivative. The trend shown agrees with the range results only in the supersonic Mach range down to $M \simeq 1.2$. The numerical values are about 67% larger than those measured in the free-flight range. It is proposed that the unsteady pitch damping coefficient, $C_{M_{\dot{\alpha}}}$, is largely in error possibly due to fin flutter or to unsteady flow effects in and out of the body slots and around fin-body gaps which are not considered in the code. However, for transonic and subsonic speeds, the code fails to predict the trend as well as the values. The lack of including $C_{M_{\dot{\alpha}}}$ for those speed regimes seems to be the reason for such failure.

Figure 14 shows the longitudial stability chart for small α's and moderate deflection angles, δ, at Mach number 0.5. It is shown that the NSWCAP code overpredicts both C_M and C_N for all cases, more than the DATCOM code does. For the same α, the discrepancy increases with increase in δ. Similar results are also shown in Figure 15 for Mach number 0.95. It is noticed that the discrepancy increased for this transonic speed as was noticed earlier in Figures 5 and 6 for C_{N_α} and C_{M_α}. The DATCOM code shows better results than the NSWCAP, especially for large δ due to the inclusion of the equivalent angle of attack approach of Reference 17.

The roll damping coefficient was computed for both configurations only by the NSWCAP code since the DATCOM code does not presently have this capability. The results for B-T configuration are shown in Table 3, where reasonable agreement with the wind tunnel results can be observed especially when excluding the transonic speed range. However, the results become extremely large for the B-W-T configuration, and is attributed to lack of consideration of wing-tail interference effects in that code.

V. AREAS OF NEEDED DEVELOPMENT

In Table 4, a list is given for areas of needed development in both codes. This list was compiled through the application to the Copperhead projectile case as well as to other cases. The order in which they are listed does not reflect the order of importance, because the latter depends on the objectives of each user of the codes.

VI. CONCLUSIONS

Through the application of the two codes-NSWCAP and Missile DATCOM-to the C· :rhead projectile geometry, the following conclusions have been drawn.

1. The DATCOM code generally gave slightly better results, compared with experiment, than those of the NSWCAP.

2. Both codes badly estimated the slopes of the normal force and pitching moment coefficients due to fin slot and fin gap effects which are not included in either code.

3. The effects of the deflection angles of the control surfaces are not explicitly computed in either code. Both codes failed to provide this information which is essential to guided projectile configurations.

4. The dynamic derivatives of the NSWCAP code are not accurate for this configuration. Furthermore, they are not calculated in the present version of the DATCOM code.

5. Both codes gave poor estimates for all aerodynamic coefficients in both the subsonic ($M < .8$) and transonic ($0.8 < M < 1.2$) speed regimes.

6. The DATCOM code, being developed more recently, is written in a modular form allowing ease of modification and checking. The NSWCAP, being a pione·r code, lacks this feature.

Other areas of needed development in both codes were identified and listed in Table 4 for future development. These codes serve an important function and should be developed to better meet user's needs.

TABLE 1. Copperhead Wing and Tail Fin Geometry.

Wing Fin	Dimensions
Semi-Span (exposed) (in)	7.149 (181.58 mm)
Chord (root and tip, theoretical parallel to body (in)	3.051 (77.49 mm)
Area (single panel, one surface)	20.309 (1.31×10^4 mm^2)
Sweep Angle (degrees), baseline	20
Root chord thickness ratio	0.0743
Tip chord thickness ratio	0.0197
Leading edge location of root chord (in)	32.32 (820.93 mm)
Tail Fin	
Semi-span (exposed) (in)	5.974 (151.74 mm)
Chord (root and tip, theoretical) parallel to body (in)	3.051 (77.49 mm)
Area (single panel exposed) (in^2)	16.891 (1.09×10^4 mm^2)
Sweep angle (degrees), baseline	20
Root chord thickness ratio	0.0743
Tip chord thickness ratio	0.0196
Leading edge location of root chord (in)	
Fins 1,3	48.640 (1235.47 mm)
Fins 2,4	47.992 (1218.99 mm)

TABLE 2. Comparison of Code Results with Measured Data

Launch Configuration (B-T)

Mach Number, Angle of Attack	Prediction Method	C_D	C_{M_α} (C.G.) Rad^{-1}	C_{N_α} Rad^{-1}	X_{CP} (Cal-Base)	(C_{M_q} + $C_{M_{\dot{\alpha}}}$) Sec/Rad
M = 1.77, α = 2.9°	Range Test Results*	.740	-0.06	5.51	3.69	-99
	NSWC Code	.654	-2.930	7.253	3.30	-210.12
	DATCOM Code	.698	-1.77	6.915	3.454	----†
M = 1.47, α = 1.8°	Range Test Results*	.760	-0.88	5.07	3.53	-200
	NSWC Code	.671	-9.606	8.445	2.56	-228.9
	DATCOM Code	.733	-6.648	8.073	2.89	----†

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M = 1.20, α = 1.1°	Range Test Results*	.803	-10.52	6.96	2.24	-132
	NSWC Code	.663	-22.14	11.33	1.74	-248.6
	DATCOM Code	.746	-18.53	11.35	2.08	----†
M = 0.81 α = 0.9°	Range Test Results*	.398	-10.56	8.31	2.43	15
	NSWC Code	.296	-22.78	11.88	1.78	-252.8
	DATCOM Code	.320	-18.14	10.33	1.95	----†

* R. McCoy, March 1981, Reference 10.
† DATCOM Code does not compute this coefficient.

TABLE 3. NSWCAP Code Results for Roll Damping Cofficient

C_{ℓ_p} [RAD/SEC]$^{-1}$

Launch Configuration (B-T)
δ = 0°, α = 0°

Mach Number	0.5	0.8	0.9	0.95	1.2	1.5	1.8
NSWCAP Code	-14.07	-15.84	-19.06	-20.16	-20.65	-14.6	-11.32
Wind Tunnel	-10.50	-11	-11.4	-12	-16	-11.1	-9.8

Maneuvering Configuration (B-W-T)
δ = 0°, α = 0°

Mach Number	0.5	0.8	0.9	0.95	1.2	1.5	1.8
NSWCAP Code	-34.97	-38.74	-45.0	-47.0	-50.92	-38.5	-30.49
Wind Tunnel	-20	-22	-23.5	-24.2	-28	-25.2	-23

TABLE 4. Capability Comparison and Areas of Needed Development

NSWCAP Code	Missile DATCOM Code
I. <u>Fins</u>	
1a) Only 2 or 4 fin panels only, in cruciform "Plus" position only	1a) Only 2 or 4 fin panels*, arbitrary roll angle
b) No roll angle aerodynamics	1b) Arbitrary roll orientation
2) Limited to two sets of fins	2) Limited to two sets of fins**
3) No body fin-slot effects	3) No body fin-slot effects
4) No fin-body gap effects	4) No fin-body gap effects
5) No fin side-sweep angle effects	5) No fin side-sweep angle effects
6) No interdigitated wing and tail fins	6) No interdigitated wing and tail fins
7) No aft-body fins	7) No aft-body fins
8) No wing-tail interference	8) Includes a linear vortex correction for down-wash effects
9) No wrap-around fins	9) No-wrap around fins
10) Limited fin cross-section geometry options	10) Limited fin cross-section geometry options
11) Gives erroneous results for perfect delta fin (or close to perfect delta planform	11) Gives much worse results for perfect delta fin (or close-to-perfect delta planform
12) Only tip and root fin cross-sections be specified	12) Multi fin cross-section geometries can be specified (Max. of 10)
13) Assumes parallel line of sources for fin geometry	13) Does not assume parallel line of sources for fin geometry
14) Does not include lifting surface non-linearity at high angle of attack	14) Includes the equivelant angle of attack for non-linearity at high α
II. <u>Body Aerodynamics</u>	
1a) Computes base pressure drag	1a) Computes base pressure drag but does not add it to axial or drag forces
b) Base pressure drag deteriorates at large α (>10°) (overpredicted)	b) Base pressure drag is not function of α

*Arbitrary number of fins capability is now being added to the newer version of the code.
**A third set of fins is being added in the newer version of the code.
***Presently bein, added in the newer version of the code.

Continued

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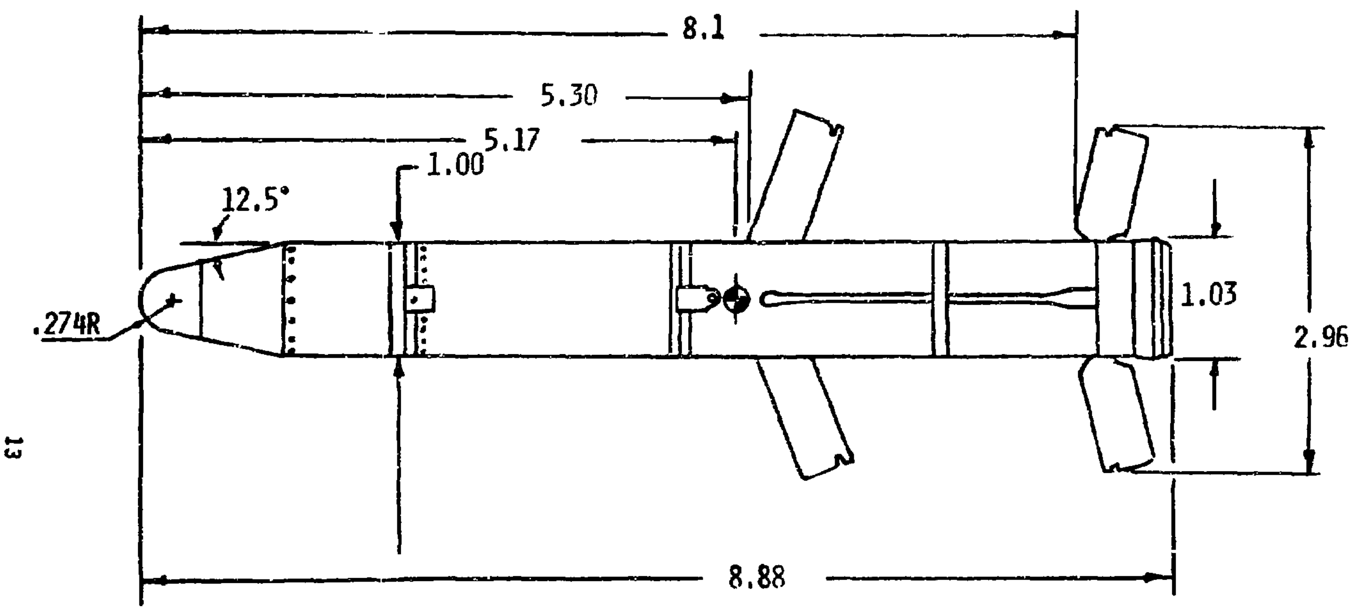
2) No surface roughness or grooving effects 3) Includes rotating band contribution to C_D 4) Calculates high Mach number cases for blunt nose 5) Yields fair blunt-nose hypersonic aerodynamics ($M > 3$) 6) Yields poor subsonic and transonic blunt nose aerodynamics ($M < 1.2$) 7) No forebody vortex shedding effects 8) No intermediate body vortex shedding effects	2) Includes surface roughness, but no grooving effects 3) Does not include rotating band effect on C_D 4) Does not accept any nose bluntness at high supersonic speeds ($M = 4-5$) 5) Yields very poor blunt-nose hypersonic aerodynamics ($M > 3$) 6) Yields fair subsonic and transonic blunt nose aerodynamics 7) No forebody vortex shedding effects 8) No intermediate body vortex shedding effects
III. Vehicle (Body and Fins) Dynamics 1) Computes roll damping C_{ℓ_p} and pitch damping $(C_{M_q} + C_{M_{\dot{\alpha}}})$ coefficients 2) $C_{M_{\dot{\alpha}}}$ is not computed for subsonic or transonic speeds ($M < 1.2$) (set to zero) 3) $(C_{M_q} + C_{M_{\dot{\alpha}}})$ is not adjusted to include effects of deflection angle of fins (i.e. it remains constant with δ) 4) C_{ℓ_p} is fairly computed for one set of fins only. However, it is largely in error for wing-tail combination, (no wing-tail interference effects)	1) Does not compute any dynamic derivatives***
IV. Fin Control 1) Only two fins allowed pure pitching No simultaneous yawing or combined yawing/pitching 2) No expressions or derivatives for control surface effectiveness; $(C_{N_\delta}, C_{M_\delta})$	1) Independent four-fin deflection angles 2) No expressions or derivatives for control surface effectiveness $(C_{N_\delta}, C_{M_\delta})$

Continued

Continued

3) $(C_{M_q} + C_{M_{\dot{\alpha}}})$ is not corrected for δ (remains constant with variations in δ)	3) $(C_{M_q} + C_{M_{\dot{\alpha}}})$ is not calculated
4) C_{N_α} (and C_{M_α}) for any case with fin deflection is calculated as $C_N/\Delta\alpha$, and is void when $\alpha = 0.0$	4) No difficulty in computing C_{N_α} and C_{M_α} for configurations with control surface deflection
V. <u>General Features</u>	
1) Takes about 40 CPU seconds for a single Mach number and angle of attack case (on a VAX-11/780)	1) Faster by a factor of 1.5 (approximately)
2) Accepts a single angle of attack, and performs a loop for up to 20 Mach numbers	2) Accepts several Mach numbers and performs a loop for many angles of attack (minimum of two) for each Mach number
3) Has no difficulty with redundant input data	3) Gives erroneous results if redundant (but consistant) input data is given
4) Uses input in feet only (combined with some input in calibers)	4) Can use either in, ft, cm or meter units



DIMENSIONS IN CALIBERS
1 CALIBER = 6.0 INCHES (155MM)

Figure 1. Configuration of the XM712 Copperhead projectile.

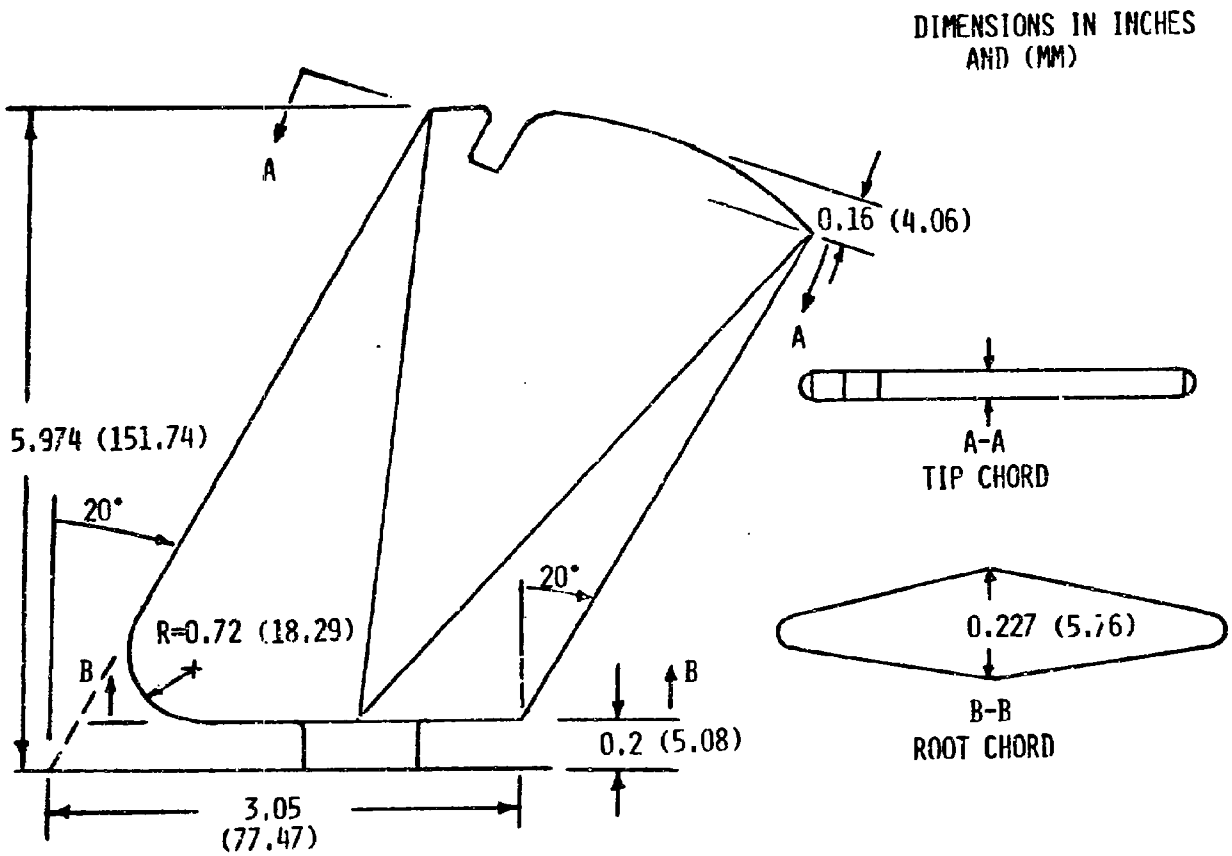


Figure 2. Copperhead tail fin configuration.

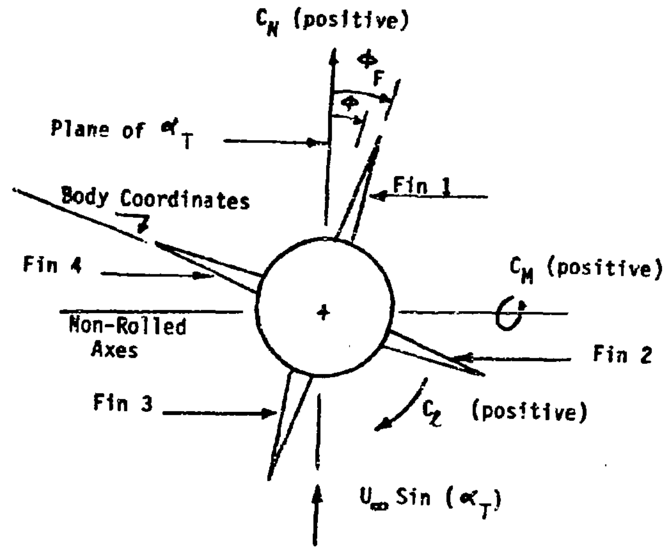


Figure 3. Nomenclature and signs (view from rear looking forward).

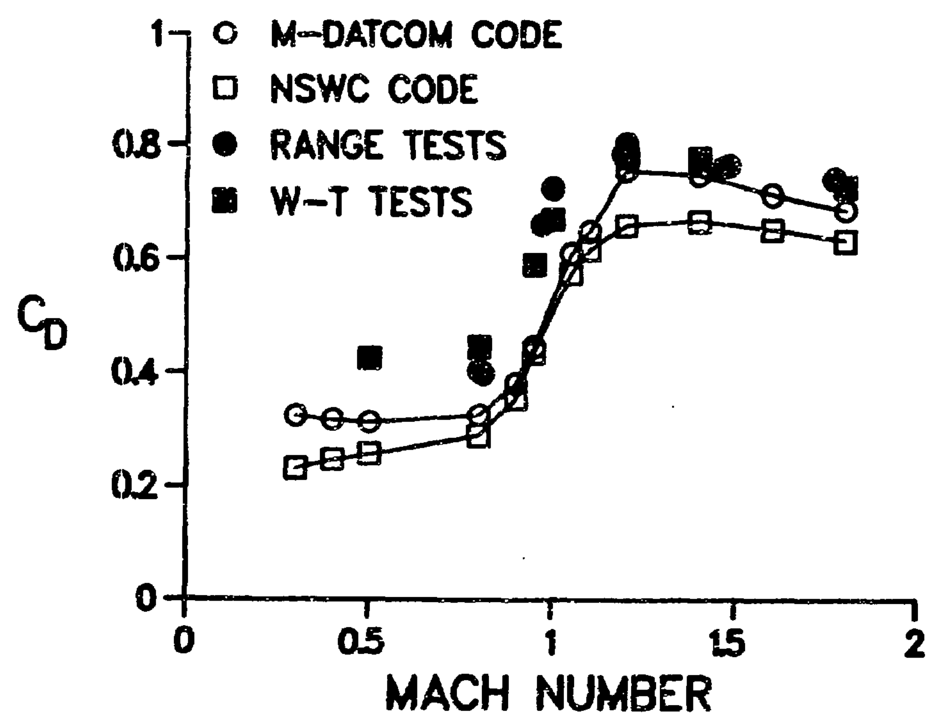


Figure 4. Total drag coefficient comparison for the launch configuration.

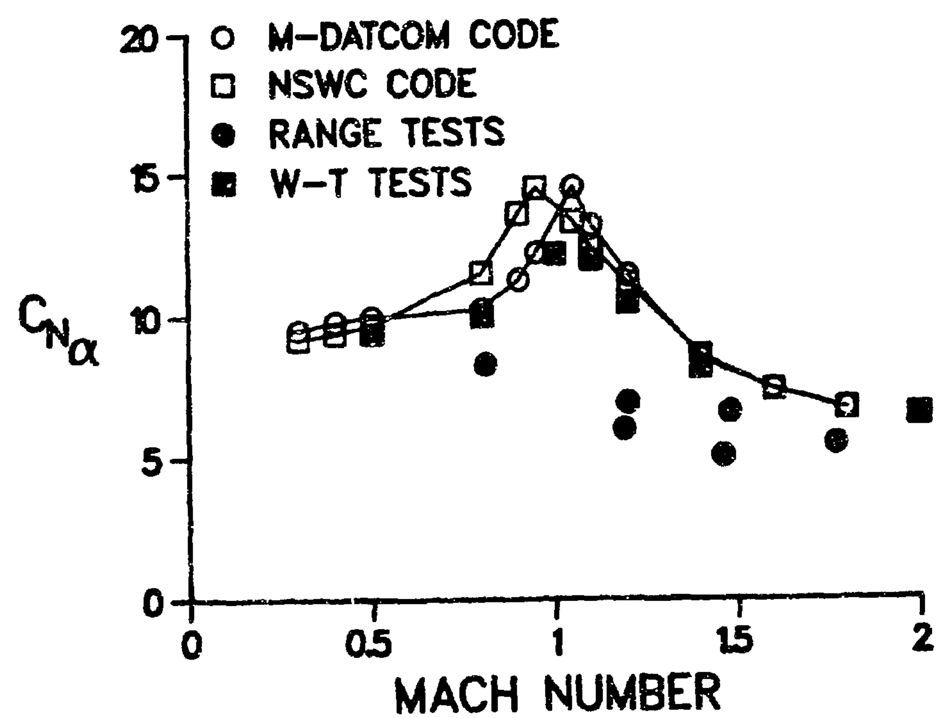


Figure 5. Normal force slope comparison for the launch configuration.

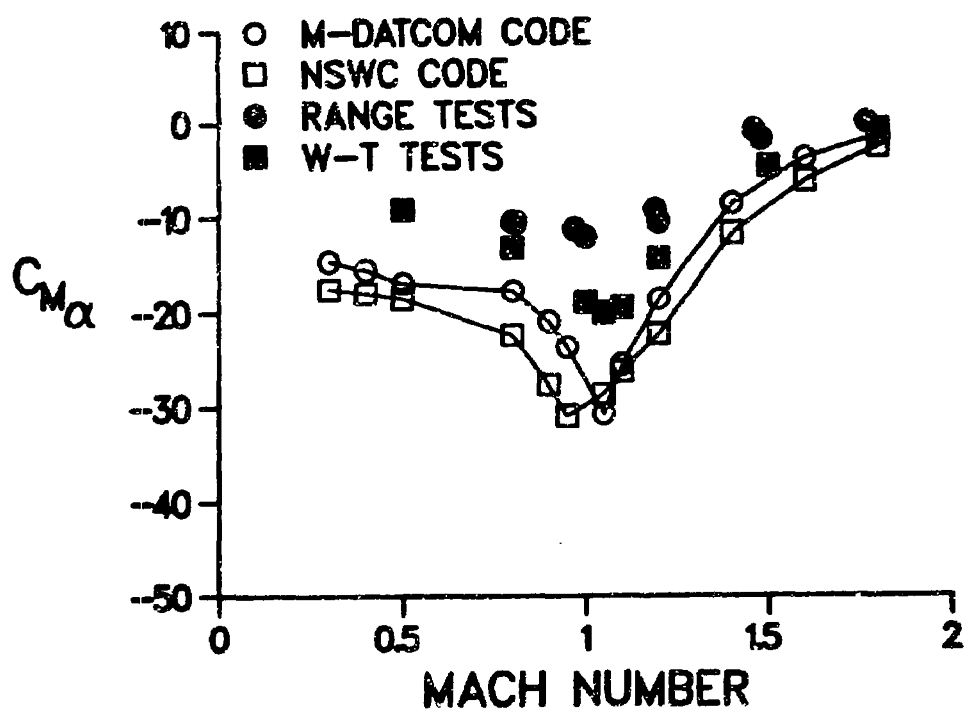


Figure 6. Pitching moment slope comparison for the launch configuration.

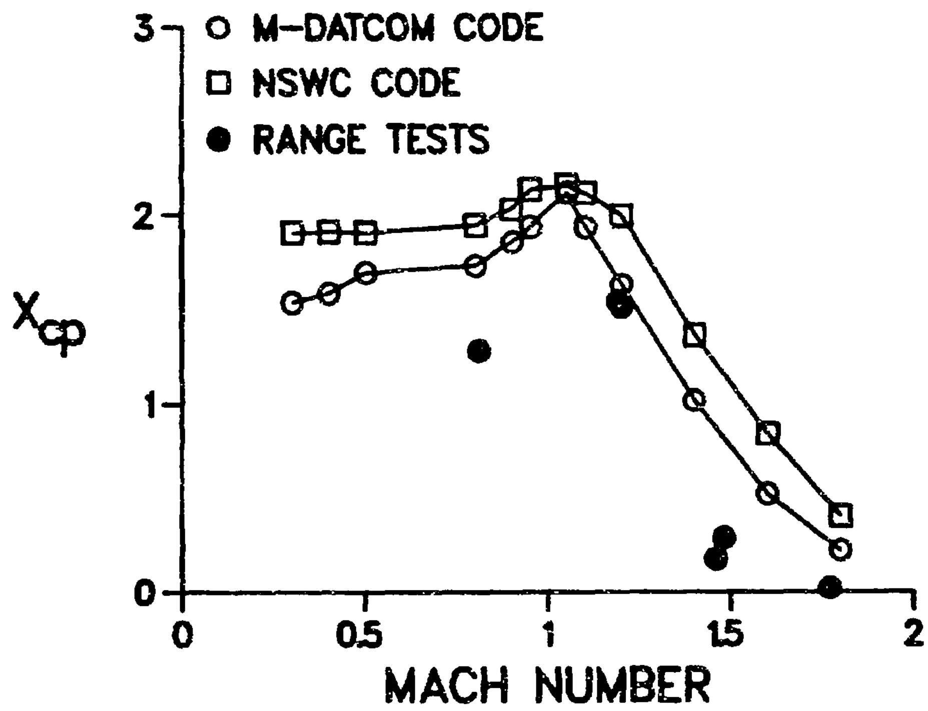


Figure 7. Location of center of pressure for the launch configuration.

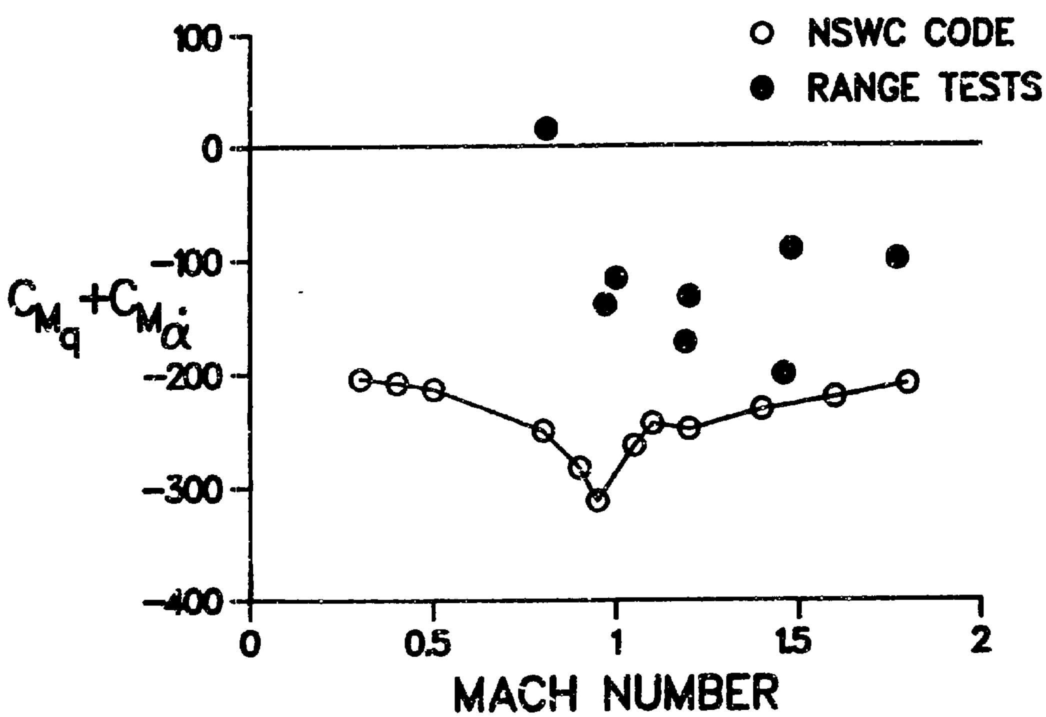


Figure 8. Pitch damping coefficient comparison for the launch configuration.

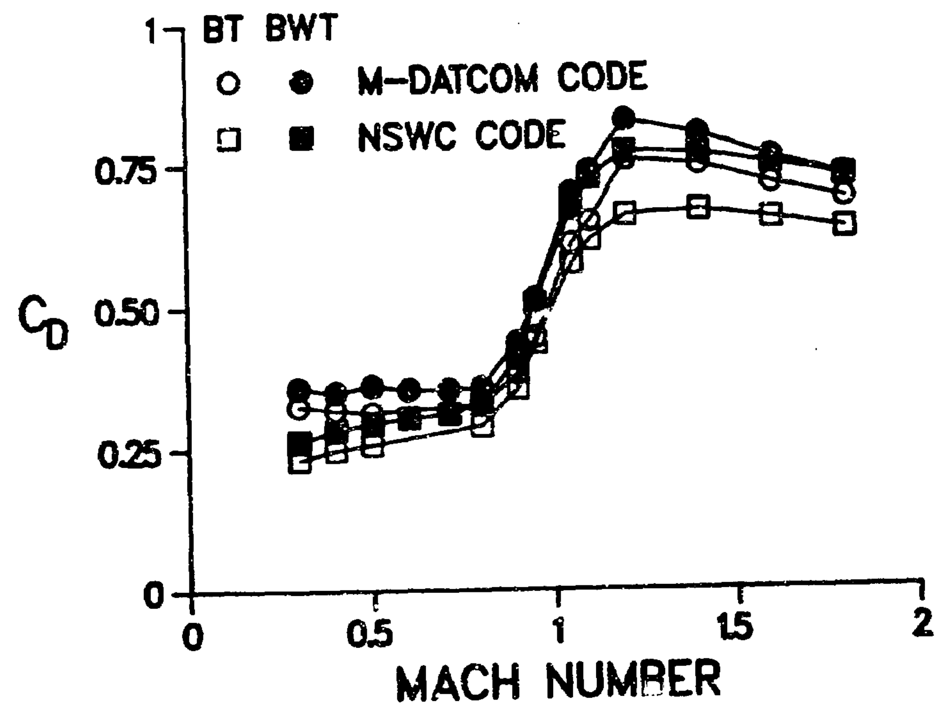


Figure 9. Total drag coefficient for both launch and maneuver configurations.

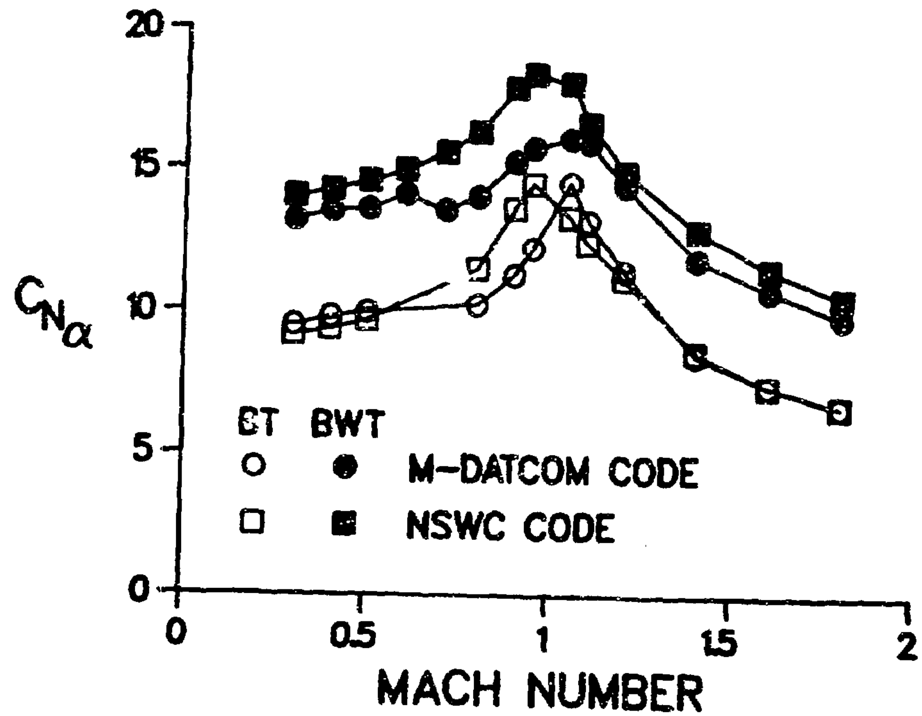


Figure 10a. Normal force slope coefficient for both launch and maneuver configurations.

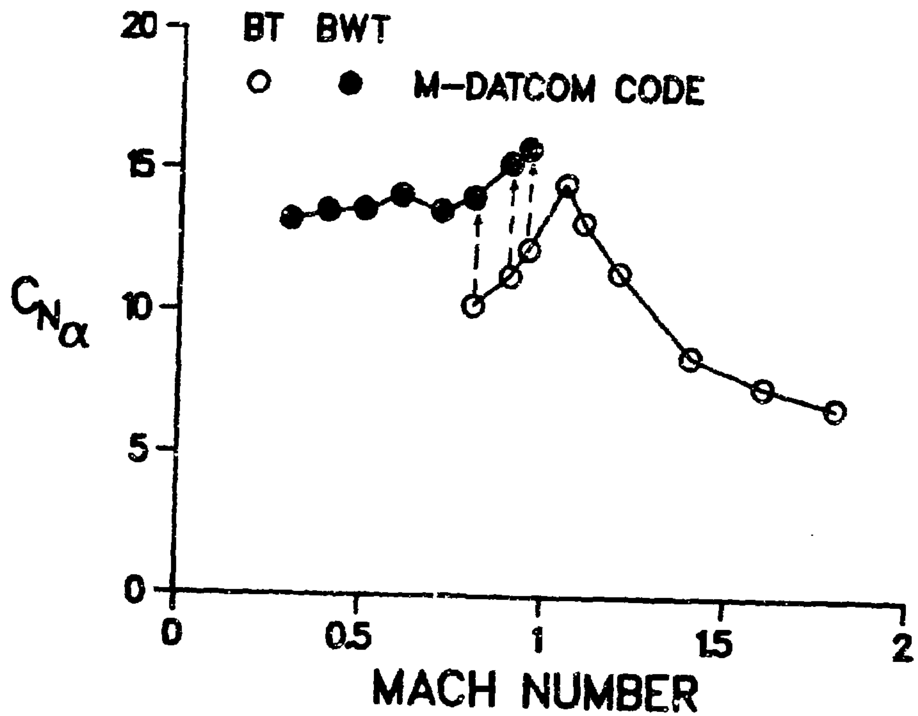


Figure 10b. Change in normal force slope coefficient from launch to maneuver configurations.

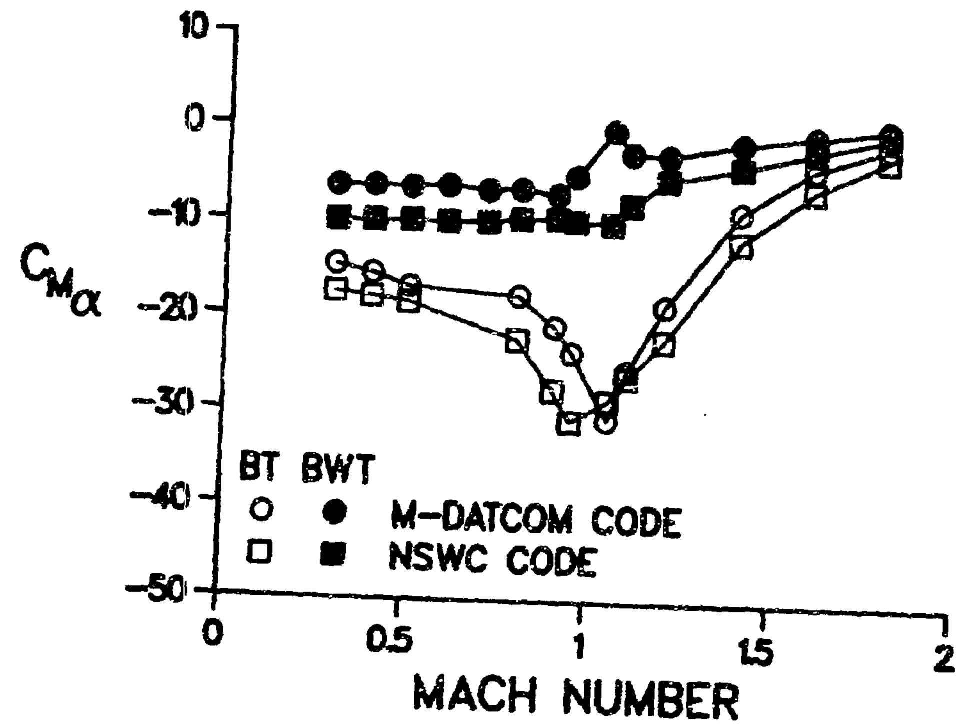


Figure 11a. Pitching moment slope for both launch and maneuver configurations.

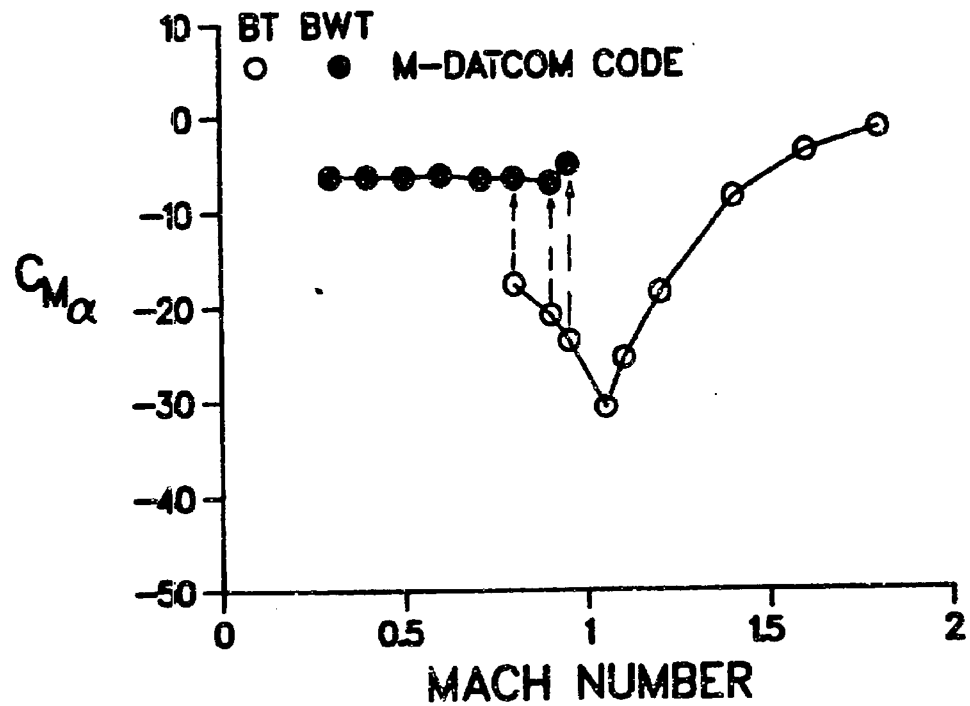


Figure 11b. Change in pitching moment slope from launch to maneuver configuration.

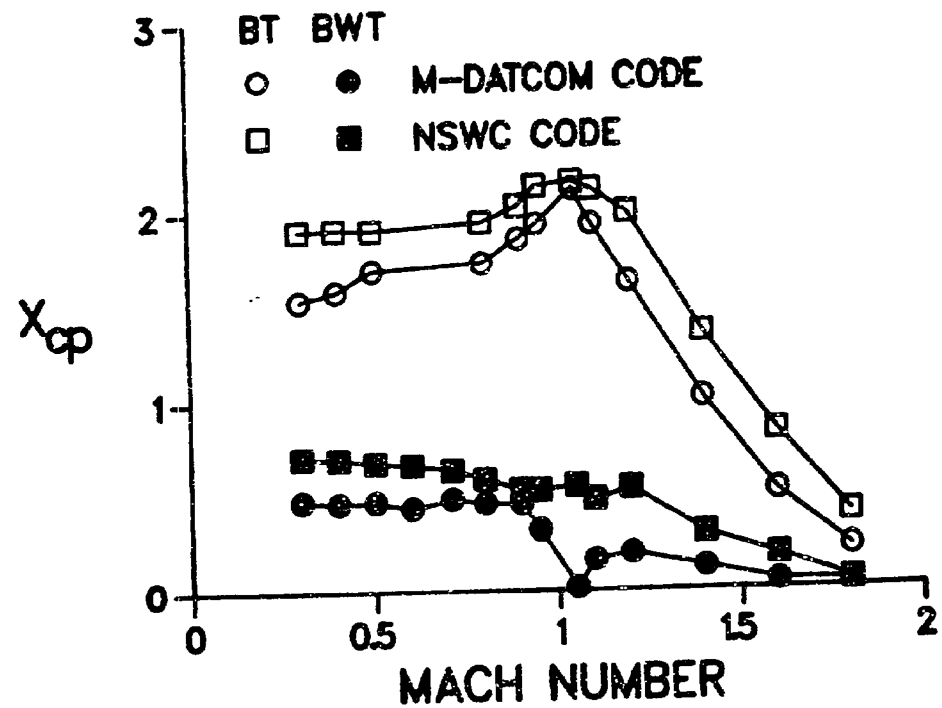


Figure 12a. Location of center of pressure for both launch and maneuver configurations.

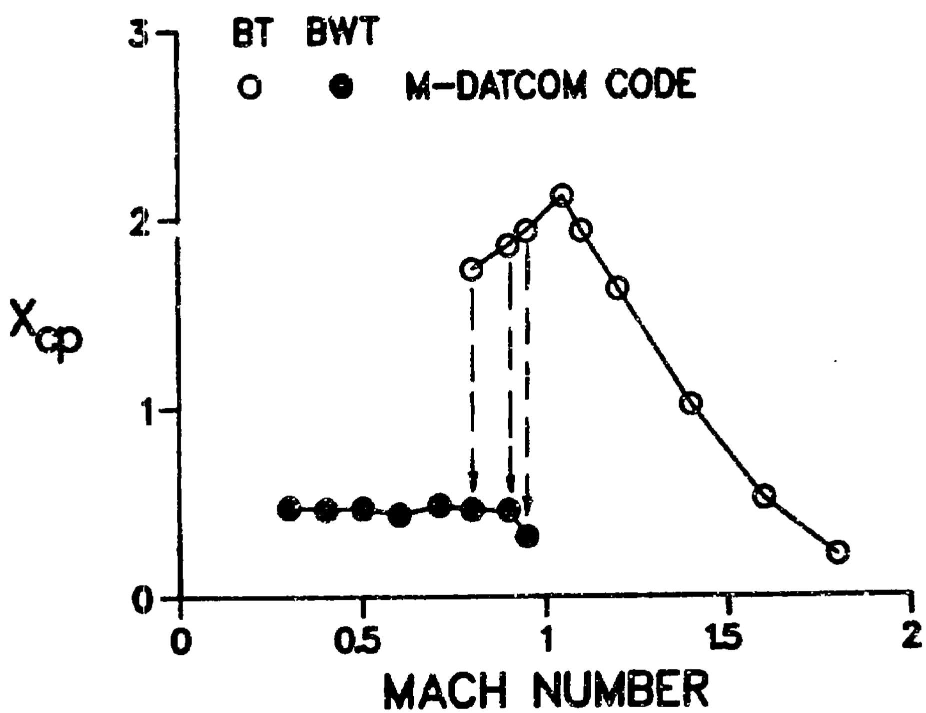


Figure 12b. Change in location of center of pressure from launch to maneuver configuration.

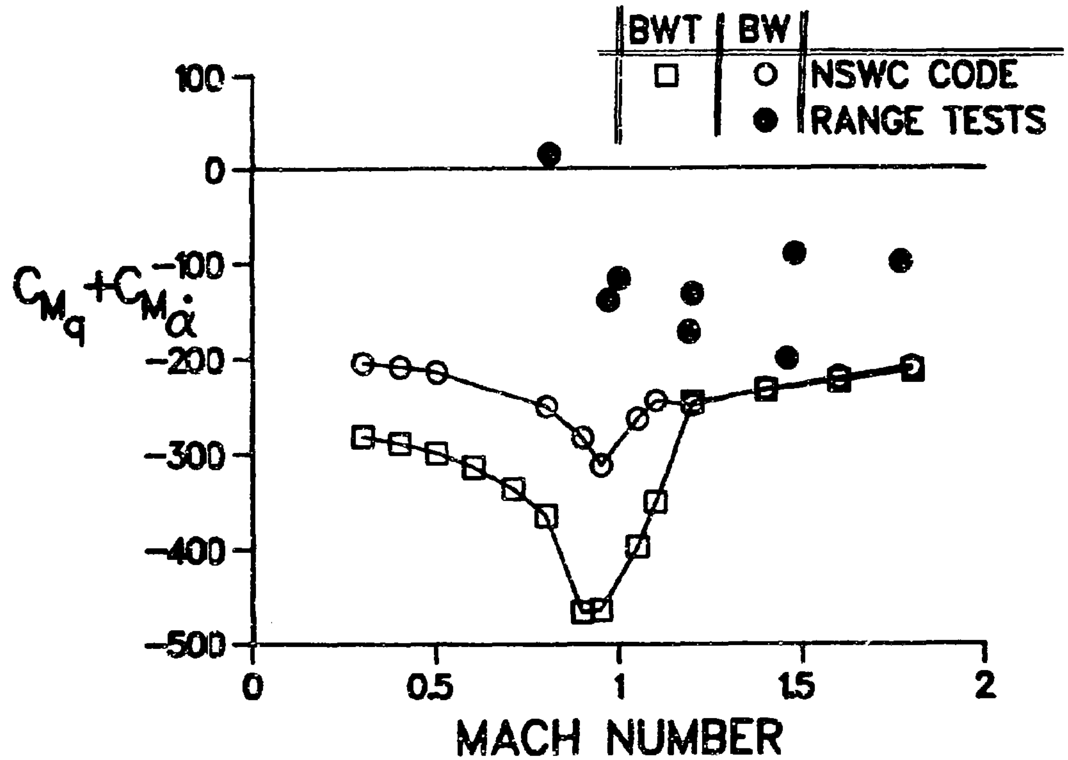


Figure 13. Pitch damping coefficient for both launch and maneuver configurations.

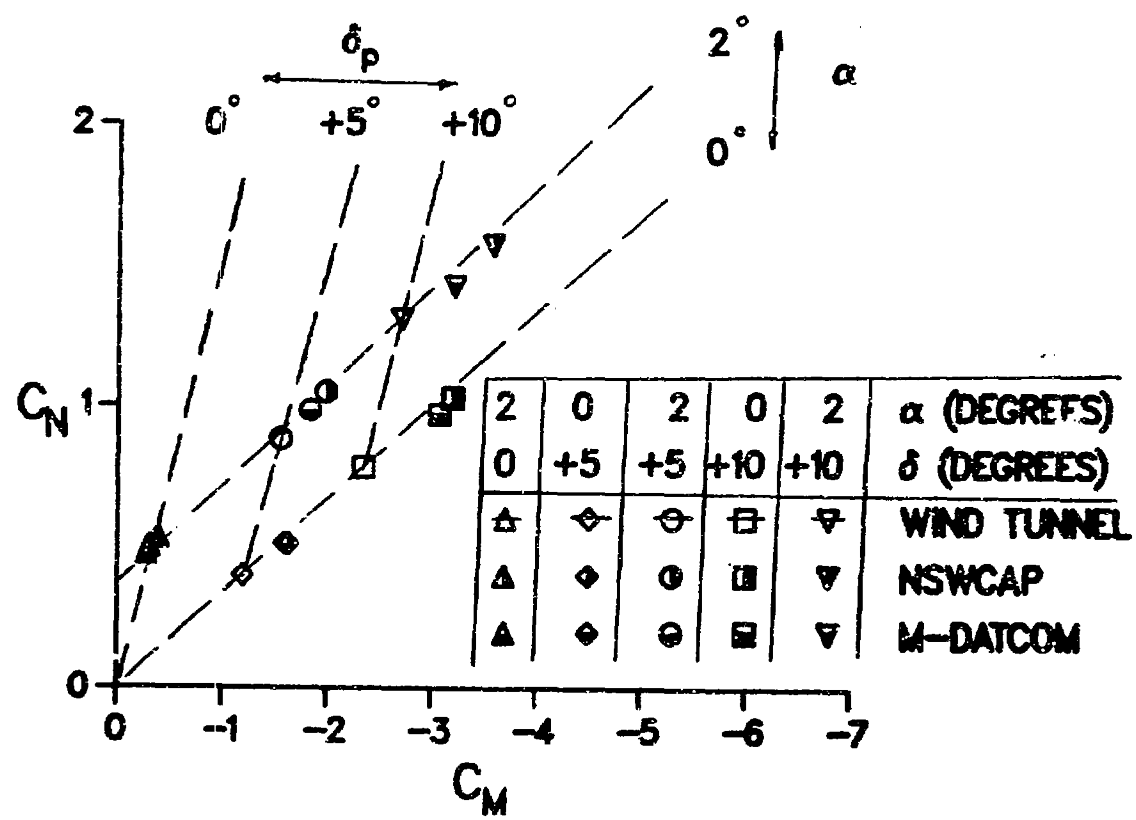


Figure 14. Maneuver configuration longitudinal stability at M = 0.5.

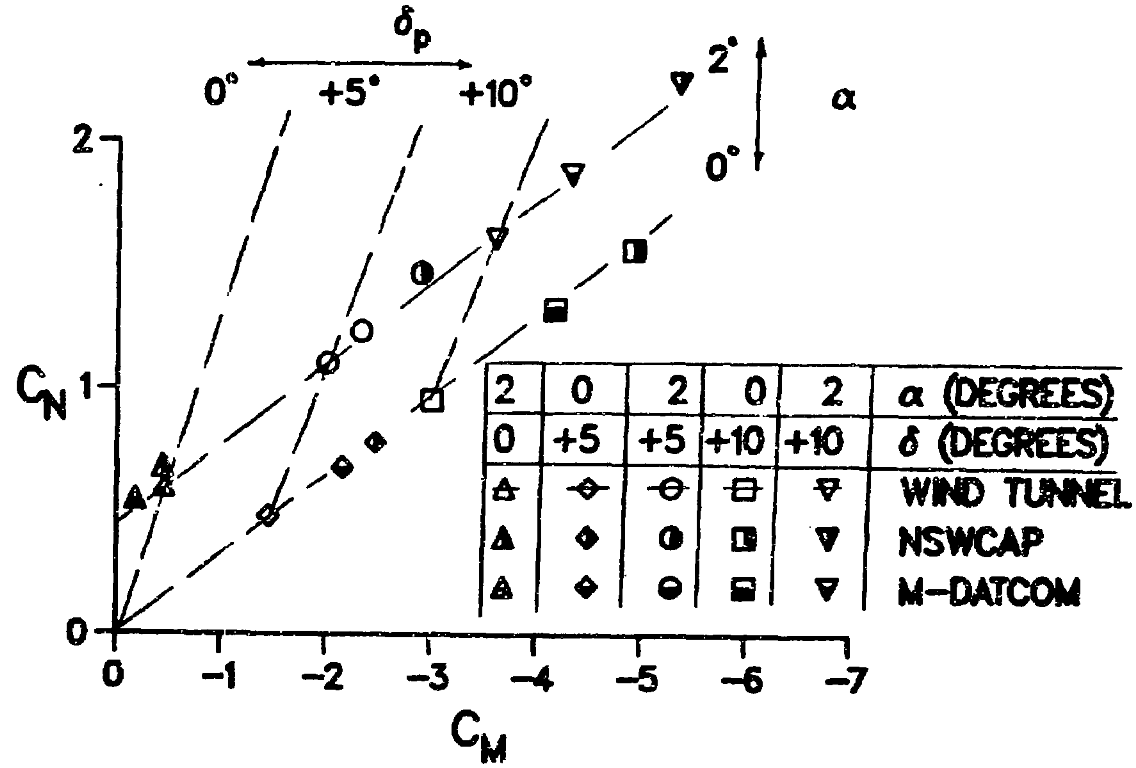


Figure 15. Maneuver configuration longitudinal stability at M = 0.95.

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LIST OF SYMBOLS

C_D = Total drag coefficient, drag force/$0.5\rho_\infty U_\infty^2 S_{ref}$

C_ℓ = Roll moment coefficient, rolling moment/$q_\infty S_{ref} L_{ref}$ - positive if clockwise (viewed from rear looking forward)

C_{ℓ_p} = $\partial C_\ell / \partial p$

C_M = Pitching moment coefficient, pitching moment/$q_\infty S_{ref} L_{ref}$ (positive when nose up)

C_{M_α} = $\partial C_M / \partial \alpha$ (1/Rad)

C_n = Yawing moment coefficient, yawing moment/$q_\infty S_{ref} L_{ref}$ (positive when nose to right)

C_N = Normal force coefficient, normal force/$q_\infty S_{ref}$

C_{N_α} = $\partial C_N / \partial \alpha$ (1/Rad)

C_Y = Side force coefficient

D = Body diameter

D_{ref} = Body reference diameter

L = Body length

L_{ref} = Reference length, usually the body diameter

M_∞ = Free stream Mach number

P = Spin (roll) rate (radian/sec)

q = Pitching motion rate (radian/sec)

q_∞ = Free stream dynamic pressure, $0.5\rho U_\infty^2{}_\infty$

S_{ref} = Reference area, $\pi D^2_{ref}/4$

t = Time

X_{CP} = Location of center of pressure, measured from the C.G. towards the base of the projectile

α = Angle of attack, positive when producing a positive normal force, degrees

α_T = Total angle of attack, including side slip angle, degrees

LIST OF SYMBOLS (Continued)

$\mathring{\alpha}$ = $\partial\alpha/\partial t$

δ = Fin deflection angle - for fin 1,2,3,4: positive when producing a negative (counter clock-wise rolling moment (DATCOM notation)
- for fins 2,4: positive when trailing edge is down (NSWCAP notation)

ϕ = Roll angle of the body cross- section

ϕ_F = Fin orientation angle, measured clock-wise from the vertical line of the α_T plane

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