

**DAHLGREN DIVISION
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NSWCDD/TR-00/009

**IMPROVEMENTS IN PITCH DAMPING FOR THE
AEROPREDICTION CODE WITH PARTICULAR
EMPHASIS ON FLARE CONFIGURATIONS**

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WEAPONS SYSTEMS DEPARTMENT

APRIL 2000

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REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 2000	3. REPORT TYPE AND DATES COVERED Final	
4. TITLE AND SUBTITLE Improvements in Pitch Damping for the Aeroprediction Code with Particular Emphasis on Flare Configurations			5. FUNDING NUMBERS	
6. AUTHOR(s) Frank G. Moore, Tom C. Hymer				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Commander Naval Surface Warfare Center Dahlgren Division (Code G04) 17320 Dahlgren Road Dahlgren, VA 22448-5100			8. PERFORMING ORGANIZATION REPORT NUMBER NSWCDD/TR-00/009	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) New capability has been added to the NSWC aeroprediction code to allow aerodynamics to be predicted for Mach numbers up to 20 for configurations with flares. This new capability includes extending the static aerodynamic predictions for Mach numbers less than 1.2, improving the body alone pitch damping for Mach numbers above 2.0, and developing a new capability for pitch damping of flared configurations at Mach numbers up to 20. This new capability for flared configurations was validated for several different configurations in the Mach number range of 2 to 8.8. In general, pitch damping predictions of the improved capability was within 20 percent of either experimental data or computational fluid dynamics calculations. This accuracy level is believed to be quite adequate for dynamic derivatives in the preliminary design stage. These new additions to the aeroprediction code will be transitioned to users as part of the 2002 version of the code (AP02).				
14. SUBJECT TERMS aerodynamics, Aeroprediction Code, Mach number, flares, pitch damping			15. NUMBER OF PAGES 51	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORTS UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

FOREWORD

The 1998 version of the aeroprediction code (AP98) used an empirical method to compute pitch damping of bodies alone. This method was based on a 1970's version of a model developed by Bob Whyte of General Electric (GE) (Bob has since left GE and formed his own company). The method was a data base that used aerodynamics of Army and Navy spin stabilized shells as a means to estimate aerodynamics of other configurations. The Whyte code (referred to as the "GE Spinner" code) worked well for configurations that had Mach numbers less than about 3.0. However, for many missile configurations at high Mach numbers, or configurations that used flares for stability, the GE Spinner code gives erroneous answers, since it was not developed with those conditions in mind. The work presented in this report develops new semiempirical technology to address the weak areas of the GE Spinner code for the pitch damping coefficient.

The work described in this report was supported through the Office of Naval Research through the Surface Weapons Systems Technology Program managed at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) by Mr. Robin Staton. Tasking from this program was provided by Mr. Roger Horman and Mr. John Fraysse. Also, some support was provided by the Ballistic Missile Defense Program through Mr. George Long. The authors express appreciation for support received in this work.

Approved by:



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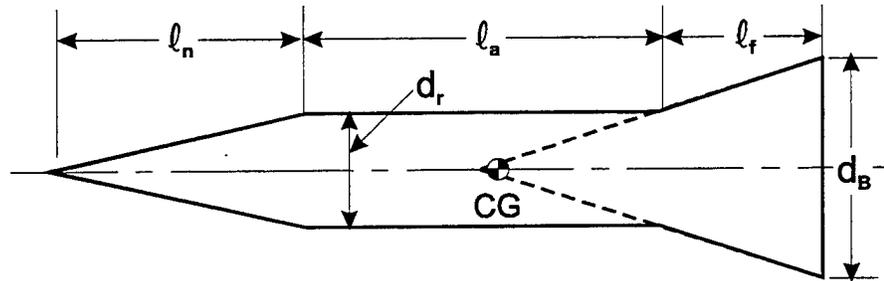
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1.0 INTRODUCTION

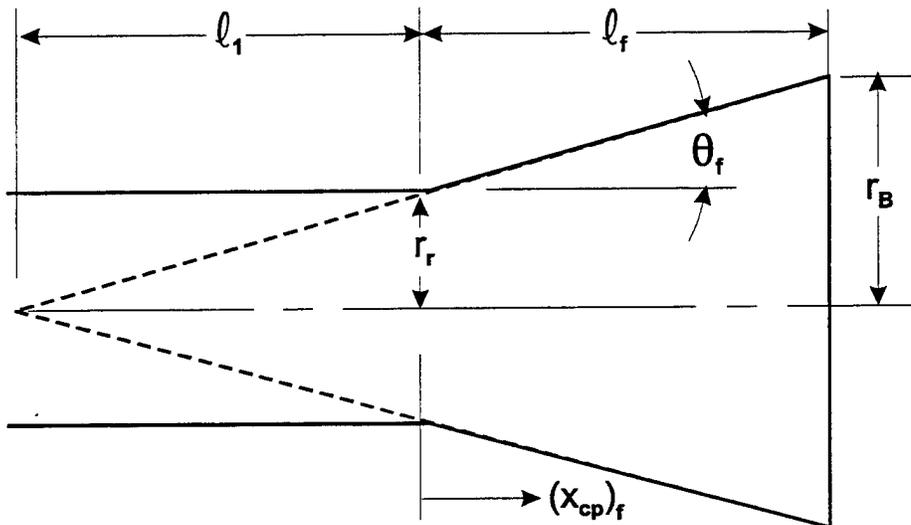
The 1998 version of the NSWCDD Aeroprediction Code (AP98)¹ is the most complete and comprehensive semiempirical code produced to date. It includes the capability to predict planar aerodynamics in the roll positions of $\Phi = 0$ deg (fins in “+” or plus orientation as viewed from the rear of the missile) and $\Phi = 45$ deg (fins in “x” or cross roll orientation as viewed from the rear of the missile) over a broad range of flight conditions and configuration geometries with good average accuracy, computational times and ease of use. Flight conditions include angles of attack (AOA) up to 90 deg, control deflections of up to ± 30 deg, and Mach numbers up to 20. Configuration geometries include axisymmetric and nonaxisymmetric body shapes with sharp, blunt, or truncated nose tips, with or without a boattail or flare. Up to two sets of planar or cruciform fins are allowed. New technology has recently been developed² to allow both six- and eight-fin options in the fin considerations as well. Also, many of the constants used in the aeroprediction code have been refined³ based on a more recent wind tunnel data base,⁴ allowing more accurate aerodynamic estimates at angle of attack. Average accuracies are ± 10 percent for normal and axial force and ± 4 percent of body length for center of pressure. Average accuracy means that enough AOAs or Mach numbers are considered to get a good statistical sample. On occasion a single data point can exceed these average accuracy values. Ease of use has been significantly enhanced over older versions of the Aeroprediction Code (APC) through a personal-computer-based pre- and post-processor package.⁵ This package has allowed inputs for configuration geometries to be simplified significantly by many automated nose shape options.

While the AP98 is a very powerful tool, several limitations and areas of improvement still remain. Most of these needs are driven by the desire of future weapon designers to perform trade studies on new and innovative concepts that may fall outside of the current capability of the AP98. An example of this type of requirement is the multi-fin requirement that has just been completed.² Another example of this type of requirement is to include the capability to deflect the rear segment of a fin (sometimes referred to as flaperon or aileron) for control, as opposed to the entire fin. Also, the capability to predict drag accurately for all power on conditions is desired. Finally, improvement in aerodynamics of projectiles that use a flare for stability (as opposed to fins) is needed. This report will deal with the last problem area of improving aerodynamics of configurations that use a flare for stability. Figure 1 illustrates the typical geometrical parameters associated with a flare. The two most important parameters are the flare length and angle, which can also be expressed in terms of the flare base to forward or reference diameter.

The problem of inaccurate aerodynamic predictions for flared configurations from the APC first came to the author's attention a couple of years ago in the form of the pitch damping moment coefficient predictions for a flared projectile concept at a AIAA meeting. The increased interest in the use of flares for stability in recent years, particularly for higher Mach numbers (see



A. Cone-Cylinder-Flare Configuration



B. Expanded View of Flare

FIGURE 1. TYPICAL FLARE CONFIGURATION WITH THE SIGNIFICANT GEOMETRICAL PARAMETERS

References 6-8 for example), has also led the author to feel that improvements in the aerodynamic predictions of flared projectiles were needed.

As a result of the increased interest in flared projectiles for higher Mach number applications, the author decided to take a relook at the APC to determine its weak areas with respect to flared shaped projectiles. Several problem areas were identified. First of all, for the static aerodynamics, no particular attention was given for flared projectiles for $M_\infty < 1.2$. For $M_\infty \geq 1.2$, low AOA aerodynamics are computed by theoretical methods such as Second-Order-Van-Dyke (SOVD) or Second-Order-Shock-Expansion-Theory (SOSET) and reasonable estimates of static aerodynamics (C_A , C_N , x_{CP}) can be obtained from the APC. For $M_\infty < 1.2$, the capability to compute static aerodynamics needs to be incorporated into the code.

The second problem uncovered in the APC prediction of aerodynamics was for the dynamic derivative, $C_{M_q} + C_{M_{\dot{\alpha}}}$, or pitch damping moment coefficient. No capability exists at any Mach number in the APC for pitch damping moment of flared projectile shapes. In fact,

based on recent computational fluid dynamic (CFD) calculations of projectiles without a flare,^{9,10} it was found that the pitch damping moment of configurations without flares needed improvement as well. Table 1 summarizes the problems in predicting aerodynamics of flared projectile shapes.

TABLE 1. AP98 WEAK AREAS IN PREDICTING AERODYNAMICS OF FLARED CONFIGURATIONS

a) C_A , C_N , x_{CP} not available for $M_\infty < 1.2$ for flare
b) Body alone $C_{M_q} + C_{M_{\dot{\alpha}}}$ needs improvement for $M_\infty \geq 1.2$ (no flare)
c) No pitch damping contribution for flare in AP98 at any M_∞

2.0 ANALYSIS

Each of the three weak areas mentioned in the Introduction and listed in Table 1 will be discussed individually in this section of the report. The discussion will be in terms of modifications that will be made to the AP98 to allow more accurate computations of aerodynamics of flared projectiles. These modifications will then be a part of the next release of the APC which will be the AP02 in 2002.

2.1 STATIC AERODYNAMICS OF FLARED PROJECTILES

The wave component of axial force for configurations with small flare angles ($\theta_f < 15$ deg) can be calculated approximately with the perturbation theory of Wu and Aoyama¹¹ that was designed for boattails, except the angle is reversed in sign. There was a sign error in the AP98, but when this error was corrected, approximate estimates of wave drag for $M_\infty < 1.2$ could be computed from the Reference 11 method. For $M_\infty < 0.9$, the wave drag component is assumed to be zero. Base drag and skin-friction drag were already being computed within the accuracy desired using the AP98 so no changes in the methodology for these aerodynamic terms were made.

The normal force and pitching moment coefficients and center of pressure for the flares are not predicted at all for $M_\infty < 1.2$. Furthermore, numerical methods do not exist in the AP98 to allow calculations of C_N , C_M and x_{CP} for $M_\infty < 1.2$. Also, as will be discussed later in the pitch damping computations for flares, C_N , C_M and x_{CP} for a flare will be needed at all Mach numbers.

To compute $(C_{N_\alpha})_f$ and $(x_{CP})_f$, one of several options are available. The first is to utilize the available values in the APC. Unfortunately, these values are only available for $M_\infty \geq 1.2$ where pressures are computed and integrated over the body surface. Also, the logic of the APC is such that this would require considerable changes to allow these calculations to be performed

and brought forward into another subroutine. The second option would be to exercise the APC twice, once with a flare and once without and subtract the C_{N_α} 's and C_{M_α} 's to obtain the flare normal force coefficient derivative and its center of pressure. Again, this is not a very desirable alternative since the APC must be exercised twice to get a single number. A third option, which appears more attractive, is to exercise the APC code offline, compute values of $(C_{N_\alpha})_f$ and $(x_{CP})_f$ for $M_\infty \geq 1.2$ and store these in a table lookup as a function of geometric and freestream parameters. For $M_\infty < 1.2$, slender body theory (SBT) can be used to approximate values of $(C_{N_\alpha})_f$ and $(x_{CP})_f$. The fourth and most attractive option is to use available cone tables¹² or approximate conical formulas to compute $(C_{N_\alpha})_f$, use SBT to approximate the center of pressure of the flare and $(C_{N_\alpha})_f$ for $M_\infty < 1.2$, and to include these parameters in a table lookup as a function of geometry and Mach number. This last option can be used since we are assuming the flare is a conical frustrum or can be approximated by a conical frustrum. The last option is the one that will be used in this analysis as it has the advantage of being at least as accurate as current computations in the APC due to use of an exact cone solution from Reference 12. Also, this approach offers the opportunity to obtain results in a straightforward and direct way from the APC as opposed to more costly approaches of logic change in the APC or cycling through the APC twice to obtain results for the flare alone.

The C_{N_α} results for the total cone of Reference 11 must be corrected to include only the frustrum portion of the cone and also put in the appropriate reference area format. Referring to Figure 1, the percent of conical shape that is a flare is:

$$\frac{A_f}{A_c} = \frac{\pi [r_B^2 - r_r^2]}{\pi r_B^2} = 1 - \left(\frac{r_r}{r_B} \right)^2 \quad (1)$$

Now the value of C_{N_α} obtained from Reference 12 is based on the cone base area. Hence, Equation (1) must be multiplied by A_B/A_r to place it in the same reference area as other C_{N_α} components for the total configuration of Figure 1. Thus, to relate the value of the C_{N_α} from Reference 12 for a cone of given angle at a given Mach number to that of a flare we have

$$(C_{N_\alpha})_f = (C_{N_\alpha})_c \left[1 - \left(\frac{r_r}{r_B} \right)^2 \right] \left(\frac{r_B}{r_r} \right)^2$$

or

$$(C_{N_\alpha})_f = (C_{N_\alpha})_c \left[\left(\frac{r_B}{r_r} \right)^2 - 1 \right] \quad (2)$$

Equation (2) is valid at all Mach numbers and for all geometries. However, $(C_{N_\alpha})_C$ is available from Reference 12 for conditions where the flow is supersonic and the shock wave is attached to the conical tip. For conditions where these two assumptions are not met, SBT will be assumed in conjunction with interpolation. SBT gives

$$(C_{N_\alpha})_C = 2.0 \tag{3}$$

This value of $(C_{N_\alpha})_C$ will be assumed for $M_\infty \leq 0.8$. The value of $(C_{N_\alpha})_C$ from Reference 12 can be used for low AOA calculations of most reasonable flares down to M_∞ of about 1.2. Linear interpolation between SBT and Reference 12 will be used for $0.8 < M_\infty < 1.2$. Figure 2 gives results of Equations (2) and (3) as a function of Mach number and the parameter d_B/d_r . Again, $(C_{N_\alpha})_C$ of Equation (2) and Figure 2 is based on Reference 12 supersonically, Equation (3) subsonically, and linear interpolation of these two methods transonically.

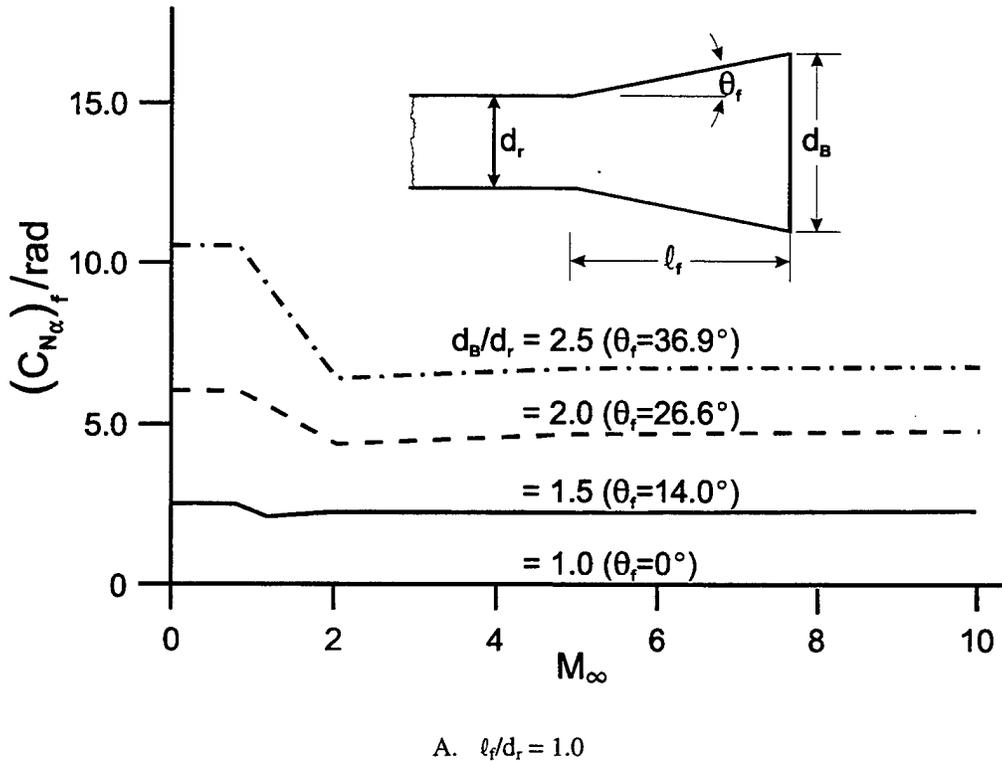
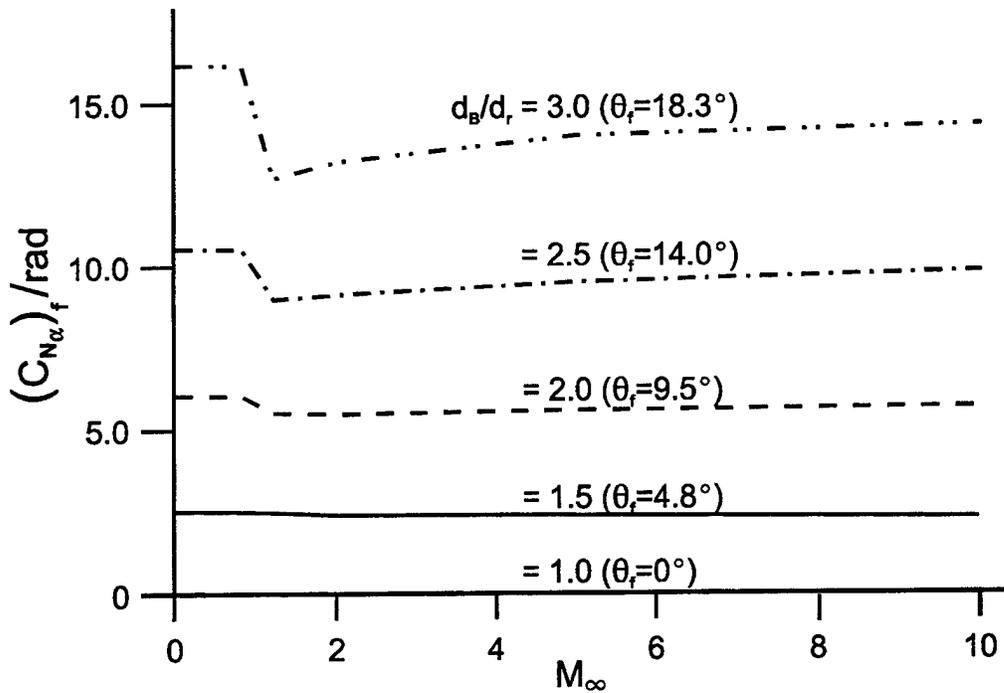
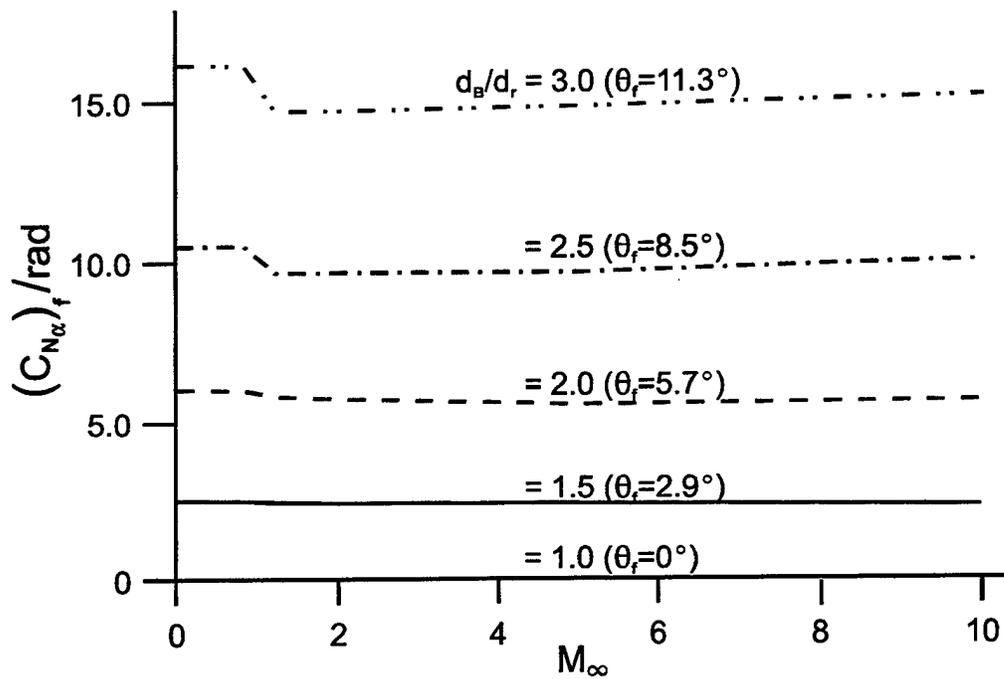


FIGURE 2. NORMAL FORCE COEFFICIENT DERIVATIVE OF FLARES BASED ON SBT AND NASA TR 1135¹²



B. $l_f/d_f = 3.0$



C. $l_f/d_f = 5.0$

FIGURE 2. NORMAL FORCE COEFFICIENT DERIVATIVE OF FLARES
 BASED ON SBT AND NASA TR 1135¹² (CONT.)

In examining Figure 2, it is seen that the $C_{N\alpha}$ for a flare can get quite large if the flare is long or if the flare is short but has a large flare angle. This is why use of a flare is quite popular at higher Mach numbers, where the $C_{N\alpha}$ for a fin decreases substantially with Mach number increase.

The SBT center of pressure for a cone is the same as that from exact theory. The center of pressure is at $2/3$ of the cone length. However, for a conical frustrum, the center of pressure in general will vary between $0.5 \ell_f$ and $2/3 \ell_f$, depending on the flare angle. For flare angles approaching 0, the value of $(x_{CP})_f$ approaches $0.5 \ell_f$ whereas for large flare angles, $(x_{CP})_f$ approaches $2/3 \ell_f$. Referring to Figure 1, the center of pressure of the flare can be calculated from

$$\bar{x}_{CP} = \frac{x_{CP}}{\ell_1 + \ell_f} = \frac{\int_{\ell_1/(\ell_1 + \ell_f)}^1 \bar{x} A'(\bar{x}) d\bar{x}}{\int_{\ell_1/(\ell_1 + \ell_f)}^1 A'(x) dx} \quad (4)$$

where $A(x) = \pi \bar{r}^2(\bar{x})$; $\bar{r} = r/(\ell_1 + \ell_f)$

Also,

$$A'(x) = 2\pi \bar{r} \bar{r}' = 2\pi \bar{x} \tan^2 \theta_f \quad (5)$$

Substituting Equation (5) into Equation (4), integrating and carrying out the algebra, one obtains:

$$\bar{x}_{CP} = \frac{2}{3} \left[\frac{1 - (\ell_1/(\ell_1 + \ell_f))^3}{1 - (\ell_1/(\ell_1 + \ell_f))^2} \right] \quad (6)$$

but since $\frac{\ell_1}{\ell_1 + \ell_f} = \frac{r_r}{r_B}$,

Equation (6) can be written in a more convenient form as

$$\bar{x}_{CP} = \frac{2}{3} \left[\frac{1 - (r_r/r_B)^3}{1 - (r_r/r_B)^2} \right] \quad (7)$$

Equation (7) can also be written in a more useful form in terms of x_{CP}/ℓ_f versus $x_{CP}/(\ell_1 + \ell_f)$ which is Equation (7). In terms of x_{CP}/ℓ_f , one can write

$$\frac{x_{CP}}{\ell_f} = \frac{2}{3} \left(\frac{1}{1-r_r/r_B} \right) \left[\frac{1-(r_r/r_B)^3}{1-(r_r/r_B)^2} \right] \quad (8)$$

One can also shift the point where x_{CP} is measured from the cone tip to the point where the flare begins by a simple translation where

$$(\bar{x}_{CP})_f = \frac{(x_{CP})_f}{\ell_f} = \frac{x_{CP} - \ell_1}{\ell_f}$$

or

$$(\bar{x}_{CP})_f = \frac{2}{3} \left(\frac{1}{1-r_r/r_B} \right) \left[\frac{1-(r_r/r_B)^3}{1-(r_r/r_B)^2} \right] - \frac{r_r/r_B}{1-r_r/r_B} \quad (9)$$

Results of Equation (9) are computed and plotted in Figure 3 as a function solely of the parameter r_r/r_B . As seen in the figure, when the body consists of a cone ($r_r = 0$), then the center of pressure is at $2/3$ of the cone or flare length (which are one and the same). On the other hand, when the flare angle goes to zero so that $r_r/r_B = 1.0$, the center of pressure goes to $x_{CP}/\ell_f = 0.5$. For most typical flare lengths and angles, x_{CP}/ℓ_f will vary from about 0.54 to 0.60.

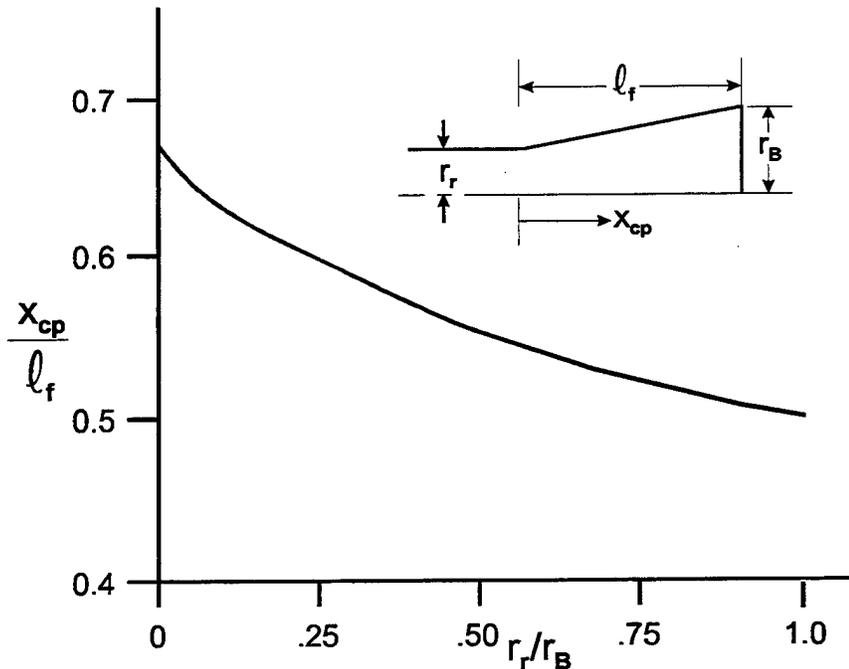


FIGURE 3. SLENDER BODY THEORY CENTER OF PRESSURE OF FLARE

Equation (9) results can be changed to body diameters by multiplying Equation (9) by ℓ_f/d to obtain:

$$\left(\frac{x_{CP}}{\ell_f}\right)\left(\frac{\ell_f}{d}\right) = \frac{(x_{CP})_f}{d} \quad (10)$$

The combination of Figures 2 and 3 give the C_{N_α} and x_{CP} for flares at all Mach numbers. C_N is simply

$$C_{N_f} = (C_{N_\alpha})_f \alpha \quad (11)$$

for small angles of attack. Since most flare configurations are designed to fly at small angles of attack, Figures 2 and 3 and Equations (10) and (11) determine two of the desired static aerodynamic terms for a flare. The pitching moment coefficient of the flare about some reference location is then

$$C_M = -\left(\frac{x_{CP} - x_{CG}}{d}\right) C_{N_f} \quad (12)$$

2.2 BODY ALONE PITCH DAMPING MOMENT

The body alone dynamic derivatives are all computed based on an empirical model developed by Whyte,¹³ called "Spinner." The version that is incorporated into the AP98 is basically the same version as initially included in the APC series in 1977. The technology of Reference 13 was based on curve fits of data using standard spin stabilized rounds. The curve fits have key parameters of length, boattail length, and Mach number for the dynamic derivative predictions. Magnus force and moments are also estimated at both 1 and 5 deg angles of attack to incorporate some nonlinearity due to AOA in the Magnus moment. The data bases upon which the empirical curve fits were based were primarily limited to about 5.5 calibers and Mach numbers less than 5.0 (newer versions of Spinner may now be available which remove these limits). However, length was considered in a linear sense for roll damping moment and one of the data bases had length as a parameter for pitch damping moments as well.

Since the late 1960's and early 1970's, the Army Research Laboratory (ARL) at Aberdeen, Maryland has developed a very good CFD capability to compute both static and dynamic derivatives of projectiles, with and without flares. References 6, 7, 9, and 10 are some of the reports generated by ARL using CFD. As a result of these many CFD computations, and comparison to data, one can now fine tune the older "Spinner" Model¹³ to be more representative of a broader class of configurations.

In comparing the AP98 (in essence the "Spinner" model) predictions of pitch damping moment to ballistic range data and CFD predictions of References 6, 7, 9, and 10, a problem existed. The Spinner results appeared to be reasonable for $M_\infty \leq 1.2$ but overpredicted

$C_{M_q} + C_{M_{\dot{\alpha}}}$ as Mach number increased. The higher the Mach number, the worse the predictions became. On the other hand, the errors followed a fairly smooth pattern, allowing a correction to be derived based on CFD results from References 6, 7, 9, and 10.

The modified pitch damping moment coefficient for bodies without a flare present is therefore

$$C_{M_q} + C_{M_{\dot{\alpha}}} = (C_{M_q} + C_{M_{\dot{\alpha}}})_S F_1 \quad (13)$$

where $(C_{M_q} + C_{M_{\dot{\alpha}}})_S$ is the value obtained from the AP98¹ which basically uses Reference 13. F_1 is an empirical decay factor for Mach number derived using the AP98 and References 6, 9, and 10. Here, F_1 is a function of Mach number and total length of the projectile and is defined by the following model.

$$\begin{aligned} \text{a) } \ell/d \leq 5.0 \\ F_1 = 1.0 & \quad ; M_\infty \leq 1.2 \\ F_1 = 0.0043 M_\infty^2 - 0.151 M_\infty + 1.175 & \quad ; 1.2 < M_\infty \leq 5.0 \\ F_1 = 0.53 & \quad ; M_\infty > 5.0 \end{aligned} \quad (14)$$

$$\begin{aligned} \text{b) } \ell/d = 8 \\ F_1 = 1.0 & \quad ; M_\infty \leq 2.0 \\ F_1 = 0.0031 M_\infty^2 - 0.0884 M_\infty + 1.164 & \quad ; 2.0 < M_\infty \leq 5.0 \\ F_1 = 0.8 & \quad ; M_\infty > 5.0 \end{aligned} \quad (15)$$

$$\begin{aligned} \text{c) } 5 < \ell/d < 8 \\ F_1 = F_1(\ell/d=5) - \left(\frac{\ell/d-5}{3} \right) [F_1(\ell/d=5) - F_1(\ell/d=8)] \end{aligned} \quad (16)$$

$$\begin{aligned} \text{d) } \ell/d \geq 12 \\ F_1 = 1.0 & \quad ; M_\infty \leq 2.0 \\ F_1 = 0.0011 M_\infty^2 - 0.111 M_\infty + 1.178 & \quad ; 2 < M_\infty \leq 5.0 \\ F_1 = 0.9 & \quad ; M_\infty > 5.0 \end{aligned} \quad (17)$$

$$\begin{aligned} \text{e) } 8 < \ell/d < 12 \\ F_1 = F_1(\ell/d=8) - \left(\frac{\ell/d-8}{4} \right) [F_1(\ell/d=8) - F_1(\ell/d=12)] \end{aligned} \quad (18)$$

2.3 PITCH DAMPING MOMENT OF BODIES WITH FLARES

A typical body configuration with a flare present is shown in Figure 1. As already mentioned, the AP98 code does not calculate a value of additional pitch damping due to the presence of a flare. The approximate method used here to represent the flare is basically to use the Reference 14 approach where

$$\left(C_{M_q} + C_{M_{\dot{\alpha}}}\right)_f = -2 \left(C_{N_{\alpha}}\right)_f \left(\frac{x_{CP} - x_{CG}}{d}\right)_f^2 \quad (19)$$

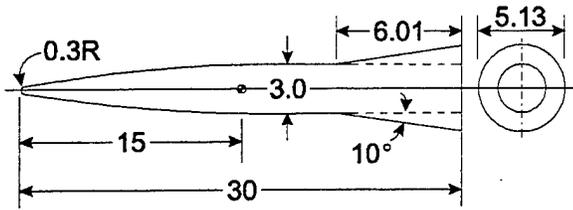
Equation (19) was used in Reference 14 to approximate the pitch damping moment coefficient of a wing, but here the flare replaces the wing planform area. $\left(C_{N_{\alpha}}\right)_f$ of Equation (19) is defined by Equations (2) and (3) and Figure 2. $\left(x_{CP}\right)_f / d$ of Equation (19) is defined by Equation (10) and Figure 3. Finally, since Figure 2 already includes the approximate reference areas, Equation (19) is appropriate as it stands. Equation (19) only includes that portion of the flare area external to the cylindrical part of the body (see Equation (1)). This is because the body alone pitch damping moment discussed in Section 2.2 already includes the cylindrical part of the afterbody.

3.0 RESULTS AND DISCUSSION

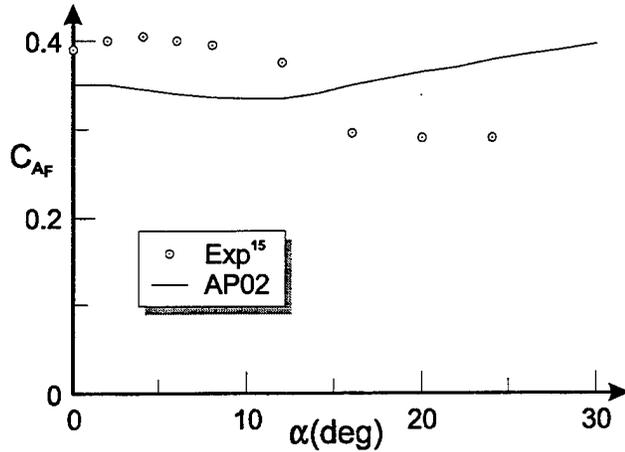
3.1 STATIC AERODYNAMICS OF FLARED CONFIGURATION

In this section of the report, we will show the comparison of the approximate methods to predict aerodynamics of flared configurations to both CFD and experimental results. Static aerodynamic predictions of flared configurations will be considered first. Unfortunately, the author was only able to find data in the literature for Mach numbers of 2.0 and greater. Hence, the new inclusion into the APC of flare static aerodynamics for $M_{\infty} < 1.2$ cannot be validated at present. However, existing static aerodynamic predictions for low supersonic to hypersonic Mach numbers can be assessed. It is suspected that the reason for the lack of static aerodynamic data at low Mach numbers for flare stabilized configurations is that the practical application of flare configurations is at high Mach number. This is because fins lose their effectiveness as stabilizing devices as Mach number increases, along with posing problems for leading edge heating and ablation. On the other hand, flares are just as effective at high Mach number as at low Mach number in providing stability, although they give high drag compared to fins, particularly at low Mach number.

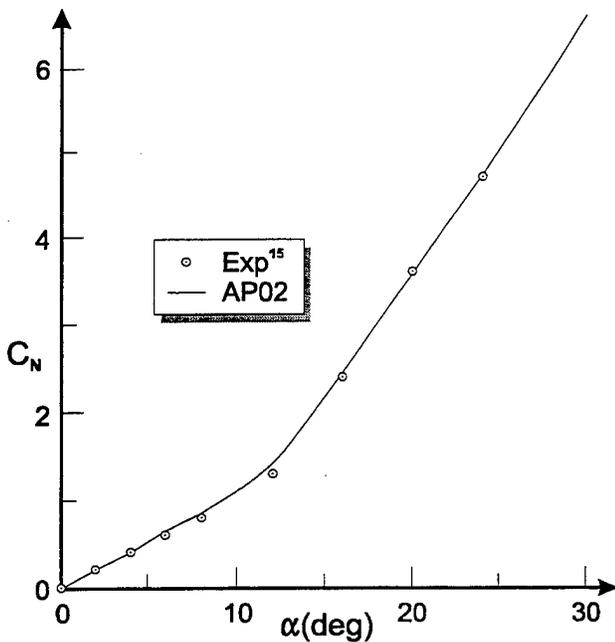
The first case considered for static aerodynamics validation is shown in Figure 4 and is taken from Reference 15. This configuration is a blunted Von Karman ogive-cylinder-flare case with a 10 deg, 2 caliber flare. Wind tunnel data was taken at $M_{\infty} = 2.0$ and R_N/ft of 2×10^6 without a boundary layer trip present. Comparison of the theory (here shown as AP02) to experiment for the forebody axial force, normal force, and pitching moment coefficients is given



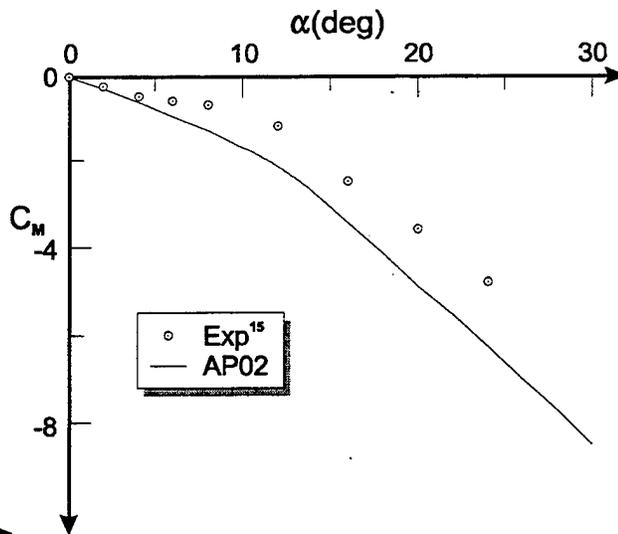
A. Body with 10° Flare¹⁵
(all dimensions in inches)



B. Forebody Axial Force Coefficient



C. Normal Force Coefficient



D. Pitching Moment Coefficient

FIGURE 4. COMPARISON OF THEORY AND EXPERIMENT FOR STATIC AERODYNAMICS
OF A BODY-FLARE CONFIGURATION ($M_\infty = 2.01$, $R_N/ft = 2 \times 10^6$)

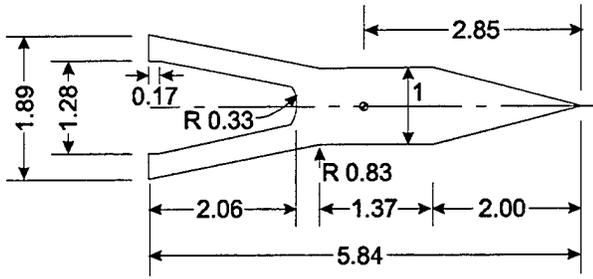
in the figure. The axial force is not as accurate as desired. However, this could be due to the fact that the base pressure term was subtracted from the total axial force. This term was larger than the friction and wave drag terms combined. Hence, a small error in measuring the base pressure of 5 to 10 percent could account for most or all of the discrepancy between theory and

experiment for the axial force coefficient of Figure 4B. Normal force predictions are excellent and pitching moments are quite acceptable. The average center of pressure error is less than 4 percent of the body length, which means the predictions are within the ± 4 percent of body length error bound accuracy goal stated for the AP02. The average normal force error is under 2 percent. Since no total axial force measurements were given, an accuracy assessment on the axial force cannot be given.

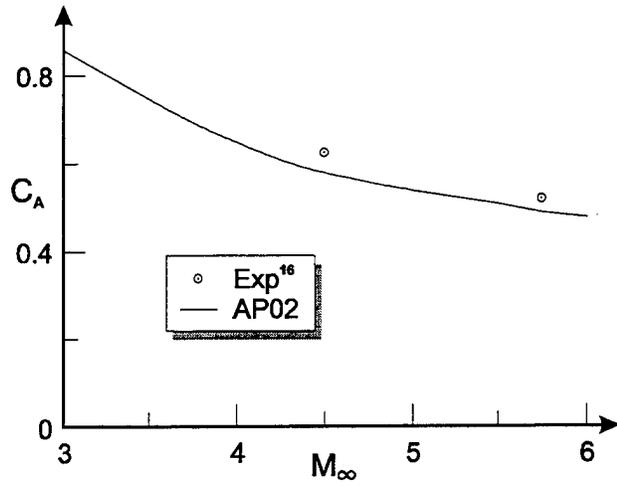
The second case considered is a fairly short (5.84 calibers), cone-cylinder-flare configuration called the CAN4 projectile.¹⁶ A schematic of the configuration is shown at the top of Figure 5. Figure 5 also gives the axial force coefficient along with the normal force and pitching moment coefficient slopes near $\alpha = 0$ deg. Ballistic range data consists of several tests around $M_\infty = 4.5$ and 5.75. These data points were fairly closely scattered together and fairly close in value so an approximate average is shown on Figure 5 at the Mach numbers of 4.5 and 5.75. As seen in the figure, the AP02 calculations are about 6 to 8 percent lower than the ballistic range for axial force, within 1 percent of ballistic range data for C_{N_α} and predicts C_{M_α} as being too stable. In terms of center of pressure, the error in C_{M_α} will give the center of pressure error as less than 2 percent of the body length, or about 0.1 caliber. All these errors are well within the stated accuracy goals on static aerodynamics of ± 10 percent on axial and normal force coefficient and ± 4 percent of the body length for center of pressure.

The third case considered for static aerodynamics of flared projectiles is shown in Figure 6 and is called CAN1A projectile.¹⁷ It is also a very short configuration (6.06 calibers) with a very large flare angle (27.6 deg). It was tested in the wind tunnel at $M_\infty = 8.2$ from α of -10 deg to $+10$ deg. The experimental data of Reference 17, along with the AP02 computations and Missile Datcom Computations (also obtained from Reference 17) are given in Figure 6. Coefficients given in Figure 6 include lift, drag, and pitching moment. Both the approximate codes gives reasonable predictions for all the aerodynamics with the AP02 and Missile Datcom giving about equal predictions for pitching moment. However, the AP02 is slightly more accurate than the Missile Datcom for both axial force and lift force coefficient predictions. Neither of the approximate codes predicts the nonlinearity in aerodynamics that occurs due to the flow separation behind the shoulder of the cone and ahead of the flare. This nonlinearity is primarily evident between ± 8 deg AOA.

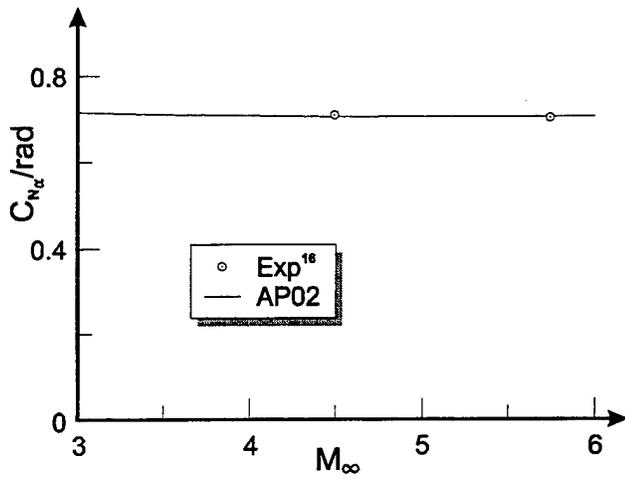
The last flared configuration where static aerodynamics were found in the literature is shown in Figure 7. It is a very long (23.14 calibers) configuration with a flare that is 4.24 calibers in length and flare angle that varies from 0 to 20 deg. Data were given in Reference 18 at $M_\infty = 4.4$, 5.9, and 8.8. All three cases showed similar trends and the AP02 predictions were similar, so only the $M_\infty = 5.9$ case is shown in Figure 7. Aerodynamics shown include the forebody axial force coefficient and the normal force and pitching moment slopes near $\alpha = 0$ deg. No experimental data was given in Reference 18, only Parabolized Navier-Stokes (PNS) calculations at sea level conditions where fully turbulent flow was assumed. The AP02 predictions agree quite well with the PNS calculations for all the aerodynamic coefficients at all flare angles.



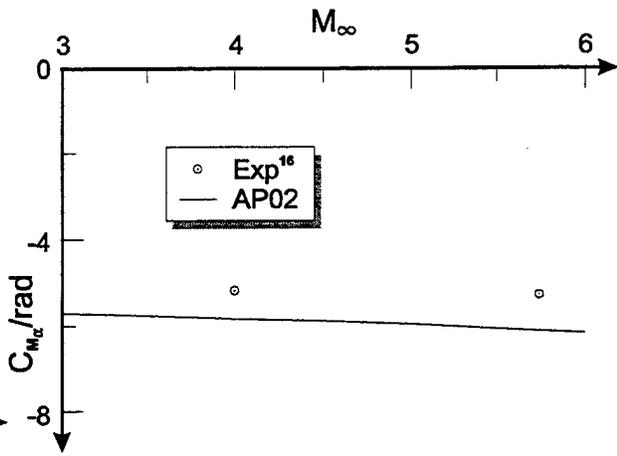
A. Schematic of CAN4¹⁶ projectile
(all dimensions in calibers)



B. Axial Force Coefficient

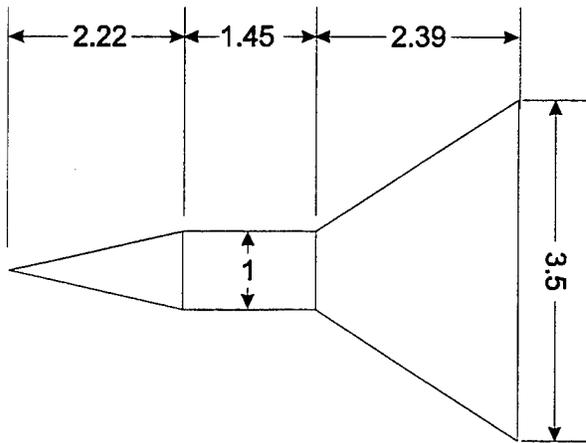


C. Normal Force Coefficient Slope

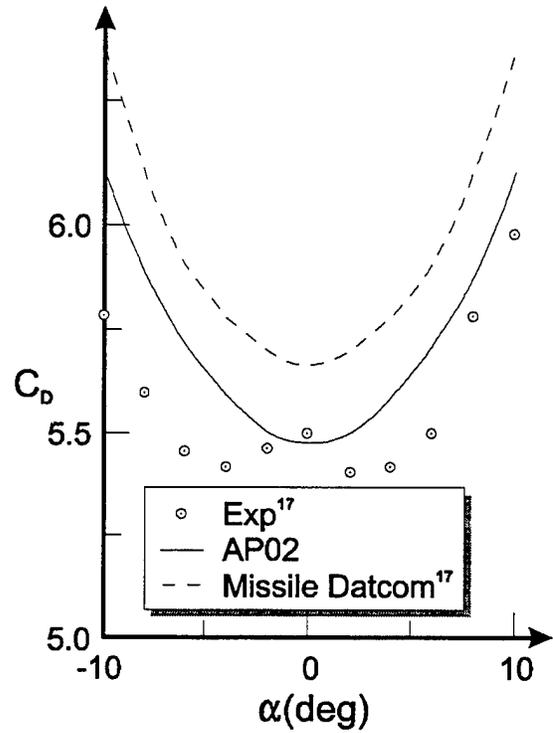


D. Pitching Moment Coefficient Slope

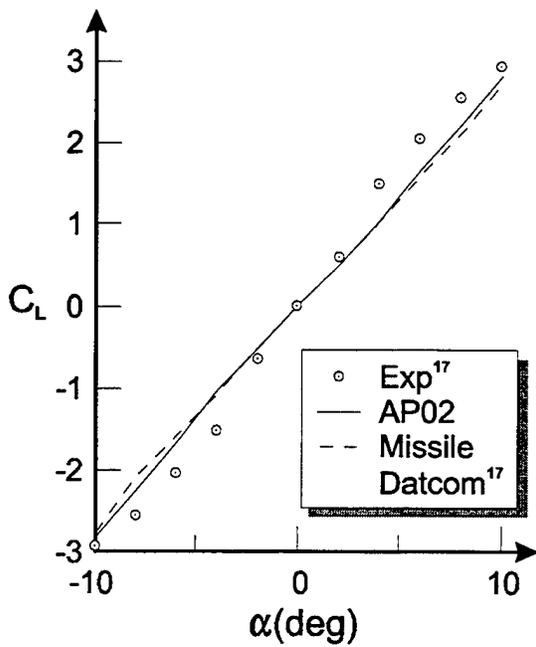
FIGURE 5. STATIC AERODYNAMICS OF THE CAN4 PROJECTILE AT HIGH MACH NUMBER



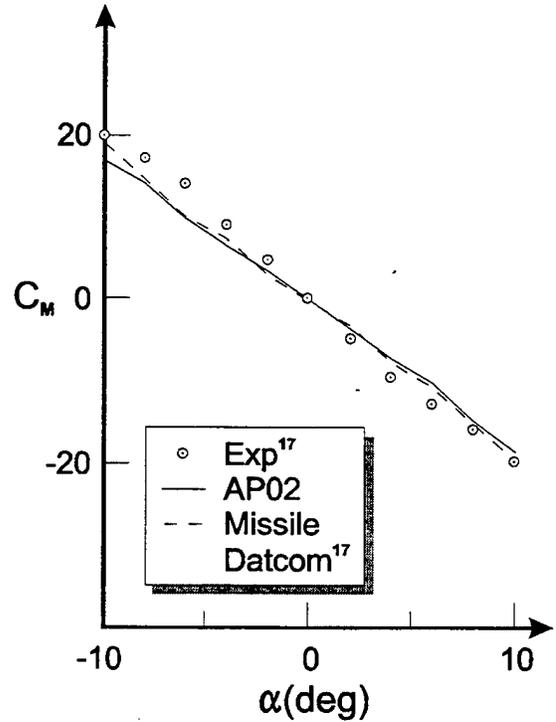
A. Schematic of CAN1A Projectile¹⁷
(all dimensions in calibers)



B. Drag Coefficient

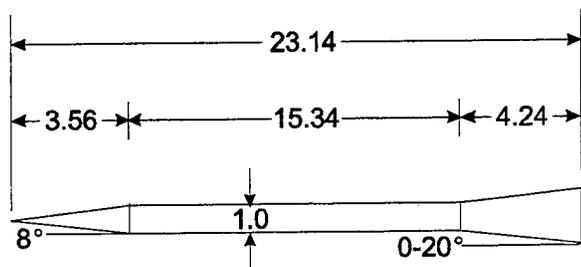


C. Lift Coefficient

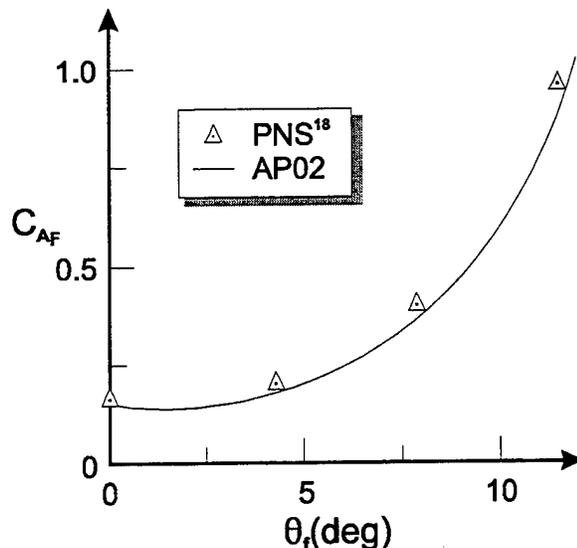


D. Pitching Moment Coefficient

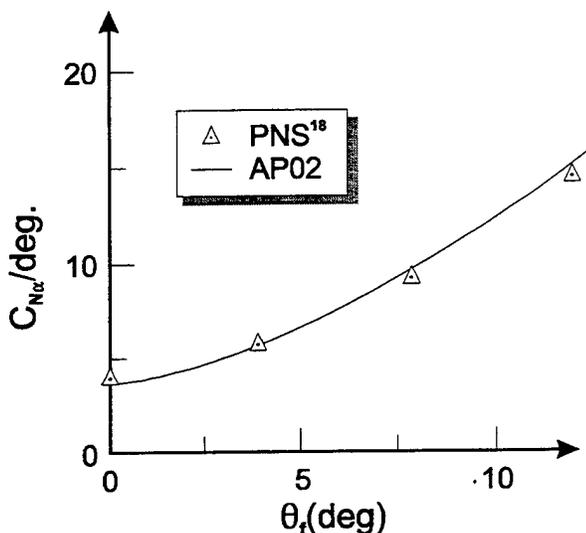
FIGURE 6. STATIC AERODYNAMICS OF THE CAN1A PROJECTILE AT $M_\infty = 8.2$



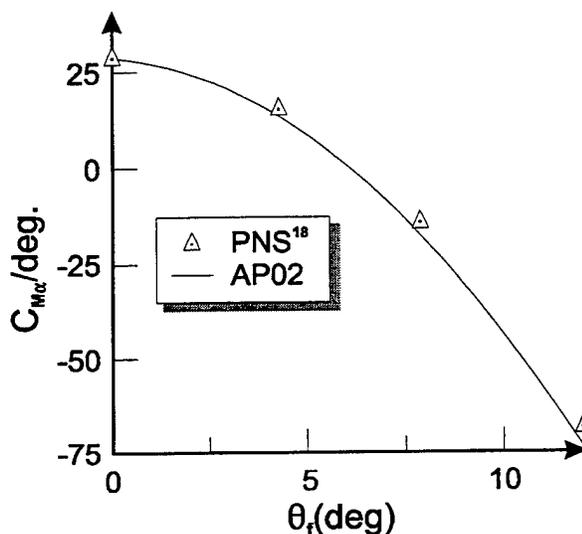
A. Schematic of F829 Cone-Cylinder-Flare Configuration¹⁸ (all dimensions in calibers) (one caliber=27.05 mm)



B. Forebody Axial Force Coefficient



C. Normal Force Coefficient Slope



D. Pitching Moment Coefficient Slope

FIGURE 7. STATIC AERODYNAMICS OF F829 CONFIGURATION ($M_{\infty} = 5.9$, $\alpha \approx 0$ deg)

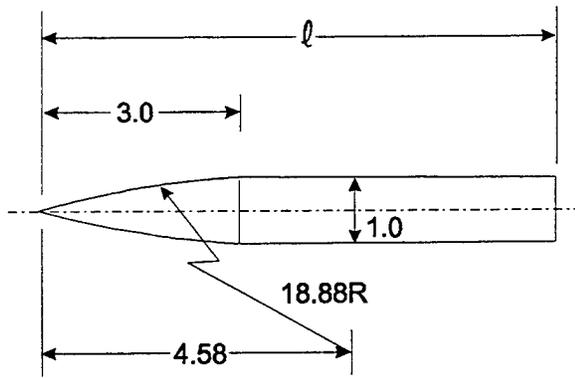
3.2 PITCH DAMPING MOMENT OF BODY ALONE CONFIGURATIONS

The next aerodynamic term to be considered in the validation process is body alone pitch damping moment where no flare is present. The modifications to the AP98 predictions (which are basically taken from the old GE Spinner program¹³ were discussed in Section 2.2 of this report. A recent report from the Army Research Laboratory (Reference 9) showed PNS

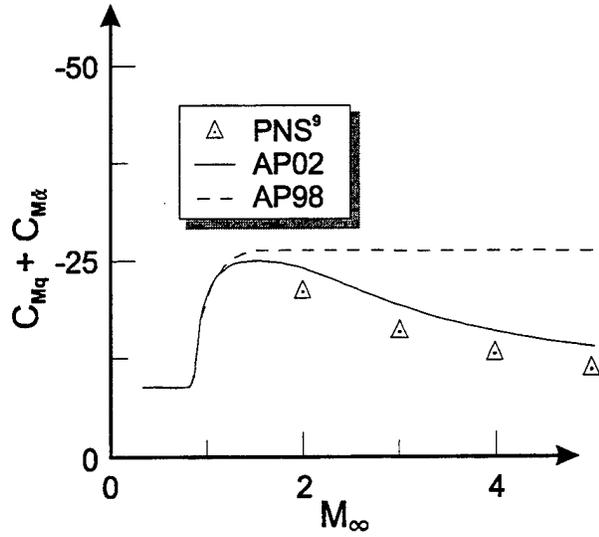
calculations of pitch damping on a 5, 6, and 7 caliber configuration with (SOCBT) and without a boattail (SOC). Computations were available from $M_\infty = 2$ to 5. These results were instrumental in the author concluding that the AP98 pitch damping computations for a body alone needed improvement for higher Mach numbers. Figure 8 shows the comparison of the Section 2.2 improvements in the AP02 compared to the AP98 predictions and PNS predictions for pitch damping moment. While the AP02 does not agree perfectly with the PNS computations, it shows drastic improvement over the AP98 for $M_\infty \geq 2.0$ at all the body lengths (5, 6, and 7 calibers) shown in Figure 8. The center of gravity was held to a constant percent of the total body length of 60 percent in these calculations. A note of caution is given here to the reader. The Reference 9 (and all Army results) use a nondimensionalization of qd/V_∞ for the pitch damping whereas the Navy uses $qd/(2V_\infty)$. Hence, all Army results had to be multiplied by 2 to compare to Navy results.

Figure 9 gives the complimentary results for the SOCBT case. Here, the AP02 predictions agree much closer to the PNS calculations than for the SOC configuration. For both the SOC and SOCBT cases, the AP02 predictions are much closer to the PNS computations than are the AP98 calculations.

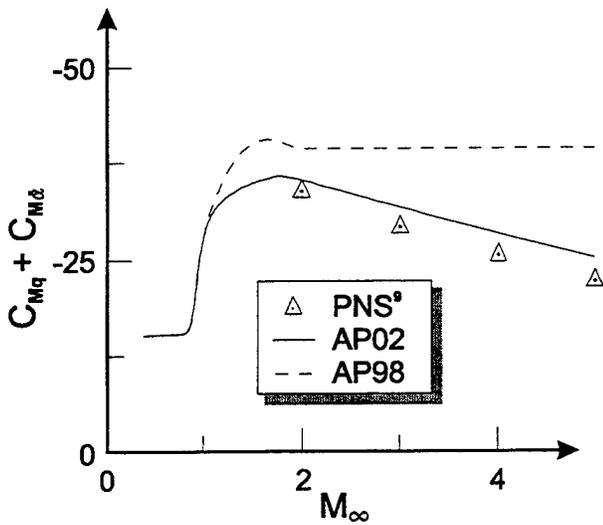
The last body alone case considered for validation of the improved pitch damping predictions is given in Figure 10. This configuration is the Army-Navy-Spinner (ANSR) case which consists of a 2.0 caliber tangent ogive nose followed by a 3, 5, and 7 caliber cylindrical afterbody. Total body lengths are therefore 5, 7, and 9 calibers. Results were given in References 9 and 10 consisting of PNS calculations and ballistic range data. Data were available for all configurations for M_∞ between 1.3 and 2.5 and for the 7 caliber case, for M_∞ between 0.8 and 2.5. Also several center of gravity locations were given in References 9 and 10, but only the case where the center of gravity was at about the 60 percent location (which is typical of most ammunition) is shown here. A couple of points are of interest. First of all, for Mach numbers below about 1.5, the old AP98 predicts pitch damping quite adequately. Also for Mach numbers as high as 2.5, predictions are not that bad for the AP98, so only minor improvements are shown using the AP02 for this configuration due to the low Mach numbers considered. This makes sense because the Reference 13 methodology was based on available data, which in the 1970's consisted mainly of shells with $0.8 \leq M_\infty \leq 2.5$ and lengths of 4 to 7 calibers. The second point to note from Figure 10 is that for the longest configuration ($l = 9$ calibers), there is a large scatter in the ballistic range data, but the predictions still appear to be reasonable, given the large scatter in data.



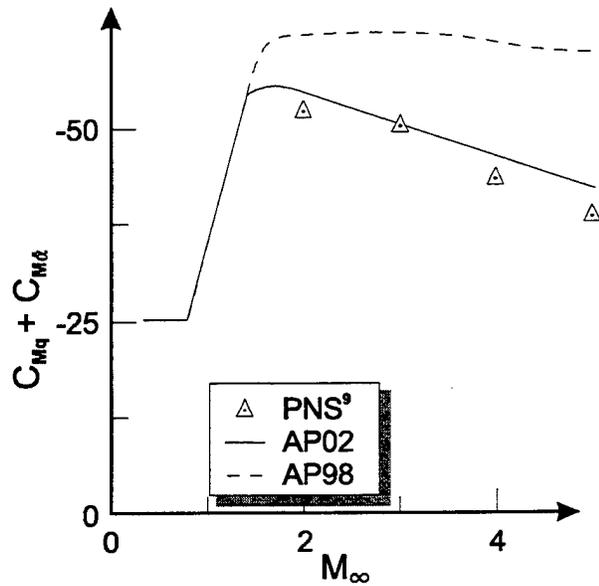
A. Schematic of the SOC Configuration⁹
 (all dimensions in calibers)
 (one caliber=57.2 mm)



B. $l = 5$, $x_{CG} = 3$

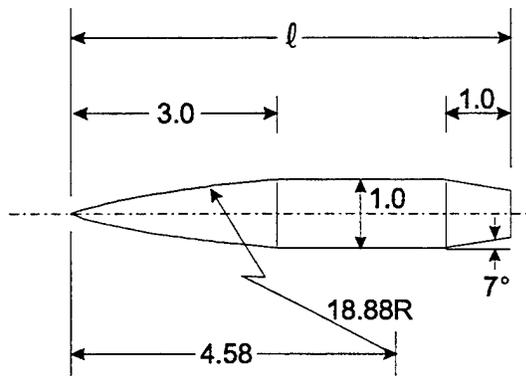


C. $l = 6$, $x_{CG} = 3.6$

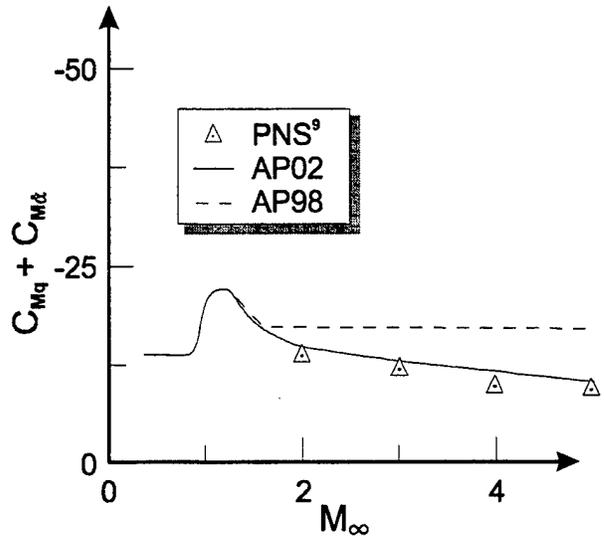


D. $l = 7$, $x_{CG} = 4.2$

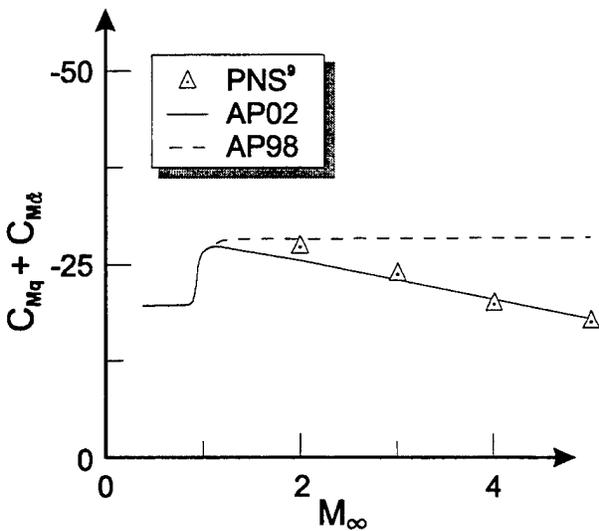
FIGURE 8. PITCH DAMPING MOMENT COEFFICIENT PREDICTIONS FOR THE SOC CONFIGURATION



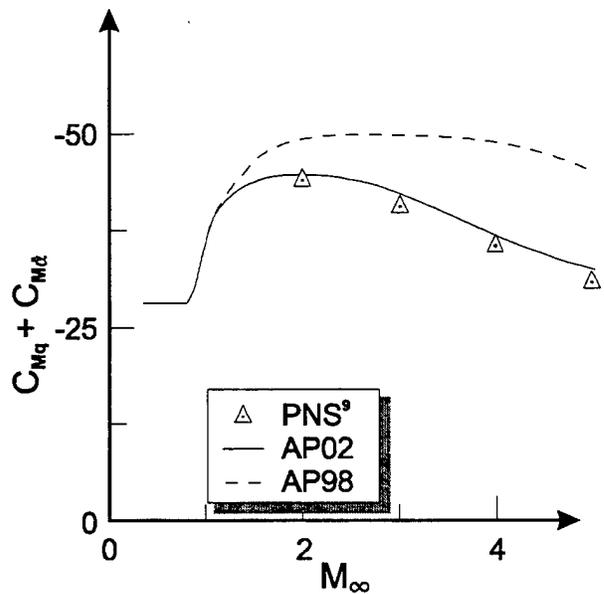
A. Schematic of the SOCBT Configuration⁹
 (all dimensions in calibers)
 (one caliber=57.2 mm)



B. $l = 5, x_{CG} = 3$

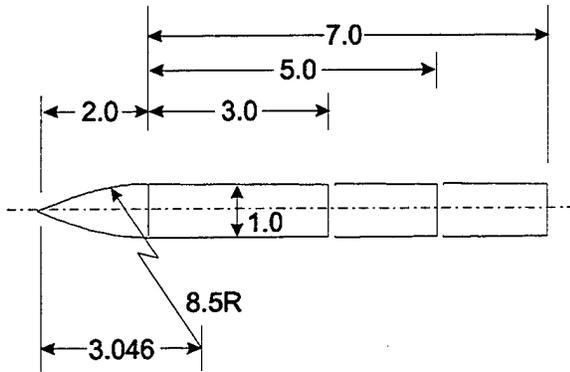


C. $l = 6, x_{CG} = 3.6$

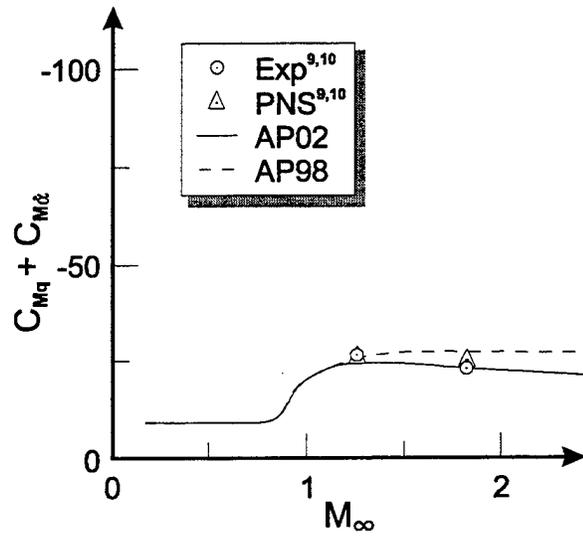


D. $l = 7, x_{CG} = 4.2$

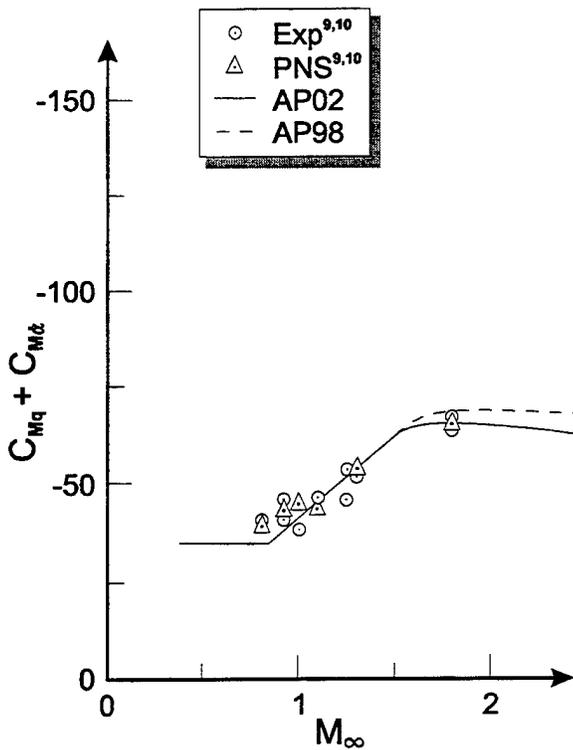
FIGURE 9. PITCH DAMPING MOMENT COEFFICIENT PREDICTIONS FOR THE SOCBT CONFIGURATION



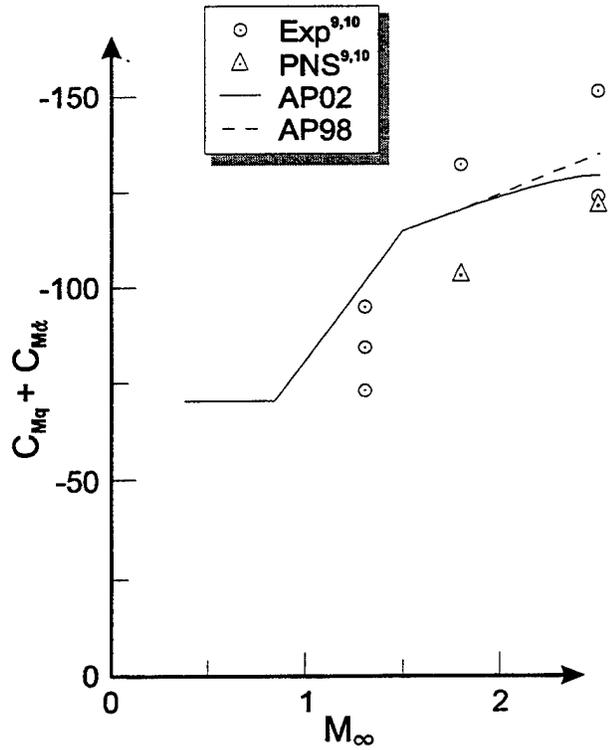
A. Schematic of the ANSR⁹
(all dimensions in calibers)
(one caliber=20 mm)



B. $l = 5, x_{CG} = 3$



C. $l = 7, x_{CG} = 4.0$



D. $l = 9, x_{CG} = 5.0$

FIGURE 10. PITCH DAMPING MOMENT COEFFICIENT PREDICTIONS COMPARED TO EXPERIMENT FOR ANSR

3.3 PITCH DAMPING OF FLARED CONFIGURATIONS

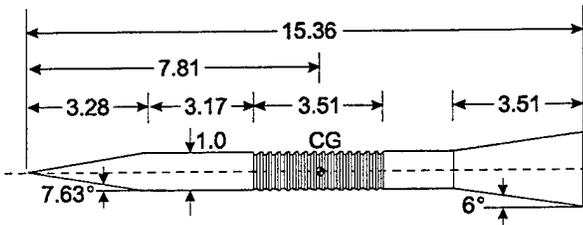
We are now ready to validate the AP02 predictions of pitch damping moment for flare configurations. Recall that this was the primary reason for this report and the improvements to the AP98, as the AP98 did not give any additional pitch damping due to the presence of a flare. Figure 11 gives the first case considered. It is termed the CS-V4-1 configuration in Reference 7. This configuration consists of a blunt cone-cylinder-flare, where the flare angle is 6 deg and the flare length is 3.51 calibers. The overall configuration length is 15.36 calibers. The configuration of Figure 11 shows rifling grooves, but a smooth body was assumed in the PNS and aeroprediction calculations. Pitch damping results are shown in Figure 11 for Mach numbers 0.4 to 5.0 from the AP02 and AP98. PNS results are shown from $M_\infty = 3$ to 4.5 and ballistic range results are shown at $M_\infty = 4.0$. Note the AP02 methodology agrees much closer to the experimental data and PNS results than does the AP98. The AP98 results are basically those of a cone-cylinder that is 15.36 calibers long.

Figure 12 shows pitch damping results for a configuration similar to that of Figure 11, except the flare is longer, 4.49 versus 3.51 calibers, and the overall Figure 12 configuration length is longer (16.34 versus 15.36 calibers) than that of Figure 11. Again, AP98 and AP02 results are shown for Mach number of 0.4 to 5 whereas PNS calculations were available for Mach number of 3 to 4.5 and ballistic range data was available for $M_\infty = 4.0$ only. The AP02 results match the PNS calculations quite nicely with the AP98, being much lower than the PNS results due to not accounting for the flare. The ballistic range data are somewhat lower than the PNS data and AP02 for this configuration, possibly due to the impact of the grooves on the pitch damping.

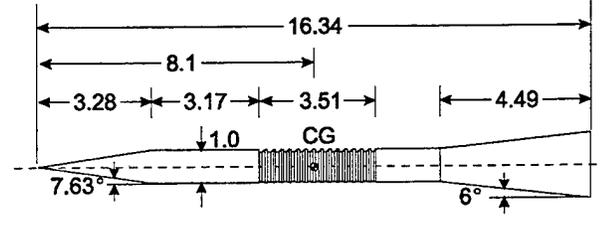
The third case considered for pitch damping is the CAN4 projectile which was previously considered for static aerodynamics in Figure 5. The pitch damping results are shown in Figure 13 in terms of AP98 and AP02 for Mach numbers 2 to 6 and CFD and ballistic range results at $M_\infty = 4.4$ and 5.72. The AP02 results agree very well with the CFD results and both are 10 to 15 percent lower than the experimental data. Errors of ± 20 percent are quite reasonable and so these results are quite acceptable for dynamic derivative predictions. However, the older AP98 gives unacceptable results.

The fourth flared configuration where experimental pitch damping data or CFD computations was found in the literature is shown in Figure 14.⁶ This configuration is also a cone-cylinder-flare of 12.28 calibers total length. It has a flare with a 15 deg flare angle that is 2.67 calibers in length. Only one CFD data point was given in Reference 6 at $M_\infty = 4.4$ in. However, AP02 and AP98 computations are shown for Mach numbers of 2 to 6.0. The AP02 results are about 12 percent lower than the data point at $M_\infty = 4.4$ ($C_{M_q} + C_{M_\alpha} = -550$ versus -625), which is considered to be acceptable prediction accuracy. However, the AP98 predictions are about 60 percent too low.

The final configuration where CFD or experimental pitch damping data was found was also taken from Reference 6 and results are given in Figure 15. It consists of a 13.16 caliber cone-cylinder-flare where the flare angle varies from 4 to 14 deg. Again, only $M_\infty = 4.4$ data was



CS-V4-1 Flare Stabilized Projectile Geometry⁷
 (all dimensions in calibers)
 (one caliber=8.28 mm)



CS-V4-2 Flare Stabilized Projectile Geometry⁷
 (all dimensions in calibers)
 (one caliber=8.28 mm)

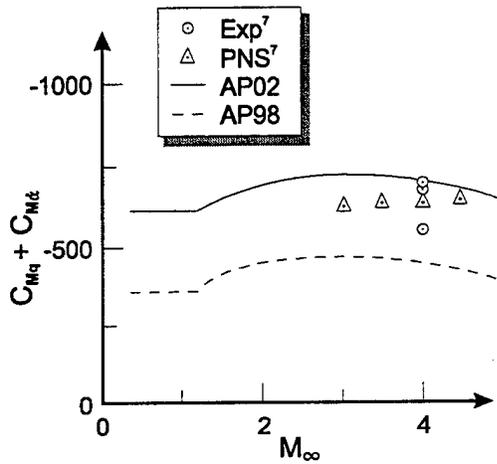


FIGURE 11. COMPARISON OF THEORY AND EXPERIMENT FOR PITCH DAMPING MOMENT COEFFICIENT OF CS-V4-1 CONFIGURATION

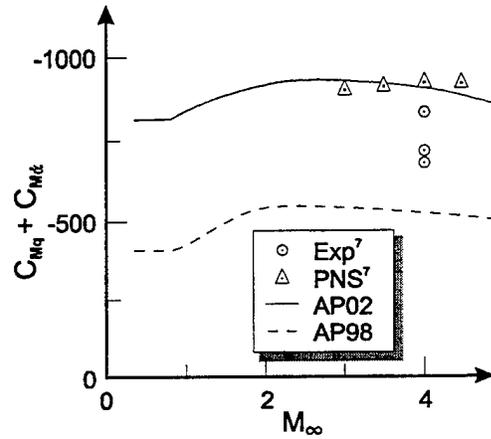
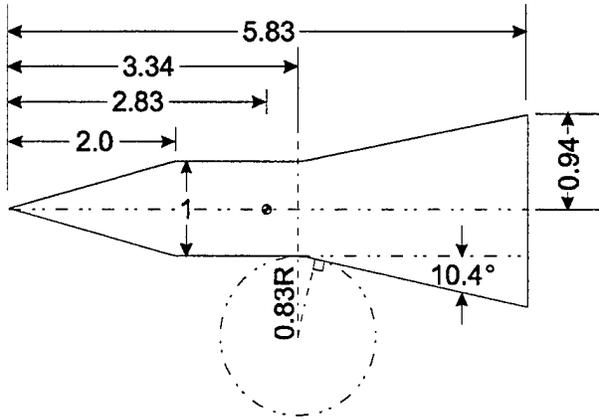
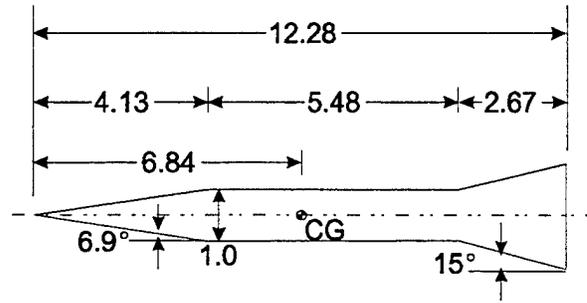


FIGURE 12. COMPARISON OF THEORY AND EXPERIMENT FOR PITCH DAMPING MOMENT COEFFICIENT OF CS-V4-2 CONFIGURATION



CAN4⁸ Projectile Schematic
(all dimensions in calibers)



Flared Projectile Configuration⁶
(all dimensions in calibers)

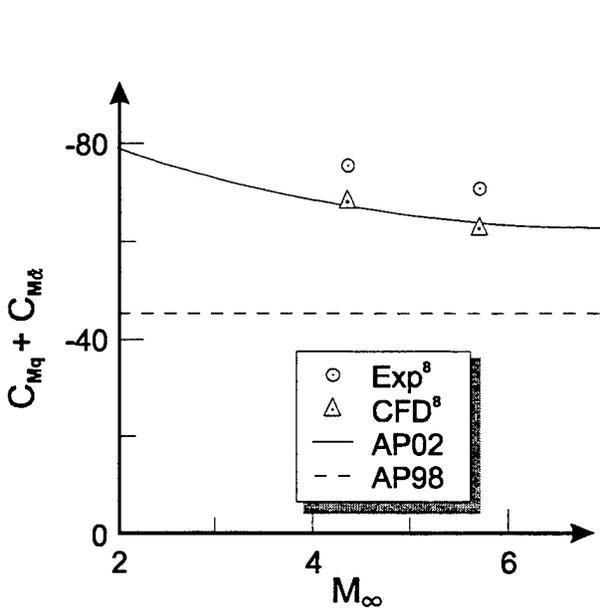


FIGURE 13. COMPARISON OF THEORY AND EXPERIMENT FOR PITCH DAMPING MOMENT COEFFICIENT OF CAN4 PROJECTILE

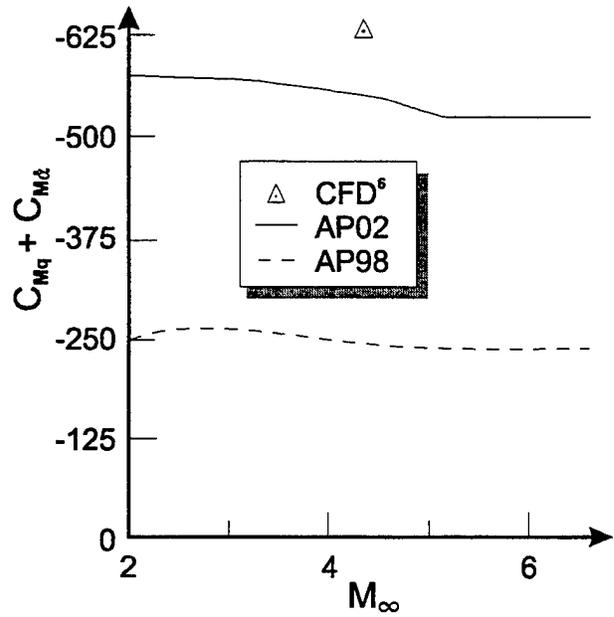
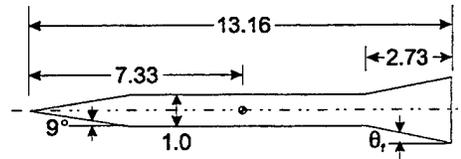


FIGURE 14. COMPARISON OF THEORY FOR PITCH DAMPING MOMENT COEFFICIENT OF FLARED PROJECTILE CONFIGURATION



Control Projectile Configuration^s
(all dimensions in calibers)

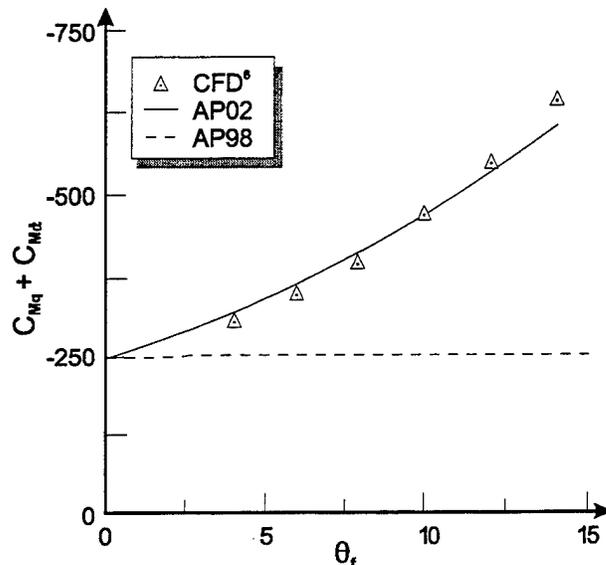


FIGURE 15. COMPARISON OF THEORETICAL PREDICTIONS OF PITCH DAMPING
MOMENT COEFFICIENT FOR VARIOUS FLARE ANGLES ($M_\infty = 4.4$)

given in Reference 6. Notice the good agreement of the AP02 to the CFD computations. Here the worst error of the AP02 compared to the CFD is under 6 percent for the $\theta_f = 14$ deg case. Again, the AP98 gives unacceptable agreement to the CFD, except for small θ_f .

4.0 SUMMARY AND CONCLUSIONS

To summarize, new capability has been added to the NSWC aeroprediction code to allow static aerodynamics to be computed for flared configurations at all Mach numbers. Improvements have been added to pitch damping predictions for high Mach numbers for body alone configurations (no flare present). Finally, new capability has been added to allow pitch damping computations to be made for flare configurations for all Mach numbers where the aeroprediction code is operational (Mach numbers 0 to 20).

In comparing the new aeroprediction code (AP02) to experimental data and both Parabolized and Full Navier-Stokes predictions, the following conclusions were drawn:

- a) Comparison of static aerodynamic predictions for configurations that have flares to experimental data and CFD computations appears to show the AP98 and AP02 give predictions within the standard accuracy goals for configurations with wings or tails. That is average accuracy of ± 10 percent for axial and normal force and ± 4 percent of the body length for center of pressure.
- b) Comparison of AP02 pitch damping predictions for bodies without flares to the AP98, experimental data and CFD computations showed the AP02 predictions to be superior to the AP98 for $M_\infty > 2$ for all cases considered. The average accuracy goal of ± 20 percent was met for the AP02 but not with the AP98.
- c) Comparison of the AP02 pitch damping predictions for bodies with flares to the AP98, experimental data and CFD computations showed the AP02 predictions to be within the desired average accuracy goal of ± 20 percent, whereas the AP98 could be off as much as 60 to 70 percent due to failure to account for the flare.
- d) No data (either static or dynamic) was found for flared configurations for Mach numbers below 2.0. Hence, the new capability for both static aerodynamics for $M_\infty < 1.2$ and pitch damping for flared configurations could not be adequately validated for low Mach numbers. While the author would like to have data for validation in this Mach number range, it is impractical from a usage standpoint. This is due to the fact that fins are better at both stability and drag for moderate supersonic Mach numbers and lower than flares.
- e) While the pitch damping methods for flared configurations have not been validated for Mach numbers below 2.0, the author believes they can still be used with confidence in preliminary design tradeoffs to compare flared configurations to those with wings. This is due to the accuracy of the methodology for Mach numbers above 2.0 and the consistency of the methodology for Mach numbers above and below 2.0.

5.0 REFERENCES

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2. Moore, F. G.; McInville, R. M.; and Robinson, D. I., *A Simplified Method for Predicting Aerodynamics of Multi-Fin Weapons*, NSWCDD/TR-99/19, Mar 1999.
3. Moore, F. G. and McInville, R. M., *Refinements in the Aeroprediction Code Based on Recent Wind Tunnel Data*, NSWCDD/TR-99/116, Dec 1999.
4. Allen, J. M.; Hensch, M. J.; Burns, K. A.; and Oeters, K. J., *Parametric Fin-Body and Fin-Alone Database on a Series of 12 Missile Fins*, NASA LRC TM in publication, May 1996.
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6.0 SYMBOLS AND DEFINITIONS

AOA	Angle of Attack
APC	Aeroprediction Code
AP02, AP98	2002 and 1998 versions of the APC, respectively
CFD	Computational Fluid Dynamics
NSWCDD	Naval Surface Warfare Center, Dahlgren Division
PNS	Parabolized Navier-Stokes
SB, SBT	Slender Body, Slender-Body Theory
A_{REF}	Reference area (maximum cross-sectional area of body, if a body is present, or planform area of wing, if wing alone)(ft ²)
A_B	Base area = $\pi d_B^2 / 4$
C_A	Axial force coefficient
$C_{A_B}, C_{A_f}, C_{A_w}$	Base, skin-friction, and wave components, respectively, of axial force coefficient
C_{A_F}	Forebody axial force coefficient ($C_{A_F} = C_{A_f} + C_{A_w}$)
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Pitching moment coefficient (based on reference area and body diameter, if body present, or mean aerodynamic chord, if wing alone)
C_{M_α}	Pitching moment coefficient derivative (per radian)

$C_{M_q} + C_{M_{\dot{\alpha}}}$	Pitching damping moment coefficient $[C_M(q)/(qd/2V_\infty) + C_M(\dot{\alpha})/(\dot{\alpha}d/2V_\infty)]$
$C_M(q)$	Pitching moment coefficient due to a constant pitching rate of q
$C_M(\dot{\alpha})$	Pitching moment coefficient due to a constant vertical acceleration of $\dot{\alpha}$
C_N	Normal force coefficient
C_{N_α}	Normal-force coefficient derivative (per radian)
cal	Caliber(s) (one body diameter)
d_B	Body diameter (ft) at base
d_r	Reference body diameter (ft)
deg	Degree(s)
l, l_n, l_a, l_f	Body length, nose length, afterbody length, and flare length, respectively
l_I	Distance from cone apex to flare-cylinder juncture
M_∞	Freestream Mach number
N	Normal force (lbs)
r	Local body radius (ft)
R_N	Reynolds number
V_∞	Freestream velocity (ft/sec)
x_{CP}, \bar{x}_{CP}	Center of pressure (in feet or calibers from some reference point that can be specified) in x direction
x, y, z	Axis system fixed with x along centerline of body
α	Angle of attack (deg)
Φ	Roll position of missile fins ($\Phi = 0$ deg corresponds to fins in the plus (+) orientation; $\Phi = 45$ deg corresponds to fins rolled to the cross (x) orientation)

θ_f Flare angle (deg)

Subscripts

C Cone

CG Center of gravity

f Flare

∞ Freestream conditions

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