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IMPROVEMENTS TO THE NSWC AERODYNAMICS PREDICTION PROGRAM OF PAR--E+C
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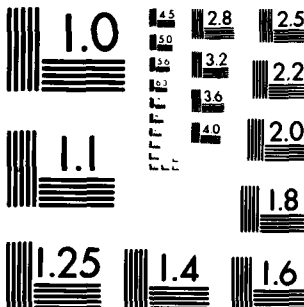
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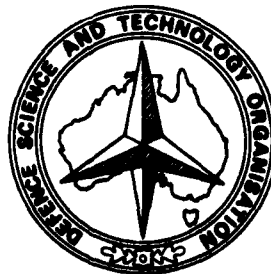


TECHNICAL REPORT

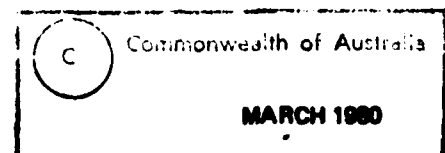
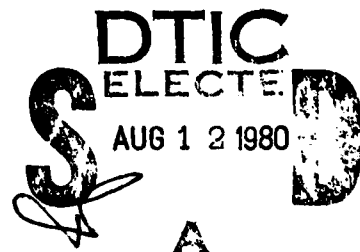
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IMPROVEMENTS TO THE NSW AERODYNAMICS PREDICTION PROGRAM OF
PARTICULAR SIGNIFICANCE FOR BOMBS

L.M. SHEPPARD



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TECHNICAL REPORT
WSRL-0146-TR

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IMPROVEMENTS TO THE NSW AIRCRAFT AERODYNAMICS PREDICTION PROGRAM OF PARTICULAR SIGNIFICANCE FOR BOMBS

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L.M. Sheppard

S U M M A R Y

During use of the NSW missile aerodynamics prediction program, a number of deficiencies have been found. Because these deficiencies are important on bombs, simple but effective corrections have been devised. Details are given of a revised expression for boattail normal force at subsonic and transonic speeds. This is necessary because the program gives normal force results that are much too large in magnitude when the base diameter is small. Also included is a correction for boattail centre of pressure.

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Comparisons are made with experimental data from a number of sources, in order to show that the modified program is effective and useful.

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POSTAL ADDRESS: Chief Superintendent, Weapons Systems Research Laboratory,
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TABLE OF CONTENTS

	Page No.
1. INTRODUCTION	1
2. NORMAL FORCE AND CENTRE OF PRESSURE OF BOATTAIL	1
2.1 Comparisons of bomb predictions with experimental data	4
3. AXIAL FORCE ON BOMBS	6
3.1 Truncated nose pressure drag	6
3.2 Excrescence drag	7
3.3 Comparisons with flight data	8
4. AXIAL FORCE AT TRANSONIC SPEEDS	10
4.1 Nose shoulder viscous separation drag	10
4.2 Wave drag of blunt noses at zero angle of attack	10
5. CONCLUSIONS	11
NOTATION	12
REFERENCES	13

LIST OF FIGURES

1. Variation of G factor with Mach number M	2
2. The M823 bomb	2
3. Normal force and centre of pressure of M823 body, $\alpha=0.1^\circ$	4
4. Normal force and centre of pressure of M823 bomb, $\alpha=5.0^\circ$	5
5. Normal force and centre of pressure of 105 mm shell, $\alpha=5.0^\circ$	5
6. Bluff bomb	5
7. Normal force and centre of pressure of body of bluff bomb, $\alpha=5.0^\circ$	6
8. Normal force and centre of pressure of bluff bomb, $\alpha=5.0^\circ$	6
9. Axial force on M557A and M557B bombs	8
10. Axial force on bomb with lugs and fuses	9

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1. INTRODUCTION

The NSWC missile aerodynamics prediction program(ref.1) provides design data simply and quickly. The accuracy is such that the data can be used for preliminary design and for assessment of both existing and proposed missiles. Consequently, the program can be used instead of wind tunnel tests when good, but not precise, aerodynamic data are needed. The program has been designed to be of practical use for tactical weapons, most of which operate below Mach number 3. Quite general body and wing geometries can be handled. The general accuracy aim is 10% for static forces, 20% for dynamic forces and 0.5 calibre for centre of pressure. The errors are larger at transonic speeds.

The NSWC program appears to have been designed for shells and guided missiles, not for bombs. The aim of the present work was therefore to explore the applicability of the program to bombs and, where necessary, to improve the quality of the predictions. As will be seen later, some improvements were found to be necessary. The program is a very useful design and assessment tool and illustrates how helpful modern computers can be in providing aerodynamic estimates. The response is rapid too, and for a complex wing-body-canard configuration less than 20 s CPU time is required for one Mach number on the IBM 370/3033 computer at DRCS.

Section 2 examines the normal force and centre of pressure predictions for boattails and shows why the program's predictions are inadequate when the base diameter is small. A revised procedure is advocated based on some bomb body tests carried out at the Aeronautical Research Laboratories(ref.2). In Section 3, the problems of estimating the axial force on bombs with fuses, lugs and truncated noses are examined. New procedures are devised for handling the viscous separation drag of truncated noses at subsonic and transonic speeds, and for estimating excrescence drag. The procedures are validated using some data obtained from gas gun tests(ref.3) and full scale flight tests(ref.4) at the Weapons Systems Research Laboratory. Some other aspects of axial force prediction are examined in Section 4. The conclusions follow in Section 5.

2. NORMAL FORCE AND CENTRE OF PRESSURE OF BOATTAIL

At subsonic and transonic speeds, the boattail contribution to the normal force is calculated by using a correction factor to multiply the prediction of slender body theory(ref.5). Following the notation of reference 5, the correction factor is set equal to $(G/2)$. The correction factor depends solely on Mach number, and reaches a maximum value of 1.825 at high subsonic speeds. Thus, on a boattail with the base small, the total negative normal force may be greater in magnitude than the positive normal force generated on the nose and centre section. Therefore the total normal force may be negative. A modified prediction method is therefore essential for bombs, which usually have small bases. The defect is not noticed on the shells and guided missiles examined by Moore and Swanson(ref.1) because these usually have large bases with diameters about the same as that of the cylindrical centre section. i.e. the base diameter is about one calibre.

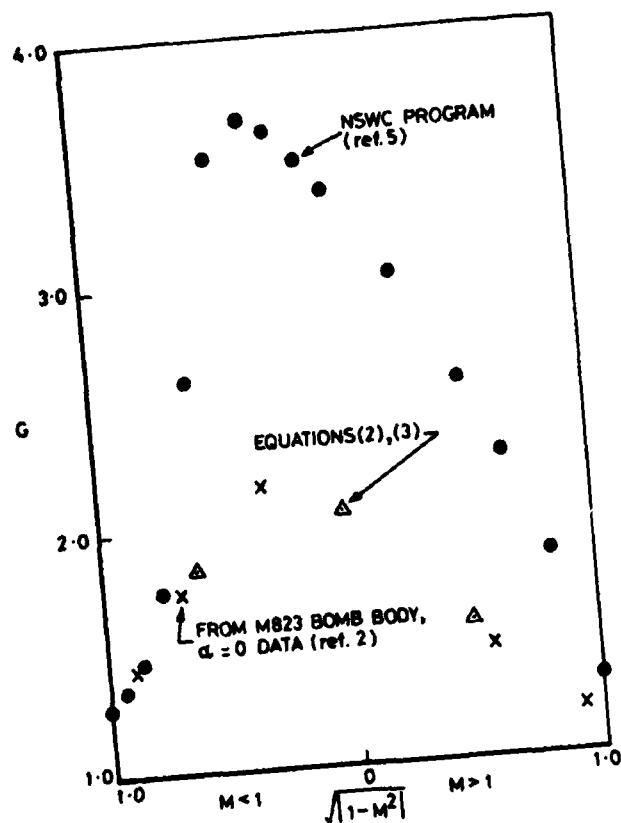


Figure 1. Variation of G factor with Mach number M

NOTE: Fin section is an extended double wedge. Thickness is 3%. Parallel section runs between 30% and 90% chord.

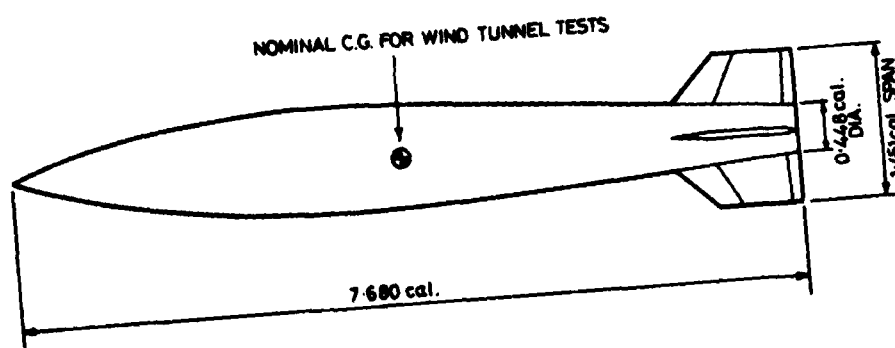


Figure 2. The M823 bomb

Figure 1 shows the way in which the correction factor G varies with Mach number. To show how inadequate these values of G are for bombs with small bases the M823 bomb (ref. 6) has been chosen. This is a good bomb to choose because there is no flow separation near the base. The shape of the M823 bomb is shown in figure 2. For evaluating correction factors, the M823 body without fins has been used and the resulting correction factors are shown on figure 1. The aerodynamic derivative data at zero angle of attack in reference 2 have been used to derive correction factors which are such that the NSW prediction method gives normal force results in agreement with the wind tunnel data (ref. 2).

The question that now arises is how to modify the correction factors from reference 5 given in figure 1. A simple formula that could be used is to replace the factor G by

$$k [G/k]^{R_b/R_{ref}} \quad (1)$$

which reduces to G when the base radius R_b is the same as the reference radius R_{ref} , equal to one half calibre. Consequently the modified values of G, denoted by G_{mod} , will be changed by only a small amount when the base radius is large as in the cases examined by Moore(ref.5). A check with the M823 body results in figure 1 leads to the conclusion that $k = 1.4$ provides reasonable G_{mod} factors for the M823 bomb body when the Mach number M is less than 1. So the final formula is

$$G_{mod} = 1.4[G/1.4]^{R_b/R_{ref}}, M \leq 1. \quad (2)$$

For the M823 bomb, $R_b/R_{ref} = 0.448$. A modified formula with k dependent on Mach number turns out to be necessary at supersonic speeds. For G greater than unity, the chosen formula, consistent with equation (2) at $M=1$, is

$$k = [1.4 - (2/3)\beta], \beta \leq 0.6 \quad (3a)$$

$$\text{where } \beta = \sqrt{M^2 - 1}$$

$$\text{and } k = 1, \beta \geq 0.6. \quad (3b)$$

For G less than unity, the value of G remains unaltered.

The modified G results from equations (2) and (3) are shown on figure 1 for the M823 bomb body. Agreement with the G values obtained from Secomb's wind tunnel data(ref.2) is very good. The form introduced in equation (1) is therefore believed to be adequate for all values of R_b/R_{ref} .

Equations (3) provide corrected G values at supersonic speeds. Since, however, the NSWC prediction program requires G values only for Mach numbers less than 1.2, the dominant correction is provided by equation (3a). Provided that the slender body correction method is never used above Mach 1.2, equation (3a) or an equivalent result could be used for all supersonic speeds.

A similar procedure has been used for boattail centre of pressure, again using Secomb's data(ref.2) for the M823 bomb body. The distance from the start of the boattail to the predicted centre of pressure is multiplied by the factor

$$[K + (R_b/R_{ref})]/[K + 1.0]$$

$$\text{where } K = 1.0, M < 0.5 \quad (4a)$$

$$\text{and } K = 0.2 + 5(M - 0.9)^2, 0.5 \leq M \leq 1.2. \quad (4b)$$

The NSWC program does not require a value of K for higher speeds. However, if ever needed the value to use is

$$K = 0.65, M > 1.2.$$

It should be noted that the centre of pressure corrections of equations (4), although significant, are less important than the normal force corrections of equations (2) and (3).

2.1 Comparisons of bomb predictions with experimental data

The modifications given in equations (2), (3) and (4) enable improved predictions of bomb aerodynamics to be made with the NSWC program.

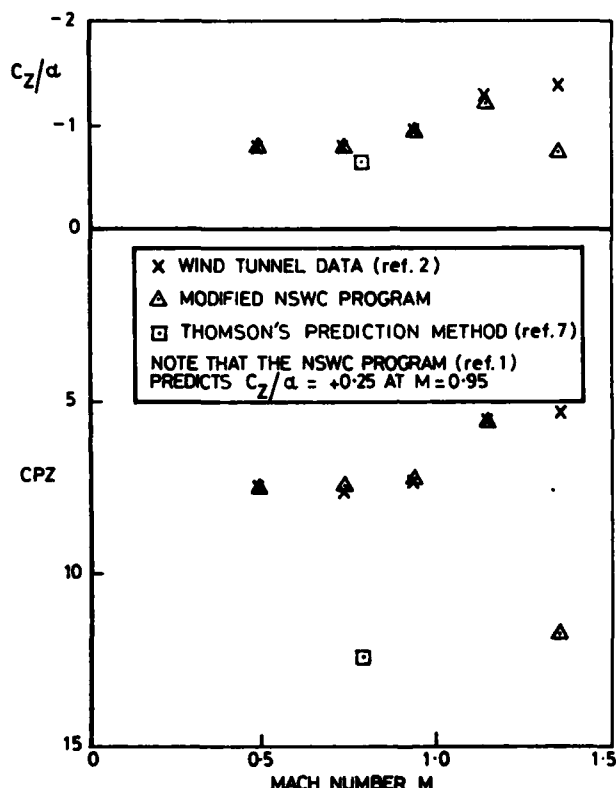


Figure 3. Normal force and centre of pressure of M823 body, $\alpha = 0.1^\circ$

Figure 3 compares with experiment (ref. 2) the predictions of normal force and centre of pressure for the M823 bomb body. The agreement is very good, confirming that the k factor for boattail normal force and the K factor for boattail centre of pressure do indeed represent the experimental data very effectively at subsonic and transonic speeds. The predictions are not so good at Mach 1.35. Shown on figure 3 are results from Thomson's boundary layer method (ref. 7) for the M823 bomb body at $M=0.8$. The errors are greater than the 10% normal force, 0.5 cal. centre of pressure aimed for in the NSWC program. It seems therefore that, in general, errors somewhat larger than those desired are likely on bodies with extensive boattails. What then are the results for the complete M823 bomb? Figure 4 shows the experimental results from reference 6 compared with the program's normal force predictions at an angle of attack of 5 degrees. The normal force predictions are very good at subsonic and transonic speeds, and are consistent with the stated overall accuracy capability of the program. The centre of pressure predictions are excellent. However, the normal force prediction at Mach 1.25 is not so good.

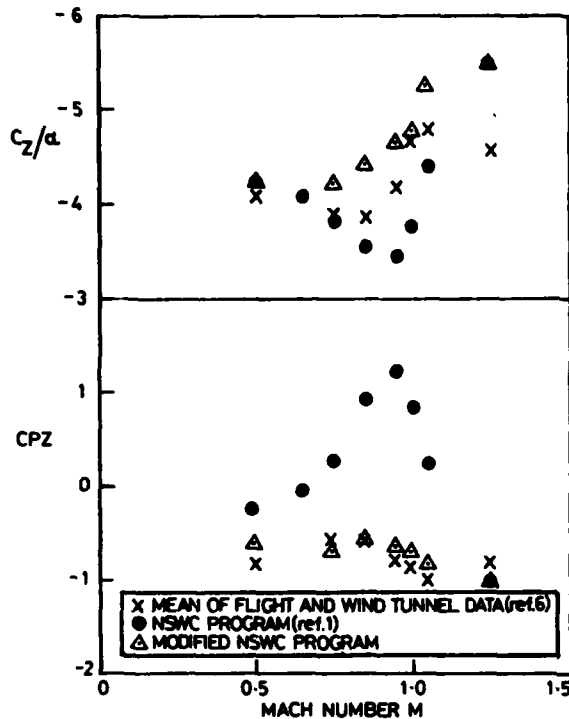


Figure 4. Normal force and centre of pressure of M823 bomb, $\alpha = 5.0^\circ$

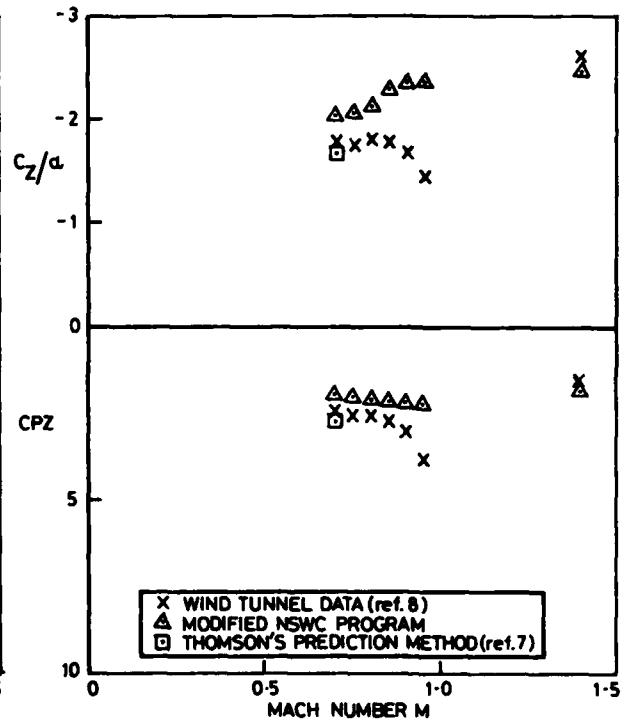


Figure 5. Normal force and centre of pressure of 105 mm shell, $\alpha = 5.0^\circ$

Jermey(ref.8) has measured normal force and centre of pressure on a spinning shell in a wind tunnel. The full scale shell is 105 mm in diameter. In this case, the unmodified NSWC program will perform equally as well as the modified program because the base diameter of the shell is nearly one calibre, which means that the normal force and centre of pressure corrections will be very small. Jermey's results are compared with program predictions and with Thomson's boundary layer method(ref.7) in figure 5. Again, the performance of the NSWC program is seen to be good. The errors are larger at transonic speeds than at Mach 0.7 and Mach 1.4.

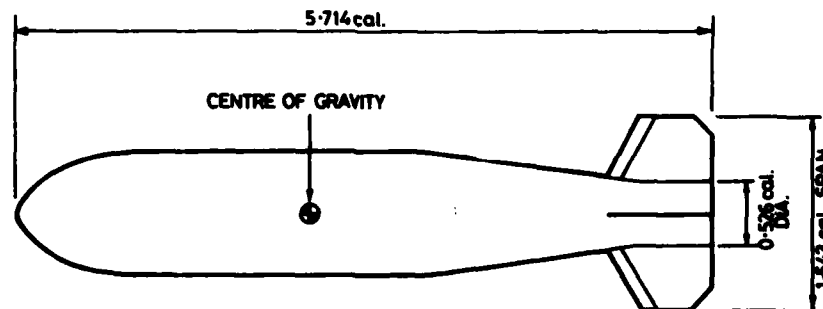


Figure 6. Bluff bomb

Finally, we come to an extreme bluff bomb shape(ref.9) shown in figure 6. This is extreme in the sense that methods starting from slender body theory may work rather poorly. The results shown in figures 7 and 8 are very interesting and include wind tunnel measurements made by Robinson(Ref.10). Surprisingly, the performance of the modified program is very good. The centre of pressure error is comparatively small for both the body alone and the complete bomb.

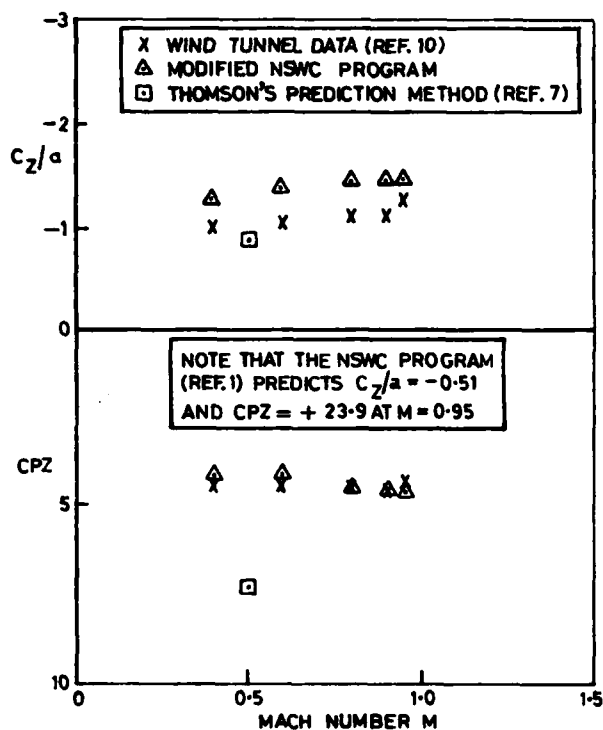


Figure 7. Normal force and centre of pressure of body of bluff bomb, $\alpha = 5.0^\circ$

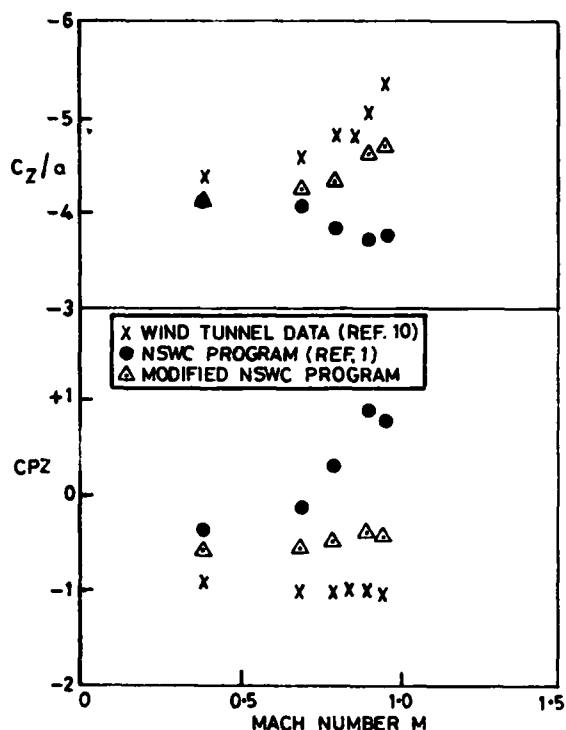


Figure 8. Normal force and centre of pressure of bluff bomb, $\alpha = 5.0^\circ$

Some comparisons have also been made for the M557A bomb (ref. 6). This bomb is known to have a flow separation near the base. In fact, the M823 bomb is the same as the M557A except near the base. The results, which are not shown, give comparisons that indicate a generally somewhat worse performance of the program, as might be expected in view of the flow separation on the M557A bomb. The conclusion is simply that the NSW program will produce less satisfactory results when significant flow separations occur. In the case of the M557A bomb, when compared to the M823 bomb, the normal force errors are increased by about 20% but the centre of pressure error is decreased by about 0.1 calibre. On another bomb with known flow separations, the normal force prediction is better by about 10% than on the M557A, but the centre of pressure prediction is worse by about 0.2 calibre. Even so, useful predictions are obtained.

3. AXIAL FORCE ON BOMBS

Bombs often have a nose fuse attached to a truncated nose, one or two lugs and perhaps a tail fuse. There is therefore a need to estimate the contributions to axial force from the truncated nose and from excrescences on the bomb. The following sections show how this can be done. The predictions are validated by comparison with experimental measurements.

3.1 Truncated nose pressure drag

A viscous flow separation occurs around the sharp edge of a flat truncated nose flying at subsonic or transonic speeds. An immediate problem is where to find relevant data on the resulting increase in pressure drag, ΔC_d . The author was able to find some useful data in references 11 and 12, which enable some comparisons to be made between

truncated noses and rounded or streamline noses. Configurations 14, 47, 86 and 114 of reference 11 suggest that the pressure drag increment, ΔC_A , is about 0.6. The drag coefficient increment at subsonic speeds is given by Hoerner(ref.12) as 0.65 on figure 21 page 3-12. At Mach numbers greater than about 1.2, the NSWC program(ref.1) predicts an inviscid drag difference between rounded and truncated noses of 0.53. A simple effective formula to use is therefore

$$[\Delta C_A]_{\text{truncated nose}} = 0.53 [R_n/R_{\text{ref}}]^2, \quad M = 1.19 \quad (5a)$$

$$\text{and } [\Delta C_A]_{\text{truncated nose}} = 0.65 [R_n/R_{\text{ref}}]^2, \quad M \leq 0.8$$

where R_n is the truncated nose radius and, as before, R_{ref} is the reference radius. A linear variation in axial force increment, $[\Delta C_A]_{\text{truncated nose}}$, is assumed between the subsonic and supersonic values.

The above result for subsonic speeds has been applied to a practice bomb with $R = 0.24$ cal. A full scale model was tested by Pope(ref.3) in a gas gun. This bomb had a truncated nose with a fuse and a single lug. The bomb is therefore treated as a bomb with a truncated nose and an excrescence of the same frontal area as the lug. When allowance is made for the small excrescence, as discussed in Section 3.2 below, the truncated nose axial force is found to be much less than predicted. The axial force arising from the truncated nose is therefore assumed to decrease more rapidly than R_n^2 as R_n decreases. The following equation, incorporating an additional linear decrease with R_n , gives agreement with Pope's flight data for the practice bomb(ref.3).

$$[\Delta C_A]_{\text{truncated nose}} = 0.65 [R_n/R_{\text{ref}}]^2 - 0.56 [1 - (R_n/R_{\text{ref}})] [R_n/R_{\text{ref}}]^2, \quad M \leq 0.8 \quad (5b)$$

Equations (5a) and (5b) provide the necessary axial force predictions. As before, a linear variation is assumed between $M=0.8$ and $M=1.19$.

3.2 Excrescence drag

Hoerner(ref.12) and Stoney(ref.11) contain relevant data. Figure 7 of page 8-3 in reference 12 suggests that the excrescence drag coefficient of a square plate is about 1.1 at low speeds. For the two-dimensional case of a body on a wall, the drag coefficient is quoted on page 8-3 as about 1.25. At transonic speeds, figure 33 page 20-13 suggests a drag coefficient value of about 1.2 while, at the supersonic speed of Mach 1.7, figure 36 page 20-14 suggests a drag coefficient of about 0.8 for an axisymmetric plate on the nose of a body of revolution. In summary, therefore, a constant drag coefficient of about 1.2 seems reasonable at subsonic and transonic speeds, but lower values are necessary at supersonic speeds.

Stoney(ref.11) quotes two-dimensional data for both front face pressure and base pressure. The total drag is about 1.0 at subsonic and transonic speeds, about 0.6 near Mach 2 and about 0.4 at Mach 3. So a decrease with Mach number M such as $(1.2/M)$ provides a reasonable description of the drop in drag at supersonic speeds. In order to provide continuity of the drag coefficient estimates, the constant value 1.2 is used up to Mach 1 and $(1.2/M)$ is used above Mach 1. The recommended formulae for the axial force increments are therefore

$$[\Delta C_A]_{\text{excrescences}} = 1.2, \quad M \leq 1 \quad (6a)$$

$$\text{and } [\Delta C_A]_{\text{excrescences}} = 1.2/M, \quad M \geq 1. \quad (6b)$$

Note that the reference area for the coefficients in equations (6) above is the frontal area of the excrescences.

3.3 Comparisons with flight data

Results from full scale flight tests of M557A and M557B bombs are given in reference 6. The axial force results are shown in figure 9, where they are compared with predictions from the modified NSWC program. Agreement is good for the slender, pointed nose M557A bomb, which is almost the same as the M823 shape shown in figure 2. Note, however, that the axial force at higher transonic speeds, near Mach number 1.1, is in error by more than it is at low supersonic speeds near Mach number 1.25. This confirms that prediction errors are likely to be larger at transonic speeds than elsewhere.

The M557B bomb is more significant for our present considerations as it has a truncated nose of radius $R = 0.468$ cal. and therefore provides a severe test of the modified program.ⁿ The nose is short, only 0.747 cal. long, and the stabilizing tail has unswept leading and trailing edges. The axial force on the M557B bomb is dominated by the very bluff, truncated nose which provides about 90% of the total axial force over the range of Mach numbers shown in figure 9. Figure 9 shows that the axial force prediction errors are smaller at the higher speeds. At the lower Mach numbers, the axial force errors exceed 10%. At the higher Mach numbers, in contrast, the axial force errors are less than 10%. Overall, the modified NSWC program works very well.

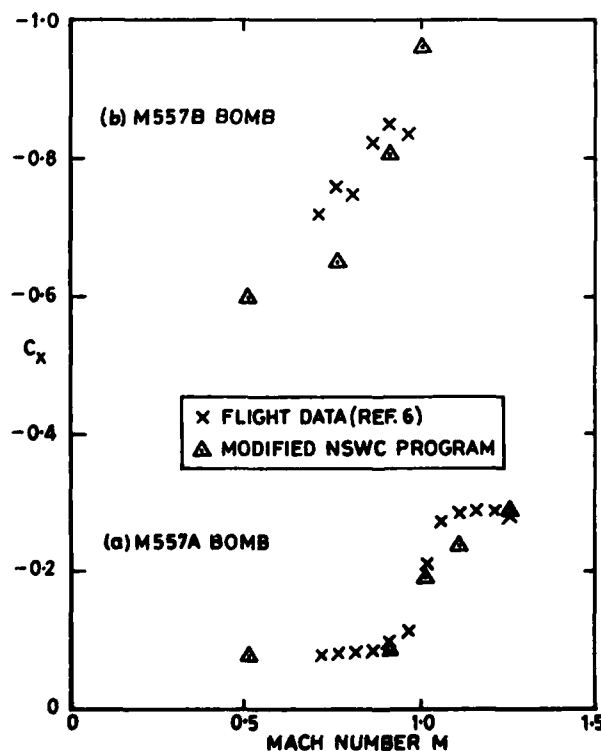


Figure 9. Axial force on M557A and M557B bombs

Full scale flight tests of a second bomb flying at transonic speeds have been analysed by Dudley(ref.4) to obtain axial force data. Pope(ref.3) has measured the axial force on a half scale model at Mach 0.3 using a gas gun. The bomb is a slender, streamlined shape with a truncated nose, a nose fuse, two lugs and a tail fuse. Since the nose fuse protrudes in front of the truncated nose, the nose is treated simply as a truncated nose. The frontal areas of the lugs and rear fuse were, at first, added up to give the total frontal area of the excrescences. This may, however, provide too much frontal area as the second lug is probably shielded by the first lug and the rear fuse may be only partly effective in producing drag. Firstly, Pope's results(ref.3) for bombs with, and without, both fuses and lugs are used to determine how much of the tail fuse should be included in the drag estimates. The axial force coefficient increment, arising from the truncated nose and excrescences, is measured to be 0.10. The same value can be obtained from the computer program by assuming that about one third of the rear lug and one third of the tail fuse are effective in producing drag i.e. the frontal area is calculated from one and one third lugs and from one third of the frontal area exposed by the rear fuse to the local air flow.

The next step is to compare predictions at transonic speeds where the axial force arising from shock waves is large. The results for the complete bomb are shown in figure 10. Agreement is good, within 15% throughout much of the Mach number range. However, it should be noted that the blunt nose wave drag modification of Section 4.2 below is included in the predictions shown on figure 10. Without this modification, the axial force predictions at transonic speeds would be worse.

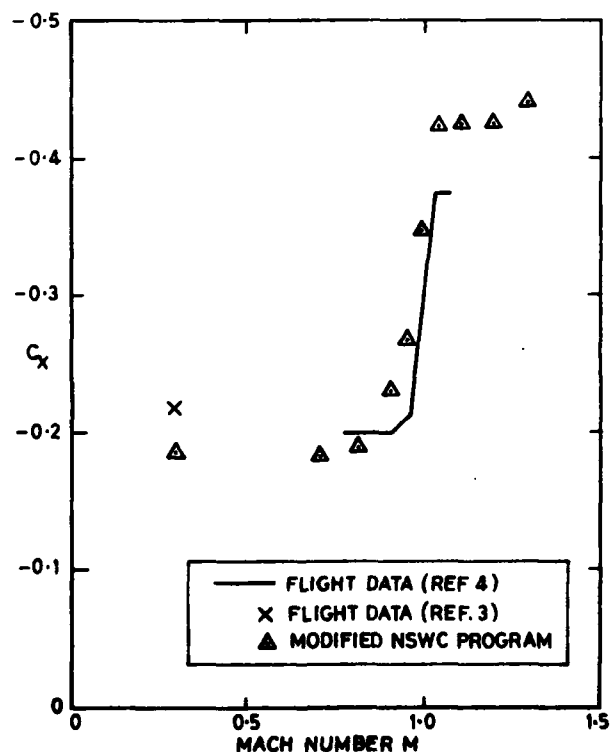


Figure 10. Axial force on bomb with lugs and fuses

4. AXIAL FORCE AT TRANSONIC SPEEDS

Improvements of general applicability have been made to axial force computations at transonic speeds. The first concerns viscous flow separation when there is a discontinuity in slope where the nose joins the cylindrical centre section. The second concerns bodies with very bluff noses.

4.1 Nose shoulder viscous separation drag

The allowance made at subsonic speeds(ref.1) has been extended unaltered through transonic speeds.

$$\text{i.e. } [\Delta C_A]_{\text{nose shoulder}} = 0.012 (\theta_1 - 10), \theta_1 > 10^\circ, \quad (7)$$

where θ_1 is the angle jump in degrees where the nose joins the centre section. When $0 \leq \theta_1 \leq 10^\circ$, the viscous separation drag is taken to be zero.

4.2 Wave drag of blunt noses at zero angle of attack

The existing program(ref.1) applies to noses with small amounts of blunting. For large amounts of blunting, Chaussee's results for spherically blunted ogives(ref.13) provide the necessary basic data. Unfortunately, the predictions of drag-rise Mach number are poor. An inspection of Chaussee's data(ref.13) shows how implausible the wave drag data are below about Mach 0.8. An estimate of drag-rise Mach number M_D is therefore required so that the predictions can be improved. A simple analytic result that gives plausible values for a hemisphere ($R_n = R_{\text{ref}}$) and a pointed ogive ($R_n = 0$) is

$$M_D = M_{D0} - (R_n/R_{\text{ref}}) (M_{D0} - 0.7) \quad (8a)$$

$$\text{where } M_{D0} = 1 - [0.3/(L + 0.5)]. \quad (8b)$$

Note that L is the nose length in calibres and that M_{D0} is estimated from the drag-rise Mach numbers given in reference 5 for a pointed body, when $R = 0$. When $R = R_{\text{ref}}$ and the nose is a full hemisphere the estimated drag-rise Mach number is 0.7, a plausible value. The hemisphere contribution to the wave drag is taken to vary linearly with M , from zero at $M = M_D$ up to an estimated analytic value, $1.3(M-0.7)(R_n/R_{\text{ref}})^3$, at $M = M_D + 0.1$. The total nose wave drag, $C_{A(w)}$, is estimated from Chaussee's numerical results(ref.13); the following simple analytic expression provides a reasonable representation of the numerical results:

$$C_{A(w)} = C_{A(n)} \left[1 - \left(R_n/R_{\text{ref}} \right) \right] + 1.3(M-0.7)(R_n/R_{\text{ref}})^3, \quad (9)$$

$$M_D + 0.15M < 1.19$$

where $C_{A(n)}$ is the pointed nose wave drag at Mach number M .

The purpose of equations (8) and (9) is to provide an interim correction to the NSWC program. For this reason, simplified analytic representations are employed, rather than tables of data. When Chaussee's results have been replaced by ones giving satisfactory predictions of drag-rise Mach number, a suitable set of tables can be prepared.

5. CONCLUSIONS

Substantial improvements have been made to the NSWC missile aerodynamics prediction program(ref.1). In particular,

- (1) Normal force prediction on bombs is now satisfactory, with errors similar to those for other missiles.
- (2) Satisfactory predictions can now be made of truncated nose viscous separation drag at subsonic and transonic speeds.
- (3) Bluff body wave drag predictions at transonic speeds have been extended to cover the region near the drag-rise Mach number.
- (4) An allowance is included for the drag of excrescences such as lugs and fuses.
- (5) The effective frontal area of tail fuses seems to be about one third of the frontal area exposed to the local air flow.
- (6) The nose shoulder viscous separation drag has been extended through transonic speeds.
- (7) Normal force and centre of pressure predictions on bodies alone with extensive boattails may not be very good.

NOTATION

CPZ	centre of pressure of normal force
C_X	axial force coefficient
C_Z	normal force coefficient
$C_{A(n)}$	wave drag coefficient of pointed nose at transonic speeds and $\alpha=0$
$C_{A(w)}$	wave drag coefficient of blunt nose at transonic speeds and $\alpha=0$
G	double the correction factor used to multiply the boattail normal force prediction of slender body theory
G_{mod}	modified correction factor
k	normal force constant, equation (1)
K	centre of pressure constant, equations(4)
L	nose length (calibre)
M	Mach number
M_D	drag-rise Mach number
M_{Do}	drag-rise Mach number of pointed nose
R_b	base radius
R_n	radius of truncated nose
R_{ref}	reference radius (of centre section), one half calibre
α	angle of attack
β	$\sqrt{M^2-1}$
θ_1	angle jump in degrees, at nose shoulder where nose joins cylindrical centre section
ΔC_A	increment in axial force coefficient, with subscript denoting truncated nose or excrescences or nose shoulder

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