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Predictions of Low Aspect Ratio Missile Aerodynamics

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The ability of a finite volume Euler code, ZEUS, to predict low aspect ratio missile aerodynamics accurately is evaluated. By using grid clustering near the body, the results from ZEUS compare well with wind-tunnel data for Mach numbers between 3 and 4.5 and angles of attack up to 20 deg. The interference factor, $K_{W(B)}$, represents the ratio of the fin normal force in the presence of the body to the fin-alone normal force. Euler $K_{W(B)}$ calculations are within 12% of wind-tunnel data over the entire angle-of-attack range. The interference factor, $K_{B(W)}$, is the ratio of the incremental body force due to the presence of the fins to the fin-alone normal force. The Euler predictions of the ratio $K_{B(W)}/K_{W(B)}$ are generally within 15% of experimental data. The final parameter examined is K_ϕ, which is the ratio of the incremental fin normal force in the presence of the body due to sideslip to the fin-alone normal force. Currently no wind-tunnel data have been found for comparison. Euler K_ϕ predictions differ considerably from slender body theory predictions due to vorticity and shock waves; however, they compare well with previous Euler solutions. This research shows that ZEUS can be used to extend the preliminary design database reliably to low aspect ratio missiles.

Nomenclature

AR	= aspect ratio formed by joining two fins at their root chord
C_{N_B}	= body-alone normal force coefficient
C_{N_M}	= normal force coefficient of the missile
$C_{N_{W(B)}}$	= normal force coefficient of fin in presence of body
$C_{N_{\alpha_W}}$	= normal force curve slope of fin-alone
C_r/R	= ratio of root chord to body radius
C_t/R	= ratio of tip chord to body radius
$K_{B(W)}$	= incremental body interference factor, $\Delta L_{B(W)}/L_W$
$K_{W(B)}$	= fin interference factor $L_{W(B)}/L_W$
K_ϕ	= sideslip interference factor; see Eq. (3)
$L_{B(W)}$	= normal force of body in presence of fin
L_{N_B}	= normal force of body-alone
L_{N_M}	= normal force of missile body and fins
L_W	= normal force of fin-alone
$L_{W(B)}$	= normal force of fin in presence of body
M	= freestream Mach number
q	= dynamic pressure
S_W	= fin planform area
S/R	= ratio of fin span to body radius
t/C_r	= ratio of fin thickness to root chord
Z	= missile axial coordinate measured from nose
Z/R	= ratio of z coordinate to body radius
Z_{BL}/R	= ratio of body-length to body radius
Z_{LE}	= z location of the fin leading edge
Z_N/R	= ratio of tangent-ogive nose length to body radius
α	= angle-of-attack of fin
α_{eq}	= equivalent angle of attack
β	= angle of sideslip of fin
δ	= all-moving fin angle of attack
$\Delta C_{N_{B(W)}}$	= incremental normal force coefficient of body in presence of fin
ΔC_{N_W}	= Lucero correlation parameter; see Eq. (7)
$\Delta L_{B(W)}$	= increment normal force on body due to fins
$\Delta\alpha_v$	= vortex contribution to α_{eq}
λ	= taper ratio, C_t/C_r
Λ	= fin leading-edge sweepback angle, deg.

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Introduction

WHEN stowage requirements for compactness are considered in missile design, the missile fins typically are small and have low aspect ratios. There is a current need for supersonic aerodynamic data for missiles with low aspect ratio fins because there has been very limited experimental and numerical research in this area. Lucero[1,2] developed empirical curves to predict the normal force coefficient for a variety of low aspect ratio missile configurations at Mach numbers from 2.5 to 7.7. He developed the curves using data from 29 combinations of Mach number and missile configurations with α up to 20 deg. The missile fins included thick and thin lifting surfaces, generally arranged in the "+" cruciform configuration. Lucero's empirical curves work well for missile preliminary design, but improved nonempirical methods are needed to broaden the preliminary design database for low aspect ratio missiles.

Nielsen[3] used data from the Triservice-NASA Data Base[4] and the fin-alone data from Stallings and Lamb[5] to produce interference factors $K_{W(B)}$ and $K_{B(W)}$. He calculated $K_{W(B)}$ and $K_{B(W)}/K_{W(B)}$, which are measures of the mutual interference between the wing and the body. The Triservice-NASA Data Base contains measured body and fin normal force coefficients for a variety of missile configurations. The smallest aspect ratio examined by Nielsen was 0.5; however, data are needed for AR values as low as 0.05.

A third interference factor of interest in low aspect ratio aerodynamics is K_ϕ, which is a measure of the effect of sideslip on the fin normal force in the presence of the body. Currently, there are no known experimental data for K_ϕ. Jenn and Nelson[6] used the Euler code SWINT to generate K_ϕ for missiles with delta fins for AR from 2.4 to 4, but did not present K_ϕ values for lower aspect ratios. S/R values were varied from 1 to 6, but SWINT only provided accurate K_ϕ values for S/R greater than 2.5 because grid clustering was not used. For S/R less than 2.5, slender body theory (SBT) results from Ref. 7 were used.

Component Build-up Methods

Component build-up methods allow quick analysis of general missile configurations for preliminary design. A specific component build-up method is the equivalent angle-of-attack method.[8,9] This method uses interference factors to account for the mutual interference between missile components. The nonlinear lifting characteristics are accounted for in the interference factors, which are normalized by the fin-alone normal force. Mathematically, the equivalent angle of attack is defined as

$$\alpha_{\text{eq}} = K_{W(B)}\alpha + (4/AR)K_{\phi}\beta\alpha + \Delta\alpha_v \tag{1}$$

where the terms on the right-hand side represent the effects from body upwash, fin sideslip angle, and vortex interaction, respectively. Equation (1) is valid for α less than about 20 deg; extensions of the method to higher α are developed in Ref. 10.

The interference factor $K_{W(B)}$ is the ratio of the fin normal force in the presence of the body to the fin-alone normal force. K_{ϕ} is the ratio of the incremental fin normal force in the presence of the body due to sideslip to the fin-alone normal force. Mathematically, these interference factors are represented by

$$K_{W(B)} = L_{W(B)}/L_W \tag{2}$$

$$K_{\phi} = \left[\frac{L_{W(B)_{\beta\neq 0}} - L_{W(B)_{\beta=0}}}{L_W}\right]_{\alpha} \frac{AR}{4\beta} \tag{3}$$

Once $K_{W(B)}$ and K_{ϕ} are known, the normal force coefficient for the fin in the presence of the body is found by multiplying α_{eq} by the fin-alone lift-curve slope, such that

$$C_{N_{W(B)}} = C_{N_{\alpha_W}}\alpha_{\text{eq}} \tag{4}$$

The interference factor $K_{B(W)}$ is defined as

$$K_{B(W)} = \frac{\Delta L_{B(W)}}{L_W} \tag{5}$$

where $\Delta L_{B(W)}$ is the incremental body normal force due to the presence of the fin $(L_{N_M} - L_{N_B})$. The equivalent angle-of-attack method finds the incremental body force due to the presence of the fin by

$$\Delta C_{N_{B(W)}} = \frac{K_{B(W)}}{K_{W(B)}} C_{N_{W(B)}} = K_{B(W)} C_{N_{\alpha_W}}\alpha \tag{6}$$

for β and $\Delta\alpha_v = 0$.

ZEUS

An accurate and efficient method is needed to predict the wing–body interference factors $K_{W(B)}$, $K_{B(W)}$, and K_{ϕ} for a large range of low aspect ratio missile configurations. Euler numerical codes have proved accurate over a broad range of missile configurations.[11] They accurately predict pressure distributions and convect vorticity, although they do not predict vortex shedding due to viscosity. Viscous effects become important at Mach number near 4.5 and angles of attack above 15 deg.[11,12] Under these circumstances, the flow separates from the body to form two strong leeside vortices. Euler codes do not accurately predict this separation and overpredict the leeside pressure. However, the leeside pressure is usually negligible compared to the windward pressure, so the lift force is still reasonably accurate.

ZEUS[13,14] (Zonal Euler Solver) is a reliable and robust numerical Euler code that solves the three-dimensional Euler equations for flowfields between the missile and its bow shock. A spatial marching method is used, and the flowfield solution is obtained using a second-order Godunov[15,16] method in conjunction with the Riemann[17] problem. ZEUS computations begin at an initial dataplane located at $Z/R = 0.3$. The conditions on the initial dataplane are generated by a one-dimensional conical starting solution that takes the calculations across the bow-shock. The code is extremely robust and flexible. The ability of ZEUS to produce accurate results is well documented.[14,18–21] This includes a wide spectrum of applications from missiles with noncircular body cross-sections to spinning projectiles used in tank guns. Many more examples exist, but these references show the versatility of ZEUS.

The objective of this research is to determine if ZEUS can accurately predict the normal force for low aspect ratio missiles. Comparisons are made with Lucero,[1,2] Nielsen,[3] and Jenn and Nelson.[6] All ZEUS computations were performed on the IBM 4381 mainframe computer at the University of Missouri–Rolla. When $\alpha = 3$ deg, typical CPU times were 30 min, but at $\alpha = 20$ deg, the CPU times approached 3 h.

Methodology

Lucero[1,2] presented his results in terms of the parameter ΔC_{N_W}, which is simply the missile normal force coefficient minus the missile body-alone normal force coefficient,

$$\Delta C_{N_W} = C_{N_M} - C_{N_B} = C_{N_{W(B)}} + \Delta C_{N_{B(W)}} \tag{7}$$

because $C_{N_M} = C_{N_B} + C_{N_{W(B)}} + \Delta C_{N_{B(W)}}$. Equation (7) can be written in terms of lift as

$$\Delta C_{N_W} = \left[L_{W(B)}/L_W + \Delta L_{B(W)}/L_W\right] C_{N_{\alpha_W}}\alpha \tag{8}$$

since $L_W = q\, S_W\, C_{N_{\alpha_W}}\alpha$. It is important to remember that $L_{W(B)}$ is a total force, whereas $\Delta L_{B(W)}$ is an incremental force. Also, note that

$$\Delta C_{N_W} = \left[K_{W(B)} + K_{B(W)}\right] C_{N_{\alpha_W}}\alpha \tag{9}$$

All of the ZEUS numerical calculations revolve around $L_{W(B)}$, $\Delta L_{B(W)}$, and L_W. To predict $L_{W(B)}$, ZEUS integrates the pressures on the fin for the flowfield surrounding a fin–body configuration. To predict $\Delta L_{B(W)}$ two computer runs were needed. First, a body-alone configuration was examined to determine L_{N_B}. Second, the fin–body configuration was used to determine L_{N_M}. Additional postprocessing was needed to calculate K_{ϕ} because two computer runs are required for $L_{W(B)}$: one with sideslip and one with $\beta = 0$ [see Eq. (3)]. The axial stepping for each case was not equal, so interpolation was used to obtain data at the same axial locations to ensure accurate K_{ϕ} calculations. Finally, L_W was determined by ZEUS. It was generally within 10% of the experimental data from Stallings and Lamb.[5]

All body-alone and forebody calculations were done using an 18×24 $(r \times \phi)$ grid mesh with pitch-plane symmetry. For $L_{W(B)}$, a 36×36 mesh with grid clustering was used over the finned section. For $\Delta L_{B(W)}$, an 18×24 mesh without grid clustering was used over the finned section. When analyzing the body force, ZEUS gives better accuracy with a coarse mesh. With a fine mesh, ZEUS produces spurious crossflow effects that lead to inaccurate body force predictions.[22] For K_{ϕ} calculations, pitch-plane symmetry cannot be utilized. As a result, grid sizes on the forebody and finned sections were 18×48 and 36×72, respectively. Because low aspect ratio fins typically have S/R values of 2 or less, a grid clustering function from Ref. 23 was implemented to ensure that a large number of grid points were located on the fin. The clustering criteria used in this research required that the grid have at least 10 spanwise points on the fin at the fin trailing edge, because the shock is farthest from the body at this point. ZEUS distributes the grid points between the body and the bow shock, so these criteria ensured at least 10 spanwise grid points on the fin at any axial location along the constant span portion of the fin.

Euler $K_{W(B)}$ and $K_{B(W)}$ results were compared directly with the wind-tunnel results from Nielsen.[3] The Euler results were also compared indirectly with the empirical data from Lucero.[1,2] Euler K_{ϕ} results could only be compared with the numerical work of Jenn and Nelson[6]; experimental K_{ϕ} results could not be found.

Missile Configurations

Table 1 gives the specific missile configurations used to compare previous data to ZEUS calculations in this research.

Figure 1 is a schematic of the general missile configuration. Every configuration had four fins in the "+" cruciform configuration. However, a two-fin, planar configuration was evaluated to compare with the planar K_{ϕ} results from Jenn and Nelson.[6]

The empirical analysis of Lucero[1,2] consisted of fins with a thickness ratio (t/C_r) of 0.01442 with 10 deg beveled leading and trailing edges. The Triservice-NASA Data Base used by Nielsen[3] had fins with a thickness ratio (t/C_r) of 0.05 and a diamond-shaped chordwise cross section. ZEUS can model fin thickness, but for simplicity, infinitely thin fins were used. Jenn and Nelson[6] also used infinitely thin fins in their research with SWINT.

Table 1 Missile configurations

Case	Z_{BL}/R	Z_N/R	S/R	C_r/R	λ	Λ	Z_{LE}/R	AR
Lucero[a]								
a (3)	20	7	1.34	8.66	1.0	0.00	11.34	0.08
b (4)	20	7	1.66	8.66	1.0	0.00	11.34	0.15
c (5)	20	7	2.34	8.66	1.0	0.00	11.34	0.31
Nielsen[b]								
a (F32)	24.67	6	2.00	5.33	0.5	69.44	15.61	0.50
b (F32)	24.67	6	2.00	4.00	1.0	0.00	16.53	0.50
Jenn and Nelson[c]								
a	40.33	6	6.00	8.33	0.0	59.04	32.00	2.40

[a]Refs. 1 and 2. $M = 2.96$ and 4.63; $0 \leq \alpha \leq 20$ deg; $\beta = 0$ deg.
[b]Ref. 3. $M = 3.5$ and 4.5; $0 \leq \alpha \leq 20$ deg; $\beta = 0$ deg.
[c]Ref. 6. $M = 3.5$; $\alpha = 3$ deg; $\beta = 0$ and 3 deg.

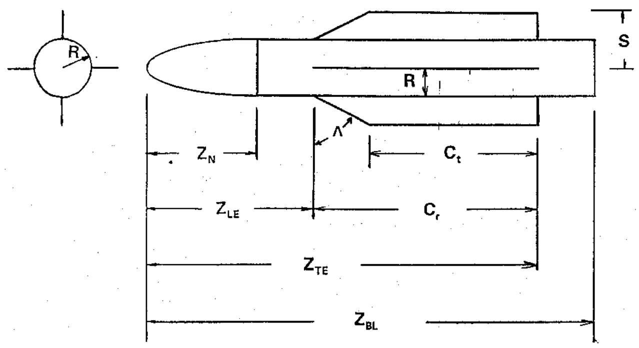

Fig. 1 Missile geometry configuration.

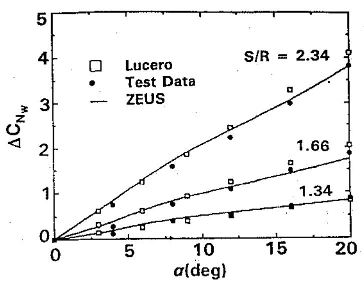

Fig. 2 ZEUS-Lucero comparison at Mach 2.96.

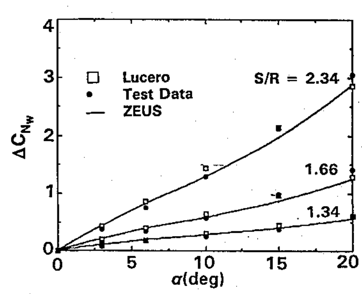

Fig. 3 ZEUS-Lucero comparison at Mach 4.63.

Results and Discussion

Lucero Comparisons

Figures 2 and 3 show comparisons of ZEUS results with the empirical results of Lucero.[1,2] The figures show ΔC_{N_W} vs α for three fins with S/R values of 2.34, 1.66, and 1.34. Figure 2 shows data at Mach number 2.96, and Fig. 3 shows data at Mach number 4.63. The Euler results compare very well with Lucero and with test data from Spearman and Trescott[24] for each case. Even at the high Mach number range and high α range where viscous effects are more prevalent, the Euler results are still within 15% of the test data. This clearly shows how the large windward pressures dominate the viscous effects in determining the lift.

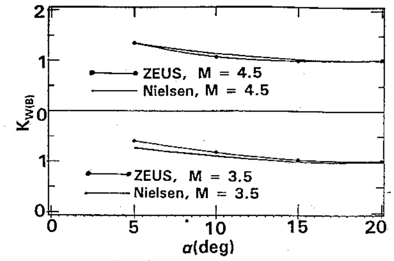

Fig. 4 ZEUS-Nielsen $K_{W(B)}$ comparison for $\Lambda = 59.44$ deg, $S/R = 2$, $AR = 0.5$. (Fin F32 of Ref. 3.)

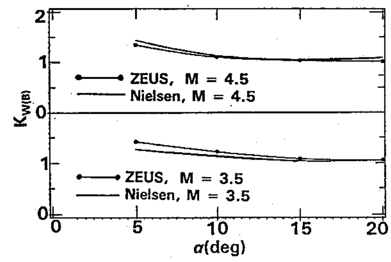

Fig. 5 ZEUS-Nielsen $K_{W(B)}$ comparison for $\Lambda = 0$ deg, $S/R = 2$, $AR = 0.5$. (Fin F33 of Ref. 3.)

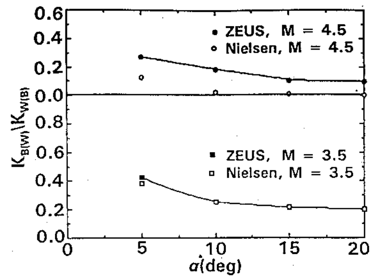

Fig. 6 ZEUS-Nielsen $K_{B(W)}/K_{W(B)}$ comparison for $\Lambda = 69.44$ deg, $S/R = 2$, $AR = 0.5$. (Fin F32 of Ref. 3.)

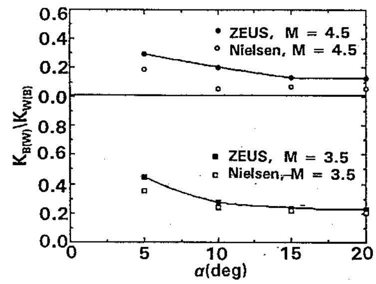

Fig. 7 ZEUS-Nielsen $K_{B(W)}/K_{W(B)}$ comparison for $\Lambda = 0$ deg, $S/R = 2$, $AR = 0.5$. (Fin F33 of Ref. 3.)

Nielsen Comparisons

Nielsen[3] reduced a partial set of data from the Triservice-NASA Data Base[4] to generate $K_{W(B)}$ and $K_{B(W)}$. Figures 4 and 5 show $K_{W(B)}$ vs α comparisons between ZEUS results and Nielsen[3] for $\Lambda = 69.44$ and 0 deg, respectively. Each figure shows comparisons at Mach number 3.5 and 4.5. Both figures show excellent $K_{W(B)}$ agreement at all angles of attack and both Mach numbers. Figures 6 and 7 show similar comparisons for $K_{B(W)}/K_{W(B)}$. Agreement between theory and experiment at Mach number 3.5 is good, but there are large differences at Mach 4.5. At Mach 4.5, for the entire range of α, Nielsen[3] shows virtually no change in the body force, whereas the Euler equations predict a small change. This is in the Mach number range where Euler codes do not accurately predict the leeside vortex separation from the body. Because $K_{B(W)}$ is a measure of the change in the body force, the vortex separation has a bigger impact on $K_{B(W)}$ than $K_{W(B)}$, which is driven by the

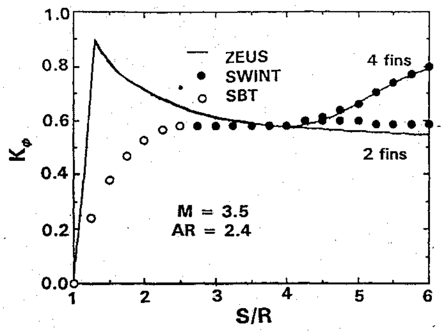

Fig. 8 Comparison of K_ϕ from the ZEUS and SWINT codes. K_ϕ vs S/R for delta-fins at Mach 3.5 with $\Lambda = 59.04$ deg and $AR = 2.4$.

windward pressure. Still, at Mach 3.5 the $K_{B(W)}$ values are accurate for the entire range of α.

Jenn and Nelson[6] used the Euler code SWINT to analyze fin–fin interference in sideslip. They considered delta-fin missile configurations with two, three, four and six fins located symmetrically around the fuselage. S/R ranged from 1 to 6 for each fin. Figure 8 shows data from SWINT calculations for a fin with an aspect ratio of 2.4. The K_ϕ values for the four-fin case break away from the K_ϕ values for the two-fin case near $S/R = 4$. This occurs because of shock and expansion wave interaction from the top and bottom fins.

Figure 8 also shows the current K_ϕ predictions from ZEUS, along with those from SWINT. Jenn and Nelson[6] used SBT to predict K_ϕ at low S/R values because the numerical results in this region were inaccurate. At a very small S/R value, the ZEUS clustered results also become inaccurate, but the previous comparisons with Lucero[1,2] imply that the clustered results are accurate for S/R values as low as 1.34.

The results from ZEUS and SWINT are similar in trend and magnitude for S/R values greater than 4. For S/R values between 3 and 4, ZEUS and SWINT produce K_ϕ values of the same magnitude, but the slopes are different. ZEUS shows K_ϕ to increase as S/R drops below 3, whereas SBT K_ϕ predictions smoothly approach zero.

Though ZEUS shows K_ϕ to increase as S/R decreases, there has to be a S/R value where K_ϕ reaches a maximum and starts to approach zero. As S/R approaches 1, K_ϕ must approach zero because the fin spans become infinitely small and sideslip will not affect the lift. In reality, the viscous boundary-layer effects become important as S/R approaches 1. These effects would cause K_ϕ to approach zero, but investigating this is beyond the scope of the present research. Consequently, the K_ϕ curves have been fared to zero starting near $S/R = 1.25$.

Currently it is thought that the Euler K_ϕ results differ from SBT because of vorticity effects. SBT is based on linear-potential theory and is, therefore, irrotational. Jenn and Nelson[6] showed the effects of shock waves and expansion waves on K_ϕ, but they occur at S/R values greater than or near 4 or greater. The vortex effects occur at small S/R values where the grid mesh used by Jenn and Nelson[6] was too coarse to detect them.

The emphasis of this research was to predict $K_{W(B)}$, $K_{B(W)}$, and K_ϕ; however, body-alone lift is also needed to calculate total missile lift. Data for L_B and the body-alone center of pressure are available in Ref. 25. The data are correlated and presented as a function of angle of attack from 0 to 30 deg for several Mach numbers, ranging from 0.6 to 10. The data correlations are compared to ZEUS predictions and experimental results.

Conclusions

Euler ΔC_{N_W} predictions for low aspect ratio missiles using clustered grids agree with the empirical work of Lucero.[1,2] Although the Euler equations are inviscid, the predictions are shown to be accurate for Mach numbers of 2.96 and 4.63 for α up to 20 deg. The Euler equations can be used to predict $K_{W(B)}$ accurately for preliminary design.

The body–fin interference $K_{B(W)}$ has also been analyzed. At Mach 3.5, the $K_{B(W)}$ predictions are within 15% of experiment for α up to 20 deg. At Mach 4.5, $K_{B(W)}$ predictions do not agree with wind-tunnel data. Vortex separation due to viscosity is the most likely reason for the disagreement.

The K_ϕ results from ZEUS agree with SWINT for S/R values greater than 3, as they should. For S/R values between 1 and 3, Euler K_ϕ predictions are larger than the results from SBT, probably due to vorticity. Because most low-aspect ratio fins have S/R values less than 2, this is a significant development in the understanding of K_ϕ.

Acknowledgments

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