Modeling Supersonic Missile Fin-Body Interference for Preliminary Design

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Aerodynamic interference between adjacent surfaces plays an important role in the performance of missiles. Fin-body interference factors are used in the Missile Datcom method to predict missile aerodynamic characteristics using the equivalent angle-of-attack method. This investigation presents a simple, accurate, and rapid method to determine fin-body interference factors for preliminary design. Linearized potential theory is used to evaluate the effect of body upwash on the local velocity along the fin leading edge as a function of fin span. A panel method is applied to determine the change in equivalent angle of attack due to body upwash. Planar fin configurations are considered with the fins located symmetrically on the missile body; however, the results also apply to cruciform configurations. The fin-body interference factors are presented as a function of Mach number and changes in missile geometry, such as fin leading and trailing edge sweep, fin vertical position on the fuselage, and fuselage cross-sectional shape. Circular and elliptic fuselage cross sections are considered. The method is shown to be quite accurate.

Nomenclature

A_w	= area of wing (two fins)
A_i	= area of panel
AR	= aspect ratio
B	= body semiaxis in crossflow direction ($\phi = 180$ deg)
B/R	= ratio of fuselage semiaxes
e	= eccentricity
H/B	= ratio of fin vertical position to fuselage semiaxis
$K_{W(B)}$	= fin-body interference factor due to upwash
K_ϕ	= fin-body interference factor due to sideslip
L_W	= lift of fin alone
$L_{W(B)}$	= lift of fin in presence of body
m,n	= velocity factors
M	= Mach number
R	= body semiaxis perpendicular to crossflow ($\phi = 90$ deg)
S	= fin span measured from the body centerline
S/R	= ratio of fin span to body semiaxis
V_C	= velocity in the crossflow plane on the fin alone
V_N	= normal velocity component
V_{NW}	= crossflow velocity perpendicular to fin
V_T	= tangent velocity component
V_∞	= freestream velocity
x,y	= coordinate axes based on the center of missile body
α_{eq}	= missile equivalent angle of attack
α_F	= missile angle of attack
$(\Delta\alpha_{eq})_V$	= equivalent angle of attack due to vortex interactions
β_F	= missile sideslip angle
ϵ	= fin leading edge semivertex angle
θ	= slope of streamline
μ	= Mach angle
τ	= fin trailing edge semivertex angle
ϕ	= angular coordinate, measured from bottom of fuselage

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Introduction

In preliminary design configuration changes are common; consequently, simple, accurate, and rapid methods are needed to calculate aerodynamic derivatives and interference factors for tradeoff studies. A commonly used method is the component buildup method.[1,2] As the name indicates, the overall loads on the airframe are "built up" by summing the aerodynamic characteristics of the major airframe parts in isolation (body, fin, tail) and then using interference factors to account for the additional loads due to their mutual interference. For tactical missiles, the interference effects are often first order and nonlinear.

Component buildup methods are used in Missile Datcom, which was developed by Vukelich and Jenkins[3] and extended to include arbitrary shaped bodies and large angles of attack by Stoy and Vukelich.[4] The component buildup method is based on the equivalent angle of attack. It models the nonlinear lifting characteristics of missile fins by defining the equivalent angle of attack as

$$\alpha_{eq} = K_{W(B)}\alpha_F + 4K_\phi\alpha_F\beta_F/AR + (\Delta\alpha_{eq})_V \tag{1}$$

where terms on the right-hand side represent the contributions due to body upwash, fin sideslip, and vortex interaction, respectively. The equivalent angle-of-attack method is derived, and its accuracy is demonstrated in Refs. 5 and 6. The fin-body interference factor $K_{W(B)}$ is very useful in calculating aerodynamic coefficients of missiles. The effect of sideslip on fin normal force is represented by K_ϕ. It has been investigated in Refs. 7–9. This paper concentrates on finding $K_{W(B)}$ for different missile configurations and flight conditions.

The effect of body upwash on the fin lift is characterized by $K_{W(B)}$, which is defined as the ratio of the lift on the fin in the presence of the body to the lift on the fin alone,

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

Fin-body interference has received much attention in the literature for missiles with their fins located on the body centerline. Values of $K_{W(B)}$ were determined using linearized potential theory (LPT) in Ref. 7. Experimental wind-tunnel results for $K_{W(B)}$ are given in Ref. 10 for a wide variety of missile configurations and flight conditions.

The variation of $K_{W(B)}$ for fins located above or below the body centerline for missiles with circular fuselage cross sections is reported in Refs. 8 and 11. In these references, $K_{W(B)}$

was numerically computed using a finite-difference Euler code (SWINT) for various fin geometries and fin vertical positions. A numerical paneling method was used in Ref. 12 to determine $K_{W(B)}$ for incompressible flow as a function of fin vertical position and span.

Missiles with noncircular fuselage cross sections are of current interest because they may offer improved performance over conventional cylindrical cross-sectional shapes for bank-to-turn and airbreathing missiles.[13] Elliptic cross sections offer possible improved storage, carriage, separation, and aerodynamic performance. Slender body theory (SBT) has been applied to missiles with elliptic cross sections in Ref. 14. The numerical code SWINT, which solves Euler's equations, has been used to obtain $K_{W(B)}$ for missiles with elliptic cross sections in Ref. 15.

The objective of this research is to develop a simple, rapid, and accurate method to determine $K_{W(B)}$ for different body cross-sectional shapes and fin geometries for use in preliminary design. Figure 1 shows the missile configuration used in this investigation and presents some of the basic parameters used in the analysis.

Analytical Methodology

The methodology used in this investigation follows that used in Refs. 8 and 11. In these references, LPT was used to analytically determine the velocity normal to the fin as a function of fin span for circular cross-sectional fuselages. LPT has been shown to work well for supersonic missiles at small angles of attack because the crossflow velocity ($V_C = V_\infty \alpha_F$) is subsonic. For this research the expression for the crossflow velocity field will be developed in general so that it applies to both elliptic and circular cross-sectional fuselages using potential theory results from Zahm.[16] The geometry is shown in Fig. 2.

The equation for an elliptical fuselage cross section with semiaxes B and R is $(x/R)^2 + (y/B)^2 = 1$. For B greater than R, the eccentricity e is $\sqrt{(B^2 - R^2)}/B$. The eccentricity of a confocal ellipse $(x/R')^2 + (y/B')^2 = 1$ centered on the fuselage and located in the external flowfield is also e, with B' and R' replacing B and R. To determine the velocity components

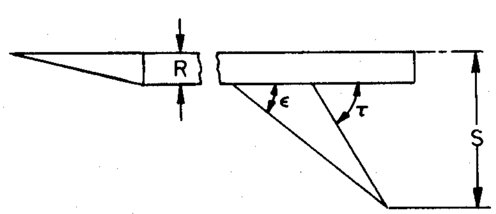

Fig. 1 Typical missile configuration.

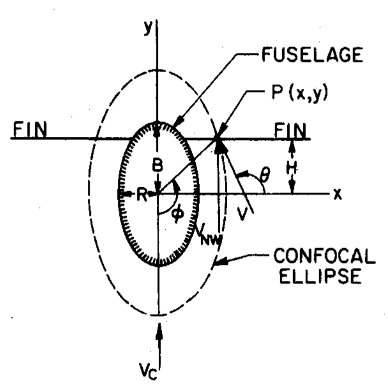

Fig. 2 Schematic of the missile crossflow plane.

at point $P(x,y)$, it is necessary to evaluate R' and B' for the confocal ellipse that passes through the point. The equations for R' and B' are written in terms of e as

$$R' = \sqrt{x^2 + y^2(1 - e^2)} \tag{3a}$$

$$B' = \sqrt{x^2/(1 - e^2) + y^2} \tag{3b}$$

where e contains the fuselage parameters R and B. The slope of the confocal ellipse at $P(x,y)$ is given by

$$\tan\theta = -(B'/R')^2(x/y) \tag{4}$$

This is the reference angle for the velocity components V_N and V_T, normal and tangent to the confocal ellipse at $P(x,y)$, respectively. Note that the line joining the origin and $P(x,y)$ makes angle ϕ with respect to the y axis, where

$$\tan\phi = (R'/B')^2 \tan\theta \tag{5}$$

At point $P(x,y)$, the velocity components are a function of B, R, B', R', and angle θ. From Ref. 16 the velocity components normal and tangent to the ellipse are

$$V_N = -(1 - n)V_C \cos\theta \tag{6a}$$

$$V_T = (1 + m)V_C \sin\theta \tag{6b}$$

where $V_C = V_\infty \alpha_F$ and

$$n = R(R + B)/[R'(R' + B')] \tag{7a}$$

$$m = R(R + B)/[B'(R' + B')] \tag{7b}$$

Note that V_N is positive along the outward normal and V_T is positive in the counterclockwise direction.

In the limiting case of a circular missile fuselage ($B = R$, $B' = R'$, $\theta = \phi$, and $e = 0$), the velocity components reduce to

$$V_N = -[1 - (R/R')^2]V_C \cos\theta \tag{8a}$$

$$V_T = [1 + (R/R')^2]V_C \sin\theta \tag{8b}$$

For an infinitely small fin, the flow over the fin-body is the same as the flow over the body alone. In this limit for elliptical cross-sectional fuselages ($B' = B$ and $R' = R$), the velocity components reduce to $V_N = 0$ and $V_T = (1 + R/B)V_C \sin\theta$ on the fuselage. The effect of the missile body cross-sectional shape is to double the crossflow velocity for circular cross sections ($B/R = 1$) and to quadruple the crossflow velocity for elliptic cross sections with $B/R = 0.33$ at $\theta = \pi/2$.

Panel Upwash Analysis

$K_{W(B)}$ is equal to the ratio of the fin angle of attack in the upwash flowfield of the body and the fin angle of attack in the freestream flow. This ratio is shown to be a ratio of velocities V_{NW} and V_C in Ref. 11, so that $K_{W(B)}$ becomes

$$K_{W(B)} = V_{NW}/V_C \tag{9}$$

LPT gives the body upwash velocity (crossflow velocity) as a function of spatial location in the flow. This velocity can be used to calculate $K_{W(B)}$. The velocity normal to the fin is a function of spanwise position. It can be written as

$$V_{NW} = V_T \sin\theta - V_N \cos\theta \tag{10}$$

Thus, using Eqs. (6), the upwash velocity at any spanwise position becomes

$$V_{NW}/V_C = (1 - n)\cos^2\theta + (1 + m)\sin^2\theta \tag{11}$$

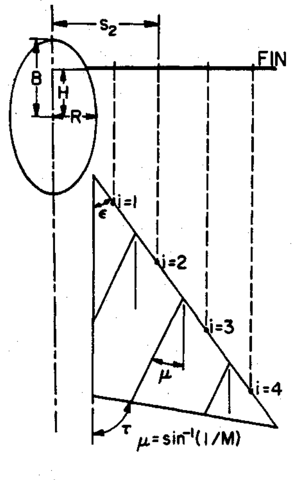

Fig. 3 Paneling geometry used to determine $K_{W(B)}$ for $I = 4$.

Figure 2 shows the missile cross section used for this research. The fins are located at a distance H above the fuselage centerline. For a fin located on the fuselage centerline, Eqs. (9–11) predict the limiting cases of $K_{W(B)}$ to be 1) 1 for a large fin on a small body ($S/R \approx \infty$) and 2) $(1 + R/B)$ for a small fin on a large body ($S/R \approx 1$). In the first case, the fin span is very large compared to the body radius (i.e., $\theta \approx \pi/2$, $m \approx 0$), so that $V_{NW} \approx V_C$ and the interference vanishes driving $K_{W(B)}$ to unity. The second case involves the crossflow velocity pattern adjacent to the elliptical cylinder surface at $\theta = \pi/2$, so that $m \approx R/B$ and $V_{NW} \approx V_C(1 + R/B)$.

In this analysis panel theory is used to determine the $K_{W(B)}$ for arbitrary values of S/R. The panel nomenclature and geometry are shown in Fig. 3. The panels are bounded by Mach lines so that their size and geometry change as a function of Mach number. At very large Mach numbers, the panel boundaries become parallel to the chord line. Using Mach lines for panel boundaries reduces the fin area influenced by large upwash velocities near the fin root relative to the case where panels have boundaries parallel to the fin chord. The inward pointing Mach line was used as a panel boundary so that part of the fin leading edge would always be on a panel boundary as the panels become small.

The analysis involves the sum over the I panels to give $K_{W(B)}$ as

$$K_{W(B)} = \frac{2}{A_W} \sum_{i=1}^{I} (V_{NW}/V_C)_i A_i \tag{12}$$

where V_{NW}/V_C is given by Eq. (11) and $A_w = \sum_{i=1}^{I} A_i$. The velocity ratio was evaluated at point $P(x,y)$, located on the fin leading edge at the midpoint of area A_i. As the number of panels increases (I increases), the value of $K_{W(B)}$ converges to a constant.

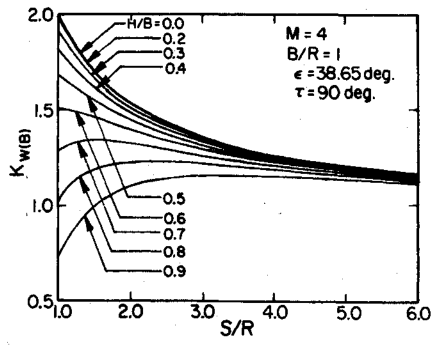

Fig. 4 Effect of fin vertical position on $K_{W(B)}$ for $M = 4$ and $B/R = 1$.

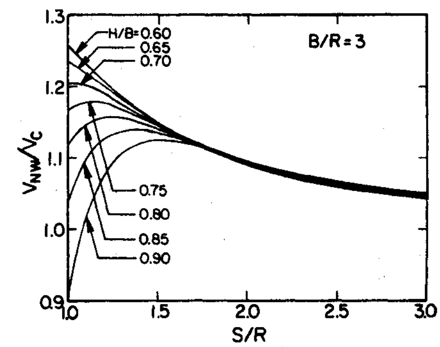

Fig. 5 Velocity normal to the fin at large values of H/B.

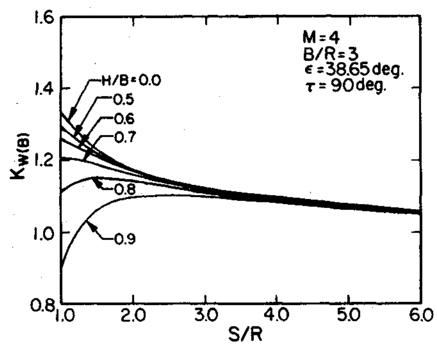

Fig. 6 Effect of fin vertical position on $K_{W(B)}$ for $M = 4$ and $B/R = 3$.

Results and Discussion

A computer code was developed to calculate the value of $K_{W(B)}$ for different fin-body configurations and missile flight conditions. The analysis considers only one fin and assumes symmetry about the body centerline. Thus, the results apply to symmetrical planar and cruciform configurations with infinitely thin fins. Calculations are presented for three leading edge semivertex angles ($\epsilon = 30.96$, 38.65, and 45.00 deg) corresponding to aspect ratios of 2.4, 3.2, and 4.0 (based on $\tau = 90$ deg). Four other parametric variations were considered: 1) M was varied from 2 to 6; 2) H/B was varied from -0.9 to 0.9; 3) τ was changed from 50 to 150 deg; and 4) B/R was varied from 0.33 to 3.0. $K_{W(B)}$ was calculated for $1 \leq S/R \leq 6$. Typical values of S/R for missiles range from 2.5 to 4.0.[17]

The results for $K_{W(B)}$ are presented graphically as a function of S/R. The parameter S/R is hard to define when the fin is moved off the fuselage centerline because two identical fins at different vertical positions have slightly different spans, or different values of S/R. For the purposes of data comparison, this small adjustment was not practical. Consequently, all of the values of S/R used in the data presentation were determined as if the fin were located on the missile centerline. This implies that S is evaluated as the sum of the body radius (R) and the exposed fin semispan. Therefore, S/R always varies from one to infinity regardless of the fin vertical position.

Fin Vertical Position, H/B

The change in $K_{W(B)}$ due to moving the fin vertically on the fuselage was analyzed for circular and elliptical body shapes ($B/R = 1.0$ and 3.0). LPT predicts the same value for $K_{W(B)}$ when the fin is moved a specific distance above or below the body horizontal centerline because the crossflow velocity field is symmetrical with respect to the fuselage centerline. This is in agreement with the results of Refs. 8 and 11 for circular body cross sections. Figure 4 shows that there is a significant decrease in $K_{W(B)}$ for small fins ($S/R \approx 1$) as H/B increases from

0 to 0.9. For fins far away from the body centerline (i.e., H/B greater than 0.6), the maximum value of $K_{W(B)}$ moves outward to S/R values greater than 1. This can be explained by considering the velocity distribution at different H/B positions as shown in Fig. 5. Recall that as H/B increases the fin root chord location approaches the stagnation point at the top of the fuselage. Thus, the normal velocity V_{NW} goes to zero and $K_{W(B)}$ goes to zero. As one moves away from the fuselage to larger S/R values, V_{NW} increases to a value slightly greater than V_C and then decreases back to V_C as S/R becomes very large. As S/R increases to very large values, the crossflow velocity becomes normal to the fin for all values of H/B. Consequently, the values of $K_{W(B)}$ converge to 1 at large values of S/R for all values of H/B.

The effect of fin vertical position on $K_{W(B)}$ for an elliptic fuselage ($B/R = 3$) is shown in Fig. 6. The effect of H/B is negligible for fins with $S/R > 3.0$, whereas the effect of H/B is significant up to values of S/R greater than 4 for a circular fuselage cross section ($B/R = 1$) as shown previously in Fig. 4.

Trailing Edge Sweep, τ

Figure 7 shows $K_{W(B)}$ as a function of S/R for a range of trailing edge semivertex angles for a circular cross-sectional body with a fin at $H/B = 0$. As the trailing edge semivertex angle is increased from 50 to 130 deg, $K_{W(B)}$ at a specific value of S/R decreases. This occurs because increasing τ increases the fin area near the fin tip relative to the fin area near the root. This increases the importance of the fin tips relative to the fin roots and, in turn, decreases the value of $K_{W(B)}$. In other words, the effective angle of attack V_{NW}/V_∞ is lower near the tip than it is near the fuselage for $B/R = 1$. The net effect is a decrease in $K_{W(B)}$ for increases in τ at all values of S/R. Figures 8 and 9 show the effect of changing τ on $K_{W(B)}$ for elliptical body cross sections with $B/R = 3$ and $B/R = 0.33$, respectively. In general, smaller values of τ yield larger values of $K_{W(B)}$, or larger positive fin-body interference at a specific value of S/R for all cross-sectional shapes.

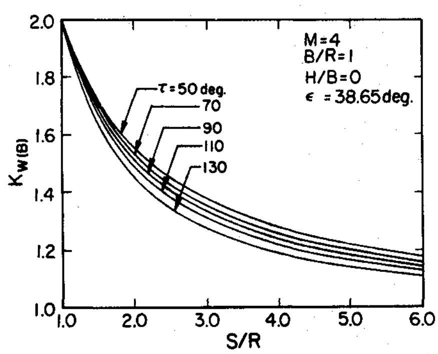

Fig. 7 Effect of trailing edge sweep on $K_{W(B)}$ for $M = 4$ and $B/R = 1$.

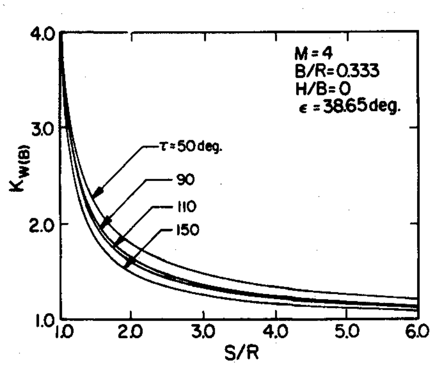

Fig. 8 Effect of trailing edge sweep $K_{W(B)}$ for $M = 4$ and $B/R = 0.333$.

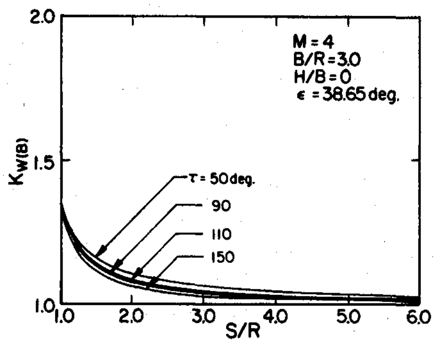

Fig. 9 Effect of trailing edge sweep on $K_{W(B)}$ for $M = 4$ and $B/R = 3$.

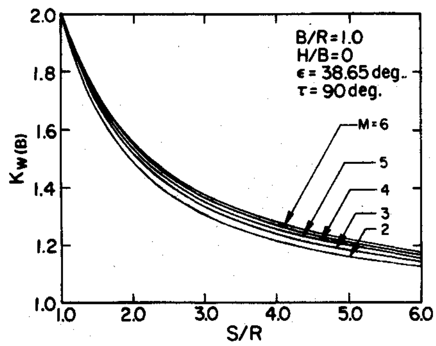

Fig. 10 Effect of Mach number on $K_{W(B)}$ for $B/R = 1$ and $H/B = 0$.

Mach Number, M

Figure 10 shows $K_{W(B)}$ as a function of S/R for missiles with circular fuselage cross sections at Mach numbers from 2 to 6. For a specific value of S/R, $K_{W(B)}$ increases as the Mach number increases. Since the model is based on LPT, which is independent of Mach number, the only Mach number effects are due to the change in the panel shape with Mach number. In the panel analysis, increasing the Mach number aligns the panel edges closer to the direction of the freestream velocity. This causes the panel near the fin root to increase in area. The crossflow velocities are larger at the fin root than they are at the fin tip, so that panels near the fin root become more important in determining the value of $K_{W(B)}$. This, in turn, causes the value of $K_{W(B)}$ to increase with Mach number at a specific value of S/R. Figures 11 and 12 show the effect of Mach number on $K_{W(B)}$ for missiles with $B/R = 0.333$ and $B/R = 3$, respectively. The fin-body interference factor becomes less sensitive to Mach number at large values of B/R.

Body Ellipticity, B/R

In the limit of infinitely small fins, when B/R decreases from 3.0 to 0.33, LPT predicts that $K_{W(B)}$ will increase from 1.33 to 4.0. Figure 13 shows calculations of $K_{W(B)}$ as a function of S/R for several values of B/R. At small values of S/R, $K_{W(B)}$ is very sensitive to the value of B/R. $K_{W(B)}$ decreases rapidly as a function of S/R (for S/R less than 3) for B/R less than 1. In general for B/R greater than 1, $K_{W(B)}$ is smaller than it is for B/R less than 1. In the limit, as B/R goes to infinity, the value of $K_{W(B)}$ goes to 1 for all S/R because in this limit the missile fuselage has zero width. Thus, the crossflow becomes equivalent to that over a vertical flat plate and does not have to turn to go around the fuselage. The effect of changing B/R becomes small at large S/R.

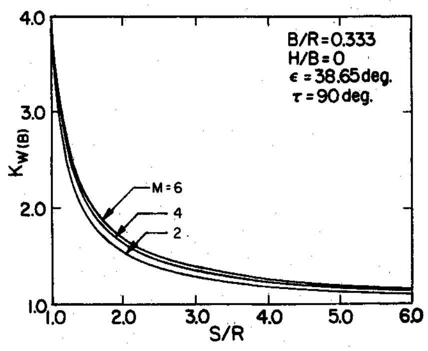

Fig. 11 Effect of Mach number on $K_{W(B)}$ for $B/R = 0.333$ and $H/B = 0$.

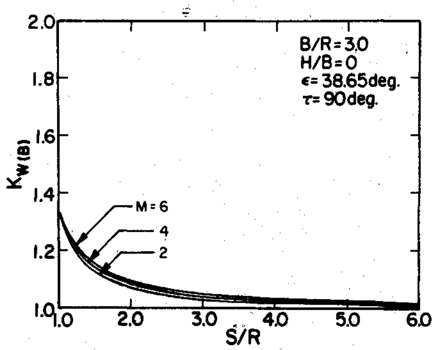

Fig. 12 Effect of Mach number on $K_{W(B)}$ for $B/R = 3$ and $H/B = 0$.

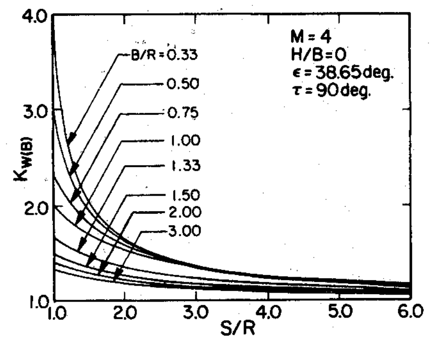

Fig. 13 Effect of body ellipticity on $K_{W(B)}$ for $M = 4$ and $H/B = 0$.

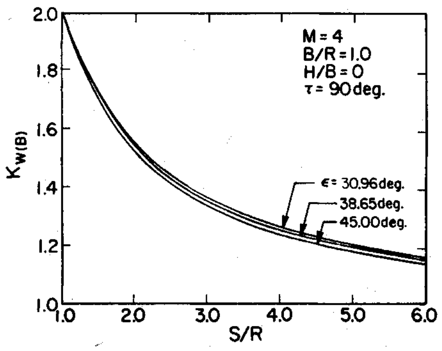

Fig. 14 Effect of leading edge sweep on $K_{W(B)}$ for $M = 4$ and $H/B = 0$.

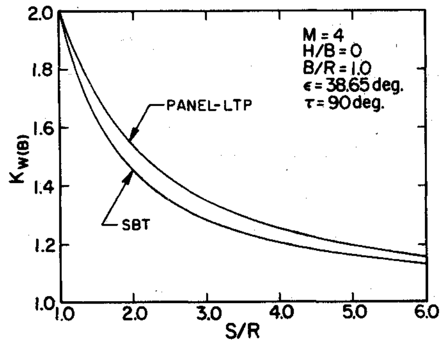

Fig. 15 Comparison of LPT-panel model results with SBT results from Nielsen.[7]

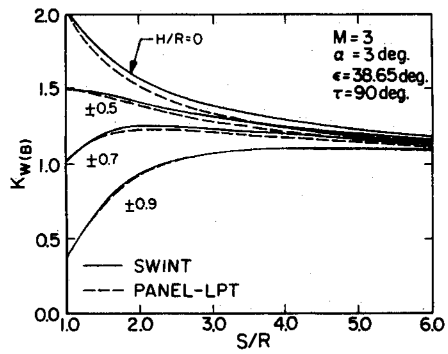

Fig. 16 Comparison of LPT-panel model results with Euler equation numerical results from Jenn and Nelson[11] for circular body cross sections.

Leading Edge Sweep, ε

Figure 14 shows that $K_{W(B)}$ is not very sensitive to changing the leading edge semivertex angle from 31 to 45 deg. In general, increasing the leading edge sweepback (decreasing ε) increases the value of $K_{W(B)}$ at a specific value of S/R.

Comparison to Previous Work

A concern that immediately comes to mind is how accurate are the LPT-panel method results? Figure 15 shows $K_{W(B)}$ as predicted by Nielsen[7] using SBT and $K_{W(B)}$ as predicted herein by the LPT-panel model at Mach 4 for a circular fuselage cross section with a delta-wing. Recall that the SBT results are not a function of Mach number, whereas the LPT results are a slight function of Mach number. The values of $K_{W(B)}$ from the LPT-panel model are slightly higher than the SBT calculations with a maximum difference of 10% at S/R about 2.

A comparison of $K_{W(B)}$ obtained using the LPT-panel method for a circular cross-sectional fuselage and Euler equation numerical results obtained by Jenn and Nelson[11] is shown in Fig. 16 for several H/B positions. The differences are less than 5%; consequently, the LPT-panel model is quite accurate, and it should be a good preliminary design tool.

Conclusions

A panel model based on LPT was used to determine the effect of variation of fin geometry (ε and τ), fin vertical position (H/B), and body cross-sectional shape (B/R) on the fin-body interference factor $K_{W(B)}$ for fin span to body radius ratios (S/R) between 1 and 6. For small fin spans, $K_{W(B)}$ decreases symmetrically as the fin is moved vertically up or down from the fuselage centerline. At large fin spans, $K_{W(B)}$ approaches 1 for all fin vertical positions. At fin vertical positions far from the fuselage centerline and at small S/R values, $K_{W(B)}$ becomes less than 1, indicating unfavorable interference. For circular fuselage cross sections and infinitely small fins ($S/R \approx 1$), $K_{W(B)}$ varies from 2.0 for $H/B = 0$ to 0.4 for $H/B = \pm 0.9$, or from strong positive interference to strong negative interference. The change in $K_{W(B)}$ with fin vertical position for an elliptical cross-sectional centerbody ($B/R = 3$) was found to be negligible for S/R greater than 2.5, but at small fin spans, $K_{W(B)}$ is very sensitive to the fin vertical position because of the possibility of unfavorable interference at S/R less than 1.5.

$K_{W(B)}$ decreases as the fin trailing edge semivertex angle increases from 50 to 150 deg. In general, smaller values of τ yield larger values of $K_{W(B)}$ for all S/R values. Also, $K_{W(B)}$ becomes less sensitive to τ as the body ellipticity (B/R) increases. The effect of leading edge sweep angle on $K_{W(B)}$ is similar to that of the trailing edge sweep angle. As ϵ increases from 30 to 45 deg, $K_{W(B)}$ decreases for all S/R. Fin-body interference is very sensitive to body ellipticity (B/R), especially in the fin span to body radius ratio relevant to missiles ($S/R = 2.5$–4.0).

Results for $K_{W(B)}$ from the LPT-panel model compare well with numerical results obtained from the Euler equations at small angles of attack. The LPT-panel model is not applicable at high angles of attack because of the formation of vortices and when complicated geometries are involved because it does not account for shockwaves between fins. Also, the analysis is inaccurate in the evaluation of the sideslip interference factor K_ϕ. But for planar, infinitely thin, two- and four-fin configurations with no sideslip, the model gives accurate results.

The model developed herein can be used by missile aerodynamicists for preliminary estimates of $K_{W(B)}$. The method is simple, fast, and fairly accurate. Further research is needed to determine $K_{W(B)}$ at higher angles of attack and Mach numbers at which vortices, crossflow shockwaves, and viscous effects must be considered. Future research[17] will explore supersonic missile aerodynamics using a numerical Euler equation solver called ZEUS[18] (Zonal Euler Solver) to find interference factors for missiles having more complex fin-body configurations and fin geometries.

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