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Evaluation of Component Buildup Methods for Missile Aerodynamic Predictions

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This paper presents an evaluation of component buildup aerodynamic methods for missile design. The methods presented define the methodology which could be incorporated into a handbook and computer program for missile aerodynamic predictions. Selected criteria and recommended aerodynamic prediction methods for isolated components, interference, inlet/airframe interactions, vortices, and propulsion system effects are presented for use in conceptual or preliminary design. The methods investigated include theoretical, semiempirical, and empirical techniques presently used in industry. Although many methods are available, gaps in methodology do exist and are identified.

Nomenclature

$A\!\!\!R$ = exposed panel aspect ratio
b = exposed panel span
C_A = axial force coefficient
C_D = drag coefficient
C_N = normal force coefficient
C_m = pitching moment coefficient
d = body diameter
ℓ = body length
M = Mach number
R_N = Reynolds number per foot of length
p = roll rate, rad/s
q = pitch rate, rad/s
r = yaw rate, rad/s
s = exposed panel semispan
α = angle of attack
β = sideslip angle or Mach similarity parameter
δ = deflection angle
λ = panel taper ratio
Λ = leading-edge sweep angle
ϕ = roll angle

Subscripts

b = at the base
f = due to friction
m = at the maximum point on the body
p = due to pressure (used for pressure drag)
W = due to wave (used for wave drag)

Introduction

THE timely design and analysis of missiles requires the use of rapid and accurate analytical procedures for predicting aerodynamic stability and control characteristics. The most complete published compendium of available methods is the USAF Stability and Control Datcom.[1] However, it emphasizes aircraft designs and does not address the range of parameters such as angle of attack and bank angle unique to missiles. Many missile methods are available in the literature and computer programs. However, there is no comprehensive evaluation of their applicability and accuracy.

This paper presents an evaluation of the results[2] of a study performed to determine the feasibility of developing a handbook and/or computer program for use by the missile design community. A definition of the ranges of geometric and flight conditions applicable to design was used to scope the effort. It summarizes the available methods and identifies additional development requirements.

The goals of missile and aircraft design are similar: develop a configuration to meet the mission requirements with a reasonable manufacturing cost. However, the means of achieving these goals are different for missiles because the design process is shorter and budgets are lower. Hence aerodynamic analysis must be performed accurately, quickly, and inexpensively.

As shown in Fig. 1 the design of a missile is a function of many nonaerodynamic factors. The choice of seeker, warhead, launcher, and propulsion system have a large impact in aerodynamic design. For example, a parametric on warhead size results in different diameter missiles. Hence the methods must be capable of addressing a large range of component parameters. The prediction technique best suited to perform parametric studies is the component buildup technique. It is usually less expensive than "paneling codes," has been extensively applied, enables rapid analysis, and permits substitution of alternate methods or empirical results.

Appropriate ranges of geometric and flight conditions were defined from over 800 test programs from the Aeromechanics Survey[3] and missile design experience. Each of the conditions was assigned a "priority." The priority 1 and 2 conditions reflect current and advanced design requirements, respectively. Table 1 summarizes the ranges of geometric and flight condition parameters used to assess method applicability.

The methods selection process was performed using the set of qualitative assessment criteria presented in Table 2. Existing theory to test data comparisons were used where available. Each method was examined to determine its applicability to the priority 1 conditions. Candidate methods were then grouped by aerodynamic coefficient and configuration component and compared with others. Theoretical methods were most desirable because they are more flexible in handling a wide range of parameters. Methods were identified for axisymmetric bodies, arbitrarily shaped bodies, lifting

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Table 1 Priority range of conditions

Parameter	Symbols	Priority 1	Priority 2
Angle of attack, deg	α	$-20 \leq \alpha \leq 30$	$-180 \leq \alpha \leq 180$
Sideslip angle, deg	β	$-20 \leq \beta \leq 20$	$-180 \leq \beta \leq 180$
Roll angle, deg	ϕ	$0 \leq \|\phi\| \leq 45$	$0 \leq \|\phi\| \leq 180$
Mach number	M	$0 \leq M \leq 6$	$0 \leq M \leq 10$
Reynolds number/ft	R_N	$3 \times 10^5 \leq R_N \leq 2 \times 10^7$	$10^3 \leq R_N \leq 3 \times 10^7$
Fin deflection/incidence, deg	δ	$0 \leq \delta \leq 30$	$0 \leq \delta \leq 60$
Roll rate, rad/s	p	$0 \leq \|p\| \leq 1$	$0 \leq \|p\| \leq 8$
Pitch rate, rad/s	q	$0 \leq \|q\| \leq 1.5$	$0 \leq \|q\| \leq 3$
Yaw rate, rad/s	r	$0 \leq \|r\| \leq 1.5$	$0 \leq \|r\| \leq 3$
Body fineness ratio	$(\ell/d)_B$	$6 \leq (\ell/d)_B \leq 20$	$1 \leq (\ell/d)_B \leq 30$
Nose fineness ratio	$(\ell/d)_N$	$0.5 \leq (\ell/d)_N \leq 5$	$0 \leq (\ell/d)_N \leq 7$
Fin exposed span to diameter	b/d	$1 \leq b/d \leq 6$	$0 \leq b/d \leq 10$
Fin aspect ratio	$\mathcal{R}$	$0.6 \leq \mathcal{R} \leq 4$	$0.1 \leq \mathcal{R} \leq 10$
Fin planform	...	Triangular, trapezoidal	All
Wing/tail orientation	...	In-line	All
Control method (wing or canard)	...	All movable fin	All

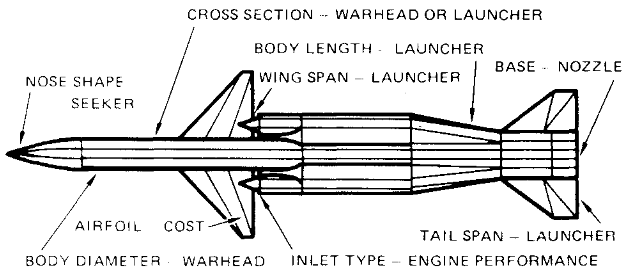

Fig. 1 Factors that affect missile design.

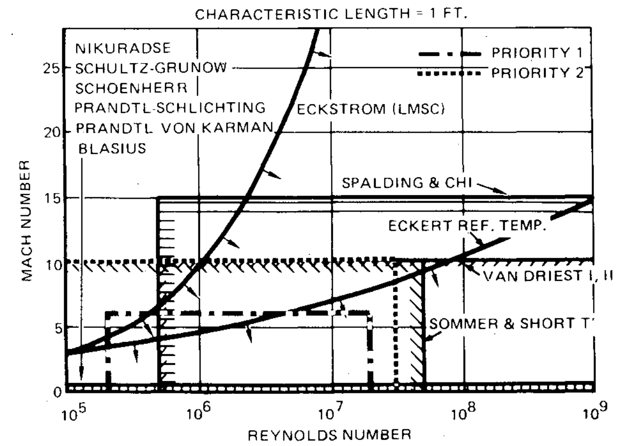

Fig. 2 Applicability of friction methods.

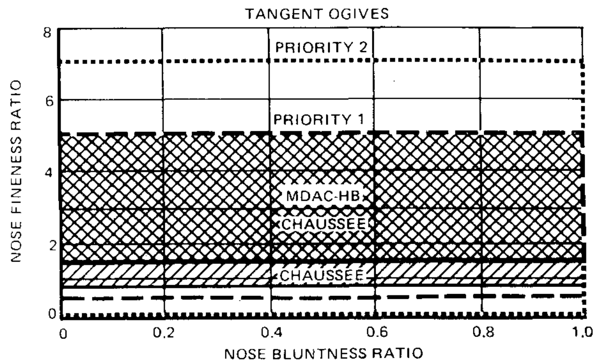

Fig. 3 Transonic nose wave drag method applicability.

surfaces, component interference, configuration synthesis, control devices, dynamic derivatives, and airbreathing inlet effects. Body prediction methods were emphasized since the body dominates the aerodynamic characteristics of missiles. The recommended methods are described in the following sections.

Body Alone Methods

Table 3 summarizes the method selection results for axisymmetric bodies. The methods, categorized according to Mach regime and component, are described below.

Subsonic Speeds

Pressure Drag

Semiempirical methods, which are theoretically based and correlated with experiment, achieve sufficient accuracy for prediction of body nose pressure drag. Hoerner[4] has correlated zero-lift drag test results with body fineness ratio and friction drag to derive the widely used "form factor" correction to friction drag.

Skin Friction

The selection of a skin friction method was performed by assessing the applicable ranges of many methods as shown in Fig. 2. At incompressible speeds the Schoenherr and Schultz-Grunow techniques[5] fully cover the priority 1 range of conditions. The Spalding-Chi[6] and Van Driest[7] theories also apply. However, the Van Driest II theory, as modified by Clutter,[8] is recommended at all Mach numbers because it accounts for roughness effects and includes heat transfer.

Base Drag

The prediction of base drag, with or without jet effects, is highly empirical. Hoerner[4] has correlated subsonic unpowered base drag to forebody drag for a large number of geometries. His is the recommended method. Power-on effects are more difficult to predict but empirical results are available.

Normal Force and Pitching Moment

Inviscid normal force and pitching moment are usually not affected by nose shape at subsonic speeds for typical "missile-like" configurations. Hence results from the slender body theory are adequate. Although several alternate approaches have been formulated to predict angle-of-attack effects, the Allen and Perkins[9] cross-flow approach is the most widely accepted, and has been shown to provide acceptable results for preliminary design. The recommended cross-flow technique is that formulated by Jorgensen,[10] which has been modified[11,12] to handle elliptical bodies.

Axial Force at Angle of Attack

Two methods for predicting body axial force at angle of attack are (1) the method of Allen and Perkins[9] and (2) the method of Jorgensen.[10,12] Past experience[13] has shown the Allen and Perkins result to provide better accuracy within the priority 1 range of conditions.

Transonic Speeds

Many techniques are empirical in the transonic speed regime owing to calculation complexity. This section highlights the present predictive capability.

Boattail/Base Drag

An empirical compendium of boattail drag was published by Payne[14] which serves as a good starting point for configuration analysis. The design range of afterbody fineness ratios are adequately covered.

Pressure/Wave Drag

A significant contribution to transonic analysis was made by Chaussee[15] through solution of the unsteady Euler equations for various tangent ogive nose shapes and various degrees of nose bluntness. These results cover the priority 1 range of conditions (Fig. 3), and have been found to agree favorably with the empirical compendium of the McDonnell Douglas Astronautics Company (MDAC).[16] Empirical results for other nose shapes are not as comprehensive.

Table 2 Assessment criteria

1)	Method approach Theoretical Semiempirical Empirical
2)	Efficiency (handbook/computer) Number computations Complexity of logic Number, type of inputs Iterative Detail of geometry required
3)	Accuracy Existing validation Compatibility with accuracy requirements Sensitivity of output to input accuracy Derivation assumptions—theoretical Range of data—empirical geometric model
4)	Status Current use in industry Handbook method available Method coded and used locally Does it need modification Is modification state-of-the-art
5)	Range of applicability Flight conditions (Mach, α,β,ϕ) Geometry
6)	Utility of output parameters Compatibility with other methods Thoroughness
7)	General utility Understandability Traceability Modifiability
8)	Validation status Existing validation Data base available to complete validation

Normal Force and Pitching Moment

Klopfer and Chaussee[17] have applied the unsteady Euler technique to compute normal force slope and pitching moment slope in the transonic regime. The results were fit with least-squares polynominals to enable parametric analysis. As shown in Fig. 4, they cover a limited range of priority 1 capability. Nearly complete coverage can be achieved by including empirical results.[21,23] However, capability is limited to tangent ogive shapes.

The effect of angle of attack is recommended to be solved through use of the Allen and Perkins cross-flow approach. Many variations[18-23] of cross-flow drag coefficient have been empirically derived at transonic speeds. An alternate approach proposed by Darling,[24] where the cross-flow drag curve is altered as a function of the nose and afterbody geometry, is worth further investigation.

Supersonic Speeds

Wave Drag, Normal Force, and Pitching Moment

Although supersonic flow theory is easier to manipulate than those at subsonic or transonic speeds, the computations remain laborious for hand calculation. However, they are fairly routine calculations on a digital computer. Of the many methods available, it is advantageous to select one theoretical pressure calculation scheme so that a single method can be used to predict wave drag and inviscid normal force and pitching moment. The Van Dyke hybrid theory[25] limits the variety of nose shapes which can be evaluated, since the shock must be attached and the Mach lines must lie exterior to the body surface. The applicability of the hybrid theory to sharp tangent ogive shapes is illustrated in Fig. 5. A fairly large portion of the priority 1 nose fineness ratios can be analyzed

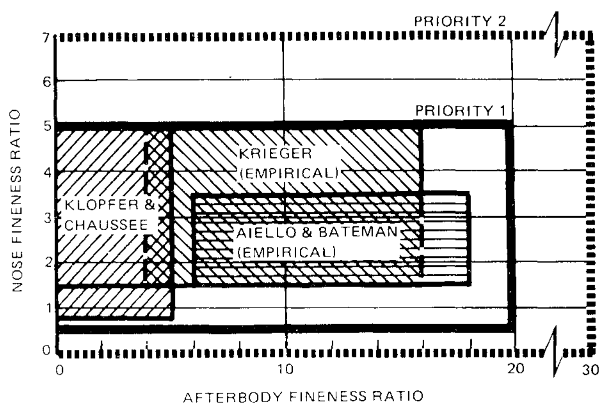

Fig. 4 Transonic capability for tangent ogive cylinder bodies.

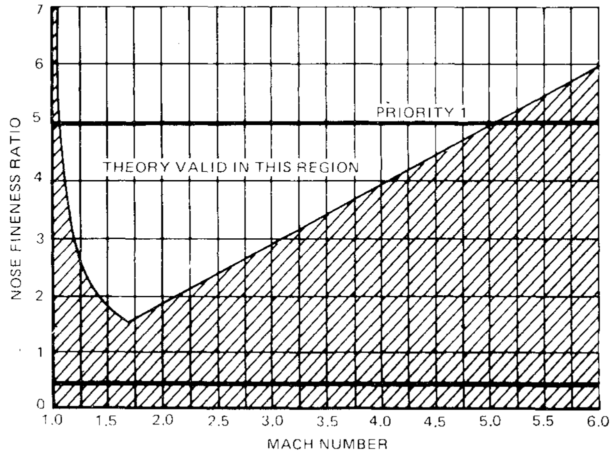

Fig. 5 Applicability of Van Dyke theory to tangent ogive shapes.

Table 3 Recommended body methods

Mach number region Component	$M \leq 0.6$ Subsonic	$0.6 < M < 1.2$ Transonic	$M \geq 1.2$ Supersonic
Nose pressure/ wave drag	Hoerner correction factor to C_{D_f}	Chaussee and empirical	Second-order shock expansion (or Van Dyke hybrid) and modified Newtonian
Boattail wave drag	...	Empirical	second-order shock expansion
Skin friction	————	Van Driest II	————
Base drag and jet effects	————	Empirical	————
Inviscid lift and pitching moment	Empirical plus Allen and Perkins	Klopfer and Chaussee plus empirical	Second-order shock expansion (or Van Dyke hybrid) and modified Newtonian
Viscous lift and pitching moment	————	Allen and Perkins cross flow	————
Axial force at angle of attack	Allen and Perkins	Empirical	Jorgensen plus empirical

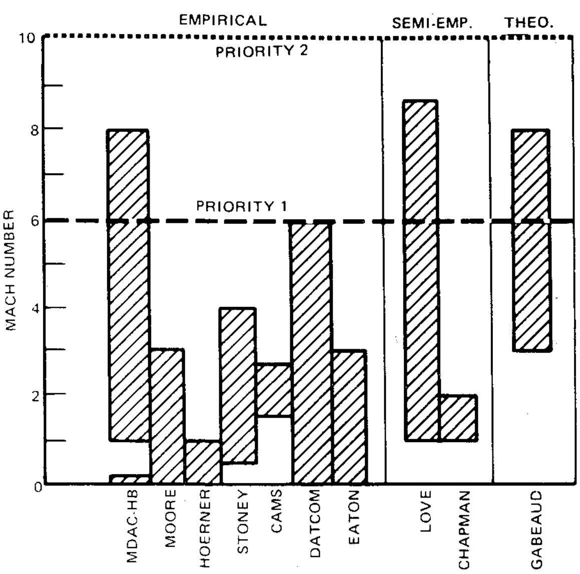

Fig. 6 Base drag methods summary.

at the lower supersonic Mach numbers. This method was modified by Moore and Swanson[26] to include nose bluntness by application of a modified Newtonian theory over the nose cap. A pressure matching condition is used to join the two solutions.

To cover the entire priority 1 Mach range requires the use of the second-order shock expansion (SOSE) method of Syvertson and Dennis.[27] It has been modified by DeJarnette[28] to include the effect of nose bluntness and has been shown[28] to give good results to Mach numbers as low as 1.5. Since SOSE can handle more general nose shapes and fineness ratios, and has been extended to the practical limit of low supersonic flow, it is recommended that this improved SOSE technique be investigated throughout the supersonic speed regime for accuracy and applicability. It may be necessary to include the hybrid theory if this analysis fails. The effect of angle of attack is recommended to be solved through use of the Allen and Perkins cross-flow concept.

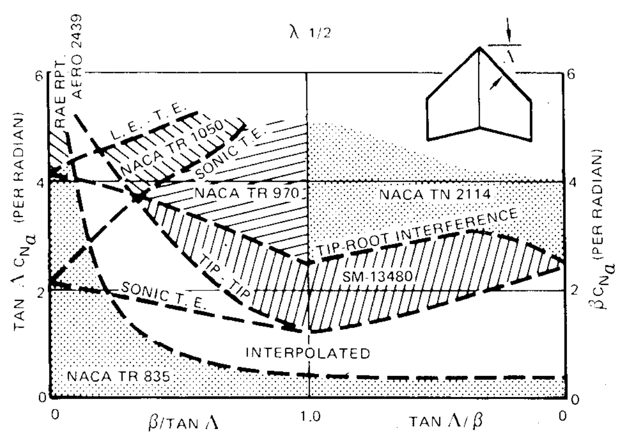

Fig. 7 DATCOM normal force slope design chart theoretical sources.

Base Drag

A qualitative comparison of base drag methods is shown in Fig. 6. The results of Love[29] are comprehensive and cover most of the priority 1 and 2 conditions. Moore[30] has developed an empirical method to account for angle of attack. It is easy to apply and ideal for preliminary design.

There is sufficient data available in the literature to perform the following method development tasks: 1) effect of base drag due to Reynolds number for laminar boundary layers (high altitude conditions); 2) effect of body fineness ratios less than 5; and 3) effect of boattailing at supersonic speeds. Much of the necessary data has been assembled by MDAC[16] to enable predictions or to develop analytical methods.

Axial Force at Angle of Attack

As the Mach number increases, there is a tendency for axial force to increase slightly with angle of attack up to a body incidence of 70-80 deg. There are no methods that predict this trend, forcing some analysts[21] to use zero angle-of-attack axial force predictions up to 80-deg angle of attack. The Allen and Perkins drag method is recommended in the priority 1 range of conditions since it has been shown[13] to yield

Table 4 Recommended lifting surface methods

Component / Mach number region	$M \leq 0.6$ Subsonic	$0.6 < M < 1.2$ Transonic	$M \geq 1.2$ Supersonic
Inviscid lift and pitching moment	Lowry-Polhamus or lifting surface theory	Empirical	Linear theory
Viscous lift and pitching moment	Empirical	Empirical	Empirical
Pressure or wave C_{A_O}	Datcom	Empirical	Linear theory
Skin friction drag		Van Driest II	
Leading-edge bluntness drag	———	Crosthwait	———
Trailing-edge separation drag	———	Empirical	———
C_A at angle of attack	———	Datcom or empirical	———

adequate results. At higher body incidences the use of experimental data is preferred. The Jorgensen[10] technique can be applied as an estimate.

Arbitrarily Shaped Body Methods

Little methodology exists to predict the aerodynamics of more arbitrarily shaped geometries, although some subsonic empirical methods are presented in the Datcom.[1] The most well-known development is that of Jorgensen,[11] where the potential and viscous terms of normal force and pitching moment have been corrected to more properly account for the section shape. Since "paneling codes" can be expensive, the use of the Jorgensen method in the preliminary design environment is tentatively recommended.

Lifting Surface Methods

The method recommendations for lifting surfaces are summarized in Table 4. At low angles of attack there are many theoretically derived results for inviscid lift and center of pressure at subsonic and supersonic speeds. The designer must resort to empirical correlations to determine the effect of angle of attack. The most comprehensive compendium of lifting surface methodology is the USAF Stability and Control Datcom.[1]

Normal Force and Pitching Moment

At subsonic speeds, the Lowry-Polhamus[31] formula is the easiest to apply. The Multhopp lifting surface theory[32] can be applied with greater confidence for lower aspect ratio panels, but it is difficult to utilize. A modified Multhopp technique[33] has been applied parametrically to derive design charts.[34] Since the use of the Lowry-Polhamus formula is generally regarded to be adequate for lower aspect ratio panels, it is the desired technique for hand computations. Both methods can be applied to straight-tapered and cranked surfaces.

At supersonic speeds, Datcom[1] has compiled an extensive array of theoretical results in the form of design charts as shown in Fig. 7. Figure 8 shows that they cover a significant percentage of the priority 1 range of straight-tapered surfaces. The results of the Royal Aeronautical Society (RAS)[35] are also available, but have a much smaller range of geometric capability. Non-straight-tapered panels are excluded from theoretical treatment at supersonic speeds. The reversibility theorem allows the application of the Datcom charts to swept-forward panels.

The Polyhamus suction analogy[36] has been used for low aspect ratio panels. It has been recently used by Lecat and Rietschlin[37] at subsonic, transonic, and supersonic speeds. Bradley[38] has also used the technique for arbitrarily shaped panel geometries. However, the Polhamus suction analogy has too small an application range for the range of panel aspect ratios desired, and its use is limited in the design environment.

The current means of predicting panel normal force and moment characteristics at angle of attack is through use of

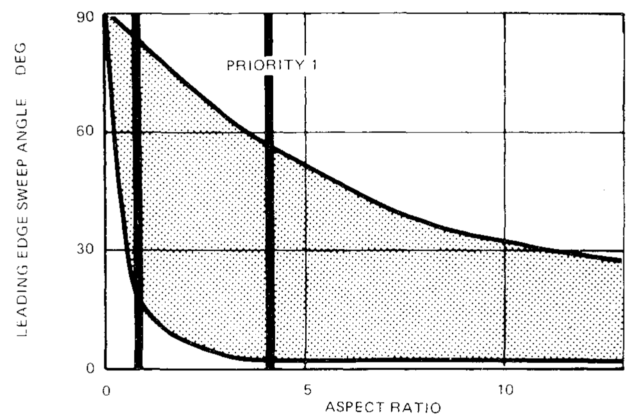

Fig. 8 Applicability of DATCOM charts.

empirical results. Stallings and Lamb[39] have summarized the experimental results available at present. The available data base encompasses aspect ratios between 0.5 and 2.0 and Mach numbers from 0.6 to 3.0. This data base should be expanded to higher aspect ratios and Mach numbers, and include cranked surfaces.

Axial Force

As for bodies, a "form factor" correction from Hoerner,[4] which is a function of panel thickness-to-chord ratio, is used to determine the effect of pressure drag at subsonic speeds. Analysis at transonic speeds has relied extensively upon empirical correlations. Interrelationships among a variety of parameters, such as sweep angle, position of maximum thickness, aspect ratio, and leading-edge sweep, have made correlation with similarity parameters difficult. Datcom[1] has used the von Kármán similarity laws to allow prediction of transonic wave drag, but the method has been correlated to only unswept, rounded leading-edge airfoils.

At supersonic speeds, two techniques are employed to determine panel wave drag. First, Datcom[1] presents an expression for wave drag as determined from linear theory, which is a function of section lift-curve slope, leading-edge sweep angle, and effective thickness-to-chord ratio; the effect of nose bluntness is added using Crosthwait[40] empirical results over the Mach range 0.5-5.0. Combined, these methods produce an estimate of panel wave drag at supersonic speeds. A second method, proposed by Moore,[26] applies modified Newtonian theory over the panel rounded leading edge to a "matching condition," and then second-order perturbation theory is applied over the remaining surface. The accuracy of the two methods has not been determined. The simpler Datcom technique is preferred.

Finally, panel base drag must be considered for blunted trailing-edge sections. Moore[26] has presented an empirical technique which is easy to apply.

Table 5 Recommended interference methods

Component / Mach number region	$M \leq 0.6$ Subsonic	$0.6M < 1.2$ Transonic	$M \geq 1.2$ Supersonic
Wing/body interference K,k	NACA 1307, empirical		Linear theory, slender body theory, and empirical
Wing/tail interference	———	Line vortex theory	———
Body base pressure drag caused by tail fins	———	Empirical	———
Jet interference	———	Empirical	———
Fin/fin interference	———	Slender body theory	———

Table 6 Empirical interference methods data base limitations

	Baker	Aiello	Nielsen
Mach number	0.6-3.0	0.6-3.0	0.8-3.0
Angle of attack, deg	0-180	0-30	0-45
r/s	0.3-0.5	0.3-0.5	0-0.5
A	0.5-2.0	0.5-2.0	0.5-2.0
λ	0-1.0	0-1.0	0-1.0

Component Interference

Table 5 presents the recommendations on component interference methodology. Most of the treatments are the result of the application of linear, slender body, or line vortex theory, which are generally applicable at low angles of attack. Theoretical developments at higher angles of attack do not exist.

Carryover

Bank-to-turn and skid-to-turn missile configurations require different angle-of-attack (α) and sideslip-angle (β) capability. The configuration total angle of attack can become quite large and has been shown[41] to be significant, particularly for lower aspect ratio panels. Hill and Kaattari[42] have evaluated the effect of angle of attack and panel incidence on carryover interference, and show that these effects must be taken into account. Since no theoretical method is available, empiricism is required. The ranges of empirical results[18,21,41] to compute fin/body carryover interference are given in Table 6; although this data base needs extension, it is useful.

Theoretical methods have been assembled in the linear range which enable the calculation of other carryover interference effects. The four effects are 1) the effect of nonzero panel trailing-edge sweep-back (Moore[43] extension of Pitts, Nielsen, and Kaattari[44]); 2) the effect of afterbody length (Vukelich and Williams[45]); 3) the effect of panel proximity and panel-panel interference (Nielsen[41]); and 4) the effect of body ellipticity (Krieger[23]). No methods are available to analyze non-straight-tapered or forward-swept panels. Methods are also lacking to predict the effect of nonplanar or noncruciform fin arrangements, such as triform or skewed cruciform (nonorthogonal) panels.

Vortex

Interference effects induced by a complex vortex flowfield require a more sophisticated missile aerodynamic analysis for missiles. As illustrated in Fig. 9, many of the methods available are empirically based. Methods for predicting nose and afterbody vortices have been developed through data correlations[1,41] and have been shown to be adequate over the priority 1 range of conditions. The problem of vortex interference has been explored in detail by Nielsen[41,46] in order to extend aerodynamic predictions to higher angles of attack.

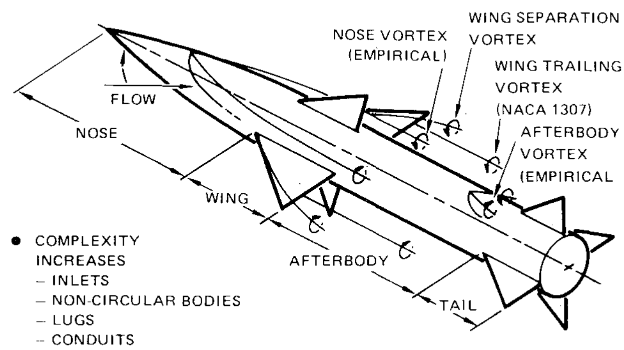

Fig. 9 Vortex considerations.

Within the requirements of the priority 1 range of conditions, the use of simple line vortex theory[44] is adequate. Priority 2 conditions require more accurate analytical techniques.

Vortex effect due to inlets, launchlugs, or conduits cannot be predicted and is often neglected.

Configuration Synthesis

Hemsch et al.[47] proposed the "equivalent angle-of-attack" concept for configuration analysis at arbitrary angle of attack and body roll angle. This method has been shown[47] to provide excellent results and is ideally suited to axisymmetric bodies and planar or cruciform panel arrangements. This approach is recommended in combination with the component buildup approach to missile aerodynamic analysis. As a byproduct it produces the prediction results necessary to evaluate panel hinge and bending moments.

Control Devices

The types of control devices employed on missiles are extremely limited. They are primarily incidence control or plain trailing-edge flap devices. Incidence control is incorporated in the "equivalent angle-of-attack" concept of Nielsen. The effect of plain flaps is thoroughly discussed in the Datcom.[1]

Dynamic Derivatives

The largest compendium of dynamic stability methods is contained in the Datcom.[1] Recently Ericsson[48,49] has extended slender body theory and Newtonian theory to more properly account for Mach number and nose bluntness effects. The Ericsson techniques have been applied up to Mach 6.0 and are recommended for use in combination with Datcom methodology. A large empirical data base is included in the SPINNER code[50] and these results are recommended for analysis of Magnus effect.

Airbreathing Inlet Effects

There is little design methodology available to predict the aerodynamic effects of inletted vehicles. Empirical results for chin-mounted inlets are available in CAMS.[51] A wide range of methods for various inlet designs have been published by McMillan et al.[52] A wind tunnel program has produced empirical results across the regime for both two-dimensional and axisymmetric inlets. Results are detailed in papers[53,54] presented at the 12th Navy Symposium on Aeroballistics. It may be possible to use these data to derive analytical prediction techniques for design.

Conclusion and Summary

Although many techniques are available to quickly and accurately predict missile aerodynamic characteristics, many gaps in methodology exist. Method development efforts to fill these method voids will supply the prediction capability required to perform cost-effective missile design. They are as follows: 1) the effect of airbreathing inlets at all speeds; 2) component interference at higher angles of attack and panel incidence angles (increase the data base range of panel aspect ratios to 4 and Mach numbers to 6); 3) panel-alone aerodynamic characteristics at angle of attack (increase the data base range of aspect ratios to 4 and Mach numbers to 6); 4) arbitrarily shaped geometries; 5) the effect of nose shape, and bluntness, at transonic speeds; and 6) the effect on configuration dynamic characteristics due to panel incidence or jet plume.

Acknowledgment

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