Missile Aerodynamics Prediction Code

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A state-of-the-art comprehensive Missile Aerodynamics Prediction (MAP) code has been developed. The code rapidly estimates six-component aerodynamic coefficients for generalized axisymmetric wing-body-tail configurations. The code can be utilized over the flight conditions of Mach number ($0 \leq M_\infty \leq 8$), angle of attack ($|\alpha| \leq 45$ deg), aerodynamic roll angle ($|\phi| \leq 90$ deg), and control surface deflection ($|\delta| \leq 30$ deg). The unification of the best methodologies available, the improvement and extension of analytical/experimental techniques, and the development of interactive computer graphics have led to the completion of this preliminary design tool. This paper summarizes current technological accomplishments, computational results, evaluation, and application of the MAP code.

Nomenclature

A_{gap} = unporting gap area
C_A = axial drag coefficient, axial drag force/qs
C_{A_W} = axial wave drag coefficient, axial wave drag force/qS
C_{D_0} = subsonic zero-lift drag coefficient, (subsonic drag force/$qS)_{\alpha=0\ \mathrm{deg}}$
C_f = viscous friction force coefficient, viscous friction force/qS
C_ℓ = roll moment coefficient, roll moment/qSd
C_m = pitch moment coefficient, pitch moment/qSd
C_N = normal force coefficient, normal force/qS
C_n = yaw moment coefficient, yaw moment/qSd
C_Y = side force coefficient, side force/qS
d = maximum body diameter
ℓ = total body length
M_∞ = freestream Mach number
q = dynamic pressure
r = radius of spherical nose tip
r_B = radius of cylindrical afterbody
S = maximum cross-sectional area of the body, $\pi d^2/4$
S_{wet} = total wetted surface area of the body, excluding the base
α = angle of attack, angle measured between freestream velocity vector and body longitudinal axis, positive nose up
ϕ = roll angle, angle measured between z axis and the first control surface, positive clockwise (see Fig. 6)
δ = control deflection angle, positive leading edge up (see Fig. 7)
$\delta_1,\delta_2,\delta_3,\delta_4$ = flipper deflection angle, positive leading edge up (see Fig. 6)
δ_e = elevator deflection angle, positive leading edge up (see Fig. 6)

Introduction

ADVANCED missile systems projected for the 1990s must be capable of speeds up to Mach 8, have greater maneuverability (with angles of attack up to 45 deg), and be designed for minimum drag and operation at longer ranges. Department of Defense (DoD) agencies have recognized the need to improve missile aerodynamic prediction capabilities to accomplish efficient design of these advanced systems. Accurate prediction of generalized axisymmetric airframe aerodynamics is needed.

Missile aerodynamic prediction codes obtained through research and development are potentially applicable to present and future DoD missiles. The use of these prediction methodologies permits external preliminary missile design without expensive wind tunnel tests, reduces design time and cost, and supports concept evaluation and proposals in a timely manner. Numerous other applications can also be realized.

The state-of-the-art rapid aerodynamic design and analysis computer codes and simple engineering methods include NSWC Aeroprediction,[1-5] NEAR Missile II,[6,7] USAF Supersonic/Hypersonic Arbitrary Body Program (SHABP),[8] AEDC High Angle of Attack Program,[9] Army/Martin Marietta High Angle of Attack Methodology,[10,11] NASA Jorgensen Engineering Method,[12] Rockwell Aerodynamic Preliminary Analysis System (APAS),[13] Hughes AEROP I,[14] and Air Force Digital DATCOM.[15] The methodologies have been surveyed and evaluated.[16] Among these codes (Fig. 1), the Aeroprediction and Missile II codes are selected as those that possess the most thorough and compatible theoretical/experimental methodology bases for axisymmetric missile application.[16] The preliminary version of Missile DATCOM is currently undergoing evaluation at government laboratories. It was developed by selecting and reconstructing a mixture of available theoretical, semiempirical, and empirical techniques.[17]

Rather than reconstructing a code based on a mixture of techniques, a practical and useful code can be developed by further research as well as improving and extending the proven state-of-the-art methodologies available. The current paper employs the Aeroprediction code as the baseline methodology, and the Missile II code as a supplemental technique for nonzero roll attitudes. The improvement and extension of the unified methodologies, the integration of newly developed analytical/experimental techniques, the improvement in usability, and the development of interactive computer graphics have led to the completion of a single rapid engineering tool for missile applications. This tool, named the Missile Aerodynamics Prediction (MAP) code, has been developed primarily for preliminary design and analysis of axisymmetric missile configurations.

This paper presents a short overview, technological accomplishments, computational results, evaluation, and applications of the MAP code.

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Overview

The procedures to obtain six-component aerodynamic coefficients are summarized in Fig. 2. The new technological extensions and improvements of the baseline methodology available in the Aeroprediction code are listed in Table 1. Relevant references have been included here.

Basically, the methods used to compute inviscid body-alone aerodynamics include Gwin and Spring's[18] empiricism, Sun and Hansen's[19] techniques with Wu and Aoyoma[20] methods/empiricism, the hybrid theory by Van Dyke[21,22] and Tsien,[23] and improved second-order shock-expansion theory by DeJarnette et al.[24] for subsonic, transonic, low-supersonic, and high-supersonic speeds, respectively. The viscous cross-flow effects are treated by Allen and Perkins[25] cross-flow theory. The skin-friction drag, including pressure gradient effects, uses a summary of results obtained from the Douglas-Newmann potential flow and Squire-Young boundary-layer codes, empiricism, and the Van Driest II flat-plate theory.[26]

The aerodynamic surfaces are treated by using lifting surface theory, DATCOM empiricism, linear theory, and tangent wedge theory for subsonic, transonic, low-supersonic, and high-supersonic speeds, respectively.[1,2,27] The Pitts-Nielsen-Kaatari method[28] is used to calculate the wing-body interference effects. Control surface unporting effects due to flow spillage through gaps are treated by a combination of empirical data and supersonic linearized wing theory by Bleviss and Struble[29] and August.[30]

The Missile II methodology developed by Nielsen et al.[31] has been modified and employed in the MAP code. For missiles at arbitrary roll angles and high angles of attack, these subroutines are being utilized to compute aerodynamic characteristics. Detailed vortex tracking information is also provided by this method.

By entering design inputs (Mach number, angle of attack, roll orientation, body configuration, wing-tail geometry, atmospheric condition, and reference location), the code automatically selects the most suitable techniques for calculating aerodynamic characteristics. Computer graphics of missile geometry provide a visual check of input parameters. The six-component aerodynamic coefficients (C_N, C_m, C_A, C_Y, C_n, *and* C_ℓ), aerodynamic derivatives, and center-of-pressure location can readily be obtained. These

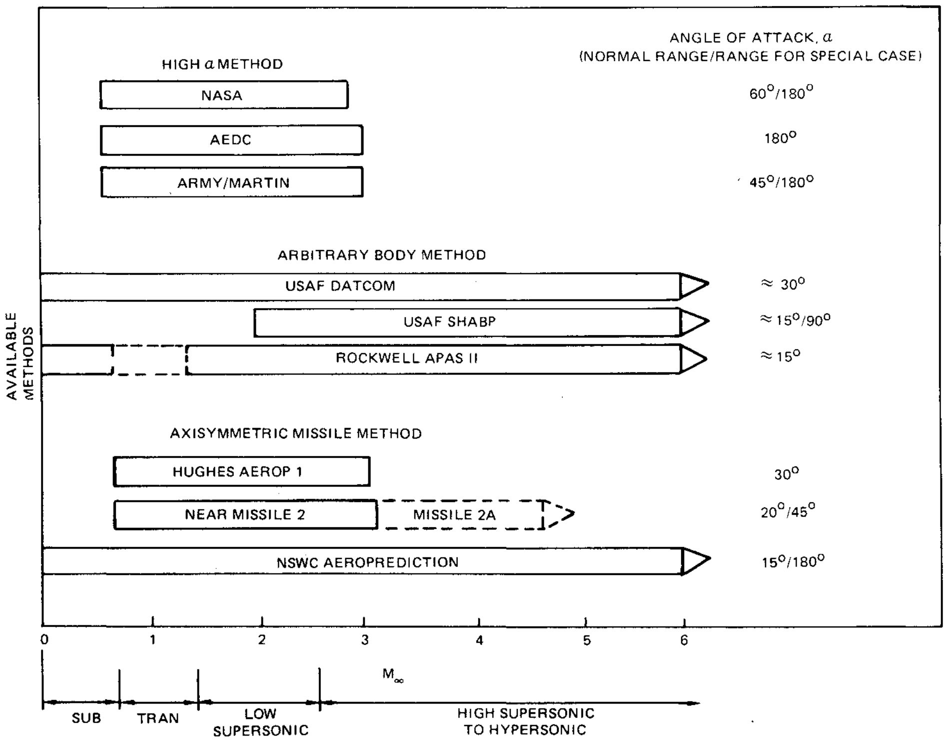

Fig. 1 Current rapid (approximate) aerodynamic prediction methods.

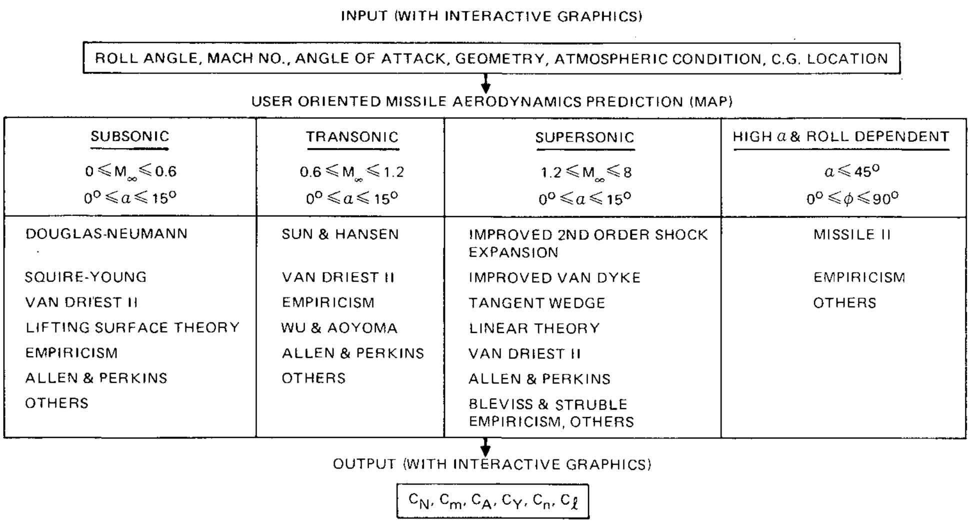

Fig. 2 Procedure to obtain aerodynamic characteristics using the MAP code.

Table 1 MAP technology extension and improvement of baseline Aeroprediction code methodology

New extensions and improvements	Previous limitation
Transonic wave drag and lift for generalized nose shapes	Limited shapes and data
Subsonic pressure gradient effects on skin friction	Flat plate
Roll-dependent aerodynamics	Zero roll angle
High angles of attack	$\alpha \leq 15$ deg
Interdigitated lifting surfaces	In-line
Control surface unporting	Untreated
Improved usability and logic	Less user-oriented
Computer-aided design with graphics	Unavailable
Single MAP Code treating M_∞, α, ϕ, and δ for generalized missile configurations	Unavailable

coefficients can be plotted and cross-plotted, as specified by the user.

The MAP code estimates aerodynamic coefficients of generalized axisymmetric missile configurations at subsonic, transonic, supersonic, and hypersonic speeds up to Mach 8, for angles of attack up to 45 deg, control deflections up to ±30 deg, and roll angles up to 90 deg. For both angle of attack and control deflections above 20 deg, our experience in exercising the code indicates that discretion should be used. As an estimate to aerodynamic characteristics for missiles, this code is complementary to wind tunnel test data. It provides reasonably accurate estimates of aerodynamic characteristics consistent with preliminary design studies. It has been evaluated extensively in preliminary design applications with proven cost-effectiveness and time savings.

Table 1 summarizes the new extension and improvement of the baseline methodology available in the MAP code. Previous limitations and weaknesses of the prior Aeroprediction code have been removed. The specific accomplishments are presented in the following section.

Technological Extension and Improvement

Generalized Transonic Drag and Lift

A new subroutine for determining transonic nose wave drag has been developed. It utilizes a comprehensive and accurate data set in conjunction with a three-dimensional Lagrange interpolation technique to rapidly determine the wave drag coefficient as a function of generalized nose coordinates and freestream Mach numbers. Rapid and accurate drag prediction capability has not been available in the past.

The data set used in this new subroutine is taken from studies[19,20] where a precise but time-consuming methodology is employed. The transonic nose wave drag coefficients were obtained from a relaxation method capable of treating the full potential equations and exact boundary conditions of axisymmetrical bodies. The studies encompass generalized nose shapes, including sphere/tangent ogive, von Kármán, paraboloid, power law, and ellipsoid (see Figs. 3 and 4).

The transonic lifting properties contained in the baseline methodology utilize limited data from an Euler code. The results are limited in fineness ratio and are generally less accurate. Empirical data[14,32] have been employed to supplement the original numerical data base.

Subsonic Pressure Gradients

A treatment for practically estimating subsonic drag of generalized missile body configurations, using simple and rapid analytical methods that include pressure gradient effects for subsonic missiles, is not readily available. Current aerodynamic prediction codes typically utilize various flat-plate skin friction theories to predict subsonic drag. The prior Aeroprediction code uses this simplified approach and underestimates the low-speed wind tunnel data of the advanced missile body-alone drag by nearly 30%. An improved semiempirical method was developed for estimating body-alone subsonic drag including pressure gradient effects[26] and is included in the MAP code.

A Douglas-Neumann potential flow program[33] was used to provide the inviscid flowfield solution for missile bodies of various fineness ratios ($5.5 \leq \ell/d \leq 22.3$), nose shapes (blunted and pointed tangent ogive of varying caliber), and afterbody shapes (with and without boattail). The potential solution (namely, velocity distribution), body geometry, and kinematic viscosity were then input into an incompressible boundary-layer program[34] to provide the viscous flowfield solution. This combination of codes is capable of numerically treating specific body-alone geometries (nose contour, afterbody, and boattail shape) and their corresponding pressure gradient effects on skin friction. The Squire-Young method,[35] which utilizes the trailing-edge-predicted flowfield characteristics, was used to account for momentum transfer in the body wake region.

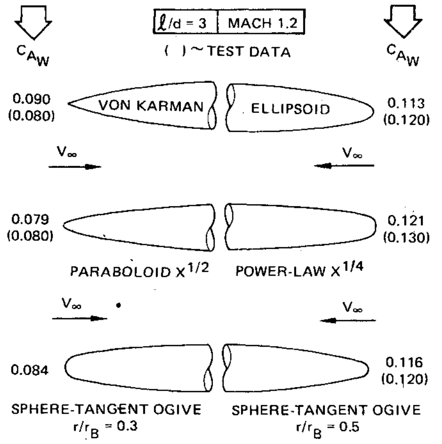

Fig. 3 Comparisons between predicted results and test data for transonic nose wave drag.

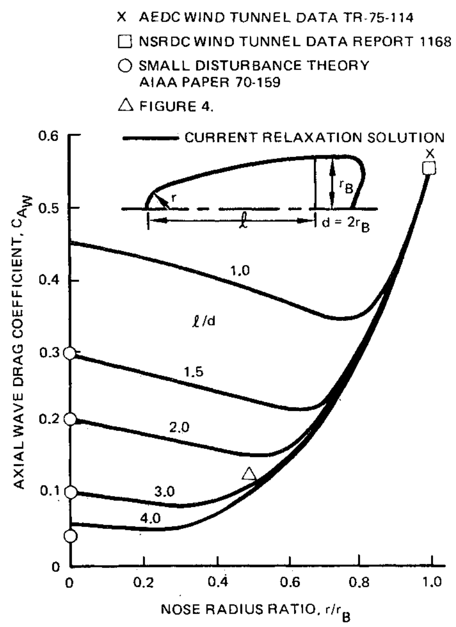

Fig. 4 Comparisons of predicted wave drag coefficients with wind tunnel data and small-disturbance solution at $M = 1.2$ for a generalized sphere-tangent ogive-cylinder body.

By combining the results of the preceding numerical treatment with the Van Driest II turbulent flat-plate theory,[36] the Hoerner form factor,[37] and wind tunnel data with/without boattails, an improved subsonic body drag prediction has been obtained (Fig. 5). This technique has been incorporated into the MAP code.

Improvement of Usability and Logic

The baseline code has been modified extensively to improve its flexibility, usability, and program logic. The improved areas include modularity, internal processing of M_∞ and α arrays from arbitrary input, automatic geometric generation and scaling, and provision for arbitrary reference length instead of maximum diameter. Limitation to low-aspect-ratio lifting surfaces within the Missile II subroutine is alleviated by automatic modification of its planform. Moderate decreases in span and increases in chord are effected while maintaining sweepback angle, surface area, and surface centroid station.

Other improvements include the removal of redundant statements and the provision of diagnostic messages. Suitable default values are provided in the code in cases where values for input are consistently known. The program contains algorithms for rectifying, where possible, human errors in input procedures.

Print options have been incorporated that allow the user to control the detail of computed results, to provide results upon computation of each M_∞,α array point, and to express summary results in either a M_∞,α hierarchy or its reverse. In addition, interactive graphic verification of input geometries without code execution reduces input errors and improves input efficiencies. The current MAP code, therefore, is more user-oriented since it provides greater flexibility, ease of application, improved reliability, and faster turnaround.

Roll-Dependent and High-α Aerodynamics

The techniques described in the Missile II subroutine provide comprehensive methodologies for treating roll-dependent and high-angle-of-attack aerodynamics. This method uses detailed vortex modeling, vortex cloud theory, and vortex tracking techniques, and is augmented by a data base. It is applicable over speeds of Mach 0.8-3.5, angles of attack up to 45 degs, and allows arbitrary roll orientations and control deflections. A correlation method based on the nonlinear equivalent angle-of-attack approach is used when loads on a control surface are calculated. With this technique, the forces predicted for the surface formed by placing two opposing control surfaces together in the absence of the body, at the equivalent angle of attack, are related to the actual control surfaces in the presence of the body.

Through the development of a new interfacing subroutine GEOMCO, and modification of internal logic, these theories have been incorporated into the MAP code. It was also discovered that the basic Missile II methodology gives different results for vortex tracking depending on dimensional units employed and origin of the body coordinate system with respect to the nose tip. These significant discrepancies have been rectified so that consistent results for lateral stability and control characteristics can be obtained in the MAP code. Figure 6 shows comparisons of control surface effects for a typical missile at arbitrary roll orientations. These results demonstrate that the MAP code can handle control surface, roll-dependent aerodynamics at a given angle of attack.

Control Surface Unporting

As control surfaces rotate, gaps are created between the surface's root chord and the missile body. The spillage of flow through the gaps reduces control effectiveness as the deflection angle increases. Available streamwise gapped subsonic wind tunnel data[38] and supersonic linearized wing theory[29] were used to estimate control surface effectiveness losses for a typical missile as a function of Mach number and control surface deflection.[30] An empirical correction to the analytical prediction of gap losses at transonic speeds is included. This latter effect is attributed to shock-induced boundary-layer separation. Figure 7 shows the computed results with and without predicted gap effects compared with wind tunnel data. The results demonstrate the improvement of prediction accuracy achieved by including gap effects. Losses in control surface effectiveness due to gap effects are included in the MAP code.

Interactive Computer Graphics

An interactive computer-aided design capability with graphics has been developed. Figure 8 shows the graphics system implementation on a Tektronix minicomputer linked with a CDC NOS176 mainframe computer. The goal is to assign the minicomputer specific tasks such as data input and graphics, reserving the large mainframe computer for more time-consuming computation. Currently the user can employ either the Tektronix minicomputer or card readers for interactive time sharing or batch input, respectively. The graphics output can be displayed on a screen, plotted on a drum/pen plotter, and/or stored on magnetic tape. The graphics geometric package provides instant display of missile external geometries. The aerodynamic coefficients used therein are generated by cubic spline fitting of the computed data points obtained from the MAP code. The graphics software was developed using CDC UNIPLOT/UNIPOST computer

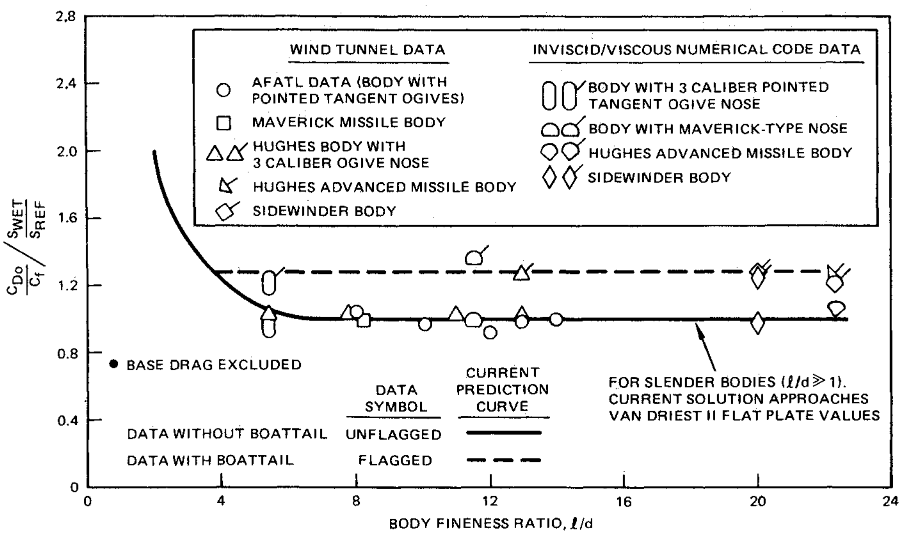

Fig. 5 Improved subsonic body drag prediction including pressure gradient effect.

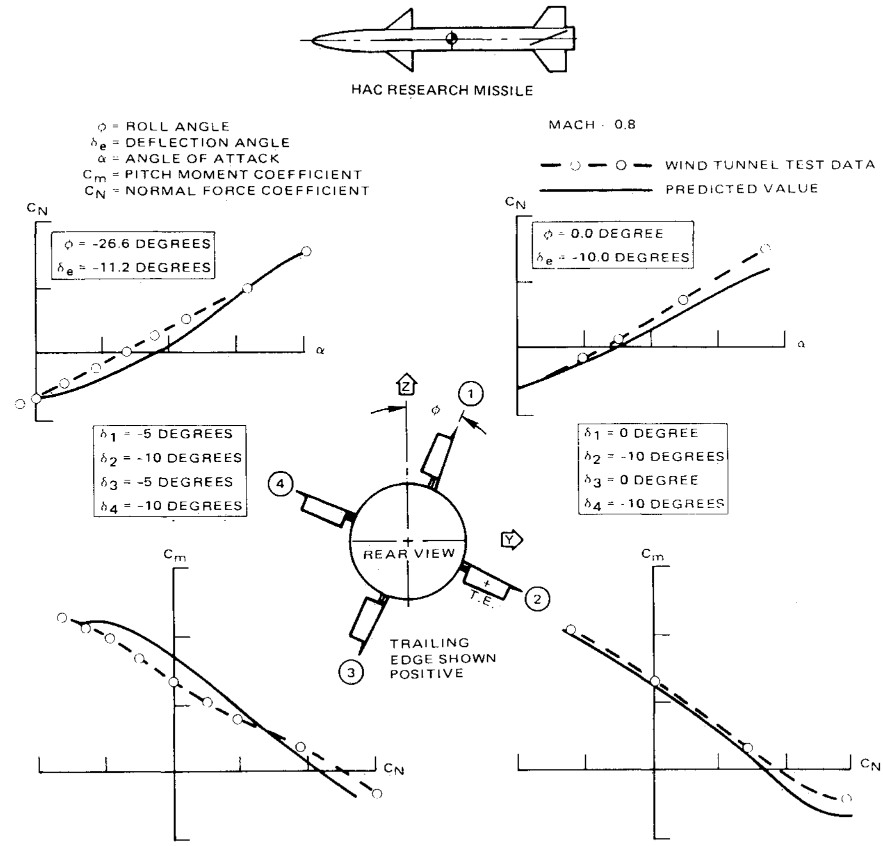

Fig. 6 Example of predicted roll-dependent aerodynamic coefficients.

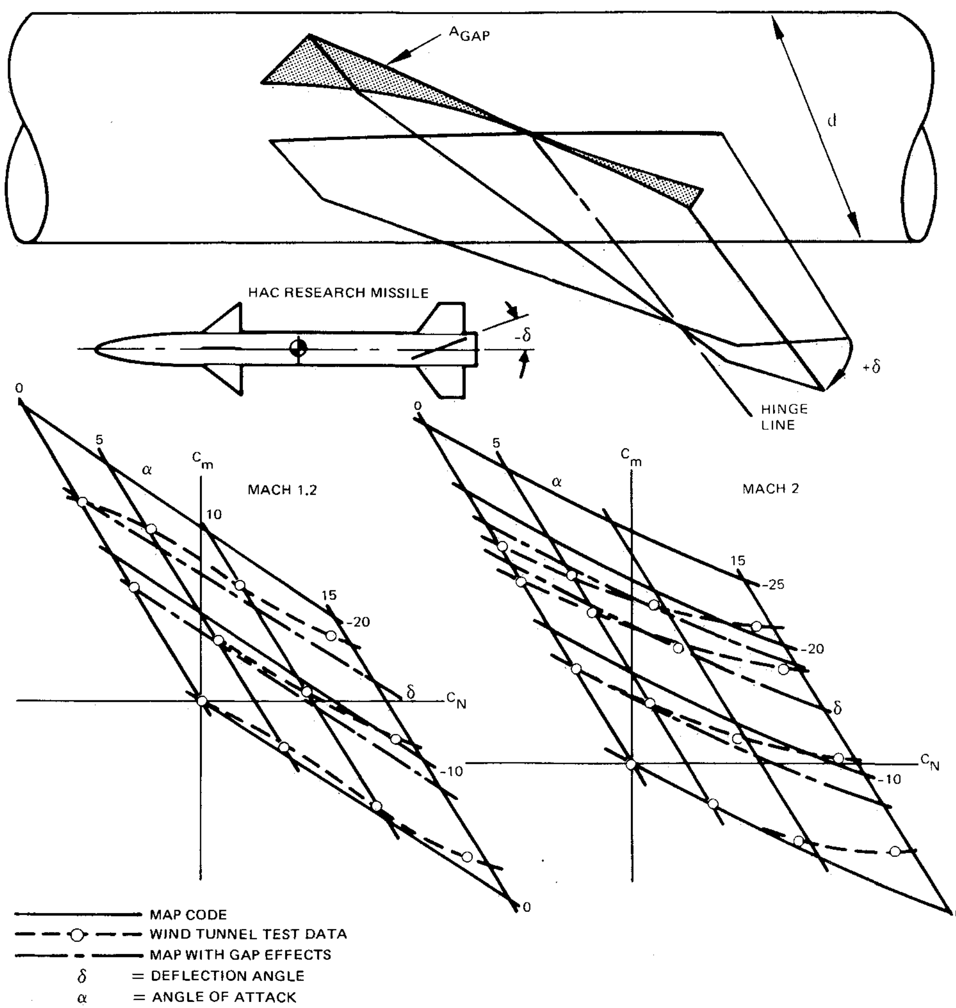

Fig. 7 Improved prediction of control surface effectiveness by including unporting (gap) effects.

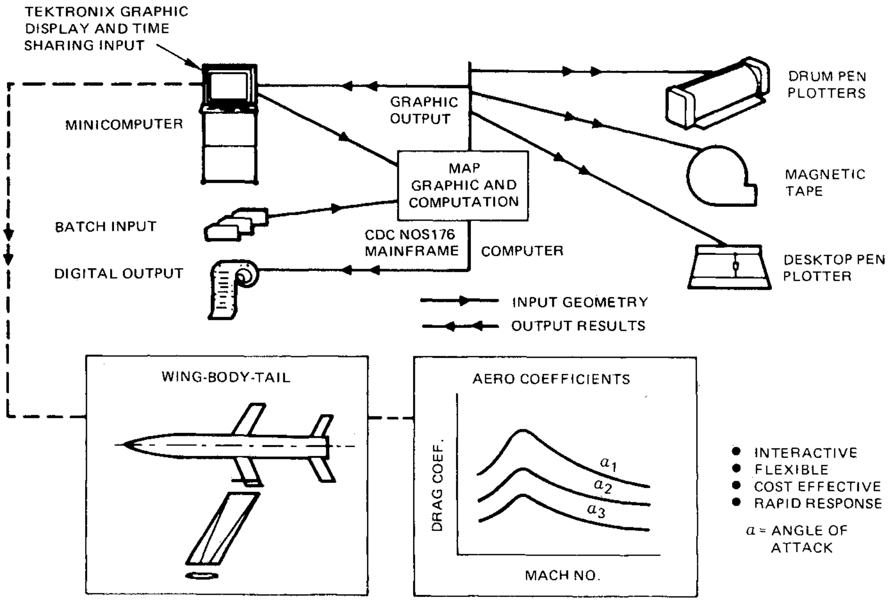

Fig. 8 Example of MAP computer graphics.

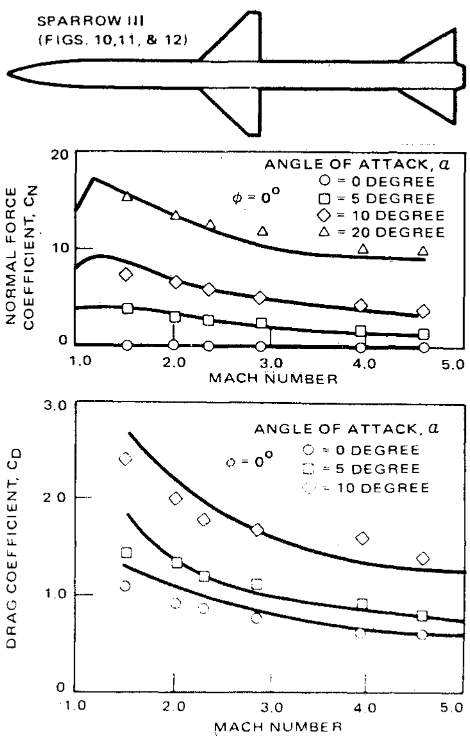

Fig. 9 Example of predicted C_N and C_D.

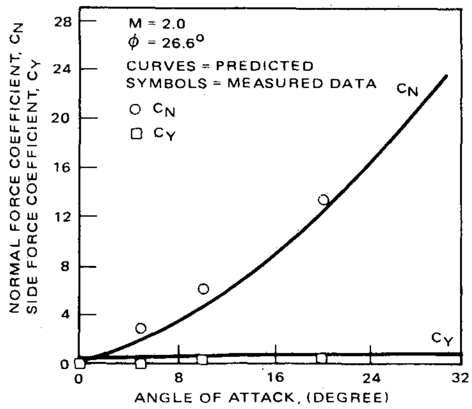

Fig. 10 Example of predicted C_N and C_Y.

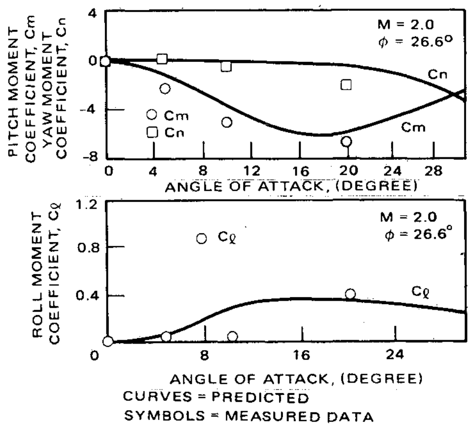

Fig. 11 Example of predicted C_m, C_n, and C_ℓ.

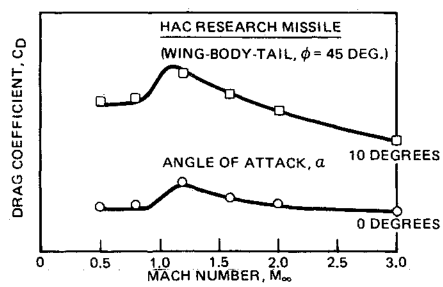

Fig. 12 Example of predicted C_D for HAC Research Missile.

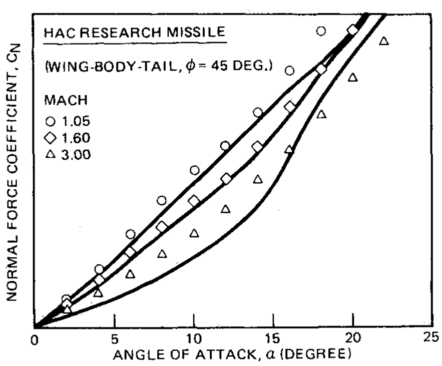

Fig. 13 Example of predicted C_N for HAC Research Missile.

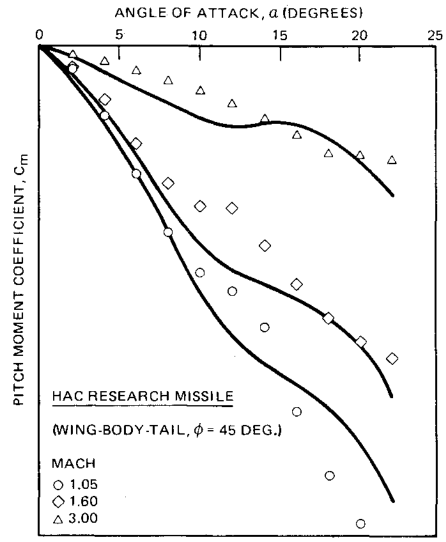

Fig. 14 Example of predicted C_m for HAC Research Missile.

language. Rapid and cost-effective preliminary aerodynamic designs and analyses of missiles can now be realized.

Computational Examples

The MAP code with its user's manual has been completed. Figures 9-11 are examples of MAP-computed six-component aerodynamic coefficients as a function of M_∞, α, and ϕ for a typical wing-body-tail missile configuration. These predicted coefficients fully describe longitudinal (C_D, C_N, and C_m), lateral (C_Y and C_n), and roll (C_ℓ) characteristics of missiles. Complete six-component coefficients of generalized axisymmetric missile configurations can now be estimated using a unified code. Aerodynamic characteristics, including stability margin and control boundaries of a preliminary missile design, can be rapidly estimated.

Figures 12-14 show the prediction of C_D, C_N, and C_m, respectively, for the HAC Research Missile. The comparison of these coefficients with measured data is good. The plots can be made utilizing the graphics capability of the MAP code. The savings in engineering time and costs, and the improvement in efficiency are significant. During preliminary design and analyses, longitudinal aerodynamics are needed most fre-

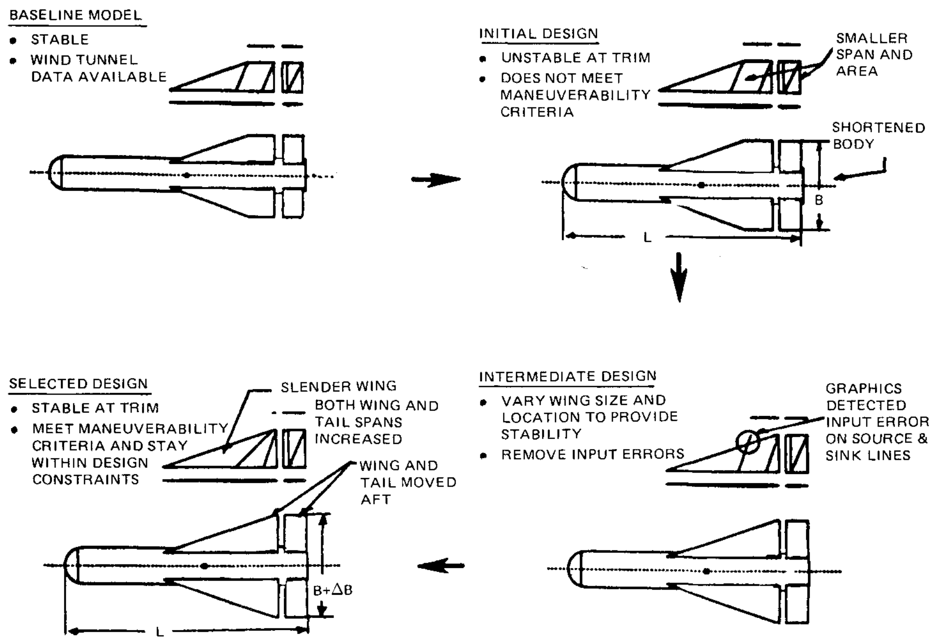

Fig. 15 Example of MAP computer graphics use in the preliminary aerodynamic design of missile derivative.

Table 2 Examples of MAP code validation and applications

Tasks	Project	Results
Engineering design trade of nose geometries	Advanced missile	Optimized nose drag with proper seeker relocations
Roll rate investigation	Advanced missile	Determined roll rate magnitude due to wing manufacturing misalignment
Support of proposal effort	Army SMART Projectile	Preliminary aerodynamic coefficients were obtained in rapid fashion
Pressure loading on Radome structural integrity	SRHIT (Short-Range Hypersonic Intercept Technology)	Predicted supersonic pressure distribution was used successfully in conjunction with NASTRAN
Preliminary aerodynamics, including trim	XR Maverick	Predicted longitudinal aerodynamics at transonic speeds for $\phi = 45$ deg
Preliminary configurational design of WASP derivative	Hughes Missile Derivative	MAP expedited the preliminary aero-dynamic design and generated trim aero-dynamics and stability characteristics

quently. Our experience has indicated that the predicted C_D, C_N and C_m are generally within 8, 13, and 15%, respectively.

Evaluation and Application

The MAP code has been evaluated by applying it to many engineering problems and various missile preliminary designs. Several examples are summarized in Table 2. These examples include engineering design trades, problem investigation, proposal support, structural loading, and preliminary configurational design. Figure 15 shows a recent application of the MAP code on the preliminary aerodynamic design of a missile that is an existing missile derivative. Although baseline wind tunnel data are available, there are insufficient data for the modified configuration. The complete trim data and stability characteristics must be obtained for $\phi = -45$ deg, $M_\infty = 0.4$ to 1.2, $\alpha = 0$ to 15 deg, and $\delta = 0$ to -20 deg. The MAP code was first compared against available wind tunnel data. It was employed through several design stages with the aid of computer graphics. The selected design was determined to be stable at trim, meet maneuverability criteria, and stay within geometric constraints.

Summary and Conclusions

1) A state-of-the-art comprehensive Missile Aerodynamics Prediction (MAP) code has been developed. The MAP code can rapidly estimate six-component aerodynamic coefficients as a function of angle of attack, roll attitude, control surface deflection, and Mach number for given axisymmetric missile configurations with the aid of interactive computer graphics. Such a comprehensive aerodynamic prediction capability has not been available previously.

2) The ranges of applicability of the MAP code are: $0 \le M_\infty \le 8$, 0 deg $\le |\alpha| \le 45$ deg, 0 deg $\le |\phi| \le 90$ deg, and 0 deg $\le |\delta| \le 30$ deg. Estimated aerodynamic results are complementary with wind tunnel data. The MAP code provides reasonably accurate estimates of aerodynamic characteristics consistent with preliminary design studies.

3) The technological extension and improvement of baseline methodology include: transonic wave drag and lift for generalized nose shapes, subsonic pressure gradient effects on skin friction, roll-dependent aerodynamics, high-angle-of-attack aerodynamics, interdigitated lifting surfaces, control surface unporting effects, improved usability and logic, and computer-aided preliminary design with graphics.

4) A user's manual for the MAP code has been completed. Furthermore, this engineering tool has been tested in many preliminary missile aerodynamic applications with proven cost-effectiveness and time savings.

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